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Determining the Probability of the Visual Detection of Sink Marks on Differently Textured Injection Molded Products

Kurt Frederick Hayden

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DETERMINING THE PROBABILITY OF THE VISUAL DETECTION OF SINK MARKS ON DIFFERENTLY TEXTURED INJECTION MOLDED PRODUCTS

by

Kurt Frederick Hayden

A Dissertation
Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
requirements for the
Degree of Doctor of Philosophy
Department of Industrial and Manufacturing Engineering
Dr. Paul V. Engelmann, Advisor

Western Michigan University
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Kurt Frederick Hayden
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CHAPTER I

INTRODUCTION AND BACKGROUND

Overview

The appearance of an injection-molded product depends greatly upon proper part and mold design. Many guidelines exist to help designers avoid product designs that are likely to develop aesthetic defects. However, for various reasons, these guidelines are sometimes violated. It is often difficult for the designer to predict the influence of these small deviations from design standards on the likelihood of defect formation in the molded product. To avoid poor product appearance, designers should understand how to reduce the effects of design rule violations.

This research investigated several factors influencing the concealment of an aesthetic defect known as a sink mark. The following pages discuss pertinent background information, the need for this investigation and the research objective. This chapter also defines the limitations and assumptions of the research.

Defining Quality

Many simple definitions of quality have been suggested, however no single definition has gained universal acceptance (Crosby, 1980; Tsuyuki, 2001). Generally, it is accepted that quality may be categorized in two groups; the
quality of a product and the quality of a service (Crosby; Juran, 1988; Tsuyuki). For the manufacturing industry, both of these categories are important factors in the overall perceived quality of products supplied by a company. Therefore, quality can be defined as the timely availability and delivery of products and services in a manner acceptable to the customer. Perhaps this definition is overly simplified; however, it does include the components of many definitions of quality.

Most definitions agree that manufacturing quality is perceived as the capacity for a customer to order a product when they want, have it delivered when they need it and have it be exactly what they need to use, per their specifications. It should be kept in mind that this definition does not include service after-the-fact: support for the product after delivery. In modern manufacturing practices, this “post-hoc” support is often assumed.

The availability and delivery times mentioned in the definition above refer mostly to the service portion of the perceived quality. It is in the definition of an acceptable product that most effort is expended. Drawings are created, critical specifications are defined and testing parameters are stipulated in an effort to precisely define the requirements of the customer and the fitness of the product for use.

Drawings and specifications all refer to objective measurements. The dimensions can be measured, failure strength can be tested and the melt temperature of the material can be measured. On the other hand, aesthetic characteristics can be difficult to qualify. Subjective features influencing the appearance of a product must be translated into objective measures to assure the consistent quality of a product. For example, color may be broken down into
spectral scales, textures can be measured for depth uniformity in shape, parting-line flash can be measured, etc.

Attribute Defects

Certain characteristics still escape truly objective measurement. In some cases, measuring methods exist, but are cumbersome and therefore not conducive to the manufacturing environment. In other situations, it may not be understood how or what must be measured to define the defect. These defects may be detectable by manual inspection, and are more easily evaluated as being present or not.

Many aesthetic defects are categorized as attribute defects. In these cases, a product is evaluated during inspection as having or not having the defect. Often, the number of occurrences of the defect is counted. If the count is below a certain threshold, the product is considered acceptable (Ott, Schilling & Neubauer, 2000). The number of occurrences of a defect acceptable in a product must be carefully considered and agreed upon by customer and supplier.

By definition, attribute defects appear to be on-or-off conditions: either existing or not existing. However, to properly assess the quality of a product it is important to understand the severity of a defect, not just recognize its occurrence. For instance, the defect known as an air trap is caused by the entrapment of gases within a molding cavity causing the product not to form in the area of entrapment. Flow simulations are able to predict the occurrence of air traps, however they do not predict the size of the air trap.
Quality Service Level

If the occurrence of a defect and its severity are predictable, a customer may choose acceptable rates of defect occurrence before the development of a product and production equipment. The immediate instinctive reaction of most manufacturers and customers is that no defects are acceptable. However, this situation should be considered more closely.

The ability to choose a service level in regard to the occurrence of a defect is useful if the cost of producing the part is high compared to the quality cost of the defect. The cost comparison depends greatly upon the severity of the defect. The true level of acceptability of the defect must be evaluated. For instance, a defect that would cause a part to become nonfunctional would have a high cost of quality associated with that defect. An aesthetic defect may not have a high of a cost of quality, especially if the area where the defect occurs is unlikely to be visible to the end user of the product. It may be decided that a 20% probability of detection of an aesthetic defect is acceptable if the defect occurs in an area of low visibility.

However, this practice should be used to reduce the occurrence of unacceptable products and not to make previously undesirable conditions tolerable. Designs should be optimized to eliminate all defects before acceptable service levels are evaluated. Modern design practices should be used to develop robust product designs and manufacturing processes that reduce the probability of creating defective products during manufacture.
Product Design Practices

Much time, effort and money can be saved in the development of a product by combining concurrent engineering practices with the philosophies of design for manufacturing and assembly (DFMEA). The inclusion of the experience of both product designers and manufacturing engineers in the development of a product maximizes initial product quality (Robinson, 1991; Harley, 1992; Walker, 2001).

These steps can help reduce the time involved in the design of a product. However, without the means to evaluate the quality effects of design changes, these practices can not be completely successful. Small changes in design specifications may greatly affect the probability of creating defective products during manufacture. It is during the DFMEA process that these small changes should be evaluated.

The process of designing injection molded plastic products is a mature discipline. Many tools and guidelines have been developed to help the product designer. Simulation packages exist to investigate plastic flow, the cooling and solidification of the melt, final product dimensions, etc. These software applications can also predict the occurrence of certain types of defects such as weld lines and air traps.

From advanced research into the properties and processing of polymeric materials, guidelines have been created to help designers improve the manufacturability of plastic products. The obvious purpose of these guidelines is to help create product geometries that will provide good parts that exhibit little, if any, inherent molding defects. In some cases, "rules of thumb" exist to condense these guidelines for use by inexperienced designers.
Occasionally it is necessary to violate certain guidelines in order to satisfy product functionality or assembly conditions. In these situations designers must pay close attention to the effects these violations may have on product quality. Plastic flow and cooling analyses are conducted to verify that the less-than-optimal design condition will not cause significant problems in the molding of the product or its final geometry or appearance.

The Process of Injection Molding

Globally, the manufacturing industry is experiencing a period of intense competition. The injection molding industry is no exception. Developing countries are becoming major suppliers of complex, high-end molded components. Companies compete on the basis of product image, product cost, design flexibility and product quality. The time required to deliver quality products to market is a critical component in the success of a product line.

Not only is there intense consumer pressure to reduce product time-to-market, but it is essential to introduce new product lines (and associated tools and equipment) with high levels of success. Mold filling, product assembly, and manufacturing process simulations are all used to predict the actual performance of tools, processes and personnel prior to the investment of capital funds in tooling, equipment and facilities. Prior to performing investigations of the predicted quality of molded products, it is important to understand the processes and equipment involved in the creation of these products.

The process of injection molding comprises a significant portion of the plastics processing industry. Injection molded products are created near-net shape and require little post-molding operations. The process is capable of
creating complex, high-tolerance products quickly and repeatedly. Equipment and tooling can be costly and capital investment costs are high.

![Illustration of a typical toggle injection molding machine indicating significant components.](source: author)

Figure 1. Illustration of a typical toggle injection molding machine indicating significant components. (source: author)

The process of injection molding begins with the melting of a polymer compound (a plastic material). That molten material is then injected into a mold under high pressure, where the material is cooled until it solidifies and the product can be ejected from the mold. Figure 1 shows an illustration of a typical injection molding machine. The mechanical components of these machines may be divided into two sections, the injection unit and the clamping unit. The injection unit contains the heated barrel and the reciprocating screw and is responsible for the melting and the injection of the plastic material into the
mold. The mold is responsible for shaping the plastic product, providing a means to extract heat from the molten material and ejecting the parts. The clamping unit holds the mold closed during the high pressures that occur during injection and provides the mechanical force to eject the parts from the mold.

Each stage of the injection molding process exhibits a variety of machine, tool, and material characteristics that are vital to the quality of the final condition of the molded product. The development of uniform temperature and viscosity in the molten material is critical. During injection, the speed of the plastic as it is injected into the mold cavities is important as this is a principal determinant of the viscosity of the material. Appropriate temperature of the mold and pressure within the plastic are crucial to prevent the formation of certain molding defects during the cooling of the molded part.

Various methods have been utilized to control the melting of the polymer. In modern practice, a reciprocating screw is used to feed the plastic material down the heated barrel while compression and frictional forces create additional heat within the material and cause the melting of the plastic. After a predetermined amount of melted plastic is formed in front of the non-return valve (NRV) at the end of the screw, the screw plunges forward at a controlled rate. The melted plastic is forced out of the barrel through the nozzle and into the sprue of the mold. Inside the mold the plastic is distributed to the cavities where the parts are formed. Figure 2 illustrates the interface between the injection unit and the mold.

After the material has been injected into the mold, the cooling stage begins. As it cools, the plastic shrinks. During this contraction, additional material is fed into the mold by the packing pressure applied by the injection
unit. The additional material compensates for the volumetric shrinkage of the plastic. This phase of the molding cycle is known as pack-and-hold. At some point, the plastic within the mold solidifies and additional material cannot be introduced.

Figure 2. Detail of the interface between the injection nozzle and the mold. The non-return valve (NRV) and the pressure from the screw maintain pressure on the plastic until the gates freeze. (source: author)

After the product has cooled, the clamping unit moves, opening the mold and exposing the molded product. Mechanisms within the mold release the solidified plastic and eject the product from the molding services. Sprues, gates and runners are removed and separated from the molded parts.
Sink as a Case Study

One common attribute defects associated with the process of injection molding is the sink mark. Sink marks are caused by the natural, characteristic contraction of polymeric material during cooling. Figure 3 illustrates the appearance of sink marks. The contraction of the polymer molecule causes volumetric shrinkage to occur in the material as a whole. Cooling simulation and finite element analyses (FEA) can be used to predict the severity of sink marks formed in a product.

Figure 3. Sample of a sink mark caused by a localized thickening of the part wall cross section. In this case, the thickening was due to circular ribs on the back side of the part.
Process engineers understand that this shrinkage must be compensated for during the molding process. As discussed previously, the shrinkage occurs during the cooling of the polymer; therefore it is during the cooling stage that additional material must be fed into the cavity. The time required for a plastic to solidify through its cross section is dependent upon product and mold design. Product design guidelines exist for part geometries that allow adequate time for compensation of material shrink before the cooling of the plastic prevents additional compensation. As mentioned previously in the Product Design Practices section, design guidelines may be violated for a variety of reasons, including product functionality. When these "rules of thumb" are disregarded it becomes difficult to mold parts without the occurrence of sink marks.

Often it is small violations of these design guidelines that are committed, resulting in the formation of sink marks exhibiting depths measuring mere hundredths of a millimeter. A common method for concealing these shallow sink marks is the application of texture to the surface of the product. However, no guidelines have been written that compare the depth or aggressiveness of the texture with the severity of the sink mark. It is not known how minor changes in texture depth affect the visibility of the sink mark.

A model of the relationship between texture depth and sink mark visibility would allow for the creation of useful tools for product designers and the quality engineers. With this model, the quality of a product's appearance could be assured by the designation of adequate texture depth to ensure a low probability of visual detection for minor sink marks. An appropriate texture depth could be selected based upon a customer-designated target for the probability of sink mark detection.
Research Objective

In other research, methods have been developed that predict the formation and geometry of sink marks. However, in those investigations, no data were collected to describe an observer's visual perception of sink marks. It was the intent of this research to investigate the factors influencing sink mark visibility and to develop a preliminary model for predicting the probability of the visual detection of a minor sink mark on a molded product.

An understanding of the factors investigated in this research and how they influence sink mark visibility can help designers develop products with minor violations of sink mark design rules while maintaining a low probability of detecting sink marks. Further, the designer can use the model developed in this work to select a texture depth that would provide an acceptable risk level in terms of customer detection of sink marks. Quality engineers may use these models to petition for minor texture changes that would reduce the probability of visually detecting of sink marks.

Assumptions

This research was designed such that subject selection would not be overly limited, the data collection instrument would be rigorous, and the results would be applicable to the plastics industry. However, as in all research, certain assumptions must be made in order to allow the work to progress. Assumptions in this study included:

1. Injection molding companies within western Michigan would allow
the researcher access to their employees.

2. The researcher would find sufficient number of acceptable subjects for the study within the university and corporate communities of western Michigan.

3. Two plaques at a time were presented to the human subjects. In order to protect the sample plaques and minimize the time required to change between pairs, the plaques were presented in a viewing fixture. The plaques were placed immediately adjacent to each other. To reduce the space between the plaques, it was necessary to present one plaque rotated 180° from the other plaque in each pair. It was assumed that the influences of texture orientation would be minimal on sink mark perception.

4. To reduce subject interview times, it was decided that similar sink marks in the experimental design would not be compared. In other words, while treatments within the experimental design were compared with other treatments, they were not compared to themselves. This assumes that the subjects would be able to determine that two plaques presented to them were identical in terms of texture color sink mark width and depth and therefore were of equal appearance.

Limitations

In order to reduce the complexity of the experimental design and constrain the size of the study, the design of the research was intentionally limited. These limitations in the experimental design were necessary in order to
reduce the amount of time required during interviews with test subjects. For example, it was desirable to include employees from local plastics manufactures as subjects in this research. However, if the duration of the interview was such that the participation of employees is too costly in terms of time commitment, it would be unattractive for companies to allow their employees to participate.

The limitations are enumerated as follows:

1. Straight ribs were used for the design of the sink-mark-forming geometries on the product. This research did not investigate the influences of screw bosses, posts or cross-rib designs.

2. As stated in the research objective, this investigation was conducted to determine if small changes in texture depth could decrease the probability of consumers detecting minor sink marks. The deepest sink used in the study was 0.035mm (0.0014 in.). This study was limited to minor sink mark depths.

3. This research was limited to a particular type of texture. Specifically, shot-blast stipples were used in these studies. Thus, the results of this study are only reflective of particular stipples.

4. While the effects of product surface luminosity were investigated, the effects of non-neutral colors were not included in this study. Only neutral colors were used to avoid the influence of potential color deficits exhibited by the subjects interviewed in the study. Therefore, conclusions drawn from the effects of the two colors used in the study should be attributed to surface luminosity changes, not to spectral color.

5. The depth and width of a sink mark is dependent upon part geometry.
In other words, the depth of a sink mark varies with the width of the rib causing the formation of the sink mark. The width of the rib also determines the width of the sink mark. Because of this complex relationship, it was not possible to mold all depth levels at both widths of sink mark.

6. In order to reduce the time required to conduct the interviews, certain comparisons between treatments were ignored. This resulted in a slightly reduced sensitivity of the study of influences of the surrounding environment on sink mark visibility. Given these design restrictions, it was not possible to conduct comparisons of identical sink mark depths and widths within a presented pair of sample plaques.

Summary

Some plastic product designs are prone to the development of aesthetic defects called sink marks. With modern plastics flow simulation and finite element analysis software it is now possible for product designers to predict and simulate the occurrence and geometries of these sink marks. However, sink marks are still a persistent problem in the injection molding industry. Customer rejects of functional products with aesthetic defects cost molders time and money in transportation, additional molding and reprocessing of materials.

Given the assumptions and limitations discussed above, this research determined how small changes in the depth of a stippled texture affected the probability of the visual detection of a sink mark by a human observer. These effects were investigated for two product colors, light grey and black. Prior to
this research, no data existed correlating texture depth with the probability of the visual detection of a sink mark.

From this research, an example of a basic predictive model was developed to describe the probability of human subjects visually detecting the aesthetic defect based upon the geometry of the sink mark, product color, and surface texture. Using predictive models, in problematic sink mark conditions, designers will be able to choose an appropriate stipple depth to provide an acceptably small probability of sink mark detection. The results presented here should be used in conjunction with methods of simulation that predict sink mark formation. In combination, these tools should allow for the prediction of the probability of an observer perceiving a sink mark on a molded product.
CHAPTER II

LITERATURE REVIEW

Overview

In order to determine proper experimental methods, factors of significance and acceptable levels for those factors, a review of relevant research was performed. To design research in sink mark perception, the researcher must understand the concepts of sink mark formation and prevention as well as the theories and testing practices of human perception. The following literature review investigates not only the industrial concepts of injection molding and defect prevention, but also includes the physiology of vision, industrial inspection and the cognitive aspects of human visual perception.

Sink Marks and Injection Molding

Sink marks have been described as a “depression or dimple on the surface of a molded part caused by the localized shrinkage of the plastic underneath the mark” (Olmsted & Davis, 2001). They are attribute defects associated with molding processes including plastic injection molding, metal injection molding, and die-casting. Sink marks are usually formed in thickened section of a product, near feature such as stiffening ribs, screw bosses or flow leaders. Molding companies have struggled to reduce the appearance of these defects as their customers are generally not willing to accept products with
visually detectable sink marks.

Sink mark visibility can be subjective and is dependent on many factors such as the acuity of the observer's vision, lighting, surface texture and presentation of the part. A review of the literature has shown that on a particular textured and painted part, sink mark depths of 0.040mm (0.0016 in.) were not visible to the trained observer, while sink marks deeper than 0.075mm (0.003 in.) were observable by all subjects (Horton, 1999). Other research has reported the threshold of sink mark visibility exists between 0.013 (0.005 in.) and 0.040mm (0.0016 in.) (Shi and Gupta, 1998). These differences may be explained by changes in the surface texture of the parts being observed. High gloss surfaces can accentuate the appearance of a sink mark by causing distortion of reflected images. To avoid this phenomenon, textures are used to hide sink marks that cannot be eliminated by design or process changes (Marchewka, 1974).

Molders have struggled for decades to eliminate sink mark defects from their products. Much research has been conducted in regards to these defects and their causes are now widely understood. An education in plastics engineering or technology will include attention to these defects as an understanding of their root causes is considered to be essential to the part designer, mold designer and process engineer.

To understand the causes of sink marks, one must understand the volumetric shrinkage characteristics of polymeric materials and how they behave during processing. In the injection molding process, heat from the machine barrel is used to melt plastic materials. However, the majority of the heat used to melt the polymer is introduced to the material by friction caused by
the actions of the plastication screw that compresses and shears the resin (Lokensgard, 2004; Rosato & Rosato, 1995). During this melting process, as heat energy is introduced to the polymer, the plastic material expands slightly. This volumetric expansion is on the order of a few thousandths of a millimeter per millimeter of volume. However, because the material is under substantial pressure within the barrel of the injection molding machine, this expansion is not generally observable.

Once the appropriate amount of material is melted, the injection phase of the injection molding process is initiated. During injection, the plastication screw acts as a plunger by moving forward at a controlled velocity to inject an amount of material into the mold. This material fills the runners, gate and a majority of the volume of each cavity in the mold. Additional heat is generated in the material by shear forces caused by the flow of the resin through the passageways of the mold (Rosato & Rosato, 1995). It follows that this additional heat increases the temperature of the melted polymer.

Following injection, the cavities are left partially unfilled. The process now begins to pack additional material into the mold at a set pressure. This packing of the material into the mold completes the filling of the cavities and compensates for any filling differences caused by variances the viscosity of the resin. The material within the mold is held under pressure until the material cools and solidifies sufficiently to allow for ejection of the product from the mold (Lokensgard, 2004; Rosato & Rosato, 1995).

Cooling of the polymer is accomplished by the removal of heat from the plastic through the cavity wall and into the cooling channels in the mold. Because the cooling is initiated at the cavity wall, the plastic solidifies from the
outside of the part wall towards the center of the part wall. The solidified portion of the part cross-section is referred to as the “frozen layer” (Rubin, 1972). Therefore the molten layer in the middle of the cross section of the part wall is “sandwiched” between two thickening frozen layers (Beaumont, Nagel & Sherman, 2002). Figure 4 illustrates the formation of the frozen layers and the entrapped area of hotter material within the molten layer.

![Illustration of the rib/wall junction showing entrapped molten material. (source: author)](image)

**Figure 4.** Illustration of the rib/wall junction showing entrapped molten material. (source: author)

Solidification of the plastic is accompanied by volumetric shrinkage of the material. Pressure within the plastic during the packing stage of the injection molding process forces more material into the cavity and compensates for part volume lost due to this shrinkage. However, as the plastic solidifies it becomes more difficult for material to flow and continue to fill the cavities compensating for shrinkage. Indeed, once the gates are solidified or “frozen”, no more material can flow into or out of the cavities (Lokensgard, 2004; Rosato & Rosato, 1995).
The composition of the material greatly affects the volumetric shrinkage of cooling plastics. Inorganic fillers and additives can help to reduce the amount of shrink while the structure of the polymer may cause it to increase. Further, shrinkage can continue for quite some time. Indeed, volumetric shrink of highly crystalline polymers can continue for days after the actual molding of the part (Rosato & Rosato 1995).

The manner in which a plastic is cooled also affects the shrink that manifests in the plastic. The rate of shrink reduces as a material is cooled. Therefore hotter sections of a plastic product shrink more rapidly than cooler areas. Hence, molten layers shrink more rapidly than cooler, frozen layers (Beaumont et al., 2002).

Additionally, the rate of cooling affects the shrink rate. For semi-crystalline polymers, the more slowly a polymer is cooled, the more crystalline-like structures can form within the material. In general, greater degrees of crystallinity result in greater potential for volumetric shrinkage. Frozen layers act as insulators, slowing the cooling of inner molten layers, increasing shrink in the inner layers (Rosato & Rosato, 1995).

Volumetric shrinkage of the molten plastic causes stresses to build within the part wall. These stresses can cause a variety of defects to occur. If the frozen layers are thick and rigid enough to withstand the tensile forces caused by the shrinkage of the molten layer, separations can form within the part wall as the forces pull the molten layer apart. These separations appear as bubbles or air pockets in the middle of the part wall and are collectively referred to as voids (Beaumont et al., 2002). However, if the frozen layers are not sufficiently rigid, sink marks will form as the tensile forces within the molten layer pull on
the frozen layer (Beaumont et al., 2002; Malloy, 1994; Rosato & Rosato, 1995).

In order for these defects to occur, the frozen layer must be sufficiently thick to prevent any additional material from being introduced into areas that are still experiencing higher rates of shrink. When a complete solid is formed through the cross-section of the part, no more material can flow to the rapidly shrinking hot areas of the part, thus it is no longer possible to properly "pack out" the part (Beaumont et al., 2002).

Causes and Prevention of Sink Marks

Design Factors

As discussed, sink mark formation can occur when a product design has a localized change in part wall thickness. Thus, any part design having a varying wall thickness could be prone to sink defects. In order to satisfy the requirements of design, stiffness and functionality, it would seem that all products would require varying wall thickness. However, not all products suffer from problematic sink marks. Therefore it is apparent that while the design of a product may make it more susceptible to sink mark formation, certain design features can be manipulated to mitigate the probability of visual detection of the sink mark.

Stiffening ribs are often identified as a cause of visually detectable sink marks. The ratio of the thickness of the base of the rib to the thickness of the wall has long been identified as an important predictor of sink mark formation (Marchewka, 1974). This ratio has been referred to as the rib-to-wall or rib/wall ratio. Figure 5 shows how this ratio affects the size of the mass molten plastic
that forms at the base of the rib. This mass becomes isolated from the packing pressure and flow as the frozen layers thicken during cooling.

Figure 5. Effect of rib/wall ratio on the size of the molten mass isolated from packing pressure as the frozen layers thicken to collapse the molten layer. (source: author)

Much research has focused on the rib-to-wall ratio as a design criterion to eliminate the formation of sink. Researchers and material suppliers have established guidelines that suggest threshold values for this ratio. However these guidelines do not always agree. Marchewka (1974) first suggested that for parts with a wall thickness of 3.175 mm (0.125 in.) the rib/wall ratio should not exceed be 3:5 (60%) and the ratio may be as low as 2:5 (40%) for thicker wall sections. Others hold that ribs should not exceed 2/3rds the wall thickness (0.67 rib/wall ratio) (Rosato & Rosato, 1995). Another research project suggests that if the gate is within 3.175 mm (0.125 in.) of the rib a ratio of 3:5 (60%) is...
acceptable and that 2:5 (40%) will prevent detectable sink if the gate is farther away (Liou, Ramachandra, Ishii & Hornburger, 1990). Most research has focused on rib/wall ratios from 3:10 (30%) to 1:1 (100%).

Figure 6. Cross section illustration of different rib/wall ratios with fillet radii shown and the effects on sink mark depths. (source: author)

Sharp corners in part designs cause concentrations of stresses in the product. To prevent stress cracking from occurring at the base of ribs, most designers specify fillets at the junction of ribs and the walls. If made too large, these radii result in effectively thickening the part wall at the base of the rib. Figure 6 shows how radii size affects the formation of sink. Once again however, guidelines for these radii do not always agree.

Rosato & Rosato (1995) suggested radii with a range of 0.635 to 1.143mm (0.025 to 0.045 in.). Marchewka (1974) suggested maximum fillet radii of 0.381mm (0.015 in.). Fillet radii should be kept as small as possible to keep sink
mark depth as shallow as possible, therefore reducing the possibility of visual
detection. However, it has been suggested that radii can help to distribute the
visual effect of a sink mark across a wider area of the surface of a part (Rosato &
Rosato).

Due to viscosity, compressibility and thickening of the plastic as it flows
farther from the gate, parts that require plastic to flow farther to fill the cavity
require more packing pressure. In order to keep the leading edge of the melt
moving, more pressure is required at the entrance to the mold. Thus, the
pressure within the melt decreases as the distance from the gate increases,
thereby creating a pressure gradient along the melt flow. Ribs positioned
farther from the gate are more difficult to properly fill and pack than those located
nearer the gate.

Marchewka (1974) included the effects of flow distance in design
guidelines. For ribs farther than 102mm (4 in.) from the gate, a rib/wall ratio
2:5 (40%) was suggested. Other research has investigated gate proximity on the
resultant depth of sink marks, and suggest that gates be located close to areas of
expected sink marks formation such as ribs and bosses (Moldflow Corporation,
2003; Tursi & Bistany, 2000).

Flow leaders are thickened sections of part walls that allow the material
to flow more freely than the nominal wall and “lead” the flow in a desired
direction. It is suggested that if gates cannot be located near expected sink
marks, flow leaders should be used to ensure the proper packing of the base of a
rib. In the flow leader, which is thicker than the nominal wall, the frozen layer
would require more time to completely solidify. Thus, the material could flow
for a longer time and allow more material to be introduced to the part,
compensating for material shrink (Rosato & Rosato, 1995). However, this solution results in higher material consumption, higher part weight and may result in the creation of new sink mark over the flow leader.

Material Factors

As discussed, volumetric material shrink combined with under-packing the mold cavity are the root causes of sink mark formation. Therefore, the shrink characteristics of the plastic designated by a material supplier are a good indicator of a product's susceptibility to sink mark formation. While volumetric shrink rates are true indicators of polymer behavior, the industry has traditionally used linear shrink rate for characterization of polymers due to their easy application in mold designs. Linear shrink rates vary from 0.0005 mm/mm to 0.100 mm/mm (Automation Creations, 2006). Beginning with Marchwea's work in 1974, most sink researchers have used various Acrylonitrile-Butadiene-Styrene (ABS) resins (Shi & Gupta, 1998). This material typically exhibits a linear shrink rate of 0.002 to 0.006 mm/mm (Automation Creations).

The molecular structure of the polymer also affects the appearance of sink marks. Different sink mark responses result from the use of semi-crystalline or amorphous resins. Semi-crystalline polymers exhibit greater net shrink than amorphous polymers and hence have a greater tendency for sink marks formation (Tursi & Bristany, 2000). Further, this same research showed that the material selected shares interactions with other design and process factors in the determination of sink mark formation.
Process Factors

The most effective methods for preventing the formation of sink marks lay in proper part and mold design (Olmsted & Davis, 2001). Adhering to the material suppliers recommended rib/wall ratios, maintaining moderate flow lengths, and limiting changes in wall thickness in the part design are the most effective means to removing the possibility of sink mark detection. Occasionally, product designs require that the designer violate design recommendations. In these cases, the process engineer can manipulate certain process variables to diminish the appearance of sink marks (Nakayama, Kodama & Motoichi, 1983). Cavity pressure, pack pressure, pack and hold time, material melt temperature, tool temperature, and cooling time were factors investigated in most published research on sink mark causes (Nakayama et al.).

Cavity pressure is the leading indicator of the dimensional quality of injection-molded products. The cavity pressure is dependant upon many process variables including pack pressure, hold pressure, melt temperature and mold temperature. Research has shown that pack pressure directly effects the pressure in the cavity during pack and hold stages. Most researchers agree the pack pressure is the most significant process variable affecting sink-mark depth (Liou et al., 1990; Nakayama et al., 1983; Ye & Leopold, 2000). As discussed above, while the plastic cools within the mold, the pack pressure allows additional material to flow into the cavity compensating for material shrink.

During cooling, plastic will continue to flow toward areas of shrink until solidification occurs. Solidification of the material surrounding the area where the sink mark occurs seals off the sink from the benefits of pack pressure, preventing additional material from being added to the sink mark. While
sufficient time for pack must be allowed, there are factors which limit the time required for the pack and hold stages. Discussed earlier, gate freeze is the solidification of the plastic material within the gates where plastic flows into the cavities. Once the gate has solidified, no more material can be introduced to the cavity. Hence, the cavity as a whole is removed from the effects of pack pressure. Additional packing after the completion of gate freeze will not help reduce the visibility of sink marks and waste valuable manufacturing time.

The time that pack pressure is applied to the melt is referred to as pack time. While pack time is critical for the reduction of sink mark visibility, the appropriate amount of pack time is easily determined by gate freeze. Other process variables such as pack pressure were found to be more significant contributors to sink mark formation (Ye & Leopold, 2000).

The temperature of the molten polymer has much influence on the injection molding process. Significantly, it affects the viscosity of the material during filling. This temperature, commonly called melt temperature, has been found to be the second most effective contributor to the formation of sink marks (Ye & Leopold, 2000). The higher the temperature of the melt, the more shrink can occur and hence the larger the sink mark that can be formed.

The manner in which the frozen layer forms has been discussed as a contributor to sink mark appearance. While the formation of a thicker frozen layer may cause voids within the part, sink mark would be less detectable. Since the cooling of the plastic by the relatively cool mold wall forms the frozen layer, mold temperature has been investigated. Malloy (1994) found that sink mark appearance can be reduced by positioning cooling lines in areas of the mold where thicker sections of the part are formed. Additional cooling line in theses
areas reduced the surface temperature of the cavity and resulted in the rapid formation of thick frozen layers. While low mold temperatures were found to reduce sink mark appearance, melt temperature was determined to have a stronger effect on sink marks (Malloy).

Melt temperature, mold temperature, the specific heat of the plastic and the thermal conductivity of the mold material interact to determine the time required to solidify the mold part. Hence it was also suspected that the time allowed for cooling was a contributor to sink mark appearance. It was postulated that the longer a part remains in the mold, the more rapidly heat can be removed from the plastic. When a part is removed from a mold, less cooling occurs because air is less conductive than the mold material. The more slowly a part cools the more crystalline-like structures can form in the material and the more the material shrinks. However, research specific to this process variable has found that cooling time is a weaker variable than melt temperature (Ye & Leopold, 2000; Tursi & Bristany, 2000). Hence, beginning mold filling with an appropriate melt temperature was more effective in reducing sink mark depth than cooling the part in the mold for longer times.

While design factors and process variables have been discussed separately, they often interact in the formation of sink marks. Certain part geometries require special consideration by the process designer in order to assure minimal sink mark visibility. Thicker ribs require more pressure to properly fill and reduce sink mark appearance (Nakayama et al., 1983). Cross-rib designs similar to the one shown in Figure 7 require 50% more pack pressure than straight rib designs (Ishii, Beiter & Hornberger, 1992).
Figure 7. Cross-rib designs as shown in this illustration require 50% more pack pressure than straight rib designs. (source: author)

Measurement of Sink

Review of relevant literature has shown that researchers have used a variety of measuring instruments to determine sink mark geometries. Most researchers prefer the use of stylus-type surface profiling instruments, commonly referred to as profilometers, surf testers, surf analyzers, etc. However, other instruments are capable of characterizing the geometry of sink marks. Literature was reviewed to determine if a faster, more reliable method of surface measurement existed.

Stylus Devices

Stylus-type surface measurement devices have often been used to
characterize surface textures. The stylus tip is connected to a linear variable differential transducer (LVDT). As the stylus moves and changes its position relative to the surface of the sample part, the electrical output from the LVDT changes. This electrical signal can be scaled to a dimensional measure. In order to assure uniform sampling distances, a motorized drive is used to move the stylus across the surface of the sample. A typical measurement resolution for these devices is just below 1μm. The lateral resolution of the measurement is dependent upon the radius of the stylus tip. Tips are available as small as 1μm (Vorburger, 2004).

The profile of a surface can be expressed as a composite of two characteristics, roughness and waviness (Song & Vorburger, 2004). Roughness is a high frequency variation in the height of the surface of an object. Roughness generally has low amplitude, measured in tenths or hundredths of millimeters and is generally associated with the “texture” of a surface profile.

Waviness, on the other hand, exhibits a lower frequency. In optical products, it is the waviness of a surface that causes distortion of an image. Together, waviness and roughness comprise the characteristics of a surface.

The effects of roughness and waviness can be separated from each other within the measured data using the appropriate mathematics (Song & Vorburger, 2004). Software has been written which uses high or low band pass filters to remove the effects of waviness or roughness, respectively. Below, Figure 8 shows the profile of an example sink mark with the measurement data mathematically manipulated to show predominately the effects of surface waviness. The sink mark appears in the data as the large, centrally located dip in the plotted line.
Using the same initial data, Figure 9 shows the results of filtering to show primarily the effects of surface roughness. While the position of the sink mark can be observed in both graphs, its depth is substantially different in each graph. Investigation of waviness requires that the high frequency surface roughness effects be removed from the data. This results in the signal being reduced to a median or “average” line or curve (Mitutoyo, 2001b). While this removes the ‘fuzziness’ of the plot seen in Figure 9, the general height of the plotted data remains the same.

Researchers interested in roughness characteristics will use filters that remove the lower frequency effects of waviness. In the case of sink mark measurement, these filters will retain the high frequency signals but remove the greater amplitude waviness. Thus the dip of the plotted line shown in Figure 9
is substantially smaller than the dip in Figure 8 (.002 mm vs. .007 mm respectively).

![Figure 9](image)

**Figure 9.** An example of sink mark profile showing the effects of both waviness and surface roughness. (source: author)

The filters have threshold factors that affect the sensitivity of the filter and significantly change the output. For various surfaces having different texture, the metrologist must appropriately adjust these threshold values to accurately represent the surface under investigation. Improper threshold values may result in over-processing of the signal data and misrepresentation of surface geometries. While standards exist for the determination of threshold values, the metrologist is responsible for properly selecting these values (Mitutoyo, 2001b).
Coordinate Measuring Machines

In the absence of traditional stylus-type instruments, researchers have used coordinate measuring machines (CMMs) to measure sink marks (Horton, 1999; Zuber, 2004). A CMM measures positions at a probe in three-dimensional space within a certain measurement envelop. These devices have been referred to as "three dimensional height gages". While rectangular envelopes are common, the size and shape of the measurement envelope may vary, including spherical and partially spherical envelopes. When using a CMM to measure sink-mark geometries, the measurement probe is moved in a straight line across the part and the position of the part surface is sampled at set intervals (Figure 10).

![Sink Mark Trace From CMM Data](image)

Figure 10. Graph of CMM data showing five sink mark profiles (source: author).

Horton (1999) determined part profiles by moving the arm across the surface of a part in increments of 0.20mm (0.0078 in.) and recording the position of the stylus. Sink marks can be seen in the above graph as localized dips in the plotted line. Problems encountered with this method of surface measurement

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included difficulties in sample rigidity and repeatedly holding sample parts and inconsistent measurement intervals due to various operator errors.

Interference Microscopy

If a non-contacting measurement method is preferred, interference microscopes provide a means for optical measurement of a surface. White light interference microscopes belong to a family of measuring instruments that use the interference patterns between two reflected beams of coherent white light to determine the distance from a lens to a reference and a sample surface. Data are collected through the use of a CCD video device to capture and analyze the interference patterns created as the focal length of the device is changed. Because the instrument is computer-controlled and image data is recorded electronically, statistical analyses of the measurements are easily conducted. Mathematical filters may also be applied to the data to remove inconvenient factors such as curve and tilt from the data (Veeco Instruments, 2006).

Interferometers can have vertical (or depth) resolutions of less than one nano-meter (nm) (Veeco Instruments, 2006). However, they are susceptible to even minor disturbances such as vibrations and air currents (Vorburger, 2004). Review of the literature has shown that sink mark depth measurements are generally within the range of hundredths of millimeters (Marchewka, 1974; Horton, 1999). It is highly unlikely that such resolution would be necessary to measure sink marks visible to the human eye. Further, it was found that the area measured by a single scan of the interferometer in the Tribology Laboratory at Western Michigan University was approximately 6 mm². A single scan was not capable of capturing the entire width of a sink mark.
Prediction of Sink Marks

It has been discussed that the best method of prevention of sink mark formation is adherence to material supplier, part design and mold design guidelines. While process engineers can manipulate certain variables to reduce the appearance of sink, it is the designer that conceives the geometries that are susceptible to the formation of sink mark defects. In an effort to create tools for designers and process engineers, much research has been conducted in the effort to predict the molding of defective products, including sink marks.

Plastic flow and mold filling simulation has been traditionally accomplished using numerical methods (Austin, 1991). Using these methods, part shrinkage and warp have been successfully predicted (Jin & Zhao, 1998). Various product characteristics may be predicted based upon these numerical methods (Moldflow Corporation, 2003). Simulation software can predict the occurrence and severity of sink marks (Beiter, 1991; Ishii et al., 1992; Shi & Gupta, 1998, 1999, 2000). These simulations provide designers with tools to evaluate design decision before committing to mold construction. Additionally, these tools allow the process engineer and the designer to work together to investigate the interactions between part and process design and how they may affect the potential for defects (Ni, 2000).

Neural networks have been used to model injection molding defects. These networks are constructed using training-by-example to program, reducing the experimentation time required for the development of other mathematical methods. The prediction of weld line defects has been investigated using neural networks (Soltani & Manoochehri, 2000). It was found that the neural network
could be used in place of traditional computational flow analysis. However the network was built from simulation data and was not verified in the field.

Another application of neural networks involved the prediction of molding defects focused on cycle-to-cycle part weight. The variability of the predicted part weight was used as an indicator of overall part quality (Moller & Rowe, 1998). Hydraulic pressure was used as an indicator of the filling characteristics of a molding cycle. As hydraulic pressure changes from shot to shot, the quality of cavity filling changes. The data collected during the molding cycles of thirty-six parts were used to train the network and variation of the viscosity was used to validate the network. While the network was quickly created, it was unable to model behavior outside of process conditions experienced during training; hence no extrapolation of the model could be conducted to create a more generally applicable tool.

Flow simulation and finite element analysis (FEA) have been used in combination to predict the location and severity of sink marks on injection-molded products (Shi & Gupta, 1998, 1999, 2000). Researchers conducted a filling analysis to determine the condition of the mold and plastic at the time of 100% cavity fill. These conditions included temperatures and cavity pressures, along with mold cavity geometry. The design of the mold cooling system and the results of the filling analysis were then entered into FEA software. A thermal shrink analysis was performed in the FEA package. Elements of the resulting FEA model were analyzed to determine the predicted geometry of the sink mark. Experimental verification showed that while the model did not always predict the correct depth of the sink mark; the trend in the simulation did follow the trends observed during experimentation (Shi & Gupta, 1998).
Beiter (1991) developed a series of experimental studies that created the geometric sink index which is expressed as:

\[ G = \frac{D}{T} \]  

Equation 1

Where:
- \( G \) = Geometric Sink Index
- \( D \) = the largest diameter in the rib/wall junction
- \( T \) = the thickness of the plastic

Note: a plate with no rib would have a \( G \) value equal to one.

Empirical equations were also developed from the data derived from these procedures (Shi et al., 1998, 1999, 2000). The simplified relationship below was the basis of these equations.

\[ D = A \times B \]  

Equation 2

Where:
- \( D \) = the largest diameter in the rib/wall junction
- \( A \) = the effect of thermal mass and
- \( B \) = the effect of packing pressure

All models developed in the reviewed literature were based upon simulation data. Validations of these models were conducted using data previously collected during earlier experiments.

Physiology of Sight

The methods through which we perceive the world around us are
comprised of many varied and interconnected systems. The human brain receives, interprets and compiles sensory inputs from the eyes, nose, ears, skin, and tongue. It is from these inputs, that the mind constructs a private, somewhat unique, perception of the world. Each type of input, whether visual, tactile or otherwise, must be sensed and encoded, transmitted, received and decoded by the brain, and then processed by the mind (Wagemans, Wichmann & Op de Beek, 2005). In this case, the mind is the cognitive, decision-making portion of the human brain.

While the mind is the decision maker, the decisions are based upon the signals it receives. The quality of the decision is dependant upon the quality of the senses. Early vision, or the capturing and encoding of visual stimulus, is determined predominantly by physiology and is responsible for many of the defects in the visual system (Burnham, Hanes & Bartleson, 1963; Wagemans et al., 2005). Therefore, to begin a discussion of human visual cognition for this research, it is necessary to build an understanding of the physiology of the human vision system.

The Structure of the Eye and the Visual System

The structure of the eye consists of light conditioning and detecting components. The components discussed below are shown below in Figure 11. The “white” of the eye is the sclera. The sclera is responsible for giving the eye shape and rigidity. The front surface of the eye is covered with a translucent membrane called the cornea. This membrane is a protruding extension of the sclera found at the front of the eye (Burnham et al., 1963).
Light enters the interior of the eye by passing through the opening of the iris and then through the crystalline lens. The function of the iris is to ensure that the appropriate amount of light will fall upon the sensing membrane of the retina. Therefore the iris will react to the intensity of a light source, dilating in dimly light environments and contracting under intense light.

![Diagram of eye components](image)

Figure 11. A horizontal cross section of the eye showing major components of the vision system. This simplified diagram illustrates the relative positions of items discussed in the text. (source: author)

The lens of the eye was, at one time, perhaps the most studied component of the eye. Many visual difficulties are attributed to the lens and the muscle that control and shape it. The muscles that control the shape of the lens are collectively called the ciliary body. The crystalline lens and the ciliary body work together to focus the light on the sensing membrane of the retina (Scholz, 1960).

On the way to the retina, light passes through two liquids. The first, the aqueous humor, is located between the cornea and the lens. The second liquid is
the vitreous humor. This second liquid located in the rear of the eyeball is viscous and transmits light from the lens to the retina (Scholz, 1960).

The retina covers the rear two-thirds of the eyeball and contains the light-sensing components of the visual system. The retina is located inside of the sclera, attached to a dark membrane called the choroid. The choroid contains a great number of blood vessels to nourish the eye (Burnham et al., 1963).

The retina itself contains rod and cone receptors that sense light and color. Rods are long slender cells that detect small amounts of light and are best utilized in dim lighting where there is little color perception. For these reasons rods are generally associated with night vision. Cones are larger than rods and are, as implied, cone-shaped. A portion of the retina called the fovea contains only cone cells. In this section, the cone receptors are more rod-shaped than in other areas of the retina.

A layer of nerve cells called the bi-polar layer collects impulses from the rod and cone receptors. This layer then passes its impulses to ganglions cells that form the optic nerve. The optic nerve leaves the eye at the papilla or blind spot. No rod or cone cells are present at the blind spot; therefore no light can be detected (Burnham et al., 1963).

The optic nerve bundles from each eye join together and re-separate at the optic chiasma. In the chiasma a crossover of some of the nerve bundles occurs. The effect of this crossover is that the images that fall on the left side of each retina are sent to the left occipital lobe and images that fall on the right side of each retina are sent to the right occipital lobe. Due to the physics of the lens system, the image formed on the retina is an inversion of the natural state,
it can be said that the images on the left side of vision are interpreted by the right occipital lobe and the images to the right by the left occipital lobe. This may form the basis of eye dominance discussed below. Figure 12 below illustrates the pathways of the optic nerve bundles.

![Figure 12](image)

**Figure 12.** A schematic of the pathways of the optic nerve illustrating the separation of the left and right signals. (source: author)

**Visual Deficits**

Proper function of the human vision system depends upon the accurate and precise functioning of the many physical components of which it is comprised. Given the complex nature of the system, it should not be surprising to discover a variety of conditions in which the functions of the system are damaged, degraded or defective, resulting in defective perception and vision. These defects may be congenital, the result of mishaps or degenerative. In
regard to this study, these defects may be grouped into issues of acuity, color, and contrast sensitivity.

Visual Acuity Deficits

The focusing mechanisms of the human eye can be affected by a variety of problems. The shape of the eye and the lens as well as the strength and reliability of the muscles of the eye all affect the clarity of vision. These structural and performance attributes of visual system result in defects such as astigmatism, near- and far-sightedness (Scholz, 1960).

Near- and far-sightedness result when the shape of the eye does not allow the image to be properly focused upon the retina. For individuals with far-sightedness (or hyperopia), the eye is shortened or smaller than normal. This condition causes the light coming through the lens to focus beyond or behind the retina. In the case of the nearsighted or myopic individual, the eye is enlarged or oblong and the light is focused in front of the retina. Both of these conditions change with age, and both can be corrected with the used of the proper corrective lens prescription (Scholz, 1960).

Astigmatism generally results from variation in the shape of the cornea. The individual with astigmatism will exhibit acceptable visual acuity within portion of their vision. However, due to the distortion of the refractive surface of the cornea, certain portions of the retina will not receive properly focused light. This condition may also be corrected with the appropriately manufactured spectacles (Scholz, 1960).
Color Vision Deficits

Color vision quality describes the ability to properly sense and identify the divisions of the visible spectrum of particle energy. The visible spectrum ranges from 380 nanometers (nm) to 780 nm, with ultraviolet existing below 380 nm and infrared above 780 nm (Birch, 2001; Burnham et al., 1963). The divisions of the visible spectrum can be seen in below in Figure 13.

![Figure 13. Division of the visible spectrum with wavelengths of light listed for certain color domains. (source: author)](image)

Trichromatic color systems define color based upon three primary colors: red, green and blue. At one time, yellow was considered a primary color. However, early investigations in color theory observed that yellow could be derived from a color mixture and therefore could not be a primary (Birch, 2001). This erroneous classification of yellow as primary persists to today.
Early color theorists developed the trichromatic systems by observing the color response of the human eye. It should therefore be no surprise that the eye senses color by using trichromatic principles. In the previous section discussing the physiology of the eye, the sensing bodies of the retina were identified as the rod and cone cells. While rod cells are used predominantly in low light conditions, it is with the cone cells that color information is collected. Each cone cell can sense light energy within a specific range. The sensitivity range results from photopigments within the cone cell. The photopigments are identified as ‘red’, ‘green’ and ‘blue’ and are described as erythrolabe, chlorolabe, and cyanolabe, respectively (Birch, 2001). Erythrolabe provides peak sensitivity near 560 nm, chlorolabe at approximately 530 nm and cyanolabe at about 420nm. For reference, rod cells have peak sensitivity near 500nm (Birch, 2001; Burnham et al., 1963). It should be noted that while the photopigments are described as ‘red’, ‘green’ and ‘blue’, the ranges of peak sensitivity do not truly reflect these names.

Deficits in color vision occur when information from one or more photopigment is incorrectly interpreted. The deficits may be congenital or acquired. Approximately eight percent of men and 0.4 percent of women are affected by congenital color blindness (Birch, 2001). Individuals with dichromatism lack one of the three photopigments. If the ‘red’ photopigments are missing or defective, the individual is described as a protanope. Dueteranopes lack the ‘green’ photopigment and tritanopes lack the ‘blue’ photopigment.

Individuals with anomalous trichromatism possess all the receptors necessary for color vision, but exhibit deficits in the development and delivery of
the nervous impulses. Problems with red vision are proanomalous, green and
deuteranomalous and blue are tritanomalous.

The first industrial accident attributed to color blindness was recorded in
1875 (a tug boat collision due to inability to distinguish red from green). This
incident illustrated that color vision deficits can be dangerous and should be
considered for industrial settings (Birch, 2001). For experimental design
considerations, it should be kept in mind that color blind individuals not only
have difficulty distinguishing between colors, but that they also have reduce
sensitivity in the regions of their deficiency. Test subject will have a difficult
time resolving visual phenomena that occur within their range of reduced
sensitivity (Birch, 2001).

Contrast Sensitivity

Visual deficits are not limited to visual acuity and color vision.
Ophthalmologists were puzzled by patients that exhibited perfect visual acuity
but were unable to read newspapers. Cambell (1983) showed that the ability to
perceive differences between levels of luminance was also a critical component of
the human visual system. The ability to distinguish between objects having low
levels of contrast was investigated and methods of testing this ability were
developed. Black-to-white sinusoidal gratings were used in these investigations
(Figure 14). Testing is now conducted when patients exhibit problems reading
and seen in low-contrast environments. Online version of these test are
available for individuals interested in self-evaluation (Bach, 2006; Vision
Sciences Research Corporation, 2006a, b).
The computer-based Freiburg Visual Acuity and Contrast Test (FrACT) was developed by Bach and distributed along with his research. At this time, the test is available and freely distributed online. The test provides a measure of visual acuity at high contrast levels as well as testing contrast sensitivity. While the contrast sensitivity test is not completely developed for use in certain operating systems, it does provide a comparative basis when working with
human subjects. Test subjects can be evaluated for major contrast sensitivity difficulties. However, at the time of this research, a refined level of contrast sensitivity could not be determined with this test. This test provides a baseline for computer evaluation of contrast sensitivity in humans.

Environmental Effects

The appearance of an object is dependent upon more than just the object itself. Every viewing experience involves an observer, an object being observed and the environment in which the object is observed. The observer and the environment in which an object is observed can affect the appearance of color as much as actual surface characteristics (Burnham et al., 1963; ASTM D1729-96, 2003; Shah, 1998). Characteristics of the viewing environment include the illuminant, the object itself, and proximal objects.

Illuminants

The appearance of an object under visual inspection begins with the light of the environment the observation will be made in. If no light exists, the object will not be visible and no observations are possible (Birch, 2001; Burnham et al., 1960; DiCosola, 1995). Since the perceived appearance of an object is dependent upon the light reflected from that object, the illuminating energy determines the "base light" color and luminance that can be observed from the object.

The natural light of the sun would be the logical standard for the classification of illuminants. However, even this constant source of illumination varies depending upon the time of day, the condition of the weather, and the
level of pollutants in the environment. Figure 15 shows the spectral power distribution for averaged natural daylight. Note that while average daylight may appear white or even yellowish, it is strongest in the blue portion of the visible spectrum. This would make objects viewed under natural light appear more blue than if they were illuminated with a source having a neutral or unbiased spectral power distribution (Birch, 2001; Burnham et al., 1963; DiCosola, 1995).

![Natural Daylight Spectral Power Distribution](image_url)

**Figure 15.** Graph of the spectral power distribution of natural daylight. The distribution exhibits more energy in the blue hues around 460 nm than at other wavelengths.

Under daylight, product attributes in the blue spectrum would appear more prominent than features of other colors. A light source with a more neutral spectral power distribution would illuminate all features equally. However, such an illuminant may be impractical for quality inspections, as no standard light source exists that has a completely neutral power spectrum.
distribution. Florescent and incandescent lighting have unique power distribution and therefore colors and objects appear different when illuminated by them. Most products will be purchased and used with limited types of illumination. Therefore, it may be desirable to inspect products with an illuminant that simulates the environment of purchase or use (DiCosola, 1995).

The International Commission on Illumination (CIE) has established standard illuminants for the inspection of opaque objects (ASTM D1729-96, 2003). These standardized illuminants can allow for the simulation of various natural and artificial light sources. Included in these standards are overcast northern sky (CIE illuminant D75), average daylight (CIE illuminant D65) and cool white (approximated by CIE illuminant F2). Figure 16 shows the spectrum power distribution for the CIE D65 illuminant.

![CIE D65 Illuminant Spectral Power Distribution](image)

Figure 16. Graph of the spectral power distribution of the CIE designated illuminant D65. Note that this artificial light source duplicates most of the characteristics of nature daylight shown in Figure 15.

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Object

For an object to be visually inspected, light must be reflected from the object. Therefore, the object must at least be partially opaque to the wavelengths of light provided by the illuminant. As stated, the wavelengths of the light emitted by the illuminant determine possible colors the object may present. An object will reflect certain wavelengths of light energy from its surface while allowing other wavelengths to be transmitted into the surface (Burnham et al., 1963). Figure 17 shows the reflection and transmittance of incident light on an object.

![Diagram of light reflection and transmittance](image)

Figure 17. Example of the interaction between an object and incident illumination. This magenta object reflects the blue and red wavelengths while allowing green wavelengths to be transmitted into the object. Strength of the reflected light is reduced by the removal of the green component of the incident light. (source: author)

Generally, inspection standards will imply or specify angles at which the object must be held during visual inspection. This is to allow for the effects of
surface glossiness to be considered and corrected for in the observations. Glossiness is determined by the smoothness or texture of the surface of an object. The less texture or variation in the surface of an object the glossier the object appears. Objects exhibiting different glossiness will reflect light in different manners. Highly glossy surfaces reflect a tight beam of light from the illuminant while less glossy surfaces will disperse the light from the illuminant (Burnham et al., 1963; BYK Gardener, 2001; ASTM D523-89, 1993). This effect can be observed in Figure 18.

![Figure 18](image)

Figure 18. This figure illustrates the relative intensity of reflected light from an opaque specimen. The light scattered from a low-gloss specimen is shown in orange while the yellow indicates high-gloss. Note the directionality of the high-gloss scatter. (source: author)

By controlling the angle at which the object is held in during inspection, the observer is controlling the position of any concentration of light that the object may reflect. In areas of intense concentration of light, the object will exhibit and increased luminosity. In these areas, the color of the light of the illuminant may overpower the color of the object and “washout” any visible...
surface features (BYK Gardener, 2000). By holding the object at different angles, the inspector can observe the color and appearance of the object in varied intensities of reflected light.

Psychological Effectors

While the methods of signal encoding, transmission, and decoding are common, each individual mind can create different methods of interpreting the signals, therefore providing preference for one signal or condition over another. The two dimensional images that are formed upon the retina contained no information as to what elements of the image comprise objects and what is the background. The human visual system must decide how to divide the image into discrete objects and background. The separation of the visual signal into its elements and the development a conceptual whole-world image are the subjects of much theoretical research. There are many theories of visual perception including gestalt theory, ecological approach, neurophysiological approaches, empiricism and computational approaches including neural networks (Gordon, 1997; Wagemans et al., 2005). For the purposes of this research the principles of gestalt theory will be discussed.

Gestalt Theory of Perception

Formative work in gestalt theory was performed by Koffka (1935), Köhler (1929) and Wertheimer (1923). The core of gestalt theory is the simplicity principle. Stated otherwise, the visual system will organize the visual input as simply as possible. Similar elements placed closely together or moved together
will be grouped together. Further, closed figures will be perceived as having smooth contours, maximal symmetry and maximal convexity. Other principles of gestalt theory include good continuation and closure. The principles of gestalt theory are often best explained through the use of optical illusions. Four principles of the theory significant to this research are discussed below.

**Emergence**

Gestalt theory holds that the human mind will search for objects and group them together to form familiar, simple objects. Figure 19 shows what may appear to be a collection of black dots on a white background. However, upon closer inspection the image of a Dalmatian will appear. This is an example of the mind grouping seemingly unconnected data into recognizable objects.

![Figure 19. An example of the gestalt principle of emergence. This image is very familiar in cognitive vision circles. (source: author, adapted from Lehar.)](image-url)
Subjective Contours

The principle of subjective contour holds that objects that seem to group together and define the edges of other objects will in fact be perceived as boundaries of a nonexistent object (Wagemans et al., 2005). The mind will perceive an imaginary boundary element (a contour) connecting existing boundaries. Further, the imaginary object may take on special characteristics, including a change in the relative brightness of the imaginary object. The imaginary square in Figure 20 below may appear brighter than the white paper that the figure is printed upon.

![Subjective Contours Diagram](source: author)

Figure 20. The principle of subjective contours shows that objects will be formed although no boundaries exist. The image of a square is formed although there are no defining boundaries. Note that a contrast difference may be at the boundary of the perceived square. The square appears brighter than the background. (source: author)
Multistability

The principle of multistability is associated with ambiguous imagery. If the image formed on the retina does not contain enough information to resolve an object's true position in three-dimensional space, the mind will pick an orientation based upon experience. However, upon further study, the mind may perceive the object in a different orientation and instantaneously switch the perception to this new alignment. This phenomenon is known as spontaneous reversal. It is interesting to note that an object will never be perceived as existing in both possible orientations simultaneously but will switch between the two (Wagemans et al., 2005).

![Figure 21](image-url)  
Figure 21. This wire frame rendering of a cube illustrates the principle of multistability. The image is ambiguous as to the orientation of the cube in three-dimensional space. Is the corner A closer than corner B? (source: author)
Resurgence of Gestalt Theory

Despite the relative ease with which the principles of gestalt theory are demonstrated, the popularity of the theory declined through the middle of the twentieth century. This decline was primarily due to an inability to mathematically model the grouping principles of the theory and to measure the effects of the principals (Wagemans et al., 2005). However, as modern computer-based experimental procedures were developed in the nineteen-eighties and nineties, research on these theories has experienced a resurgence. The neo-Gestalt psychology movement has used the modern understanding of the neural pathways of the vision system and advanced computational methods to quantitatively characterize the grouping principles of gestalt theory (Wagemans et al.; Gordon, 1997).

Visual Inspection Methods and Standards

Visual inspection has a tendency to be a subjective activity. To reduce the subjective nature of visual inspection tasks, standards have been written to assure consistent practices and viewing environments. The American Society for Testing and Measurement (ASTM) and other professional societies have developed standards for the inspection of opaque objects, color (ASTM D1729-96) and gloss (ASTM D523-89). ASTM standards have also been written to standardize the design of visual inspection processes (ASTM E 1808-96) as well as the selection and training of inspectors (ASTM E 1499-97).
For the design of visual experiments (ASTM E 1808-96), the ASTM established two categories. Threshold and matching experiments are designed to determine just perceptible differences (JPD) in stimulus. The threshold of a subject's sensitivity is determined through these experiments. Specifically, these experiments are conducted to discover how much change in physical properties is required to establish a perceptual change.

Scaling experiments comprise the second category of visual experiments. These experiments establish relationships between perceptual magnitudes and physical magnitudes. The scales used in these experiments are classified into four cases as follows. Nominal scales are simple scales where the levels of the factors are identified by name only. For example, consider color as a factor, where the nominal scale would include red, yellow, green etc. Ordinal scales are an order of a particular attribute. However, the magnitude of difference between each level on the scale may not be consistent. Relationships such as greater than, less than and equal to may be attributed to ordinal-scale data.

Interval scales have equal spacing between levels of the scale. However, the scale has no meaningful zero value. Fahrenheit and Celsius temperature scales are examples of interval scales. In addition to the relationships that can be applied to coordinate scales, addition and subtraction may be performed upon interval scale data.

Ratio scales include a meaningful zero point. Therefore ratios of numbers may be created as well as meaningful negative numbers. The absolute temperature scale of degrees Kelvin is an example of a ratio scale. In addition to previously mentioned operations, multiplication and division operations are
added to the list of functions that may be performed upon ratio-scale data.

The standard outlined several basic types of threshold experiments. Included in these experiment types are the method of adjustment, method of limits and methods of constant stimuli. In methods of constant stimuli, several magnitudes of stimuli are chosen around the anticipated threshold level. The stimuli are presented in random order with replication. From the collected data the threshold on detection and its uncertainty can be determined.

Yes-no procedures (also called pass-fail methods) are methods of constant stimuli. In these procedures observers are asked to respond yes if they detect the stimulus and no if the stimulus is not detected. The threshold level is determined by a fifty-percent yes response.

ASTM E 1808-96 also discusses the paired comparison as a method of visual experimentation. In this procedure all specimens in all possible combinations of factor levels are presented to the observer one pair at a time. The number of times some aspect of one specimen is judged greater the same aspect in the other is recorded. Interval scales may be obtained by applying Thurstone's Law of Comparative Judgments, resulting in normally distributed perceptual magnitudes (Bartleson & Grum, 1984; Torgerson, 1958).

ASTM D1729-96 – Color Inspection

The ASTM color inspection standard includes specifications for the construction of the inspection apparatus, preparation of specimens and observation procedures. Illuminants are called out per the CIE standards. The light illumination is designated to be one of three types, overcast northern-sky
light (CIE $D_{75}$), average daylight (CIE $D_{65}$) or the CIE illuminant $D_{50}$.

By the standard, ambient fields of specified color and gloss shall surround the specimens under inspection. For general inspection, the surround shall have a color with the Munsell value of N5 to N7 and a maximum chroma of 0.3. The gloss of the surround shall be no greater than 15 on the 60° gloss scale as described in ASTM D523-89 (gloss measurement).

Viewing distances are specified as 450 to 600mm (16.7 to 23.6 in.). Viewing angles are specified based upon the glossiness of the specimen. Some specimens appeared differently when the viewing geometry is changed; therefore the standard specifies that specimens should be examined with various viewing angles.

Visual Detection of Sink Marks

Marchewka (1973) performed the formative research in sink mark visibility while working at General Electric Company. Textured sample plaques were molded with structural ribs of varying thicknesses. The sample plaques were then visually evaluated to determine the visibility of the sink marks that formed over the rib.

Two textures were used in this research 0.025mm (0.001 in.) deep and 0.076mm (0.003 in.) deep. Three rib thicknesses were used, 1.5mm (0.060 in.), 2.00mm (0.080 in.), and 2.5mm (0.100 in.). The ribs were positioned at two distances from the gate 89mm (3.5 in.) and 133.3mm (5.25 in.). Little information was provided concerning the design of the visual inspection portion of the experiment. Statistics were not performed upon the data. Thus, the data were characteristically subjective and marginally useful for perception studies.
The researcher did conclude that surface finish did help to disguise sink marks that are formed due to unavoidable product design requirements.

Work performed at Western Michigan University in 1999 showed that sink marks could exist on a molded product and not be visually undetectable to an observer (Horton, 1999). A single surface texture was evaluated in the study. The texture was a marginally directional grain having a depth of 0.025mm (0.001 in.). The product evaluated in the study was an automotive console component. Five sink marks in the surface of the part were evaluated.

Parts were molded and sink mark depth was determined with a CMM. Painted and unpainted parts were evaluated. The visual acuity of test subjects was determined with the Effron visual acuity test (Horton, 1999). Ninety-three observers were evaluated. Various methods of holding and observing the product including masking methodologies were investigated. The parts were evaluated with a McBeth Spectralight II lighting system using simulated daylight illuminant (CIE D65).

The research determined that observers could not see sink marks that were 0.040mm (0.0016 in.) deep. Further all subjects could detect sink marks deeper than 0.075mm. The research suggested that a perceptual threshold existed at a sink mark depth of approximately 0.050mm (0.002 in.). The research determined significantly different thresholds for one sink mark (0.044mm and 0.050mm). However the research did not include consideration of sink mark width or environmental effects (i.e. proximity to other sink marks and part features.)
Summary

Sink marks are a common, problematic defect in the injection molding industry. Design guidelines exist for avoiding or reducing the appearance of these defects. However, some product designs require that these guidelines be violated. Software tools exist to help the part designer predict sink marks and to develop designs to reduce the severity of the mark. These same predictive tools can help the process engineer develop processes that reduce the severity of sink marks.

However, none of these simulations have the ability to tie the predicted geometry of a sink mark to the probability of visual detection by a human observer. No simulation takes into consideration the color of the molded object. No simulation exists that can tell the designer how a surface texture will affect the perception of a sink mark. Finally, no simulation predicts the probability of visual detection given a predicted geometry of a sink mark.

Industrial inspection practices are widely investigated and ASTM standards do exists for some typical inspection practices. While these standards generally apply to color inspection, they set the foundation for inspection for product defects. Reproducible inspection methods can be developed using these inspection standards as a basis for comparisons of sink marks in products having various surface texture and colors.
CHAPTER III

METHODOLOGY

Overview

The research was conducted in a series of stages. The planning stage consisted of the design of the sample part, the design of the tool that would mold the part and the development of the injection molding processes that would provide the levels of sink mark width and depth required for the experimental design. The experimental design was developed during this stage and the factor levels were determined. The next stage involved the molding of sample plaques, measurement of these plaques and selection of plaques to use in the interviews. Subject interview protocols and data collection instruments were then developed. The protocol was written and submitted to the Human Subject Institutional Review Board (H.S.I.R.B.) at Western Michigan University for approval. Upon approval of the protocol, subject interviews commenced and data were collected. This section details the steps involved in each stage of the research.

Plaque Development

Much consideration was given to the design of the product used for the molding of sample sink marks. The geometries of the product would determine the uniformity of the sink mark, the repeatability of sink mark formation and
the ease of surface measurement. Important design characteristics of the product included the ability to produce a uniform flow front during injection, a uniform pressure gradient within the melt during molding and a certain amount of flexibility in the design characteristics of the features that formed the sink marks.

It was important that the sink marks be uniform across the entire part so that measurements taken anywhere along the rib would be characteristic of the sink mark depth at all points along the rib. Uniform temperature and pressure during mold filling would increase the probability of such a condition. Most significant to the formation of these uniform conditions was the selection of and location of the gate.

Figure 22. Illustration showing the geometry of the plaque molded during experimentation and used during subject interviews.
The part was a simple 76 x 63.5mm (3 x 2.5 in.) plaque, shown in Figure 22 above. Ejection bosses were located near each corner of the plaque to also serve as locating features. A single wall thickness was used so the surface of the sample part was smooth and uniform outside the area of the sink mark. This ensured that the sink mark was easily detectable and visually dissimilar from the surface of the part. Therefore the area of visual search was less likely to be cluttered with distracting artifacts.

A single, centrally located edge gate was used to ensure uniform cavity filling. The filling pattern can be observed in Figure 23. The edge gate allowed the product to be held and transported by the sprue until the plaque was cooled and de-gated.

![Moldflow Plot](image)

Figure 23. Plot of the filling pattern of the cavity as determined by a Moldflow filling analysis.
The sink mark formed over a single rib that was located on the bottom surface of the part. The rib had two thicknesses, 3.1750 mm and 1.5875 mm (0.1250 and 0.1875 in., respectively). These rib dimensions were chosen as they are standard rib sizes and can be cut using off-the-shelf tapered end mills.

The two rib thicknesses provided two sink mark widths for analysis. The rib was positioned perpendicular to flow to minimize the pressure difference down the length of the rib. In Figure 24 it can be seen that the melt pressure distribution down the length of the rib is fairly uniform.

![Figure 24](image)

Figure 24. Plot of the pressure gradient within the plastic at end-of-fill as determined by a Moldflow filling analysis.
Material used was polypropylene (PP) homopolymer manufactured by Huntsman Chemical. Polypropylene is a common material in the injection molding industry. Its properties are well known and it is common for problematic sink marks to form in products molded in polypropylene (Beaumont et al., 2004; Rosato & Rosato, 1995; Strong, 1996). Additionally, polypropylene is easily colored, a characteristic that was necessary for the testing of different colors. It was assumed that this material would develop acceptable sink marks, as it exhibited moderate volumetric shrink rates.

Tool Development

The sample plaques were molded in a single-cavity Master Unit Die (MUD) base tool. The mold, shown in Figure 25 and Figure 26, measured 165mm by 203mm (6.5 x 8 in.) at the parting line and was water-cooled. Cooling circuits were located in the cavity and core plates of the mold. While the base material of the mold was P20, the molding surfaces were formed of 420 stainless steel.

The plastic was injected through a cold runner system consisting of a sprue with an entrance orifice of 3.5mm (0.140 in.) and an exit orifice of 6mm (0.250 in.). The plastic traveled down a single runner having a diameter of 6mm (0.250 in.) and through a 0.75mm x 6mm (0.030 x 0.250 in.) edge gate with a land length of 1.5mm (0.060 in.). Flow length from gate to end-of-fill was 61mm (2.4 in.).
Figure 25. The bottom half of the plaque mold with the adjustment screw shown on the left.

Figure 26. Photograph of the top half of the plaque mold showing the texture insert.

Figure 27. Cross section of the bottom half of the mold showing the relative positions of the adjusting wedge and the cavity wedge.
The tool design was such that the wall thickness could be adjusted in a range from 1.4mm to 8mm (0.055 to 0.315 in.). This adjustment was accomplished by the action of two wedges located within the cavity insert of the tool. The geometry of the wedges can be seen in cross section in Figure 27. The position of bottom (adjusting) wedge was selected by the adjustment of a fine threaded screw and supported the upper (cavity) wedge. The upper wedge was held against the lower wedge by spring-loaded bolts, when the lower wedge moved, the height of the upper wedge varied; in this manner, the depth of the cavity was changed.

Figure 28. Photograph of wedge and bottom of the sample plaque illustrating the relationship between the tool and the plaque geometries.
The exposed surface of the upper wedge formed the bottom of the sample plaque. The rib geometry was cut into this surface. This geometry can be observed along with the geometry of the molded plaque in Figure 28.

To allow for various textures, three different inserts were used to mold the top surface of the plaque. These inserts were bolted to the 'A' plate within the cover half of the mold. To perform texture changes, the cover half of the tool was removed from the mold base and the insert was unbolted from the tool. The sprue bushing passed through the insert. Figure 29 shows this design and illustrates the position of the sprue relative to the insert.

![The bottom half of the mold showing the texture insert. In this photograph, the insert for the moderate texture level is shown. The thermocouple can be observed in the center of the pocket for the insert.](image)

The stippled textures were applied to the areas of the insert that formed the cavity. Per conventional industrial practices, the texture was applied after
the surface of the insert had been polished to a Society of Plastics Industry (SPI) class B1 finish (Rosato & Rosato, 1996). Textures used were a fine 0.018mm (0.0007 in.) deep stipple and a coarser 0.060mm (0.0024 in.) deep stipple created by media blasting techniques. A third level of texture was included in the experimental design as a 'no texture' condition. This treatment exhibited an SPI B1 finish and simulated pre-grain conditions. The selected texture depths reflected moderate stipple found in a small review of furniture and automotive products. The fine texture was approximate to the Rawl Engravings standard RE6622 while the coarse texture approximated RE6626 (Rawl, n.d.).

A J-type thermocouple was located in the texture insert, 6mm (0.120 in.) beneath the molding surface and surrounded with thermal transfer compound to ensure efficient transfer of heat to the thermocouple. The position of the thermocouple can be seen in Figure 29. The purpose of the thermocouple was to ensure consistent cavity temperature between various trials. Consistent cavity temperatures for each process setup were desired to help reduce the variability between different attempts at molding the sink marks.

A pressure transducer was used to sense the pressure in the plastic at end-of-fill. The purpose for monitoring this variable was to reduce variability in the process between trials. It was essential to establish the cavity pressure to produce similar molding conditions for the setups for the various textures.

These data were collected in order to duplicate process conditions on different days. The ability to monitor and track the important process variables of cavity pressure and temperature improved the researcher's ability to create consistent sink mark geometries with different process setups. Thus the researcher was able to mold the glossy, un-textured plaques, characterize the
sink mark geometries and then mold the other textures with the selected process conditions.

Process Development

Molding of the sample plaques was conducted in the Plastics Processing Laboratory at Western Michigan University on a 1999 Cincinnati Milacron Roboshot 110 electric injection molding machine. The molding cell can be seen in Figure 30. The injection molding machine had a maximum clamping tonnage of 1517 MPa (110 tons). A Regloplas model 90S temperature control unit regulated mold coolant temperature. Coolant flow and temperature were monitored on each cooling circuit to ensure replication of the proper molding conditions for each setup.

Figure 30. Molding cell used during the molding of the plaques illustrating the layout of the equipment.
A Motan loading system was used to load at the injection molding machine. The material used for black plaques was a salt-and-pepper mixture of carbon black colorant supplied by Uniform Color Company. The material was hand mixed using a 50:1 plastic-to-colorant ratio by weight. Black plaques exhibited a Munsell value of N2.42 and a chroma of 0.04. For the plaques molded in grey, a mixture of carbon black and titanium oxide was used to provide a specialized shade of grey. Because carbon black was used, the resulting color was slightly biased toward the hue of blue as exemplified by its Munsel hue of 2.38PB. Value and chroma for the grey were 8.70 and 1.53, respectively. The black color was selected to reflect the popular carbon black colorant usage. The grey was design to be neutral in hue and slightly more luminescent that the standardized inspection booth color of N6-7 (D1729-96).

The formation of sink mark depth and width relate to each other as they are both dependent upon the same root causes of part geometry and process variables. It was necessary to investigate the geometries of sink marks formed by a great number of process designs. Specialized combinations of process variables and cavity depths were developed to mold plaques that exhibited a variety of sink mark widths and depths.

Process variables known to have significant effect on the development of sink marks were varied within acceptable conditions for molding fully formed plaques. The variables that were adjusted included: packing pressure, injection speed, coolant temperature, material-temperature and cavity-depth (wall thickness). The various process setups that were investigated are listed in Table 1. Cavity depths of 1.5, 2.0 and 2.5mm (0.06, 0.08 and 0.10 in.) were used for
processes. Additionally, packing pressures of 35, 70, 100 and 140 MPa (5, 10, 15 and 20 ksi) were used for each process number and cavity depth combination. Thus, a total of ninety-six machine setups were conducted.

Table 1

<table>
<thead>
<tr>
<th>Process No.</th>
<th>Coolant Temp. (°C)</th>
<th>Front Zone Temp. (°C)</th>
<th>Injection Volume (linear) (mm)</th>
<th>Injection Speed (mm/sec)</th>
<th>Max Injection Pressure MPa</th>
<th>Packing Time (sec)</th>
<th>Cooling Time (sec)</th>
<th>Mold Open Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>32.2</td>
<td>218</td>
<td>9.5</td>
<td>89</td>
<td>103</td>
<td>8</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>15.5</td>
<td>218</td>
<td>9.5</td>
<td>140</td>
<td>140</td>
<td>16</td>
<td>35</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
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<td>227</td>
<td>9.5</td>
<td>140</td>
<td>140</td>
<td>16</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>4</td>
<td>15.5</td>
<td>204</td>
<td>14.6</td>
<td>140</td>
<td>140</td>
<td>16</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>5</td>
<td>32.2</td>
<td>204</td>
<td>14.6</td>
<td>140</td>
<td>140</td>
<td>16</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>32.2</td>
<td>204</td>
<td>14.6</td>
<td>89</td>
<td>140</td>
<td>16</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>32.2</td>
<td>227</td>
<td>14.6</td>
<td>89</td>
<td>140</td>
<td>16</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>15.5</td>
<td>227</td>
<td>14.6</td>
<td>89</td>
<td>140</td>
<td>16</td>
<td>10</td>
<td>0</td>
</tr>
</tbody>
</table>

*Cavity depths of 1.5, 2.0 and 2.5mm (0.06, 0.08 and 0.10 inches) were used for all processes.

For each process and cavity depth combination, packing pressures of 35, 70, 100 and 140 MPa (5, 10, 15 and 20 ksi) were used.

The temperature of the cavity and end-of-fill cavity pressure were monitored using sensors embedded in the mold. A specialized program written using LabView data acquisition software was used to visualize the outputs from the sensors. For each process setup, the molding cell was allowed to run until the mold reached thermal stability. The process was judged to be in a condition of thermal stability when the peak temperature of the cavity (as measured by the embedded thermocouple) reached a consistent temperature for each cycle. Peak packing pressure was also confirmed for each setup.

Once the process had established thermal stability, twelve sample
plaques were collected and labeled. The plaques were allowed to cool for a minimum of five minutes on a flat surface and then the runner system was removed at the gate. The plaques were then stored in a climate-controlled environment at 20° C (72° F) for 72 hours. This time allowed for stabilization of post-molding volumetric shrink prior to measurement of the sink mark profile.

Measurement of the Plaques

A Mitutoyo Surftester was used to measure the surface profile of the plaques. The Surftester may be more commonly known as a profilometer and can be seen in Figure 31. A computer was used to record data based upon the movement of the stylus of the surftester. The software was capable of perform mathematical leveling of the data as well as filtration and statistical calculations on the data. The depth of the textures as well as the sink mark widths and depths were measured using this device.

Before parts were measured, a gage repeatability and reproducibility (R&R) study was conducted to determine sources of measurement variability in the measuring system. Analysis of variance (ANOVA) methods were used to determine the sources of measurement variation. Ten parts were selected from various process setups and each part was measured three times for three consecutive days. Potential sources were to be day-to-day variation, the gage, and the parts. Ninety-eight percent of the measurement variation was found to be from differences in the plaques. Acceptable gage R&R results in industry can attribute as low as 60% of the measurement variation to the parts.
The Mitutoyo software allowed the researcher to filter out high frequency responses caused by the surface texture on the plaques. Filtering the texture out of the signal from the stylus revealed the waviness profile of the sink mark. The act of filtering was approached carefully as over-filtration could have resulted in the degradation of the measurement signal. This would have resulted in the misrepresentation of the depth of the sink mark. The threshold values used by these filters were customizable; therefore separate filters were developed for each texture used in the study. Over-filtration of the measurement signal was avoided by using a filter having a specific threshold for the particular texture depth.
Process Selection

Plaques were first molded without texture. These plaques were used to characterize the sink marks for each process setup. The plaques from each process design were measured and the sink mark widths and depths were plotted against each other as in Figure 32. Specific processes were then selected to mold the plaques to be used during the subject interviews.

![Sink Mark Width vs. Depth For Example Processes](image)

Figure 32. Sink mark depth plotted against the width of the sink mark for a sample of process setups investigated. The formation of width and depth was interrelated and not all depths would form at all widths.

The lack of texture on the part surface simplified the determination of the sink mark width and depth because the profile measurements did not have the roughness effects from the texture. This method also reflected industrial
practice where "pre-grained" parts are molded before the surface texture is etched into the cavities. Problematic sink marks are often identified during these "pre-grain" tool trials.

Because the widths and depths were interrelated through the part design and process settings, certain depths could not be molded for all widths. In Figure 32 it can be seen that for narrow sink marks, extremely deep sink marks were not formed. This caused difficulties in the design of the experiment, as a full-cross design of depth and width levels could not be made using substantially different widths.

Figure 33. Sink mark depth plotted against the width of the sink mark for processes selected for molding sample plaques. Thresholds for sink mark visibility from Horton's study (1999) are shown on the right.
To resolve this problem, four sink mark depths were selected for use in the experiment, three at each sink mark width. The narrow sink marks, formed over the narrow rib, were to have depth levels of none, minor and shallow (0.000, 0.008 and 0.0024mm or 0.0000, 0.0003 and .0009 in., respectively). The wide sink marks were to have depth levels of none, shallow and deep (0.000, 0.0024 and 0.035mm or 0.0000, 0.0009 and 0.00014 in., respectively). These levels, and the relative widths, can be seen in Figure 33.

The selected depth levels reflected the visibility thresholds discovered in research by Horton (1999). These levels are indicated in Figure 33. The deep sink level in this research was equivalent to the upper threshold found by Horton. The shallow sink mark depth used here was below the lower threshold in Horton's work, where all respondents could perceive the sink mark.

Experimental Design

As discussed during part, tool and process development sections, factors of interest in the research included the sink mark depth and width, the depth of the surface texture and the color of the part. Given that visual responses are often non-linear (ASTM E 1499-97; Burnham, et al., 1960), the sink mark and texture depth factors were designed to have three levels. The effects of color and sink mark width were evaluated at two levels.

To remove the possible difficulties due to subject color sensitivity the colors evaluated were neutral hues, specifically black and grey. As discussed above, the black exhibited a Munsell color value of N2.42 and a chroma of 0.04. The methods used in the creation of the grey resulted in the color being slightly biased toward blue, having a Munsell hue of 3.19PB, a color value of 8.70 and a
chroma of 1.53. The effect of color on sink mark visibility was evaluated for a single width to contain the extent of the experimental design.

Constraints on the possible sink mark of widths and depths formed on a single plaque were discussed in the previous section. Because of these restrictions, concessions were made in the selection of levels for these factors. The effects of sink mark depth would be evaluated in each width separately, and the effects of sink mark width would be evaluated at the single level of the sink mark depth factor that was common between the two widths.

In total, four experiments were developed. The first two experiments separately investigated the effects of sink mark depths and textures for the each of the two sink mark widths. The third experiment examined the effects of sink mark width at the common 0.024mm (0.0009 in.) deep sink mark. The fourth experiment was designed to determine the effects of depth, texture and color on the appearance of the wide sink marks.

Within each experiment, a full cross design of all factors and levels was created. From the design, a list of the combinations of factors and levels required for all treatments was generated. Summary of the factor levels and how the levels correspond to specific plaques can be seen below in Table 2.

Pairs of plaques were shown to the subjects during the interviews. The subject would decide if the sink mark was visible on each plaque. If the sink mark was visible on both plaques, the subject would then be asked to make a qualitative decision as to which sink was more discernable. To minimize eye dominance effects on the observations, presentations of a particular plaque were balanced between the left and right position in the viewing fixture.
Table 2
Factor Levels and Plaque Identification

<table>
<thead>
<tr>
<th>Plaque*</th>
<th>Sink Mark Width Level mm</th>
<th>Sink Mark Depth Level mm</th>
<th>Sink Mark Cross-section Texture Depth Level mm²</th>
<th>Texture Depth Level mm</th>
<th>Color Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0 0.00</td>
<td>0 0.00</td>
<td>0 0.000</td>
<td>0 0.000</td>
<td>0 Black</td>
</tr>
<tr>
<td>2</td>
<td>1 3.28</td>
<td>1 0.008</td>
<td>0.0125</td>
<td>0 0.000</td>
<td>0 Black</td>
</tr>
<tr>
<td>3</td>
<td>1 3.28</td>
<td>2 0.024</td>
<td>0.0493</td>
<td>0 0.000</td>
<td>0 Black</td>
</tr>
<tr>
<td>4</td>
<td>2 5.05</td>
<td>2 0.024</td>
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<td>5</td>
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<tr>
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</tr>
<tr>
<td>7</td>
<td>1 3.28</td>
<td>1 0.008</td>
<td>0.0125</td>
<td>1 0.0254</td>
<td>0 Black</td>
</tr>
<tr>
<td>8</td>
<td>1 3.28</td>
<td>2 0.024</td>
<td>0.0493</td>
<td>1 0.0254</td>
<td>0 Black</td>
</tr>
<tr>
<td>9</td>
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<td>1 0.0254</td>
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<tr>
<td>12</td>
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<td>1 0.008</td>
<td>0.0125</td>
<td>2 0.0635</td>
<td>0 Black</td>
</tr>
<tr>
<td>13</td>
<td>1 3.28</td>
<td>2 0.024</td>
<td>0.0493</td>
<td>2 0.0635</td>
<td>0 Black</td>
</tr>
<tr>
<td>14</td>
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<td>2 0.024</td>
<td>0.0531</td>
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<tr>
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<td>3 0.035</td>
<td>0.0752</td>
<td>0 0.0000</td>
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</tr>
<tr>
<td>20</td>
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<td>2 0.024</td>
<td>0.0523</td>
<td>1 0.0254</td>
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<td>21</td>
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<td>2 0.0635</td>
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</tr>
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<td>24</td>
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<td>3 0.035</td>
<td>0.0752</td>
<td>2 0.0635</td>
<td>1 Grey</td>
</tr>
</tbody>
</table>

* Plaques 16, 19 and 22 were not used in the research

Each pair of plaques could be shown to the subject in two configurations, with each plaque presented either on the left or right. A program was written to select which of the two presentation combinations to use for each pair so that a
presentation order was create that exhibited the best balance between left- and right-side observations of each plaque. When it was not possible to find a perfect balance between left- and right-side presentations for a plaque, the program would find the best-case solution. The best-case solution would minimize the number of unbalanced plaques presentations in a particular experiment. Once the particular pairs were selected, the presentation order was randomized during the interviews. All 183 pairs used in the four experiments are shown in Appendix A.

Much consideration was given to reduce the time required to conduct subject interviews. In order to assure the inclusion of test subjects familiar with sink mark defects, it was desired to draw many of the subjects from injection molding companies. It was considered important to keep the costs of time commitment at a minimum as it was expected that shorter interviews would result in a greater number of companies willing to participate. Thus, in favor of decreasing interview time and increasing the participation of volunteer companies, the experimental resolution was selectively reduced. While all factor combinations were used in the treatments for plaque observations, comparisons with identical treatments in pairs were removed from the design.

Plaque Selection

The selected processes were used to mold plaques of all three levels of texture. Plaques were molded in black and grey to accommodate all treatments in all four experiments. These plaques were then measured to confirm that the sink marks on these plaques reflected the depths of the sink marks on the plaques without texture. Two sample plaques for each treatment in the
experimental design were then selected for use in the subject interviews.

Part Viewing Fixture

A viewing fixture was designed and built to hold the plaques during the observations and to facilitate rapid changes between the presentations of various pairs of plaques. The interviews were conducted at various locations; hence the fixture was designed to be robust and properly sized for portability. The booth in its completed form can be seen in Figure 34.

Figure 34. The inspection booth used in the experimentation. The upper surround can be removed for transportation and the carousels holding the parts are accessible through the back. (Source: author)

The observation booth was designed to conform to ASTM D1729-96
inspection standards, with minor additions. Following the standard, the interior of the booth was illuminated with a CIE D65 type illuminant and the table and surroundings were painted neutral grey. Specifically, the color of the interior surfaces of the booth exhibited a Munsell color value of N6.12 and a chroma value of 0.2.

The addition to the inspection standard was the allowances for the parts to be held by the fixture, but moved by the interview subject. Given that motion can help the human eye to perceive changes in depth and shadows, the fixture was designed to allow the subject to tilt the parts 20° away and an equal amount toward the opening in the booth. The tilting features of the fixture table can be seen in the initial design shown in Figure 35.

Figure 35. Cross section view of the design of the plaque inspection booth. Image A shows the table in a neutral position and in image B the table is tilted 20° away from the inspector. The table was also capable of tilting 20° toward the inspector. (Source: author)
The tilting caused the angle of illumination of the plaques to change and provided variation of any shadows that might be created by the sink mark. The axis of the tilting action was positioned through the center of the plaques.

Pairs of plaques were presented to the subject by indexing two carousels that held the sample plaques used in the interview. Each plaque was covered with a mask that limited the area of visual inspection to a 26 x 39mm (1 x 1.5 in.) opening centered over the sink mark. The masks were colored similar to the booth surfaces and had a Munsell color value of N6.12 and a chroma value of 0.2. By limiting the area of visual search, the time required for inspection was reduced. The appearance of the plaques as presented to the subject may be seen in Figure 36.

Figure 36. Interior of the inspection booth showing the left and right presentation positions of the plaques.
Development of Interview Protocols

After the sample plaques had been molded, the experimental design had been set, and the viewing fixture designed, the subject interview protocols were developed. Western Michigan University research policy requires that human subject research protocols be reviewed and approved by the Human Subjects Institutional Review Board (H.S.I.R.B.) prior to the subject interviews. The protocol submission documents can be found in Appendix B. Supplemental illustrations for the submission are contained in Appendix C.

Subject Recruitment

Recruitment signs and pamphlets were posted at the College of Engineering and Applied Sciences of Western Michigan University and at plastics molding companies in western Michigan. These companies were solicited through existing relationships with the Plastics Processing Laboratory at Western Michigan University. A solicitation letter (shown in Appendix D) was sent to a contact person at companies that would have interest in robust injection molding design. Access to subjects from the employees of the companies was solicited through the company's contact personnel and was documented by the signing of an access-granting letter. These letters and site approval letters from the HSIRB may be found in Appendix K.

Subjects were selected from the individuals that responded to signs, pamphlets and verbal communication that invited them to participate in the research (Appendix E). The invitation information explained the purpose and benefits of the research to potential subjects. Efforts were made to ensure that
subject participation was not compulsory.

In order to increase the sensitivity of the research instrument, subjects were required to have a corrected visual acuity of 20/20 vision or better. Visual acuity and contrast sensitivity was assessed using the computer-based Freiburg Visual Acuity & Contrast Test ('FrACT') (Bach, 2006; Wesemann, 2002). The subjects wore any needed corrective appliances (eyeglasses or contacts) during the interview sessions. Additionally, laser corrective surgery was not an exclusionary criterion (Dennis, Beer, Baldwin, Ivan, Lorusso & Thompson, 2004). Individuals who had undergone Laser Assisted In Situ Keratomileusis (Lasik) or other corrective surgeries were not excluded from this research.

Subjects younger than 18 and older than 40 years old were excluded from the subject pool for this research. This exclusionary criterion served two purposes. First, there was no need for this research to involve protected populations such as those under the age of legal consent. These younger individuals have limited purchasing power in high-end consumer markets where many plastic products are found. Secondly, research has shown that the quality of vision deteriorates with age (Dollinger & Hoyer, 1996; Madden & Plude, 1996; Plude & Hoyer, 1985). Generally the age of forty is accepted as a standard threshold for the onset of considerable changes in visual acuity.

Informed Consent Process and Confidentiality

Each test subject met privately with the interviewer for two sessions of sink mark observations. Potential subjects were told that each session would last approximately one hour and rest periods would be provided. The informed consent process emphasized non-coercive methods and no reprisal for non-
participation.

Prior to the performance of the interview, the process and background of the research was explained to potential subjects. The aspects of the experiment, such as sink marks and textures were explained to the subject. Sink marks were described and samples shown to the subject. Various stipple were shown to the subject and the effects of stipple on the visibility of sink marks were explained. The scripts contained in Appendix F were used inform and educate potential subjects.

The operation of the inspection fixture was explained and demonstrated. The protocol of the experiment, the presentation of the pairs of plaques and proper responses to the interview questions were discussed with the subject. It was explained that during the inspection process, the subject was not able to handle the parts but was allowed to tilt the part by tilting the table of the fixture.

The potential subjects were informed that if they begin feeling eye or head discomfort, they would be allowed rest periods as required. The rest periods were allowed to last until test subjects felt they could continue. The rest periods would begin immediately if the subject requested them. At no time during the interview did a test subject request a rest period.

All the information collected during the project was confidentially maintained. Names did not appear on any papers where information was recorded. No information was collected that could be used to personally identify the participants in the study. Participants were assigned an identification number and the link between that number and the subject's identity was broken after the subject completed the second interview. Per University regulations, all
informed consent forms will be retained for at least three years in a locked file in the principal investigator's office.

Once the potential subject had been made familiar with the study through the scripts and examples, they were asked to sign the informed consent form (Appendix G). Two copies of the form were given to the potential subject. One form was signed and returned to the researcher. A copy was given to the subject to keep for their personal records.

Interview Procedure

The interview sessions involved a combined visual acuity and contrast sensitivity test known as the Freiburg Visual Acuity & Contrast Test or 'FrACT' (Bach, 2006). This test allowed for the characterization of the visual ability of the subject. The subjects were asked to respond to a series of questions about images displayed on the screen of a laptop computer. The questions pertained to the subject's ability to discriminate between levels of contrast.

The subjects also completed a brief questionnaire. The attached questionnaire (Appendix H) was used to provide classifying information about the subjects such as age and level of education. Once the test and questionnaire were completed, subjects then viewed plastic parts within the viewing booth.

Paired comparisons were used in the research procedure. Subjects were simultaneously shown two parts and asked if they could see a sink mark on each part. Subjects were then asked which one of the two sample plaques exhibited the worst quality (in other words, which part would they be the least likely to buy at a store). If one sink mark was selected more often, then it was concluded that the observers were able to discriminate some difference between the two
sink marks. The only discrimination information provided was if one part is strongly preferred. It simply indicates that observers were able to tell the difference between the two parts.

Data were collected with the use of a spreadsheet form shown in Appendix I. Within the spreadsheet, subjects were identified by number only. A cross-reference sheet was used to assure the same subject number was used for the same subject during both interview sessions. At the completion of the second series of interviews, the cross-reference sheet was destroyed, eliminating the link between the subject's identity and the subject number. This removed any means connecting the subject with their responses and assured confidentiality.

Pilot Study and Interviews

A pilot study was conducted using a limited number of subjects. The purpose of the pilot study was to confirm that the fixture and data collection software would function as intended and that the levels chosen for the study would provide useful data. While the final study would use subjects from industry, six students with varying familiarity with sink marks were chosen as subjects for the pilot study. These interviews were conducted in the Plastics Processing Lab.

Off-site interviews were conducted for the primary study at willing injection molding companies. The inspection booth was taken to three companies in western Michigan and a total of 24 employees were interviewed. After the completion of the off-site interviews, six additional interviews were conducted at the Plastics Processing Lab at Western Michigan University.
Analysis Methods

After data collection was complete, the data were verified to confirm that they conformed to assumed responses. Additionally, to limit error to an acceptable level, the variability within the data was analyzed to confirm that an appropriate number of subjects had been interviewed. Mean response levels were used to graph rough subject preference.

Maximum likelihood methods incorporating log-likelihood ratios were used to analyze the main effects as well as interaction effects for each experiment. Kruskal-Wallis nonparametric analyses were performed on the main factor to confirm the findings of the log-likelihood analyses. Comparison effects were investigated and a model to predict the probability of the visual detection of sink marks was created. These analyses and results are discussed in the following chapter.

Summary

The research required the design of a product to use in the interviews, as well as the design and modification of a tool to mold the product. A manufacturing procedure was developed to allow for the duplication of molding condition on different days. Thus various textures were molded on different days yet created similar sink marks. The stylus measuring system was used to select plaques that had sink matching the factor levels of the design experiment. Interview protocols were developed and approved by the HSIRB of Western Michigan University (project # 05-08-07). Approval letters for the research protocol as well as interview sites can be found in Appendix J and Appendix K.
CHAPTER IV

RESULTS AND FINDINGS

Overview

The method of research was initiated with a pilot study incorporating two of four planned experimental designs. The purpose of each design is described in Table 3. The results and “lessons learned” from the application of the research instrument were applied toward improvement of the instrument. After the pilot study, thirty test subjects were interviewed using the improved data collection instruments.

Table 3
Summary of Experimental Design Objectives

| EXPERIMENT #1 | Establish the probability of visual detection of sink marks formed over the thin rib on black plaques. These sink marks had a mean width of 3.27 mm (standard deviation of 0.01mm). All three sink mark depths for this width were evaluated. Three texture depths were evaluated. |
| EXPERIMENT #2 | Establish the probability of visual detection of sink marks formed over the thick rib on black plaques. These sink marks had a mean width of 5.05 mm (standard deviation of 0.01mm). All three sink mark depths for this width were evaluated. Three texture depths were evaluated. |
| EXPERIMENT #3 | Establish the probability of visual detection of 0.024mm deep sink marks formed on black plaques. Two sink mark widths were evaluated. Three texture depths were evaluated. |
| EXPERIMENT #4 | Establish the probability of visual detection of sink marks formed over the thick rib on black and grey plaques. Two sink mark depths for this width were evaluated. Three texture depths were evaluated. |
The results were validated for accuracy and appropriateness and then analyzed with maximum likelihood and non-parametric methods, incorporating logit transformations and fitting to the binomial distribution. Significant contributors to the subject perception responses were discovered and their effects investigated.

Pilot Study

A pilot study was conducted to test the capabilities of the collection instruments and to provide a confirmation of the appropriateness of the chosen factor levels. The data were evaluated to establish if the chosen factor levels were effective at eliciting appropriate responses from the subjects. Table 4 summarizes the factors and levels used in the experimental designs of the pilot study.

Table 4
Design Summaries for the Pilot Study

<table>
<thead>
<tr>
<th>EXPERIMENT #1</th>
<th>EXPERIMENT #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Determine the effect of Sink Depth and Plaque Texture for Black Plaques having Sink Width Level 1 (3.27mm)</td>
<td>Determine the effect of Sink Depth and Plaque Texture for Black Plaques having Sink Width Level 2 (5.05mm)</td>
</tr>
<tr>
<td>Factor</td>
<td>Levels (mm)</td>
</tr>
<tr>
<td>Sink Depth</td>
<td>0 (none) 0.000</td>
</tr>
<tr>
<td></td>
<td>1 (minor) 0.008</td>
</tr>
<tr>
<td></td>
<td>2 (shallow) 0.024</td>
</tr>
<tr>
<td>Texture</td>
<td>0 (none) 0.000</td>
</tr>
<tr>
<td></td>
<td>1 (fine) 0.018</td>
</tr>
<tr>
<td></td>
<td>2 (coarse) 0.060</td>
</tr>
</tbody>
</table>
Subject Demographics

The pilot study was conducted in the Plastic Processing Laboratory at Western Michigan University. Seven subjects from the university community were interviewed. The subjects consisted of five men and two women. One subject was in the age range of 18 to 25 years old, four were aged 26 to 35 years old and two were between 36 and 40 years old. All subjects wore corrective lens. Three wore both contacts and glasses while four reported to wear only glasses. Of the three subjects that wore both contacts and glasses, only one reported wearing contacts more often than spectacles. All subjects were near-sighted, none reported ever having eye surgery and none reported to believe they experienced color blindness.

Mean Subject Responses

To facilitate a validation review of the appropriateness of the data collected during the pilot study, the information in Table 5 was compiled. The percent of sink marks detected at each depth, width and texture level can be observed. This value was used as an approximation of the probability of the visual detection of the sink mark for each treatment.

Sample plaques with no sink mark were included in the design of the experiments. These plaque were molded without a rib on the back, therefore no sink mark could form. It was expected that test subjects would not perceive a sink mark on these plaques. The initial review of the mean responses revealed
that no subject detected sink on plaques that did not have a sink mark. This assured that the zero stimulus levels of the study were effective and that subjects could properly identify a condition of no sink marks.

Table 5
Pilot Study: Reported Visual Detection of Sink Marks

<table>
<thead>
<tr>
<th>Plaque</th>
<th>Sink Mark Width Level</th>
<th>Sink Mark Depth Level</th>
<th>Texture Level</th>
<th>Used in Experiment</th>
<th>Total Percent Detected</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Both</td>
<td>0%</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>98%</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>100%</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>100%</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>3</td>
<td>0</td>
<td>2</td>
<td>100%</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>Both</td>
<td>0%</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>84%</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>100%</td>
</tr>
<tr>
<td>9</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>100%</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>100%</td>
</tr>
<tr>
<td>11</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>Both</td>
<td>0%</td>
</tr>
<tr>
<td>12</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0%</td>
</tr>
<tr>
<td>13</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>13%</td>
</tr>
<tr>
<td>14</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>88%</td>
</tr>
<tr>
<td>15</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>98%</td>
</tr>
</tbody>
</table>

Variance Analysis

The data were evaluated to establish how the inclusion of additional subjects in the study affected the variability in subject responses. Variance was calculated using assumptions of the binomial distribution and was expressed as a proportion of the mean response. The variance was evaluated for each plaque used in the design as well as for the total data set. For most plaques used in the
interview, the variance was 0.005 or lower by the third subject. Exceptions were plaques with textures that resulted in minimal concealment of the sink mark (probability of detection approaching 50%).

Experiment #1: Visual Detection of Narrow Sink Marks

For the plaques exhibiting narrow sink marks, variance for all plaques was below 0.01 by the sixth subject (Figure 37). Most plaques exhibited zero variance in subject observations. Variance for two plaques was higher than the others. The plaque with the fine texture and minor sink (Plaque 12) exhibited the largest variance in the experiment. This plaque had a mean probability of detection of 85%.

Figure 37. Effect of the incremental aggregation of subject responses on variance in the data of Experiment #1 in the pilot study.

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In fifty-six observations, only one subject in one trial failed to detect a sink mark on a plaque with no texture. The sink mark was a minor sink mark (0.008mm deep) and is the only source of the variability in observations for Plaque 2. The plaque with the coarse texture and shallow sink (Plaque 13) had increasing variance throughout the data indicating the need for data to be collected from additional subjects. It was assumed that this inclusion of additional subjects would cause the variance to stabilize for this plaque. Variance in the entire data set was approximately 1.29.

Analysis of Main Effects and Interactions

The responses under investigation were binary, binomial in nature and the sample size was relatively small. Therefore general ANOVA methods and the associate assumptions of normality were not necessarily appropriate. Initial investigations into the significance of the factor levels were conducted using maximum likelihood methods of model building.

Maximum likelihood methods find the most likely mean for a group of data by analyzing how well the data fit a given distribution having a certain mean. A series of likely means are analyzed. The mean that best fits the data to the target distribution is chosen as the estimate of the mean. Analytical methods can be used for performing these computations; however they exist only for particular applications. Most often, computer-based iterative numerical search methods are used.

As the response was binary and probabilities (ratios) were under
investigation, exponential regression methods were appropriate (Neter et al., 1996). Responses were blocked by subject. The logit linking function was used along with fitting to the binomial distribution for the determination of the likely means. This transformation is described in more detail later during model construction and can be seen in Equation 3. Log-likelihood ratios were utilized to determine significant effects. Significance of each log-likelihood ratios was evaluated using chi-square tests. The significance of all interaction effects between the factors was investigated. For Experiment #1, factors evaluated using these methods included sink mark depth and texture depth as well as which side of the viewing fixture was used to present the plaque to the subject.

<table>
<thead>
<tr>
<th>Pilot Experiment #1</th>
<th>Probability of Visual Detection - Likelihood Type 1 Test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Distribution: BINOMIAL</td>
</tr>
<tr>
<td></td>
<td>Link function: LOGIT</td>
</tr>
<tr>
<td></td>
<td>Effects shown in bold are significant at $\alpha = 0.05$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Degrees of Freedom</th>
<th>Log-Likelihood Ratio</th>
<th>Chi-Square</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>1</td>
<td>-1387.25</td>
<td></td>
</tr>
<tr>
<td>Viewing Position {1}</td>
<td>1</td>
<td>-1385.56</td>
<td>3.37</td>
</tr>
<tr>
<td>Sink Mark Depth {2}</td>
<td>1</td>
<td>-838.44</td>
<td>1094.24</td>
</tr>
<tr>
<td>Plaque Texture {3}</td>
<td>1</td>
<td>-164.16</td>
<td>1348.56</td>
</tr>
<tr>
<td>1*2</td>
<td>1</td>
<td>-152.45</td>
<td>23.42</td>
</tr>
<tr>
<td>1*3</td>
<td>0</td>
<td>-151.47</td>
<td>1.97</td>
</tr>
<tr>
<td>2*3</td>
<td>0</td>
<td>-151.47</td>
<td>0.00</td>
</tr>
<tr>
<td>1<em>2</em>3</td>
<td>0</td>
<td>-151.47</td>
<td>0.00</td>
</tr>
</tbody>
</table>

The results of this analysis are shown in Table 6. Both sink mark depth and texture level were found to be significant contributors to the probability of
sink mark detection ($\alpha=0.05$). Viewing position was not found to be a significant contributor to variability in the probability of sink mark detection. However, the interaction effect between depth and position was found to be significant ($\alpha=0.05$).

![Probability of Detection of Sink Marks in Experiment #1 in the Pilot Study](image)

Figure 38. Plot of the effect of sink depth on the probability of sink mark detection in Experiment #1 of the pilot study.

Figure 38 shows the main effect of the sink mark depth levels on the probability of the detection of the sink mark. In this scaled effects plot, the levels of the factor have been placed on the x-axis to reflect the relative distance between the levels of the depth factor. It can be observed from this plot that each level of the factor did exhibit a different mean probability of detection. As the sink mark depth increased, the probability of detection increased. The effects of the texture levels can be seen in Figure 39. For this factor, the plaques
having no-texture and fine-texture exhibited similar responses. The coarse
texture exhibited a significantly lower probability of detection. These within-
factor relationships will be investigated later in non-parametric analyses.

![Probability of Detection of Sink Marks in Experiment #1 in the Pilot Study](image)

**Figure 39.** Plot of the effect of texture level on the probability of sink
mark detection in Experiment #1 of the pilot study.

The interaction between the three factors investigated (depth, texture
and position) can be observed in Figure 40. In this plot, it can be seen that the
viewing position did have an effect upon the probability of detection in two
treatments. For the plaque having fine texture and a minor sink mark
(0.008mm deep) the probability of detection was lower for plaques presented on
the right side than for the plaques presented on the left. For the coarse plaque
having shallow sink marks (0.024mm deep) the probability of detection was
higher for the plaques presented on the right that for the plaques presented on
the left. For these coarse plaques, the responses in each viewing position were below the 50% detection threshold of visibility as determined by the ASTM.

Figure 40. Plot of the effects of the interactions between sink depth, texture and viewing position on the probability of sink mark detection in Experiment #1 of the pilot study.

Of great interest, this plot illustrates that the coarse texture was effective for the concealment of the sink marks. Indeed for plaques presented on the left with no sink marks were detected at any level of sink mark depth. For plaques presented on the right, only 20% of the shallow (0.024mm deep) sink marks were detected.

The variance analysis and the effects plots confirm the findings of the
means analysis. For treatments having no sink, test subjects reported no perception of sink. For glossy and fine textured plaques, most subjects reported visual detection of sink marks on plaques with minor and shallow sink marks. For treatments having fine texture (0.018mm deep), the texture did significantly (α = 0.05) reduce the probability of sink mark detection for minor sink marks (0.008mm deep). The coarse texture (0.060mm deep) appears to have significantly reduced the probability of sink mark detection of both the minor (0.008mm deep) and the shallow (0.024mm deep) sink marks.

Non-Parametric Analysis

Non-parametric Kruskal-Wallis ranking methods were used as a secondary validation of the significance of the factors found using maximum likelihood methods. Kruskal-Wallis methods test the hypothesis that the samples in the comparison were drawn from distributions with the same median. Assessments are made by analyzing variation in the ranks of the responses as opposed to the mean as is done in general ANOVA. These methods are an alternative to the F test for one-way ANOVA methods and are appropriate when the assumptions of ANOVA are violated, such as the presence of normally distributed data and the validity of the central limit theorem (Levine, Ramsey & Smidt, 2001). Assumptions of the Kruskal-Wallis Test include that the samples are independent and the response is ordinal. The probabilities under investigation range from zero to one, and are definitively ordinal. The samples from the subjects are independent, as the subjects are unaware of the plaque identifiers and minimal recognition of repeated plaques. This method also assumes that all groups have the same variability. It was
shown in Figure 37 that variability differences between most plaques are small.

The main factors under investigation in Experiment #1 were the depth of the sink mark and the depth of the plaques surface texture. The H statistic exceeded the corresponding chi-square for $\alpha=0.05$ and two degrees of freedom ($\chi^2 =3.841$), hence the effects of the depth factor were found to be significant. Table 7 shows the results of the chi-squares test between each depth level as calculated from the Kruskal-Wallis tests as well as the H statistic for the sink mark depth effect. The between-level tests indicated that there were significant differences between the means of all depth levels.

| Multiple Comparisons p values; Probability of Visual Detection
| Independent (grouping) variable: Depth Level
| Kruskal-Wallis test: $H (2, N=504) =199.8875 \ p=0.000$

<table>
<thead>
<tr>
<th></th>
<th>No Sink</th>
<th>Minor</th>
<th>Shallow</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Sink</td>
<td></td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>Minor</td>
<td>0.0000</td>
<td></td>
<td>0.3256</td>
</tr>
<tr>
<td>Shallow</td>
<td>0.0000</td>
<td>0.3256</td>
<td></td>
</tr>
</tbody>
</table>

Table 7
Kruskal-Wallis Test for Significant Effects between Depth Levels in Pilot Study Experiment #1
Sink Mark Width is 3.27mm

| Multiple Comparisons p values; Probability of Visual Detection
| Independent (grouping) variable: Texture Level
| Kruskal-Wallis test: $H (2, N=504) =161.6214 \ p=0.000$

<table>
<thead>
<tr>
<th></th>
<th>No Texture</th>
<th>Fine</th>
<th>Coarse</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Texture</td>
<td>1.0000</td>
<td></td>
<td>0.0000</td>
</tr>
<tr>
<td>Fine</td>
<td>1.0000</td>
<td></td>
<td>0.0000</td>
</tr>
<tr>
<td>Coarse</td>
<td>0.0000</td>
<td>0.0000</td>
<td></td>
</tr>
</tbody>
</table>
Significant differences were found for the texture factor as well. The comparison of the factor levels shown in Table 8 indicates that the no-texture and fine-texture condition exhibited no significant differences in mean responses. However the coarse texture was significantly different from the two other texture levels (\(\alpha = 0.05\)). Viewing position was not found to be significant (\(H=0.39\), d.f. = 1).

It should be noted that for the main effects, the findings of the non-parametric analysis agree with the log-likelihood ratio tests. The non-parametric analysis confirmed the effect relationships within the plots of the main effects of the sink mark depth and texture depth. Again, this was confirmation of the agreement of likelihood ratio tests to the non-parametric analysis. It was felt that these confirmatory results between the results of the non-parametric analysis and the log-likelihood ratio tests were validation of the methods used to investigate the interaction effects. Thus, the combination of log-likelihood testing and non-parametric analysis was used for all experiments in this research.

Analysis of Pairings with Depth and Texture Level Differences

The experiments were designed to provide for the analysis of the effects of the differences in factor levels between the plaques in the presentation pairs. For the purpose of discussions in this document, the objective plaque is the plaque upon which observation is made. The comparison plaque is the other plaque in the pair presented to the subject. These analyses were performed upon data for comparison plaques where sink was present (i.e. levels greater
than “no sink”) and subject detected sink on at least one plaque in the pair. An example of a difference between the plaques was the difference in sink mark depth, such as presenting a plaque with no sink mark with a plaque having a minor sink mark. Differences of sink mark depths as well as textures were investigated. The results of the likelihood tests of the main factors are shown in Table 9. The main factors of sink mark depth and texture depth were included in the analysis to avoid confounding these primary effects with the difference effects. The effects of presentation position as well as interactions were not included as the purpose was to determine if an effect was present at the factor level.

Table 9
Likelihood Ratios for the Determination of Significant Factor Differences within Presentations in Pilot Study Experiment #1

| Effects of Factors Differences within Presentations of Experiment #1 of the Pilot Study | Probability of Visual Detection - Likelihood Type 1 Test Distribution: BINOMIAL Link function: LOGIT Effects shown in bold are significant at $\alpha=0.05$ |
|---|---|---|---|
| | Degrees of Freedom | Log-Likelihood Ratio | Chi-Square | p-value |
| Intercept | 1 | -554.75 | | |
| Sink Mark Depth (1) | 1 | -551.23 | 7.05 | 0.0079 |
| Plaque Texture (2) | 1 | -128.73 | 844.98 | 0.0000 |
| Depth Difference (3) | 4 | -117.88 | 21.70 | 0.0002 |
| Texture Difference (4) | 2 | -70.22 | 95.33 | 0.0000 |

Depth and texture differences within the presentation pairs were found to have significant effects upon the probability of detection of sink marks. This was the first indication of an environmental effect upon the subject's perception of sink marks within the study.
Experiment #2: Visual Detection of Wide Sink Marks

For investigations of wide sink marks, cumulative variance was below 0.010 by the sixth subject for all plaques. Variance was highest for the plaque with the coarse texture and shallow sink mark (Plaque 14). The plaque with coarse texture and deep (0.035mm deep) sink (Plaque 15) was the only other plaque to exhibit greater than zero variance. Total variance was 0.012. Figure 41 shows the variance for the treatments of Experiment #2 as well as the total variance for the data for Experiment #2.

Figure 41. Effect of the incremental aggregation of subject responses on variance in the data of Experiment #2 in the pilot study.
Analysis of Main Effects and Interactions

Again, log-likelihood ratios were used to determine significant contributors and analyze the interaction effects between factors. Test subject identifier was used as the blocking variable. The factors of sink mark depth, plaque texture and viewing position (as well as their interactions) were analyzed. The results of the analysis are shown in Table 10. In sequential sum-of-squares modeling, effects are added in to the generalized model according to the strength of the effect to describe observed values. In Table 10, the log-likelihood test result for the texture effect shows zero degrees of freedom because the factor had zero degrees of freedom in the model. This does not indicate the degrees of freedom for the factor as used in experimentation.

Table 10

Likelihood Ratios for the Determination of Significant Factor Effects in Pilot Study Experiment #2

<table>
<thead>
<tr>
<th>Pilot Experiment #2</th>
<th>Probability of Visual Detection – Likelihood Type 1 Test Distribution: BINOMIAL Link function: LOGIT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Effects shown in bold are significant at ( \alpha = 0.05 )</td>
</tr>
<tr>
<td></td>
<td>Degrees of Freedom</td>
</tr>
<tr>
<td>Intercept</td>
<td>1</td>
</tr>
<tr>
<td>Viewing Position {1}</td>
<td>1</td>
</tr>
<tr>
<td>Sink Mark Depth {2}</td>
<td>2</td>
</tr>
<tr>
<td>Plaque Texture {3}</td>
<td>0</td>
</tr>
<tr>
<td>1*2</td>
<td>1</td>
</tr>
<tr>
<td>1*3</td>
<td>0</td>
</tr>
<tr>
<td>2*3</td>
<td>1</td>
</tr>
<tr>
<td>1<em>2</em>3</td>
<td>1</td>
</tr>
</tbody>
</table>

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Sink mark depth was found to be a significant contributor to the variability in the subject responses ($\alpha=0.05$). No other factor or interaction was found to have significant effect upon the probability of visual sink mark detection. This result indicates that the texture levels were not adequate to conceal the sink mark depths investigated.

The main effect of sink mark depth on the probability of visual detection of the sink mark was plotted. The plot of this effect can be seen in Figure 42. The plaques having no sink mark elicited a significantly different response than the plaques having shallow (0.024mm deep) and deep (0.035mm deep) sink marks. This plot also confirms that the responses for shallow and deep sink marks had similar responses.

![Probability of Detection of Sink Marks in Experiment #2 in the Pilot Study](image)

**Figure 42.** Plot of the effects of sink depth on the probability of sink mark detection in Experiment #2 of the pilot study.
The interaction between the sink mark depth and the texture level can be observed in Figure 43. From this effects plot it can be determined that all texture levels were ineffectual for hiding the sink mark in all treatments. There was a slight decrease in the probability of detection for the plaque having a shallow sink mark and coarse texture. While this effect was statistically significant, it could not be said that the texture level effectively concealed the sink mark.

Figure 43. Plot of the effects of sink mark depth and texture level on the probability of sink mark detection in Experiment #2 of the pilot study.
Non-Parametric Analysis

In agreement with the log-likelihood tests, the Kruskal-Wallis rank analysis showed the sink mark depth ($H=469.18$, d.f.=2) was a significant contributor to variation in the responses ($\alpha=0.05$). The effects of viewing position ($H=0.03$, d.f.=1) and texture ($H=1.16$, d.f.=2) were not found to be significant. Table 11 shows the results of multiple comparisons of the rankings of the levels of the depth factor. The effect of the no-sink level was found to be significantly different from the shallow (0.024mm) and deep (0.035mm) sink mark depths. However, minor and shallow levels were not found to be significantly different from each other. The findings on these within-factor effects are in agreement with the relationships shown in Figure 42.

Table 11
Kruskal-Wallis Test for Significant Effects between Depth Levels in Pilot Study Experiment #2

<table>
<thead>
<tr>
<th>Multiple Comparisons p values; Probability of Visual Detection</th>
<th>Independent (grouping) variable: Depth Level</th>
<th>Kruskal-Wallis test: $H (2, N=504) = 469.1751 p = 0.000$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Sink</td>
<td>Shallow</td>
<td>Deep</td>
</tr>
<tr>
<td>No Sink</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>Shallow</td>
<td>0.0000</td>
<td>1.0000</td>
</tr>
<tr>
<td>Deep</td>
<td>0.0000</td>
<td>1.0000</td>
</tr>
</tbody>
</table>

Analysis of Pairings with Depth and Texture Level Differences

As in the analysis of Experiment #1, the effects of differences within pairings were investigated. Table 12 shows the results of the main factor effects

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analysis for depth, texture and the difference in the pairs for these factors. As
in the previous analyses, sink mark depth was found to be a significant
contributor to the variability in the probability of visual detection of sink marks
($\alpha=0.05$). The effect of differences in this factor within a pair was also found to
be significant ($\alpha=0.05$). This result, similar to that found in Experiment #1, is
another indicator of the environment of an observation (condition of the
observation pair) having a significant effect upon the probability of visually
detecting a sink mark.

Also in agreement with previous analyses perform on the data from
Experiment #2, texture was not found to be a significant determinant of subject
response. It logically follows that the difference in texture levels within a pair
would not have significant effect, and indeed they did not. The ineffectiveness of
the texture level to conceal wide (5.05mm) sink marks was not deemed to be a
concern as visual perception theory suggested that the grey plaques would
exhibit lower probabilities of detection of the sink marks (Gordon, 1997).

<table>
<thead>
<tr>
<th>Effects of Factors Differences within Presentations of Experiment #2 of the Pilot Study</th>
<th>Probability of Visual Detection - Likelihood Type 1 Test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Distribution: BINOMIAL</td>
</tr>
<tr>
<td></td>
<td>Link function: LOGIT</td>
</tr>
<tr>
<td>Effects shown in bold are significant at $\alpha=0.05$</td>
<td></td>
</tr>
<tr>
<td>Degrees of Freedom</td>
<td>Log-Likelihood Ratio</td>
</tr>
<tr>
<td>---------------------</td>
<td>---------------------</td>
</tr>
<tr>
<td>Intercept</td>
<td>1</td>
</tr>
<tr>
<td>Sink Mark Depth {1}</td>
<td>1</td>
</tr>
<tr>
<td>Plaque Texture {2}</td>
<td>0</td>
</tr>
<tr>
<td>Depth Difference {3}</td>
<td>3</td>
</tr>
<tr>
<td>Texture Difference {4}</td>
<td>3</td>
</tr>
</tbody>
</table>
Summary of Pilot Study

From the data it was shown that appropriate levels were chosen for the factors to elicit a variety of responses from test subjects. The pairings were found to be an important feature of the experimental design as the differences in factor levels between the plaques within the pairs had significant effect upon the probability of visual detection of sink marks. Total variability had stabilized or had exhibited low levels after a small sample of subjects had been interviewed. One treatment (Plaque 13), however, did not exhibit decreasing variability even after seven subjects had been interviewed. This increasing variability was attributed to a treatment condition where the combination of texture and sink mark geometry existed at the threshold of visual perception. It was hypothesized that the addition of more subjects, thus increasing the size of the sample set, would decrease this variability.

Faults were found within various components of the data collection instrument. The timing routine in the data collection software was found to be cumbersome for the interviewer to utilize. The researcher was required to click a button on the spreadsheet to indicate the beginning and end of each observation period as well as enter subject responses. This resulted in five clicks per recorded observation and led to many erroneous entries that required re-keying. These difficulties made it impossible to analyze the response times and their correlations to the dependant variable of interest.

To resolve this issue, the timing routines in the data collection software were re-written for improved ease of use by the researcher and increased
accuracy in data entry. The number of entries required from the interviewer was reduced by the addition of routines that automatically entered data based upon logical assumptions. For example the entry of no difference between the two sink marks will be entered if no sink is visible on either side.

The part holding carousels in the observation booth required detents to hold the plaques adjacent to each other during the observations. Masks were required to hide plaques that were not in the observation pair. Appropriate design changes were made to the booth and the software to resolve these issues prior to the interviews for the primary study.

The protocol as approved by the HSIRB did not include provisions for the additional experiments to be included in the primary study. The protocol were revised to include methods to track the subjects between the two interviews required to complete all four experiments. The revisions to the protocol was submitted and approved by the institutional review board.

Primary Study

After modifications were made to the data collection protocols and instrument, subject interviews began at injection molding companies. Additional experimental designs were incorporated into the interviews. As discussed in Chapter 3, two one-hour interviews were used to collect data.

The design summaries for Experiments #1 and #2 described in Table 4 still apply. These experiments were not modified between the pilot study and the interview. Table 13 summarizes the objective and factor levels used in Experiments #3 and #4.
Table 13
Additional Experimental Designs Used in the Research

<table>
<thead>
<tr>
<th>EXPERIMENT #3</th>
<th>EXPERIMENT #4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Determine the effect of Sink Width and Plaque Texture for Black Plaques having Sink Depth Level 2 (0.024mm)</td>
<td>Determine the effect of Sink Depth, Plaque Texture and Color for Plaques having Sink Width Level 2 (5.05mm)</td>
</tr>
<tr>
<td><strong>Factor</strong></td>
<td><strong>Levels</strong></td>
</tr>
<tr>
<td>Sink Width</td>
<td>1 (narrow)</td>
</tr>
<tr>
<td></td>
<td>2 (wide)</td>
</tr>
<tr>
<td>Texture</td>
<td>0 (none)</td>
</tr>
<tr>
<td></td>
<td>1 (fine)</td>
</tr>
<tr>
<td></td>
<td>2 (coarse)</td>
</tr>
<tr>
<td>Color</td>
<td>0 (grey)</td>
</tr>
<tr>
<td></td>
<td>1 (black)</td>
</tr>
</tbody>
</table>

Mean Subject Responses

Mean values for the subject response were evaluated to validate the relationships between the factors and the response variables. Table 14 was compiled to perform these validations. One obvious change in the new data set was that the interview subjects reported detecting sink marks on plaques with no sink. These paradoxical responses occurred only on the plaques with texture. The plaque with no sink and no texture had no observations of sink marks. This result seemed to indicate that as texture was added to the plaques, the possibility of false positives increased, in other words observers mistakenly identified attributes of the texture to be sink marks.

The basic relationships between sink mark depth and the percent of the subject detecting the sink was comparable to the pilot study and followed logical patterns based upon theories of visual perception. The trends in the relationships between texture depth and sink mark detection also followed the
precedents set during the pilot study. For the grey plaques, probability of
detection followed expected patterns, with deeper sink marks and more shallow
texture depths having higher probabilities of detection.

Table 14
Mean Responses For All Plaques in the Study

<table>
<thead>
<tr>
<th>Plaque</th>
<th>Sink Mark Width Level</th>
<th>Sink Mark Depth Level</th>
<th>Texture</th>
<th>Color</th>
<th>Percent Detected</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>None</td>
<td>Black</td>
<td>0%</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1</td>
<td>None</td>
<td>Black</td>
<td>100%</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>2</td>
<td>None</td>
<td>Black</td>
<td>100%</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>2</td>
<td>None</td>
<td>Black</td>
<td>100%</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>3</td>
<td>None</td>
<td>Black</td>
<td>100%</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>0</td>
<td>Fine</td>
<td>Black</td>
<td>1%</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>1</td>
<td>Fine</td>
<td>Black</td>
<td>96%</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>2</td>
<td>Fine</td>
<td>Black</td>
<td>99%</td>
</tr>
<tr>
<td>9</td>
<td>2</td>
<td>2</td>
<td>Fine</td>
<td>Black</td>
<td>100%</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>3</td>
<td>Fine</td>
<td>Black</td>
<td>100%</td>
</tr>
<tr>
<td>11</td>
<td>0</td>
<td>0</td>
<td>Coarse</td>
<td>Black</td>
<td>3%</td>
</tr>
<tr>
<td>12</td>
<td>1</td>
<td>1</td>
<td>Coarse</td>
<td>Black</td>
<td>3%</td>
</tr>
<tr>
<td>13</td>
<td>1</td>
<td>2</td>
<td>Coarse</td>
<td>Black</td>
<td>27%</td>
</tr>
<tr>
<td>14</td>
<td>2</td>
<td>2</td>
<td>Coarse</td>
<td>Black</td>
<td>73%</td>
</tr>
<tr>
<td>15</td>
<td>2</td>
<td>3</td>
<td>Coarse</td>
<td>Black</td>
<td>98%</td>
</tr>
<tr>
<td>17</td>
<td>2</td>
<td>2</td>
<td>None</td>
<td>Grey</td>
<td>100%</td>
</tr>
<tr>
<td>18</td>
<td>2</td>
<td>3</td>
<td>None</td>
<td>Grey</td>
<td>98%</td>
</tr>
<tr>
<td>20</td>
<td>2</td>
<td>2</td>
<td>Fine</td>
<td>Grey</td>
<td>84%</td>
</tr>
<tr>
<td>21</td>
<td>2</td>
<td>3</td>
<td>Fine</td>
<td>Grey</td>
<td>97%</td>
</tr>
<tr>
<td>23</td>
<td>2</td>
<td>2</td>
<td>Coarse</td>
<td>Grey</td>
<td>5%</td>
</tr>
<tr>
<td>24</td>
<td>2</td>
<td>3</td>
<td>Coarse</td>
<td>Grey</td>
<td>47%</td>
</tr>
</tbody>
</table>

Treatment Responses

Subject response times for the treatments (plaques) were analyzed and
plotted. The response time for each plaque is shown in Figure 44. The
standard error and 95% confidence intervals are shown to demonstrate the
variability in the data collected. The black plaques without texture exhibited shorter response times while the grey plaques with coarse texture had the longest response times. The shortest response time was for the black plaque without texture and no sink mark. The longest response time was for the grey plaque with coarse texture and the deep (0.035mm) and wide (5.05mm) sink mark.

![Subject Response Times by Plaque](image)

**Figure 44.** Subject response times for each plaque. The grey plaques exhibited longer average response times while the black glossy plaques had faster response times.

Figure 45 shows response times for each experiment. Experiment #1 had the lowest average response time while Experiment #4 had the longest. One-
way ANOVA methods and the post-hoc test for Tukey's Homogeneous differences showed that Experiments #1 and #2 had statistically similar response times, as did Experiments #3 and #4 ($\alpha=0.05$). However the mean response times between these two groups were different.

![Response Time Characteristics by Experiment](image)

Figure 45. Subject response times for each plaque. The grey plaques exhibited longer average response times while the black glossy plaques had faster response times.

Informal exit interviews with the test subjects revealed that many felt it was more difficult to choose an answer for observations involving pairs containing a grey plaque. This was reflected by the finding of increased response time for Experiments #3 and #4, considering that the first two designs involved only black plaques while the fourth experiment involved grey plaques. The times for the third experiment may be higher as Experiment #3 was
conducted concurrently with Experiment #4.

Subject Demographics

The interviews were conducted at injection molding companies in western Michigan as well as in the Plastic Processing Laboratory at Western Michigan University. Thirty subjects were interviewed. Seven subjects were between 18 and 25 years old, ten were 26 to 35 years old and thirteen were 36 to 40 years old. All but one subject had earned a High School diploma. Sixteen subjects had attended college. Four subjects had earned graduate degrees.

Twenty-one of the thirty subjects wore corrective lens. Three subjects wore contact lens while ten reported wearing only glasses. Eight subjects wore either contacts or glasses. Eighteen subjects were near-sighted, and three were farsighted. One subject reported having had eye surgery for cataracts and one subject had color deficient vision. All subjects tested at the extreme (highly sensitive) end of the contrast sensitivity test. No subjects were excluded from the research on the basis of poor visual acuity or contrast sensitivity scores.

Investigation of Gender Effects on the Observations

Test subjects were equally representative of both genders. The effect of the gender of the subject on the ability of sink mark detection was evaluated. These results are shown in Table 15. Gender was found to be significant. As can be seen in Figure 46, female subjects were more likely to detect a sink mark and were less likely to falsely identify a sink mark. In one treatment, plaque 13, female subjects were 25% more likely to detect the sink mark than males.
Table 15
Test of the Effect of Subject Gender on the Probability of Sink Mark Detection

<table>
<thead>
<tr>
<th>Effects of Subject Gender on the probability of sink mark detection.</th>
<th>Probability of Visual Detection - Likelihood Type 1 Test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Distribution: BINOMIAL</td>
</tr>
<tr>
<td></td>
<td>Link function: LOGIT</td>
</tr>
<tr>
<td></td>
<td>Effects shown in bold are significant at $\alpha=0.05$</td>
</tr>
<tr>
<td>Degrees of Freedom</td>
<td>Log-Likelihood Ratio</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Intercept</td>
<td>1</td>
</tr>
<tr>
<td>Gender</td>
<td>1</td>
</tr>
<tr>
<td>DOE</td>
<td>3</td>
</tr>
<tr>
<td>Plaque</td>
<td>18</td>
</tr>
<tr>
<td>Gender*DOE</td>
<td>3</td>
</tr>
<tr>
<td>Gender*Plaque</td>
<td>14</td>
</tr>
<tr>
<td>DOE*Plaque</td>
<td>4</td>
</tr>
<tr>
<td>Gender<em>DOE</em>Plaque</td>
<td>2</td>
</tr>
</tbody>
</table>

Figure 46. Effects of subject gender on the probability of sink mark detection. Female subjects were up to 25% more likely to detect sink marks.
Age Effects on Observations

Age grouping used in the research were 18 to 25 years old, 26 to 35 years old and 36 to 40 years old. The age group the test subject belonged to was found to have significant effect upon the subject's ability to detect sink marks (Table 16). Figure 47 shows the effects of the subject age on sink mark detection for each plaque. Treatments exhibiting high variability in the subject responses exhibited greater shifts in the mean response due to age. These were plaques 13, 14, 20 and 24. In three of these four treatments, the younger subjects exhibited a lower probability of detecting the sink mark.

Table 16
Test of the Effect of Subject Age on the Probability of Sink Mark Detection

<table>
<thead>
<tr>
<th>Effects of Subject Age on the probability of sink mark detection.</th>
<th>Probability of Visual Detection - Likelihood Type 1 Test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Distribution: BINOMIAL</td>
</tr>
<tr>
<td></td>
<td>Link function: LOGIT</td>
</tr>
<tr>
<td></td>
<td>Effects shown in bold are significant at $\alpha=0.05$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Degrees of Freedom</th>
<th>Log-Likelihood Ratio</th>
<th>Chi-Square</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>1</td>
<td>-5495.66</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age</td>
<td>2</td>
<td>-5491.96</td>
<td>7.41</td>
<td>0.0246</td>
</tr>
<tr>
<td>DOE</td>
<td>3</td>
<td>-5090.41</td>
<td>803.10</td>
<td>0.0000</td>
</tr>
<tr>
<td>Plaque</td>
<td>18</td>
<td>-1382.28</td>
<td>7416.27</td>
<td>0.0000</td>
</tr>
<tr>
<td>Age*DOE</td>
<td>6</td>
<td>-1374.35</td>
<td>15.86</td>
<td>0.0145</td>
</tr>
<tr>
<td>Age*Plaque</td>
<td>24</td>
<td>-1326.65</td>
<td>95.39</td>
<td>0.0000</td>
</tr>
<tr>
<td>DOE*Plaque</td>
<td>4</td>
<td>-1308.61</td>
<td>36.08</td>
<td>0.0000</td>
</tr>
<tr>
<td>Age<em>DOE</em>Plaque</td>
<td>5</td>
<td>-1304.75</td>
<td>7.72</td>
<td>0.1725</td>
</tr>
</tbody>
</table>

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Figure 47. Effects of subject age on the probability of sink mark detection.

Effects of Subject Visual Acuity on the Observations

Prior to the observations, the visual acuity of the interview subjects was tested. As discussed in the methodology, if necessary for normal vision, the subject wore corrective eye appliances during the interviews. As discussed, no test subject was excluded from this research on the basis of visual acuity; all subjects had corrected (if necessary) vision better than 1.0 (20:20 fractional). The minimum subject visual acuity was 1.03, the subject with the most acute vision exhibited a score of 3.28. Average visual acuity was 1.96 with a standard deviation of 0.45.
The effect of the subject's visual acuity on the detection of sink marks was evaluated. The visual acuity was tested against the effects of the individual plaques and the experiment number. The experiment number was included in the analysis to allow for any potential variability in perception due to the influence of the comparison plaque (Table 17). The analysis revealed no significant effect from visual acuity on the probability of the subject's detection of sink marks. Additionally, no significant interactions between the plaques or experiment at the visual acuity were found. This would indicate that corrected vision in excess of 20/20 was adequate for consistent detection of the levels of sink marks used in this experiment.

<table>
<thead>
<tr>
<th>Effects of Visual Acuity on the probability of sink mark detection.</th>
<th>Probability of Visual Detection - Likelihood Type 1 Test Distribution: BINOMIAL Link function: LOGIT Effects shown in bold are significant at $\alpha=0.05$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degrees of Freedom</td>
<td>Log-Likelihood Ratio</td>
</tr>
<tr>
<td>Intercept</td>
<td>1</td>
</tr>
<tr>
<td>Subject VA</td>
<td>1</td>
</tr>
<tr>
<td>DOE</td>
<td>1</td>
</tr>
<tr>
<td>Plaque</td>
<td>1</td>
</tr>
<tr>
<td>Subject VA*DOE</td>
<td>1</td>
</tr>
<tr>
<td>Subject VA*Plaque</td>
<td>1</td>
</tr>
<tr>
<td>DOE*Plaque</td>
<td>1</td>
</tr>
<tr>
<td>Subject VA<em>DOE</em>Plaque</td>
<td>1</td>
</tr>
</tbody>
</table>
Evaluation of the Color Vision Deficient Subject

While the experiment was designed to avoid the effects of color deficiencies, it was possible that the subject reporting himself as having abnormal color vision may have divergent responses from the other test subjects. For Experiment #4, where black and grey plaques are used, the responses of this individual (test subject #3) were investigated. It was found that the mean responses for each subject were not significantly different for any given plaque (Table 18).

Table 18
Test for Significant Differences between Subject Responses for the Plaques in Experiment #4

<table>
<thead>
<tr>
<th>Effects of Subject on the probability of sink mark detection.</th>
<th>Probability of Visual Detection - Likelihood Type 1 Test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Distribution: BINOMIAL Link function: LOGIT</td>
</tr>
<tr>
<td></td>
<td>Effects shown in bold are significant at $\alpha=0.05$</td>
</tr>
<tr>
<td>Degrees of Freedom</td>
<td>Log-Likelihood Ratio</td>
</tr>
<tr>
<td>Intercept</td>
<td>1</td>
</tr>
<tr>
<td>Subject</td>
<td>1</td>
</tr>
<tr>
<td>Plaque</td>
<td>1</td>
</tr>
<tr>
<td>Subject*Plaque</td>
<td>1</td>
</tr>
</tbody>
</table>

However, more detailed investigation of subject #3 revealed that his mean percent of sink mark detections per plaque were less than that of the other subjects. The responses of the test subjects were plotted in Figure 48 below. The responses for subject #3 were drawn as a separate plot line. His probability of detection for plaque number 21 was significantly lower that those of the other subjects.
The findings of Experiment #4 were re-evaluated after the initial analysis. In the second analysis, subject #3 was removed. No significant factor or interactions were found to have changed between the two analyses of Experiment #4. Therefore, this subject was not removed from the data set.

![Probability of Sink Mark Detection in Experiment #4](image)

Figure 48. Plot of the probability of sink mark detection in Experiment #4. Plot shows the responses of subject number three separated from the other subjects.

Effects of Subject Interview Location

Test subjects represented a variety of occupational backgrounds. At the first interview location, the subjects were drawn from the Engineering and Quality Assurance departments. At location two, quality inspectors were
interviewed. At location three, the interviews were conducted with injection molding machine operators. The interviews at Western Michigan University involved graduate students with various experiences and familiarity with injection molding and sink marks.

The subjects at each industrial interview location had similar backgrounds and experience. However, between the four interview locations, familiarity with sink mark defects varied. Most of the subjects from the injection molding companies were experienced with sink mark identification. Among the graduate students interviewed at Western Michigan University there existed a wide range of familiarity with sink marks. Some of the students had no familiarity with the defect at all.

Table 19
Test of Interview Location Effects on the Probability of Sink Mark Detection

<table>
<thead>
<tr>
<th>Effects of Interview Location on the probability of sink mark detection</th>
<th>Probability of Visual Detection - Likelihood Type 1 Test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Distribution: BINOMIAL</td>
</tr>
<tr>
<td></td>
<td>Link function: LOGIT</td>
</tr>
<tr>
<td></td>
<td>Effects shown in bold are significant at $\alpha=0.05$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Degrees of Freedom</th>
<th>Log-Likelihood Ratio</th>
<th>Chi-Square</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>1</td>
<td>-5744.27</td>
<td></td>
</tr>
<tr>
<td>Location</td>
<td>1</td>
<td>-5743.84</td>
<td>0.88</td>
</tr>
<tr>
<td>DOE</td>
<td>1</td>
<td>-5347.45</td>
<td>792.77</td>
</tr>
<tr>
<td>Plaque</td>
<td>1</td>
<td>-5086.54</td>
<td>521.83</td>
</tr>
<tr>
<td>Location*DOE</td>
<td>1</td>
<td>-5086.26</td>
<td>0.56</td>
</tr>
<tr>
<td>Location*Plaque</td>
<td>1</td>
<td>-5085.40</td>
<td>1.71</td>
</tr>
<tr>
<td>DOE*Plaque</td>
<td>1</td>
<td>-5059.04</td>
<td>52.72</td>
</tr>
<tr>
<td>Location<em>DOE</em>Plaque</td>
<td>1</td>
<td>-5058.94</td>
<td>0.19</td>
</tr>
</tbody>
</table>
Using maximum likelihood methods, the effects of the interview locations were tested against the probability of detecting sink for each plaque (Table 19). This analysis was conducted to determine if the disparity in the subject's experience and familiarity with the defect had effect on the probability of sink mark detection. It was found that there were no significant differences in the mean responses for the interview locations. Additionally there were no significant interactions between the locations and the responses for each plaque.

Experiment #1: Visual Detection of Narrow Sink Marks

For the plaques exhibiting narrow sink marks, variance for all treatments was below 0.005 by the eleventh subject (Figure 49). As in the pilot study, the plaque with the coarse texture and shallow sink mark depth (Plaque 13) exhibited the highest variance. The plaque with the coarse texture and no sink mark (Plaque 11) had the next highest level of variability caused by a small number of false detections of sink marks. With the exception of Plaque 12, the remaining plaques exhibited no variance in subject observations. Total variance in the data after the inclusion of thirty subjects was approximately 0.004.
Analysis of Main Effects and Interactions

Likelihood ratio tests were performed upon the main factors and their interactions. All three main factors (viewing position, sink mark depth and texture) as well as their interactions were found to be significant. Table 20 shows the results of the likelihood test.

In the pilot study, viewing position was not found to have significant effects on sink mark visibility; however it was found to be significant in the primary study. From the relative chi-square values it can be determined that the sink mark depth and plaque texture were stronger indicators of the
probability of sink mark detection than the effects of viewing position. These factors, along with their interaction, were stronger predictors of detection than the viewing position and its interaction effects.

<table>
<thead>
<tr>
<th>Experiment #1</th>
<th>Probability of Visual Detection - Likelihood Type 1 Test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Distribution: BINOMIAL</td>
</tr>
<tr>
<td></td>
<td>Link function: LOGIT</td>
</tr>
<tr>
<td></td>
<td>Effects shown in bold are significant at $\alpha=0.05$</td>
</tr>
<tr>
<td>Intercept</td>
<td>1 -23202.00</td>
</tr>
<tr>
<td>Viewing Position {1}</td>
<td>1 -23149.10</td>
</tr>
<tr>
<td>Sink Mark Depth {2}</td>
<td>2 -13861.50</td>
</tr>
<tr>
<td>Plaque Texture {3}</td>
<td>2 -5586.60</td>
</tr>
<tr>
<td>1*2</td>
<td>2 -5500.80</td>
</tr>
<tr>
<td>1*3</td>
<td>2 -5461.90</td>
</tr>
<tr>
<td>2*3</td>
<td>2 -4629.80</td>
</tr>
<tr>
<td>1<em>2</em>3</td>
<td>1 -4621.00</td>
</tr>
</tbody>
</table>

The effect of viewing position was plotted in Figure 50. The left position exhibited approximately a five percent lower probability of detection than the right position. The practical significance of this finding should be considered.

As the design was balanced between left and right viewing positions, this effect indicates a true difference between the viewing positions. However, the practical significance of this effect is questionable, as the position of viewing is generally not controlled in “real-world” conditions and the influence of five percent may only have an effect in near-threshold conditions.
Probability of Visual Detection of Sink Marks in Experiment #1
Categorical Effects Plots ~ Viewing Position
Sink Width is 3.27 mm

![Graph](image1)

Figure 50. Plot of the effect of viewing position on subject responses in Experiment #1.

Probability of Visual Detection of Sink Marks in Experiment #1
Scaled Categorical Effects Plots ~ Sink Mark Depth
Sink Width is 3.27 mm

![Graph](image2)

Figure 51. Plot of the effect of sink mark depth on the probability of detection in Experiment #1. The x-axis has been scaled to represent the relative distance between sink mark depths.

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To investigate the effects of the various levels of sink mark depth, Figure 51 was created. The probability of detection for the plaques having no sink was approximately two percent due to false detections of sink on textured plaques.

![Probability of Visual Detection of Sink Marks in Experiment #1](image)

**Figure 52.** Plot of the effect of surface texture on the probability of sink mark detection in Experiment #1. The x-axis has been scaled to represent the relative distance between texture depths.

The effect of texture depth was plotted in Figure 52. From the plot it can be observed that the mean effect for the coarse texture was quite lower than that for plaques without texture or with fine texture. Further, the mean differences between the plaques without texture and those with fine texture were not significant ($\alpha=0.05$).

The three-way interaction between viewing position, sink mark depth,
and plaque texture are shown in Figure 53. In the two plots of this figure the differences between the left- and right-viewing positions become apparent. These differences are particularly noticeable for the treatment having coarse texture and shallow sink mark depth.

![Diagram showing Probability of Detection of Sink Marks in Experiment #1](image)

Figure 53. Plot of the effects of sink depth and texture level on the probability of sink mark detection in Experiment #1. The left and right viewing positions are shown to illustrate the treatment where position had effect on perception.

The results of Experiment #1 in the study follow the same trends as the same experiment in the pilot study. However there are differences in the mean responses. While the plaque without texture and without sink marks did not
have any responses indicating the detection of sink marks, the other two texture levels did have some reports of sink mark detection. There a 2.92% and 3.75% probability of a false positive for the fine and coarse textures, respectively. However, the response for the minor sink depth with the coarse texture showed the same probability of detection as the no-sink condition for coarse texture. Hence, the coarse texture was effective in hiding the minor sink depth.

Non-Parametric Analysis

The Kruskal-Wallis test of rankings for the effect of sink mark depth (H=945.96, d.f.=2) showed that the factor had significant contribution to the variability in sink mark perception (α=0.05). Further evaluation of the between-level effect showed that there were significant differences between all levels of the factor (Table 21). These results agreed with the findings for this factor in Experiment #1 of the pilot study, as well as the results of the log-likelihood tests for Experiment #1 for the pilot study.

Table 21

<table>
<thead>
<tr>
<th></th>
<th>No Sink</th>
<th>Minor</th>
<th>Shallow</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Sink</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00000</td>
</tr>
<tr>
<td>Minor</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00785</td>
</tr>
<tr>
<td>Shallow</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00785</td>
</tr>
</tbody>
</table>

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The rank test for the texture factor (H=539.13, d.f.=2) showed the texture to be a significant contributor to sink mark detection (\(\alpha=0.05\)). The results of the multiple comparisons of the factor levels are shown in Table 22. Significant differences were found for the ranks of the plaques with coarse texture and the plaques with fine texture and no texture. No significant difference was found between the plaques without texture and those with fine texture. All tests of significance were performed with an \(\alpha\)-value of 0.05. These findings confirm the results of the log-likelihood tests.

Table 22
Kruskal-Wallis Test for Significant Effects between Texture Levels in Experiment #1

<table>
<thead>
<tr>
<th>Multiple Comparisons p values; Probability of Visual Detection</th>
<th>Independent (grouping) variable: Texture Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kruskal-Wallis test: H (2, N=2160) =539.1333 p =0.000</td>
<td></td>
</tr>
<tr>
<td>No Texture</td>
<td>Fine</td>
</tr>
<tr>
<td>No Texture</td>
<td>1.0000</td>
</tr>
<tr>
<td>Fine</td>
<td>1.0000</td>
</tr>
<tr>
<td>Coarse</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

The position of the plaque for the observation was also tested for significant contribution to the probability of detection. The position was found to be significant to the detection of the sink mark using ranking tests (H=4.63, d.f.=1). However, multiple comparisons of the between-level differences for the factor (i.e. left, right) were inconclusive and found no significance in the effect of the position.
Analysis of Pairings with Depth and Texture Level Differences

Differences between the plaques presented were analyzed to determine their effects upon variations in the mean responses. For Experiment #1, differences in depth and texture levels were analyzed. All factors analyzed were found to have significant effects ($\alpha=0.05$) as shown in Table 23.

Table 23
Likelihood Ratios for the Determination of Significant Factor Differences within Presentations in Experiment #1

<table>
<thead>
<tr>
<th>Effects of Factors Differences within Presentations of Experiment #1</th>
<th>Probability of Visual Detection - Likelihood Type 1 Test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Distribution: BINOMIAL</td>
</tr>
<tr>
<td></td>
<td>Link function: LOGIT</td>
</tr>
<tr>
<td>Effects shown in bold are significant at $\alpha=0.05$</td>
<td></td>
</tr>
<tr>
<td>Degrees of Freedom</td>
<td>Log-Likelihood Ratio</td>
</tr>
<tr>
<td>----------------------</td>
<td>----------------------</td>
</tr>
<tr>
<td>Intercept</td>
<td>1</td>
</tr>
<tr>
<td>Sink Mark Depth {1}</td>
<td>1</td>
</tr>
<tr>
<td>Plaque Texture {2}</td>
<td>1</td>
</tr>
<tr>
<td>Depth Difference {3}</td>
<td>4</td>
</tr>
<tr>
<td>Texture Difference {4}</td>
<td>2</td>
</tr>
</tbody>
</table>

Plots were created for the effects of differences in sink mark depth and texture. For differences in sink mark depth, significant effects were found for plaques having coarse texture. The plot of the effects specific to coarse plaques is shown in Figure 54. This plot shows that for objective plaques with a sink mark, the probability of detecting the sink mark increased when the plaque was presented with a comparison plaque having no sink mark. This revealed the source of the significant effect found in this analysis as well as in the pilot study. As discussed, for this research the objective plaque is the plaque upon which observation is made, and the comparison plaque is the other plaque in the pair.
Effects of Sink Depth Differences in Presentations
For plaques with coarse texture and sink width of 3.27mm
(Where sink was present and detected in experiment #1)

<table>
<thead>
<tr>
<th>Probability of Visual Detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
</tr>
</tbody>
</table>

- **Minor Sink Depth**
  - Presented with:
    - * No Sink
    - o Minor
    - v Shallow

- **Shallow Sink Depth**
  - Presented with:
    - * No Sink
    - o Minor
    - v Shallow

Objective Plaque

- **Minor Sink** (0.008mm)
- **Shallow Sink** (0.024mm)

Figure 54. Effect of sink mark depth differences within plaque presentations where sink existed and was detected. Sink marks were more likely to be detected when presented with comparison plaque having less sink.

The effects of differences in texture levels between plaques are shown in Figure 55. There were significant effects found for the plaques having coarse (0.060mm deep) texture. However no discernable pattern appears in the effect. For treatments having minor sink (0.008mm deep), coarse texture reduced the probability of detection while coarse texture increased detection for shallow (0.024mm deep) sink marks.

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Figure 55. Effect of texture differences within plaque presentations where sink existed and was detected. The coarse texture caused different responses in the minor and shallow sink mark depths.

Experiment #2: Visual Detection of Wide Sink Marks

For the plaques with wide (5.05mm) sink marks, variance for all treatments was below 0.005 by the fifth subject (Figure 56, below). After the inclusion of 30 subjects in the data set, the plaque with coarse texture and no sink mark (Plaque 11) exhibited the highest percent variance: 0.0012. The high variability was due to false detection of sink marks on this plaque. Most plaques exhibited zero variance. Total variance in the data for Experiment #2 was 0.0019.
Figure 56. Effect of the incremental aggregation of subject responses on variance in the data of Experiment #2 of the research.

Analysis of Main Effects and Interactions

The log-likelihood ratio tests showed the sink mark depth, texture depth and their interactions were significant contributors to the variability in the probability of sink mark detection (Table 24). The finding of significant effects in the plaque texture differs from the findings of the pilot study. However, from the p-values it can be seen that the strength of the texture effect was much smaller than that of the sink mark depth. Viewing position was not found to have significant effect on the probability sink mark detection ($\alpha = 0.05$).
Table 24  
Likelihood Ratios for the Determination of Significant Factor Effects in Experiment #2

<table>
<thead>
<tr>
<th>Experiment #2</th>
<th>Degrees of Freedom</th>
<th>Log-Likelihood Ratio</th>
<th>Chi-Square</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>1</td>
<td>-21603.80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Viewing Position {1}</td>
<td>1</td>
<td>-21603.70</td>
<td>0.26</td>
<td>0.6133</td>
</tr>
<tr>
<td>Sink Mark Depth {2}</td>
<td>2</td>
<td>-2600.80</td>
<td>38005.72</td>
<td>0.0000</td>
</tr>
<tr>
<td>Plaque Texture {3}</td>
<td>2</td>
<td>-2393.30</td>
<td>415.12</td>
<td>0.0000</td>
</tr>
<tr>
<td>1*2</td>
<td>2</td>
<td>-2349.20</td>
<td>88.07</td>
<td>0.0000</td>
</tr>
<tr>
<td>1*3</td>
<td>2</td>
<td>-2339.80</td>
<td>18.84</td>
<td>0.0001</td>
</tr>
<tr>
<td>2*3</td>
<td>2</td>
<td>-2066.00</td>
<td>547.66</td>
<td>0.0000</td>
</tr>
<tr>
<td>1<em>2</em>3</td>
<td>1</td>
<td>-2066.00</td>
<td>0.00</td>
<td>0.9966</td>
</tr>
</tbody>
</table>

The effect of sink mark depth was plotted in Figure 57. In this plot, mean response for the shallow and deep sink marks appears to be similar, while the response for plaques without sink has a much lower value. This corresponds to the results for Experiment #2 of the pilot study.

The effect for texture depth was plotted in Figure 58. Between levels, the mean responses varied 1.7%. While the likelihood ratio tests determined that the texture effects were significant, this plot brings into question the practical significance of the effects of this factor. It was apparent that the different texture level had little effect in reducing the visibility of the wide sink marks.
Figure 57. Plot of the effects of sink mark depth on the probability of sink mark detection in Experiment #2. The x-axis has been scaled to represent the relative distance between sink mark depths.

Figure 58. Plot of the scaled effects of texture level on the probability of sink mark detection in Experiment #2.
As in Experiment #1, the treatment having no sink on the plaque with coarse texture exhibited false positives for sink mark detection. In this analysis, the mean response for that treatment was 2.92%. No texture was adequate to hide the deep sink marks (>99% detection), and the coarse texture only had marginal effect on the detection of shallow sink marks (91.7% detection). Again the practical significance of the effectiveness of the texture levels to hide sink on black plaques is questionable. Only in one treatment (the plaque with coarse texture and shallow sink marks) was visibility reduced by the coarse texture.

![Probability of Detection of Sink Marks in Experiment #2](image)

Figure 59. Plot of the effects of sink mark depth and texture level on the probability of sink mark detection in Experiment #2. The x-axis has been scaled to represent the relative texture depths.
Non-Parametric Analysis

The Kruskal-Wallis ranking test for viewing position ($H=0.01, \text{d.f.}=1$) and texture depth effects ($H=0.59, \text{d.f.}=2$) found no significant contribution to the probability of sink mark detection from these factors. Sink mark depth ($H=2019.92, \text{d.f.}=2$) was found to have significant effects ($\alpha=0.05$) upon the visual detection of the sink mark. Investigation of the between-level effects for sink mark depth showed that the 'no sink mark' condition was significantly different from the shallow and deep sink marks (Table 25). There was no significant difference in detection found between shallow and deep sink marks ($\alpha=0.05$).

Table 25
Kruskal-Wallis Test for Significant Effects between Depth Levels in Experiment #2

<p>| Multiple Comparisons $z'$ values; Probability of Visual Detection |
| Independent (grouping) variable: Depth Level |
| Kruskal-Wallis test: $H(2, N=2160) = 2019.923, p = 0.000$ |</p>
<table>
<thead>
<tr>
<th>No Sink</th>
<th>Shallow</th>
<th>Deep</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Sink</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>Shallow</td>
<td>0.0000</td>
<td>1.0000</td>
</tr>
<tr>
<td>Deep</td>
<td>0.0000</td>
<td>1.0000</td>
</tr>
</tbody>
</table>

Analysis of Pairings with Depth and Texture Level Differences

From likelihood ratio tests, the differences in sink mark depth and texture depth between plaques were found to have significant effect on the
perception of the sink marks. These results are shown in Table 26. The sink mark depth differences appeared to be a stronger predictor of sink mark detection visibility than plaque texture difference.

Table 26
Likelihood Ratios for the Determination of Significant Factor Differences within Presentations in Experiment #2

<table>
<thead>
<tr>
<th>Effects of Factors Differences within Presentations of Experiment #2</th>
<th>Probability of Visual Detection - Likelihood Type 1 Test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Distribution: BINOMIAL</td>
</tr>
<tr>
<td></td>
<td>Link function: LOGIT</td>
</tr>
<tr>
<td></td>
<td>Effects shown in bold are significant at ( \alpha = 0.05 )</td>
</tr>
<tr>
<td></td>
<td>Degrees of Freedom</td>
</tr>
<tr>
<td>Intercept</td>
<td>1</td>
</tr>
<tr>
<td>Sink Mark Depth {1}</td>
<td>1</td>
</tr>
<tr>
<td>Plaque Texture {2}</td>
<td>1</td>
</tr>
<tr>
<td>Depth Difference {3}</td>
<td>2</td>
</tr>
<tr>
<td>Texture Difference {4}</td>
<td>2</td>
</tr>
</tbody>
</table>

As in Experiment #1, sink marks were more likely to be detected if the objective plaque was presented with a comparison plaque having less sink mark depth. This effect was present in coarse plaques (also as in Experiment #1) and can be seen in Figure 60. For objective plaques with shallow sink marks, there was a 6.7% increase in the probability of detection if the comparison plaque had no sink mark. If the same plaque was presented with a plaque having a deep sink mark, the probability of detection was reduced by 3.7%. While these effects may be minimal, the 10% difference between the deep- and no-sink mark conditions indicates that viewing environmental can have large effects on sink mark perception.

For objective plaques having deep sink marks, the effect of these
differences was not as large. When presented with comparison plaques having deep sink marks, the objective plaques having deep sink marks had a 3% reduction in the probability of sink mark detection. Sink marks in coarse plaques were detected in all pairs with comparison plaques with shallow sink marks and no sink marks.

![Diagram: Effects of Sink Depth Differences in Presentations](image)

Figure 60. Plot of the effects of differences in sink mark depth within pairs in Experiment #2. Effect is for objective plaques having coarse texture.

Texture differences were found to have significant effects. However, as in Experiment #1, it cannot be suggested that greater or lesser differences in texture depth can decrease the probability of detection. Texture differences
exhibited the greatest influence on perception in treatments with coarse texture on the objective plaques. Figure 61 shows that objective plaques with coarse texture and shallow sink had the lowest probability of detection when the comparison plaque had no texture. This may suggest that the easy detection of sink on the plaques without texture may be influencing the subjects to overlook the sink marks on the objective plaque.

![Figure 61. Plot of the effect of differences in texture depth within pairs in Experiment #2. Effect is for objective plaques having coarse texture.](image.png)
Experiment #3: Visual Detection Differences Between Narrow and Wide Sink

This experiment exhibited the highest observation variability of any single experiment. Figure 62 shows the variance for each treatment and total variance as subjects were added to the dataset. The plaque having coarse texture and a shallow sink mark depth (Plaque 14) exhibited the highest variability. The percent variance for this plaque was 0.0065 after thirty subjects.

![Incremental Aggregation of Subject Responses](image)

Figure 62. Effect of the incremental aggregation of subject responses on variance in the data of Experiment #3 of the research.

The other plaque having coarse texture (Plaque 13) had the second highest variance of 0.0033. This high level of variability was attributed to a
treatment condition near the threshold of visual perception as will be seen in the
mean response for these plaques. All other plaques exhibited zero variance in
subject observations. Total variance in the data for this experiment was 0.0099.

Analysis of Main Effects and Interactions

Analysis of the likelihood ratios showed that the sink mark width and
plaque texture to be significant contributors to the variability in the probability
of sink mark detection. Interactions were also found to be significant ($\alpha=0.05$).
These results are presented in Table 27. From the chi-square scores, sink mark
depth was the strongest predictor of sink mark detection. Viewing position was
also found to have significant effect, however it had the smallest chi-square
score of all effects investigated in the analysis.

<table>
<thead>
<tr>
<th>Experiment #3</th>
<th>Probability of Visual Detection - Likelihood Type 1 Test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Distribution: BINOMIAL</td>
</tr>
<tr>
<td></td>
<td>Link function: LOGIT</td>
</tr>
<tr>
<td></td>
<td>Effects shown in bold are significant at $\alpha=0.05$</td>
</tr>
<tr>
<td>Degrees of Freedom</td>
<td>Log-Likelihood</td>
</tr>
<tr>
<td>------------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>Intercept</td>
<td>1</td>
</tr>
<tr>
<td>Viewing Position {1}</td>
<td>1</td>
</tr>
<tr>
<td>Sink Mark Width {2}</td>
<td>1</td>
</tr>
<tr>
<td>Plaque Texture {3}</td>
<td>2</td>
</tr>
<tr>
<td>1*2</td>
<td>1</td>
</tr>
<tr>
<td>1*3</td>
<td>1</td>
</tr>
<tr>
<td>2*3</td>
<td>1</td>
</tr>
<tr>
<td>1<em>2</em>3</td>
<td>0</td>
</tr>
</tbody>
</table>

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Figure 63 shows the effect of viewing position on visual sink mark detection. The viewing position had the effect of increasing the probability of detection by 2.4% for plaques shown on the right side of the fixture. As in previous analyses, when viewing position was found to have a significant effect, the effect increased perception for plaque presented in the right position.

![Probability of Visual Detection of Sink Marks in Experiment #3](image)

Figure 63. Plot of the effects of viewing position on the probability of sink mark detection in Experiment #3.

The effect of sink mark width is shown in Figure 64. The main effect of the sink mark width was a 14.2% increase in the probability of sink mark detection for wide sink marks as compared to narrow. The plot of the effect of texture depth is shown in Figure 65. The plaques having no texture and fine texture had statistically similar means while the coarse texture had significantly lower probabilities of detection.
Figure 64. Plot of the effects of sink mark width on the probability of sink mark detection in Experiment #3.

Figure 65. Plot of the effects texture level on the probability of sink mark detection in Experiment #3. The x-axis has been scaled to represent the relative distance between texture depths.
The three-way interactions between sink mark width, texture and viewing position is shown in Figure 66. The treatments with no texture and fine texture exhibited limited differences at either width. However, for plaques having coarse texture, there were significant differences between the two widths ($\alpha=0.05$). From the analysis of Experiments #1 and #2, it was determined that the coarse texture was at least marginally effective in concealing shallow (0.024mm deep) sink marks. For this texture, narrow sink marks had lower probability of visual detection than the wide sink marks ($\alpha=0.05$).
Non-Parametric Analysis

Kruskal-Wallis ranking tests found the factors of sink mark width ($H = 26.05$, d.f. = 1) and texture level ($H = 441.64$, d.f. = 2) to have significant effect on the probability of sink mark detection ($\alpha = 0.05$). Between-level comparisons for the texture factor showed the plaques with coarse texture to have significantly different mean responses than the plaques having no texture and fine texture (Table 28). Viewing position was not found to be significant ($H = 0.67$, d.f. = 1).

Table 28
Kruskal-Wallis Test for Significant Effects between Texture Levels in Experiment #3

<table>
<thead>
<tr>
<th>Multiple Comparisons p values; Probability of Visual Detection</th>
<th>Independent (grouping) variable: Texture Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kruskal-Wallis test: $H (2, N=870) = 441.6436$ p = 0.000</td>
<td></td>
</tr>
<tr>
<td>No Texture</td>
<td>Fine</td>
</tr>
<tr>
<td>No Texture</td>
<td>1.0000</td>
</tr>
<tr>
<td>Fine</td>
<td>1.0000</td>
</tr>
<tr>
<td>Coarse</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

Analysis of Pairings with Width and Texture Level Differences

The results of likelihood ratio tests on the differences of factors within presentation pairs are shown in Table 29. It was found that the difference in plaque texture was a significant predictor of sink mark detection, while the difference in sink mark width was not.
Table 29
Likelihood Ratios for the Determination of Significant Factor Differences within Presentations in Experiment #3

<table>
<thead>
<tr>
<th>Effects of Factors Differences within Presentations of Experiment #3</th>
<th>Probability of Visual Detection - Likelihood Type 1 Test Distribution: BINOMIAL Link function: LOGIT Effects shown in bold are significant at $\alpha=0.05$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Degrees of Freedom</td>
</tr>
<tr>
<td>Intercept</td>
<td>1</td>
</tr>
<tr>
<td>Sink Mark Width {1}</td>
<td>1</td>
</tr>
<tr>
<td>Plaque Texture {2}</td>
<td>2</td>
</tr>
<tr>
<td>Texture Difference {3}</td>
<td>2</td>
</tr>
<tr>
<td>Width Difference {4}</td>
<td>0</td>
</tr>
</tbody>
</table>

The finding of significant effects in the texture differences was further investigated with the effects plot shown in Figure 67. As in Experiments #1 and #2, the between-level effects for differences in texture were most predominant in treatments having coarse texture. Similar to the result for texture difference in Experiment #1, no pattern was apparent in the difference between the various pairs.

For wide sink marks, the presentation of a coarse objective plaque with a comparison plaque having less texture resulted in a lower probability of detection of the sink mark on the objective plaque. This finding was in contrast to the findings in Experiment #2 where no pattern was identifiable.
Effects of Texture Differences in Presentations
For plaques with sink depth of 0.024mm
(Where sink was present and detected in experiment #3)

<table>
<thead>
<tr>
<th>Probability of Visual Detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
</tr>
<tr>
<td>No Texture</td>
</tr>
</tbody>
</table>

Objective Plaques with Narrow Sink Marks (3.27mm)
Objective Plaques with Wide Sink Marks (5.05mm)

Figure 67. Plot of the effect of differences in texture depth within pairs in Experiment #3.

Experiment #4: Visual Detection Differences Between Black and Grey Plaques

The objective of Experiment #4 was to determine the effects of sink mark depth, plaque texture and color on the probability of visual sink mark detection. All treatments had 5.05mm wide sink marks and the shallow and deep sink mark depths were used. Total variance for Experiment #4 was approximately 0.009 after thirty subjects (Figure 68). Certain plaques did exhibit higher variability: the treatment having the highest variance was a grey plaque having a deep (0.035mm) sink mark depth and a coarse (0.060mm) texture (Plaque 24).
This plaque had a final variance of 0.003. The next highest percent variance values were 0.0028, 0.0013 and 0.0010 exhibited by plaques 14, 20 and 21 respectively.

![Incremental Aggregation of Subject Responses](image)

Figure 68. Effect of the incremental aggregation of subject responses on variance in the data of Experiment #4 of the research.

**Analysis of Main Effects and Interactions**

The effects of sink mark depth, texture level and their interactions were found to be significant ($\alpha=0.05$) contributors to the probability of sink mark detection. Color level was also found to be significant ($\alpha=0.05$). The strongest predictor of the response, by chi-square score, was plaque texture. The results of the chi-square scores for the likelihood ratios are shown in Table 30.
Table 30
Likelihood Ratios for the Determination of
Significant Factor Effects in Experiment #4

<table>
<thead>
<tr>
<th>Experiment #4</th>
<th>Degree of Freedom</th>
<th>Log-Likelihood Ratio</th>
<th>Chi-Square</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>1</td>
<td>-28156.80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sink Mark Depth {1}</td>
<td>1</td>
<td>-27012.50</td>
<td>2288.64</td>
<td>0.0000</td>
</tr>
<tr>
<td>Plaque Texture {2}</td>
<td>2</td>
<td>-16425.40</td>
<td>21174.31</td>
<td>0.0000</td>
</tr>
<tr>
<td>Plaque Color {3}</td>
<td>1</td>
<td>-11686.50</td>
<td>9477.67</td>
<td>0.0000</td>
</tr>
<tr>
<td>1*2</td>
<td>1</td>
<td>-11490.80</td>
<td>391.57</td>
<td>0.0000</td>
</tr>
<tr>
<td>1*3</td>
<td>1</td>
<td>-11485.40</td>
<td>10.78</td>
<td>0.0010</td>
</tr>
<tr>
<td>2*3</td>
<td>1</td>
<td>-11478.10</td>
<td>14.50</td>
<td>0.0001</td>
</tr>
<tr>
<td>1<em>2</em>3</td>
<td>1</td>
<td>-11475.80</td>
<td>4.66</td>
<td>0.0308</td>
</tr>
</tbody>
</table>

The effect of texture depth was plotted in Figure 69. From the plot, it can be observed that the mean responses for the treatments having no texture and fine texture are similar. The mean responses for plaques having the coarse texture are significantly lower than those for the other two texture levels.

The effect of plaque color is shown in Figure 70. The grey plaques exhibited a 21.7% lower probability of detection than the grey plaques. The relationship between plaque color and the probability of sink mark detection is further investigated in Figure 71.
Figure 69. Plot of the effect of texture level on the probability of sink mark detection in Experiment #4. The x-axis has been scaled to represent the relative distance between texture depths.

Figure 70. Plot of the effect of plaque color on the probability of sink mark detection in Experiment #4.
In Figure 71, the effect of sink mark depth is plotted by plaque color. For grey plaques, the plot reveals a 25.2% and an 18.3% decrease in probability of sink mark detection for shallow and deep sink marks, respectively. While the effective reduction in perception was greater for the shallow sink marks, the reduction in the deep sink marks changed detection from nearly 100% to 81%.

![Figure 71. Plot of the effects of sink mark depth and plaque color on the probability of sink mark detection in Experiment #4.](image)

Figure 72 illustrates the effects of plaque texture and color on the visibility of sink marks. It is apparent from the plot that the effect of reduced visibility as texture depth increased was accelerated on the grey plaques. In other words, the concealing effects of texture are increased by the use of the lighter product color.

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The Effect of Texture Level in Black and Grey Plaques on the Probability of Detection for Plaques in Experiment #4
Sink Width is 5.05mm

From the previous experiments it was found that the coarse texture reduced the probability of sink mark detection for shallow sink marks on black plaques below the 50% ASTM probability threshold. This can be observed most readily in Experiment #1 where the shallow sink mark on the coarse plaque exhibited a mean probability of detection of 3%. No other sink geometry was as effectively hidden by any texture on the black plaques. To investigate the effects of the color factor on specific sink mark treatments, Figure 73 was created.
Figure 73. Plot of the effects of sink mark depth and texture level on the probability of sink mark detection in Experiment #4.

For the grey plaques, the visibility of the sink marks on coarse textures was significantly reduced ($\alpha=0.05$). Indeed, for shallow sink marks the mean probability of detection was 5.8%. The grey plaques also exhibited reduced visibility of the deep sink mark in the coarse texture and the shallow sink marks in the fine texture. In summary, the grey color was effective in reducing the probability of detection in three out of four cases on textured plaques but was ineffectual on the un-textured, glossy plaque.
Non-Parametric Analysis

The effects of the viewing position factor ($H = 2.12$, d.f. = 1) was not found to have significant effect on the mean responses ($\alpha = 0.05$). The sink mark depth ($H = 139.76$, d.f. = 1) and plaque color ($H = 317.51$, d.f. = 1) were found to have significant effect upon the ranking of subject responses ($\alpha = 0.05$). The plaque texture ($H = 1137.194$, d.f. = 2) was also found to be significant ($\alpha = 0.05$). The plaque texture was the only factor investigated using multiple comparisons, as it was the only factor having more than two levels.

The results of the multiple comparisons of ranks for the texture levels are shown in Table 31. The coarse texture level was found to be significantly different from the no-texture and fine texture levels while those two levels were not found to be different. These finding are in agreement with the results of Experiments #1 and #3 where the coarse texture was found to have a concealing effect on sink mark visibility.

<table>
<thead>
<tr>
<th></th>
<th>No Texture</th>
<th>Fine</th>
<th>Coarse</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Texture</td>
<td>0.1521</td>
<td>0.0000</td>
<td></td>
</tr>
<tr>
<td>Fine</td>
<td>0.1521</td>
<td>0.0000</td>
<td></td>
</tr>
<tr>
<td>Coarse</td>
<td>0.0000</td>
<td>0.0000</td>
<td></td>
</tr>
</tbody>
</table>
Analysis of Pairings with Depth, Texture and Color Level Differences

The likelihood ratio tests for Experiment #4 revealed that the color, depth and texture differences were all significant contributors to mean responses. By the chi-square scores, the strongest predictor of the comparison effects was the texture differences followed by the color differences and then depth differences. The chi-square scores are shown in Table 32.

Table 32
Likelihood Ratios for the Determination of Significant Factor Differences within Presentations in Experiment #4

<table>
<thead>
<tr>
<th>Effects of Factors Differences within Presentations of Experiment #4</th>
<th>Probability of Visual Detection - Likelihood Type 1 Test Distribution: BINOMIAL Link function: LOGIT Effects shown in bold are significant at $\alpha = 0.05$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Degrees of Freedom</td>
</tr>
<tr>
<td>Intercept</td>
<td>1</td>
</tr>
<tr>
<td>Sink Mark Depth {1}</td>
<td>1</td>
</tr>
<tr>
<td>Plaque Texture {2}</td>
<td>2</td>
</tr>
<tr>
<td>Plaque Color {3}</td>
<td>1</td>
</tr>
<tr>
<td>Color Difference {6}</td>
<td>2</td>
</tr>
<tr>
<td>Depth Difference {4}</td>
<td>2</td>
</tr>
<tr>
<td>Texture Difference {5}</td>
<td>4</td>
</tr>
</tbody>
</table>

The finding of texture depth differences having greater effects on detection than the differences in the depth of the sink mark is counter to the findings of the previous experiments. However, plaques without sink were not used in this experiment and therefore the overall effect of sink mark depth on the probability means was reduced in this experiment. Please note that in Table 32, sink mark depth has a lower chi-square score that texture and color.
The interaction between the differences in sink mark depth difference and plaque color are shown in Figure 74. The plot is specific to the coarse texture as the plaques with no texture and fine texture had no practical variation of sink mark detection. For those plaques, detection was above 90% and the difference in sink mark depth caused variations of less than 2%.

Figure 74. Plot of the effect of differences in sink mark depth within pairs in Experiment #4 for objective plaques with coarse texture. Plots are separated by objective plaque color.

For the black objective plaque having coarse texture and shallow sink marks, presentation with a comparison plaque having a deep sink mark reduced the probability of detecting the sink mark. On grey objective plaques with...
coarse texture and deep sink, presenting with a comparison plaque having a shallow sink mark increase the probability of detecting the sink mark. By changing from the black plaque to the grey plaque, this effect was moved from the shallow sink mark to the deep sink mark level.

Figure 75. Plot of the effect of differences in texture depth within pairs in Experiment #4. Effect is for black objective plaques.

To assess the effects of the difference in texture level between the objective and comparison plaques, four graphs were created. Figure 75 shows the plots of the effect of difference in texture for objective plaques with shallow sink marks as well as the plot for objective plaques with deep sink marks. It can

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be observed in this figure that for the objective plaque with a shallow sink mark and coarse texture, the texture of the comparison plaque had an effect on the probability of the subject detecting the sink mark. When the plaque was presented with a comparison plaque having a coarse texture, the subject would detect the sink mark 90% of the time. If the comparison plaque had a fine texture, the probability of detection dropped to 72%. When then comparison plaque had no texture the detection rate dropped again to 58%.

![Categorical Plot of the Effects of Texture Differences](image)

Figure 76. Plot of the effect of differences in texture depth within pairs in Experiment #4. Effect is for grey objective plaques.

For black plaques, the effect of the difference in texture was limited to

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coarse texture and shallow sink marks. The effect of the texture differences was more powerful with the grey plaques. The effects of texture difference within pairs for grey plaques can be seen in Figure 76. Again, the effects on plaques shallow sink marks are separated from deep sink marks. For objective plaques with shallow sink marks, the effect was present in the fine and coarse textures. As with the black plaques, the pairing with comparison plaques having less texture reduced the probability of the subject detecting the sink mark on the objective plaque. For objective plaques having fine texture, the reduction was 17% between coarse and no-texture level on the comparison plaque. For coarse texture, the reduction was 13%. No subject detected sink on a grey objective plaque with coarse texture and a shallow sink mark when presented with a comparison plaque with a shallow sink mark and no texture.

The within pair texture differences did not have an effect on subject responses with black plaques having deep sink marks. The grey plaques with coarse texture did have a change in the probability of detecting deep sink marks. When a grey plaque with coarse texture and a deep sink mark was presented with a comparison plaque having a coarse texture, the detection rate was 72%. When the comparison plaque had a fine texture, the probability of detection was reduced to 49%. When then comparison plaque had no texture the detection rate dropped again to 40%.

While the within-pair differences in texture were the strongest effect in the likelihood test (by chi-square score), the color differences also presented significant effects. The effects plot for within-pair differences in color on subject response is shown in Figure 77. For the black plaques, it can be observed that when the objective plaque had a coarse texture and the objective plaque was
grey, the subject was 21% more likely to detect the sink mark. For the grey plaques, if the objective plaque had a fine texture and the comparison plaque was black, the observer was subject was 7% less likely to detect the sink mark.

![Categorical Plot of the Effects of Color Differences](image)

**Figure 77.** Plot of the effect of differences in plaque color within pairs in Experiment #4. Effect is for objective plaques having coarse texture.

It should be noted that these effects are only present in treatments where the color/texture combination in the treatment was effective in reducing the visibility of the sink mark (see Figure 73). Thus, if the texture is able to reduce the visibility of the sink mark, and if the objective plaque was molded in grey while the comparison plaque was black, the subject was less likely to detect the
sink mark on the objective plaque. The inverse relationship is also true for the reverse color relationship. Thus, the luminosity of the material containing the sink mark as well as adjoining and comparison materials contributed to the visibility of the sink mark.

Study Summary

In both the pilot and the primary study, Experiment #1 demonstrated that the coarse texture was adequate to conceal the minor and shallow sink marks of narrow widths. Experiment #2 demonstrated that no texture level tested was truly adequate to conceal the wide sink marks on black plaques.

In Experiment #3 it was revealed that wide sink marks were more visible than the narrow sink marks. The coarse texture was able to reduce the probability of detection below 50% for narrow sink marks having shallow depth. Experiment #4 showed similar texture effects for black plaques as were observed in Experiment #2. For grey plaques, the concealing effect of texture depth was accelerated.

It was shown several times that the comparison plaque influences the probability of visual detection of sink marks on the objective. This was confirmed for sink mark depth, plaque texture and color difference between the objective and comparison plaques. In Experiment #4, where color, texture and sink mark depth differences were evaluated, chi-square scores showed the differences in texture depth between the objective plaque and the comparison plaque were most influential to the probability of sink mark detection.
Model Construction

The findings of the significance of the factors and interactions lead to the selection of parameters for the model of the probability of sink mark detection. A model was developed to predict the probability of visual detection of sink marks as described by the data set. Binary responses that are limited to 0 and 1 generally have ordered probabilities that are curvilinear in appearance, and are by definition limited between zero and 1. Figure 78 shows the ordered probabilities of the observations in this research. It can be seen that the groupings did exhibit a curvilinear response. Logistic regression methods are most appropriate in these conditions.

Figure 78. Ordered probabilities for the observations in the research. The curvilinear nature suggests the appropriateness of logistic modeling methods. Predicted values from the model are shown as well.
The logit function was used to linearize the responses such that the use of general linearized modeling methods was appropriate (Neter, et al. 1996, Freund, et al. 2006). It was necessary to redefine probabilities of 0 and 1 as the logit transformation does not exist for these values. Freund, et al. (2006) suggested adjusting 0 to $1/2n_i$ and 1 to $(1-1/(2n_i))$ where $n_i$ is the observations for a given group. For these data, this reduced the 100% conditions to 98.3% and zero percent probabilities were increased to 2.17%.

Neter, et al. (1996) suggested backward stepwise removal of terms. Using this parameter selection method, parameters were removed that were not significant to the ability of the model to fit the data ($\alpha=0.05$). The backward stepwise removal method was employed, as it was important to consider the impact of all factors and interactions before reducing the size of the model.

The data were grouped by experiment, observation pair and plaque. Thus, estimates of the probability of detection were created by averaging the number of sink mark detections over the number of observations for all combinations of these grouping factors. Given the use of general linearized methods, it was important to homogenize the variance among the responses. The variance within the data was reduced by the use of weighted regression methods. The weights were calculated as shown in Equation 3. This method was suggested by Freund, et al. (2006).

\[
\hat{w}_i = n_i \hat{p}_i (1 - \hat{p}_i) \tag{3}
\]

Where
\[
\begin{align*}
    n_i & = \text{total number of observations in group } i \\
    \hat{p}_i & = \text{probability of detection for group } i
\end{align*}
\]
The input terms of the model and their units are shown in Table 33. Color values are from the Munsell scale for the value of neutral colors, no hue or chroma information is used. The delta values are calculated by subtracting the value of the factor for the comparison plaque from the value for factor on the objective plaque.

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Units</th>
<th>Range of Values in Data Set</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sink Mark Depth</td>
<td>Millimeters</td>
<td>0.000 to 0.035mm</td>
</tr>
<tr>
<td>Sink Mark Width</td>
<td>Millimeters</td>
<td>0.00 to 5.05mm</td>
</tr>
<tr>
<td>Plaque Color</td>
<td>Munsell Value</td>
<td>N2 and N8</td>
</tr>
<tr>
<td>Texture Depth</td>
<td>Millimeters</td>
<td>0.000 to 0.060mm</td>
</tr>
<tr>
<td>Sink Mark Depth Delta</td>
<td>Millimeters</td>
<td>-0.035 to 0.035mm</td>
</tr>
<tr>
<td>Color Level Delta</td>
<td>Munsell Value</td>
<td>-N6 to N6</td>
</tr>
<tr>
<td>Texture Depth Delta</td>
<td>Millimeters</td>
<td>-0.060 to 0.060mm</td>
</tr>
</tbody>
</table>

From these seven factors, the described regression techniques found 26 significant parameters, including interactions and the intercept. The model exhibited an adjusted $r^2$ value of 92.3%. To reduce the complexity of the model, included parameters were limited to fourth level interactions. This limitation resulted in a removal of only 0.3% from the adjusted $r^2$. Thus the reduced model contained 25 parameters and exhibited an $r^2$ score of 92.0% against the variation in the data. When the model was restricted to third level interactions, the $r^2$ score was reduced to 91.5%. A model constructed removing interaction above the second level resulted in an $r^2$ score of 81.7% while a model consisting of the
main predictors exclusively exhibited and $r^2$ score of 75.7%.

The parameters and statistics of each of these models can be found in Appendix L, the model including fourth level interactions will be presented here. The parameters and their coefficients of this model are shown in Table 34. Note that the effects of texture depth, sink mark depth delta and texture depth delta were pooled in the interaction parameters.

Table 34
Parameters of the Model
(Including Coefficients)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>-1.75</td>
</tr>
<tr>
<td>Sink Mark Depth</td>
<td>285.89</td>
</tr>
<tr>
<td>Sink Mark Width</td>
<td>2.24</td>
</tr>
<tr>
<td>Plaque Color</td>
<td>-0.91</td>
</tr>
<tr>
<td>Color Level Delta</td>
<td>0.61</td>
</tr>
<tr>
<td>Sink Mark Depth*Color Level Delta</td>
<td>-20.88</td>
</tr>
<tr>
<td>Sink Mark Depth*Sink Mark Width</td>
<td>-92.36</td>
</tr>
<tr>
<td>Sink Mark Depth*Texture Depth</td>
<td>-7348.26</td>
</tr>
<tr>
<td>Sink Mark Width*Texture Depth</td>
<td>-31.82</td>
</tr>
<tr>
<td>Plaque Color*Color Level Delta</td>
<td>-0.11</td>
</tr>
<tr>
<td>Plaque Color*Sink Mark Depth</td>
<td>29.00</td>
</tr>
<tr>
<td>Sink Mark Depth<em>Texture Depth</em>Depth Delta</td>
<td>33570.20</td>
</tr>
<tr>
<td>Sink Mark Depth<em>Texture Depth</em>Texture Depth Delta</td>
<td>27457.18</td>
</tr>
<tr>
<td>Sink Mark Depth<em>Sink Mark Width</em>Texture Depth</td>
<td>2426.11</td>
</tr>
<tr>
<td>Sink Mark Width<em>Texture Depth</em>Texture Depth Delta</td>
<td>-182.05</td>
</tr>
<tr>
<td>Plaque Color<em>Sink Mark Depth</em>Color Level Delta</td>
<td>3.53</td>
</tr>
<tr>
<td>Plaque Color<em>Sink Mark Depth</em>Texture Depth</td>
<td>-260.44</td>
</tr>
<tr>
<td>Plaque Color<em>Texture Depth</em>Texture Depth Delta</td>
<td>100.62</td>
</tr>
<tr>
<td>Texture Depth<em>Color Level Delta</em>Texture Depth Delta</td>
<td>-178.71</td>
</tr>
<tr>
<td>Sink Mark Depth<em>Texture Depth</em>Color Level Delta*Depth Delta</td>
<td>5594.57</td>
</tr>
<tr>
<td>Sink Mark Depth<em>Texture Depth</em>Color Level Delta*Texture Depth Delta</td>
<td>5907.54</td>
</tr>
<tr>
<td>Plaque Color<em>Sink Mark Depth</em>Color Level Delta*Depth Delta</td>
<td>-48.41</td>
</tr>
<tr>
<td>Plaque Color<em>Sink Mark Depth</em>Texture Depth*Texture Depth Delta</td>
<td>-3829.04</td>
</tr>
<tr>
<td>Plaque Color<em>Sink Mark Width</em>Texture Depth*Depth Delta</td>
<td>-23.24</td>
</tr>
<tr>
<td>Texture Depth<em>Color Level Delta</em>Depth Delta*Texture Depth Delta</td>
<td>-3849.52</td>
</tr>
</tbody>
</table>

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Comparisons of the predicted values to the ordered observed probabilities were presented above in Figure 78. The normal probability plot in Figure 79 shows that the distribution of the residuals of the model for the logit transformed observations. Deviation from normal is greatest at the extremes. Figure 80 illustrates a comparison of predicted values and observed values. Stratification of the data can be observed at the extremes of the observed values.

The model was validated against the data collected during the pilot study. Figure 81 shows the normal probability plot of the raw residuals. Again, it can be observed that the residuals are normally distributed in the center of the response and deviate at the extremes. The plot of the predicted values versus the observed values of the validation set is shown in Figure 82. Stratification again occurs in the upper and lower 10% of the responses.

Figure 79. Normal probability plot of the raw residuals for predicted values. Deviation from the normal increases as the response approach zero or 100%
Figure 80. Comparison of observed and predicted values. Stratification is present near the extremes of the observed values.

Figure 81. Normal probability plot of the raw residuals for predicted values from the validation set. Deviation from the normal increases as the response approach zero or 100%.
Figure 82. Comparison of observed and predicted values. Stratification is present near the extremes of the observed values.

In order to arrive at values for the probability of visual detection, the logit transformation was removed from the output of the model. Equation 2 was used to convert the model output to the predicted values for probability of visual perception used in Figure 78 above.

\[
\hat{p}_i = \frac{\exp(Y'_i)}{(1 - Y'_i)}
\]

Equation 4

Where

\begin{align*}
Y'_i &= \text{model estimate for group } i \\
\hat{p}_i &= \text{predicted estimate of the probability of detection for group } i
\end{align*}
It is apparent that the model becomes less reliable as the conditions approach zero and 100% probability of visual detection of the objective sink marks. However, it could be argued that in these extreme conditions (greater than 80% and less that 20%) the common sense of the designer and an understanding of the factors effecting visibility of sink marks may be as effective as the model. Evaluation of the model has shown that in marginal conditions near 50% detection, the model can be a useful tool to evaluate the effects of the great number of parameters influencing sink mark visibility.

Findings Summary

The analysis of the data showed that the coarse texture was effective for concealing shallow and minor sink mark depths for narrow sink marks on black plaques. In the case of grey plaques, the coarse texture concealed both shallow and deep sink marks. The width of the sink was found to have an effect upon the visibility of the sink mark with wider sink having a greater probability of detection. Table 35 summarizes the effectiveness of the textures to conceal the various sink marks. This effectiveness is based upon the ASTM definition of the visual threshold at 50% of subject perceiving the visual effect (in this case, a sink mark).

Analysis of the data revealed the probability of detecting a sink mark was not only dependent upon the characteristics of the part under inspection, but also upon the environment in which the observations take place. More specifically, the probability of sink mark detection on the objective plaque was influenced by the comparison part. The differences between the plaques presented in comparisons during each experiment caused variation in the mean
results for the probability of detection. This effect was quite evident. These results not only suggest important factors to include in the construction of predictive models, but also have interesting implications for shop-floor inspection methods in industry.

Table 35

<table>
<thead>
<tr>
<th>Plaque Color</th>
<th>Sink Mark Width</th>
<th>Depth</th>
<th>Texture Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black</td>
<td>Narrow</td>
<td>Minor</td>
<td>No</td>
</tr>
<tr>
<td>Black</td>
<td>Narrow</td>
<td>Shallow</td>
<td>No</td>
</tr>
<tr>
<td>Black</td>
<td>Wide</td>
<td>Shallow</td>
<td>No</td>
</tr>
<tr>
<td>Black</td>
<td>Wide</td>
<td>Deep</td>
<td>No</td>
</tr>
<tr>
<td>Grey</td>
<td>Wide</td>
<td>Shallow</td>
<td>No</td>
</tr>
<tr>
<td>Grey</td>
<td>Wide</td>
<td>Deep</td>
<td>No</td>
</tr>
</tbody>
</table>

*The ability to conceal is base upon the ASTM standard that sets the threshold of visibility at 50% detecting the effect.*

In some experiments, significant differences were found between presentations on the left- and right-viewing positions. In these cases, the right position usually exhibited a higher probability of sink mark detection. It is reasonable to suspect that this was an effect of eye dominance. While subjects were not tested for ocular dominance, literature suggests a majority of the general population is right eye dominant (Fang, Fei, Jawahir, Malott, Clare &
A model was constructed using maximum likelihood methods on logit-transformed mean subject responses. This model exhibited an $r^2$ value of 92% and was validated against the data from the pilot study. The factors selected for the model are based upon data until this research had not been collected. The work here stands as a strong proof-of-concept for the prediction of sink mark visibility.
CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Overview

The research presented here investigated factors that influence the visibility of sink marks. The effects of product texture and color were found to be significant factors in the determination of the probability of the visual detection of sink marks. Additionally, it was found that the comparison plaque had significant influence upon the observer’s perception of the sink mark. This chapter will outline the implications of these findings. Discussions and conclusions are divided into five areas: the research instrument, the effects of sink mark depth and width, the effects of product texture, the influence of part color, and influences of the comparison plaque on the visibility of sink marks.

This chapter closes with a short set of recommendations. Suggestions are made regarding areas in which the applicability of the data set may be broadened. Methods for the development of sink mark inspection protocols are proposed. Finally, factors of significance to predictive models are presented.

Components of the Research Instrument

This research required test subjects to make decisions based upon observations of numerous sample plaques. Each plaque was a treatment within
the overall experiment, representing a fixed combination of levels of each factor in the experimental design. The plaques were presented to test subjects in pairs, thus providing information about the effects of factor level differences between each plaque. In this manner, each observation made by the test subject provided a great deal of information about the factors that influence the visual detection of sink marks.

Because the subject pool was drawn predominantly from industry, it was important to constrain the duration of the interview process. By reducing the duration of the interview, the cost of participation was limited. The inspection fixture was found to be quite capable of collecting the data quickly and efficiently. Once the sample plaques were loaded into the inspection fixture, mean time between presentations was 10.6 seconds. The mean subject response was seven seconds. Thus, the mean observation time for each pair was under eighteen seconds. This demonstrates that the fixture design facilitates the rapid collection of a great deal of observations.

Analysis of the effects between the four interview locations showed that the mean responses were not sensitive to the population from which subjects were drawn from. This effect was investigated primarily to discover if the students exhibited significantly different responses than the industry professionals. The implication of the finding of no effect from the interview location indicates that students and individuals unfamiliar with sink marks can be used to model the perception of trained inspectors.

The fixture was also quite flexible in its ability to test a variety of factors simultaneously. The parts inspected are limited only by the size of the fixture's inspection window and the part-holding carousel. While this research
investigated sink marks, other aesthetic defects could be investigated using the same apparatus. Various levels of experimental factors, and indeed other defects, can be inspected simultaneously on the part-holding carousel of the fixture.

Effects of Sink Mark Width

Of the main factors in this research, the most obvious and expected results were exhibited by sink mark depth. The analysis of the data showed that regardless of texture, deeper sink marks exhibited a higher probability of detection than shallow sink marks. However, prior to this research, the effect of sink mark width on the visibility of a sink mark was more controversial and biased by personal opinion and experience.

Before the collection of this data, it was thought that a wider sink mark would distribute the visual effects of the sink mark across wider area. It could have been argued that this wider effect would avoid any abrupt changes on the product surface, reducing the ability of the human eye to detect the changes. However, this research found that the wider sink mark made the sink more visible and required deeper texture to conceal.

Effects of Product Texture

The sink mark depth levels were chosen to reflect typical problematic sink marks in industry. These sink marks have generally been reviewed by engineers and meet most of the design guidelines for the avoidance of sink mark formation. Given that, these problematic sink marks generally exhibit depths of
0.005mm - 0.040mm (0.0002 - 0.0015 in.). It was anticipated that small amounts of texture would be effective in concealing the sink marks.

Surprisingly, for treatments with no sink mark, the probability of sink mark detection increased with greater texture depth. No test subject detected sink on the black plaque with no rib (hence no sink mark) and no texture. As the depth of the texture increased, test subjects reported seeing sink marks on the plaques without sink marks. Detection of these false sink marks occurred in 1.5% of the inspections of plaques having 0.018mm (0.0007 in.) deep texture and no sink mark. On plaques with 0.060mm (0.0024 in.) deep texture and no sink marks, false sink marks were detected in 3.3% of the inspections.

Not all sink mark geometries were concealed by the chosen levels of texture. For plaques having wide sink marks, the 0.018mm (0.0007 in.) deep texture was found to be no more effective at concealing sink marks than not having texture. The 0.060mm (0.0024 in.) deep texture was able to reduce the visibility of narrow sink marks, but had only marginal effect on wide sink marks. This would indicate that shallow, problematic sink marks require fairly deep texture to conceal. The data did reveal trends in the effect of texture for sink mark concealment. In this research, texture depths greater than three times the depth of the sink mark were required to conceal sink marks on black plaques. On grey plaques, sink marks were concealed by texture depths twice the depth of the sink mark.

Conditions of Marginal Concealment

As the probability of detection decreased from 100%, the variability in the responses of test subjects increased. The increase in variability of observer
response can be used to signal a surface condition approaching a visual
threshold. This has implications for shop-floor inspection of sink marks, if not
all aesthetic defects.

Problematic sink marks are generated when minor process fluctuations
or inadequate part design cause conditions on a product’s surface to approach
the visual threshold for sink mark detection. If the texture is marginally
adequate for concealing the sink mark, the probability of detection is less than
100% but greater than 0%, hence approaching a visual threshold. In this
marginally acceptable condition, each inspector may perceive the sink mark
differently. It is inherent to this condition that some unacceptable sink marks
may be passed by inspectors.

This condition of marginal concealment was represented in the data set
by plaques 13, 14, 21, and 24. These plaques exhibited higher variability in
responses and were more influenced by environmental factors. It is in these
conditions, near a visual threshold, where the effects of gender, the environment
and the product luminosity have greatest influence on the visibility of the sink
mark.

Review of Figure 46 shows that in these conditions, woman exhibited a
higher probability of sink mark detection than men. This suggests that women
were more capable of seeing sink marks. Also, women were less likely to report
the detection of a sink mark when no sink was present in the part, hence the
female observers exhibited a lower error rate than male observers.

Effects of Luminosity

The color factor was found to affect the visibility of sink marks. Only

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neutral shades of black and grey were investigated in this research. Therefore, in these conclusions the color effects will be discussed in terms of luminosity. For plaques with fine or coarse texture, the brighter, more luminous (grey) plaques exhibited a lower probability of detection than less luminous (black) plaques having the same sink mark treatment. This relationship was observed in Figure 71 of Chapter 4.

While luminosity by itself was not effective in reducing the detection of sink marks on plaques without texture, an interesting and significant interaction was found between the product color and the plaque texture. Previous discussion identified that increasing texture depth was effective in concealing increasing sink mark depths and widths. The brighter, more luminous plaques exhibited an increase in the strength of this effect. In Chapter 4 this relationship was shown in Figure 72.

The contributory effect of luminance was strongest in near-threshold conditions. In other words, when the texture was adequate to reduce the probability of detecting the sink mark below 80%, the contribution of the product color was greatest. For example, the coarse texture was most effective in hiding the sink marks. This can be observed in various graphs throughout Chapter 4. When the grey plaques were evaluated, the reduction in detection from the black condition was greatest for plaques with coarse texture (Figure 72). As a guideline to designers dealing with problematic sink marks, while the visibility of a sink mark can be reduced with the application of the appropriate texture depth, additional reduction can be realized by using brighter, more luminous neutral colors.
Plaques were presented in pairs during observations conducted in this research. This is similar to inspection methods used for aesthetic defect in the molding industry. In the performance of these industrial inspections, a product from the molding machine is compared to a part that the customer has certified as having an acceptable appearance.

Quality engineers attempt to control the variability in the inspection process through the use of inspection standards. These inspections are generally conducted in controlled-lighting environments at the startup of the molding process. However, the customer-certified sample part may or may not be molded in all product colors. This research found that the appearance of the comparison part has influence over the visibility of the sink mark under inspection.

Significant interaction effects were discovered between the probability of sink mark detection and the environment of the observation, specifically the appearance of the comparison plaque. All treatments of factors were paired with all other treatments. In other words, in each experiment, every plaque was paired with all other plaques in the experiment.

It was found that differences in sink mark depth as well as product texture and luminosity affected the probability of a test subject to detect the objective sink mark. While effects were found for differences in sink mark depth between plaques, the effects of differences in texture and color were strongest. These findings have implications on the effectiveness of conventional inspection methods using sample comparisons to identify sink marks.

From the results of this study, it can be concluded that if the comparison
sink mark on a certified sample is deeper than the sink mark on the part under inspection, the objective sink mark will be more difficult to detect. If the comparison sink mark is shallower than the objective sink mark, it will be easier to identify the objective sink mark. Therefore, when the certified product has a similar luminosity and texture as the product being inspected, the comparison-based inspection method should be reasonable and effective.

However, if the certified plaque is a different color or texture, the effects of these differences may make the inspection less likely to identify the sink mark. For instance, if the objective part is brighter than the sample part, the probability of detecting the objective sink mark will be reduced, allowing the possibility of an inspector passing an unacceptable product.

Implications for Visual Inspection Protocols

It is common in the plastics industry for customers to provide injection molding companies with samples of acceptable levels of aesthetic defects. To confirm that the molded product meets the customer’s expectations, the molders use these acceptance standards at the start of a molding process and at various times during production. The individual performing the inspection holds both parts and compares one to the other using direct and indirect lighting.

As discussed above, the findings of this study support these industry accepted visual inspection methods. In the case of a sink mark on a certified part being deeper than the suspect sink mark, the inspector will be less likely to detect the suspect sink mark. If the suspect sink mark is deeper, the inspector will be more likely to detect it when comparing the sink against a shallower sink mark on the certified sample. These conditions are described in Figure 83.
Figure 83. Inspection conditions for cases where the certified sample and the inspected part have the same luminosity and texture. 'p' is the probability of detection of a sink mark on the object plaque.

However, these conditions are true only if the part under inspection is the same luminosity and texture as the certified sample. It is evident that the customer-certified sample should be of the same color and texture as the part under inspection. This reduces the possibility of passing on unacceptable products to the customer. Additionally, the possibility of rejecting acceptable parts will be diminished.

When the suspect part is darker than the certified sample, the inspector will be more likely to detect the sink mark. However, if the certified sample is more luminous than the certified sample, there is an increased probability of the inspector passing a product with an unacceptable sink mark depth. This condition is described in Figure 84.
### Figure 84

Inspection conditions for cases where the certified sample and the inspected part have different luminosity. ‘p’ is the probability of detection of a sink mark on the object plaque.

<table>
<thead>
<tr>
<th>Suspect Part</th>
<th>Customer Certified Sample</th>
<th>Inspection Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Same Luminosity</td>
<td>Same Luminosity</td>
<td>$p = x$</td>
</tr>
<tr>
<td>Brighter</td>
<td>Darker</td>
<td>$p &lt; x$ (Appears shallower)</td>
</tr>
<tr>
<td>Darker</td>
<td>Brighter</td>
<td>$p &gt; x$ (Appears deeper)</td>
</tr>
</tbody>
</table>

### Figure 85

Inspection conditions for cases where the certified sample and the inspected part have different texture depths. ‘p’ is the probability of detection of a sink mark on the object plaque.

<table>
<thead>
<tr>
<th>Suspect Part</th>
<th>Customer Certified Sample</th>
<th>Inspection Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Same Texture</td>
<td>Same Texture</td>
<td>$p = x$</td>
</tr>
<tr>
<td>Deeper Texture</td>
<td>Shallower Texture</td>
<td>$p &lt; x$ (Appears shallower)</td>
</tr>
<tr>
<td>Shallower Texture</td>
<td>Deeper Texture</td>
<td>$p &gt; x$ (Appears deeper)</td>
</tr>
</tbody>
</table>
An inspector will be more likely to detect suspect sink marks when the texture is deeper on the certified part than on the inspected part. If the certified sample has shallower texture than the suspect part, the inspector will be less likely to detect the suspect sink mark. This condition is described in Figure 85.

Recommendations

Due to the scarcity of previous scientific investigations on sink mark perception, much remains to be explored in this area. The following suggestions are made to further this research. These recommendations fall into three categories: broadening the applicability of the data set, inspection protocols and model building suggestions.

Improvement of the Applicability of the Data Set

In the current data set, the 0.060mm (0.0024 in.) deep texture was most effective for the concealment of the various sink marks. The 0.018mm (0.0007 in.) deep texture was only marginally effective in concealing the sink marks investigated in this study. Aggressive stipplest on plastics products can be as deep as 0.1mm (0.004 in.) (Rawl, n.d.). The predictive nature of the data set would be improved with the inclusion of deeper texture levels.

Media blasting methods created the stipplest investigated in this research. Etching methods are often used to create stipplest. These etched stipplest may have different influence on the visibility of sink marks. The investigation of various etched stipplest would broaden the scope of this data.
Product Design Considerations

For product designers, the findings on the influence of the comparison plaque should suggest the need for careful consideration of the textures and colors used in close proximity to each other. Ill-considered two-tone finishes may accentuate the appearance of sink marks. Visually, a sink mark will be more apparent if it exists on dark components located close to lighter components (Figure 77). In conditions where a bright and a dark colors are near each other in assembly or on a single part, efforts should be made to place sink-forming geometries, such as ribs and bosses, in the brighter colored areas. In this condition, the concealing characteristics of the between-color effects will be used to reduce the visibility of any potential sink marks.

Suggestions for Predictive Models

The effects of the viewing environment should be considered in the development of a model to describe the probability of visual detection of sink marks. Modeling the probability of detection based upon only the geometric characteristics of the sink mark and its associated part is not adequate.

Suggested factors for model building include the following:

- Sink Geometry – The size and shape of the sink mark set a ‘baseline’ for visual detection of the sink mark. As investigated here, inputs to the model may include width and depth.
- Surface Texture Depth – This research investigated blasted stippled textures only. Stipple textures could be modeled based upon texture depth.
- Product Color – This research suggests that luminosity should be
use as an input to models of the probability of sink mark visual
detection. Luminosity had an inverse effect upon the visibility of
sink on textured surfaces.

- Relative Texture – Relative texture was shown to influence the
  appearance of adjacent sink marks. Texture of components in
  proximity to the sink mark should be included in predictive
  models. It should be considered if adjoining textures are deeper or
  shallower than the objective sink mark.

- Relative Color – The color of the components in close proximity to
  the objective plaque should be considered. Brighter colors will
  increase the appearance of sink on darker proximal components

- Exposure time – As the conditions approached visual thresholds,
  the test subjects spent more time inspecting the plaques before
  making decisions about the visibility of the sink mark. This
  implies that they were having difficulty identifying and judging
  the sink marks. If the sink mark is in a remote location, the
  exposure time is small and the probability of detection may be
  reduced. Thus, exposure time has a direct relationship with the
  probability of visual detection of sink marks.

The relative strengths of many significant factors that influence sink
mark visibility have been identified. It was surprising to discover the degree to
which the controlled exposure of the sink marks was influenced by comparison
plaques. These environmental effects should not be ignored in the development
of inspection protocols and predictive models.
It should be kept in mind that no aesthetic defect is examined in a vacuum of perceptual inputs. No sink mark stands alone in our field of vision. The surrounding environment and the qualities of the observation experience affect the ability of an inspector or customer to perceive the defect. Ultimately, the attention and resolve of the individual observer determines the visibility of a sink mark.
APPENDIX A

Plaque Presentation Pairs
### Experiment #1 - From Interview #1

Objective: Determine the effect of Sink Depth and Plaque Texture for Width Level 1

Note: Width and Depth levels 'zero' indicate no sink.

<table>
<thead>
<tr>
<th>Pair #</th>
<th>Left-hand Plaque</th>
<th>Right-hand Plaque</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Plaque</td>
<td>Depth</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
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<td>36</td>
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</tbody>
</table>
Experiment #2 - From Interview #1

Objective: Determine effect of Sink Depth and Plaque Texture for Width Level 2

Note: Width and Depth levels 'zero' indicate no sink.

<table>
<thead>
<tr>
<th>Pair #</th>
<th>Left-hand Plaque</th>
<th>Right-hand Plaque</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Plaque</td>
<td>Levels</td>
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<td>Width</td>
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Experiment #3 - From Interview #2

Objective: Determine effect of Sink Width and Plaque Texture for Depth Level 2

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Experiment #4 - From Interview #2

Objective: Determine effect of Sink Depth and Plaque Color & Texture for Width Level 2

Note: Depth levels 'zero' indicate no sink.

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Experiment #4 - From Interview #2 <continued>

Objective: Determine effect of Sink Depth and Plaque Color & Texture for Width Level 2

Note: Depth levels 'zero' indicate no sink.

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ABSTRACT

Customer demands for high-quality, defect-free injection-molded plastic products are continually increasing. Additionally, consumers are expecting a greater variety of options in products, with increasingly reduced delivery times. In order to satisfy these expectations, product developers use computer software to simulate the processing of the plastic as well as the final appearance of the product. Much effort is expended to ensure that computer-generated renderings of simulated prototypes accurately represent the size, shape, color and surface texture of the final product.

At the same time, the effects of attribute defects such as sink marks or splay are often difficult to simulate in renderings. Injection molding simulation software can predict the occurrence of these defects, but the severity of their appearance in the final product can be questionable. While customers routinely reject products because of these attribute defects, it benefits the manufacturer to understand the effects of these defects on the appearance of the product.

In the case of the defect known as sink marks, it is well understood in the industry that surface textures can be used to hide minor occurrences of the defect. However the exact nature of this relationship has not been completely explored. It is known that the surface texture scatters the light and interferes with the observer's ability to see the sink mark. However it is not understood how deep (or coarse or aggressive) the texture must be in order to hide sink marks of given depths. Figure 1 in Appendix C shows the appearance of sink marks on a textured surface.

PURPOSE/BACKGROUND INFORMATION

This research is intended to study how surface texture effects the visual detection of an injection molding defect called a sink mark. A sink mark is shallow depression or dimple on the surface of a
finished plastic part due to shrinkage or improper filling of the mold cavity. Human observers will evaluate a series of injection-molded parts that exhibit various depths of sink marks and have various levels of texture. The project will take place in the Plastics Processing Laboratory at Western Michigan University's Parkview Campus. Human observers will view pairs of parts in an inspection fixture illuminated by a moving fluorescent inspection lamp. The length of involvement for each observer will be two sessions on separate days each lasting approximately sixty minutes.

**SUBJECT RECRUITMENT**

Recruitment signs and pamphlets will be posted at the College of Engineering and Applied Sciences and at volunteer plastics molding companies. Volunteer companies will be solicited through existing relationships between the Western Michigan manufacturing community and the Plastics Processing Laboratory at Western Michigan University. A solicitation letter (shown in Appendix D) will be sent to contact personnel at target companies that have an interest in robust injection molding. Access to subject from the employees of the companies will be solicited through the company's contact personnel and will be documented by the signing of an access granting letter. The informed consent process and form will emphasize non-coercive methods and no reprisal for non-participation.

Subjects will be selected based upon their response to signs and pamphlets that invite them to participate in the research (Appendix E). The invitation information shall explain the purpose and benefits of the research to potential subjects and efforts will be made to present subject participation as non-compulsory, coercion will be avoided. The Student Investigator’s office phone number will be provided on the sign and/or pamphlet. Potential subjects will be asked to contact the investigator about the research. Once potential subjects have expressed an interest in learning more about participating, an appointment will be set-up. During this appointment, they will be informed as to the purpose of the research, the activities involved and potential risks.

In order to increase the sensitivity of the research instrument, subjects must possess visual acuity correctable to 20/20 vision. Visual acuity and contrast sensitivity will be assessed with the Freiburg Visual Acuity & Contrast Test ("FrACT") (Bach, 2006; Wesemann, 2002). The subjects will wear any necessary corrective appliance (eyeglasses or contacts) during the viewing session.
Additionally, laser corrective surgery is not an exclusionary criterion (Dennis et al., 2004). Individuals with who have undergone Laser-Assisted In Situ Keratomileusis (Lasik) or other corrective surgeries are not excluded from this research.

Subjects younger than 18 and older than 40 years old will not participate in this research. The exclusionary criterion is for two purposes. First, there is no need in this research to involve protected populations under the age of legal consent, as they have limited purchasing power in the high-end consumer markets where many plastic products are found. Secondly, research has shown that the quality of vision deteriorates with age (Dollinger, 1996; Madden and Plude, 1996; Plude and Hover, 1985). Generally the age of forty is accepted as a standard threshold for the onset of considerable changes in vision.

INFORMED CONSENT PROCESS

The process and background of the research will be explained to the potential subject prior to signing the informed consent form. The aspects of the experiment, such as sink marks and textures will be explained to the subject. Sink marks will be described and samples will be shown to the subject. Various stipple will be shown to the subject and the effects of stipple on the visibility of sink marks will be explained. This information will be given as part of the informed consent process so that potential subjects will be aware of what they will be asked to identify. The researcher will use the scripts contained in Appendix F to inform and educate potential subjects.

The potential subject will be shown the inspection fixture and its operation will be explained and demonstrated. The potential subject will be informed that the researcher will present the pairs of parts to be evaluated, while the potential subject will make decisions about the sample parts based upon visual inspection. During the inspection process, the subject will not be able to handle the part but will be allowed to tilt the part by tilting the table of the fixture. Illustrations of the design and the motion of the table are shown in Appendix C.

Potential subjects will be told that each session will last approximately one hour and rest periods will be provided. Potential subjects will be further informed of the potential for discomfort to their eyes. Most observers working in a plastics company evaluate parts at the molding press for eight hours. They usually take two breaks and then a lunch period to help provide
the rest they need. The viewing of parts will only take about forty minutes; therefore the risk of discomfort to the observer's eyes will be a minimal risk (Horton, 1997; Ebaraj et al., 1999).

The potential subject will be informed that they will be allowed rest periods as required if they begin feeling eye or head discomfort. The rest period will last until active subjects feel they can continue. If time becomes a factor in completing the survey in the allotted amount of time, the subject will be released from the study. The rest periods will be available when active subject requests them.

The coding of the data and the subject identity will be explained to the potential subject. The subject will be informed that the survey will comprise of two (2) sessions performed on different days. The potential subject will be told that the research is a component of Kurt Hayden's dissertation research and the results will be published in the dissertation and in professional journals. Once the potential subject has been made familiar with the study through the scripts and examples, they will be asked to sign the informed consent form (Appendix G). Two copies of the form will be give to the potential subject, one to be signed and returned to the researcher and one for the subject to keep.

**RESEARCH PROCEDURE**

The session will involve a combined visual acuity and contrast sensitivity test known as the Freiburg Visual Acuity & Contrast Test or 'FrACT'. The test will allow for characterization of the visual ability of the subject, and not as a screening tool. The subject will also complete a brief questionnaire. The attached questionnaire (see Appendix H) will be used to provide general information about human observers such as age and level of education. Once the test and questionnaire are complete, observers will view plastic parts with different levels of sink marks.

The subject will be asked to participate in the Bach Freiburg Visual Acuity Contrast Test. This test will provide a measure of the subject's contrast sensitivity. The subject will be asked to respond to a series of questions about images displayed on the screen of a laptop computer. The questions pertain to the subject ability to discriminate between levels of contrast. This test will take approximately three minutes to perform.

After completing the three tests, observers will be asked to view a
series of plastic parts with various levels of sink marks. The subject will also be asked if they can see a sink mark on each part. Paired comparisons will be used in the research procedure. When using this procedure, subjects are shown two parts and asked which one of the two is preferred. If one part is picked more strongly, then it can be concluded that some of the observers are able to tell the difference between the two parts. The only discrimination information provided is if one part is strongly preferred. It simply means that observers are able to tell the difference between the two parts.

Data will be collected with the use of a spreadsheet form shown in Appendix I. Within the spreadsheet, the subject will be identified by number only. A cross-reference sheet will be used to assure the same subject number is used for the subject during both survey sessions. At the completion of the second series of surveys, the cross-reference sheet will be destroyed, eliminating the link between the subject's identity and the subject number. This will remove any means to identify to subject with their responses.

METHODOLOGY

The design of experiment includes three factors (sink mark depth, sink mark width, and depth of surface texture) each having three levels. An incomplete block design will be used. ANOVA methods will be used to analyze the main effects as well as select interaction effects. Linear and non-linear regression techniques will be applied to the data in an attempt to model the probability of the visual detection of sink marks for given texture depths. Decision tree and classification tree methods will be used to map perceived improvements in the sink mark appearance and relate them to the factors of the experiment.

The result of the analysis will be published as the main component of Kurt Hayden's Doctorial Dissertation at Western Michigan University. Additionally, peer-reviewed journal articles will be written from the results of this study. Such articles may also be presented at academic and professional conferences.

RISKS, COSTS AND PROTECTIONS

A potential risk may involve discomfort to the eyes of subjects from viewing a number of plastic parts. Each observer will view multiple sets of plastic parts. The testing will be conducted in controlled lighting and the sample parts will be illuminated with
an industrial standard daylight inspection lamp. These lamps are the inspection lamps called for by American Standards for Testing and Measurement (ASTM) for color, graphics and part inspection, thus the known risks are minimal (ASTM D1729-96 and ASTM E1499-97). Rest periods are included in the methodology to reduce the risk of eye fatigue.

An additional cost to the participant is the time required to participate in the study. Further potential cost to the subject may include tired eyes, soreness and fatigue. To minimize the potential for such effects, rest periods will be provided to the subject upon request.

**BENEFITS OF RESEARCH**

The short-term benefits of this research involve a determination of how the depth of surface texture affects the visibility of sink marks. This effect can be mathematically modeled from the data collected in this research. By incorporating these models into plastic simulation software, long-term benefits can be provided to the plastic design industry. The simulation software can be used to develop images that demonstrate the appearance of a product before expensive production molds and equipment are purchased. These preliminary investigations save manufacturers money and time in product development.

Other than the satisfaction of participating in research to improve our collective understanding of injection molding design and optimization, the participants will gain no individual benefits from this study.

**CONFIDENTIALITY OF DATA**

All the information collected during the project will be confidential. Therefore, names will not appear on any papers where information is recorded. No information will be collected that can be used to personally identify the participants in the study. Participants will be assigned a random identification number. All forms will be retained for at least three years in a locked file in the principal investigator's office.
APPENDIX C

Illustrations
Figure 1.
Photograph of sink marks on an injection-molded product.
Figures 2 & 3.
Illustrations of the ride side view of the Sample Part Viewing Fixture showing the table pivoted at +20 and -20 degrees.
Figures 4 & 5.
Illustrations showing the over-the-shoulder view of the Sample Part Viewing Fixture and the table pivoted at +20 and -20 degrees.
APPENDIX D

Example Solicitation Letter
June 20, 2006

Good Day Mr/Ms ____________,

My name is Kurt Hayden and I am a student at Western Michigan University (WMU) pursuing my Ph.D. in Industrial Engineering. Since 1997, I have performed research with Dr. Paul Engelmann at WMU involving injection molding process and mold design optimization. I am currently conducting data-collection surveys as a component of my dissertation.

While many guidelines exist to help product designers and process engineers avoid most sink marks, these defects still appear in mold products. Occasionally, part or mold design compromises must be made that increase the probability of molding visually detectable sink marks. In these cases, product designers can attempt to hide the sink mark with the use of surface textures. It is well understood that texture helps hide surface defects, however no guidelines have been developed regarding how deep the surface texture must be to suitably hide certain depths of sink marks.

I am asking for access to your employees to use as subjects in my research. I would like to individually interview a small number of employees at your facility in two separate one-hour long interviews. As part of the survey, the interview subjects are given a vision test and answer a short questionnaire. The remainder of the survey is conducted with the use of an inspection fixture in which two sample plaques are shown next to each other. The interview subject is asked if they can see the sink marks and which sink mark is “worse”. This procedure is repeated for a number of pairs of sample parts.

Enclosed is a copy of the Informed Consent Form the test subjects are required to sign. This form details the interview methods as well as the benefits, risks and protections to the subject. If you are interested in moving forward I will require a letter on your organization's letterhead granting me permission to interview your employees. I look forward to partnering with your company in this research. I will be in touch with you soon. Please contact me with any questions you may have.

Regards,

Kurt Hayden

Doctoral Associate
Department of Industrial & Manufacturing Engineering
Western Michigan University
APPENDIX E

Advertisements
LOOK!

Yes, Look.

The Plastics Processing Laboratory at Western Michigan University is looking for subjects for an investigation into visual inspection.

We are interested in recruiting individuals between the ages of 18 and 40 with corrected or natural 20/20 vision. Research subjects will be asked to view a series of molded parts and look for defects on the part. The length of subject participation is approximately 60 minutes.

The inspection will be performed

__________________________ On _____________________________

For more information or to set up an appointment contact Kurt Hayden at (269) 276-3385.
The Plastics Processing Laboratory at Western Michigan University is looking for subjects for an investigation into visual inspection.

We are interested in recruiting individuals between the ages of 18 and 40 with corrected or natural 20/20 vision. Research subjects will be asked to view a series of molded parts and look for defects on the part. The length of subject participation is approximately 60 minutes.

The inspection will be performed in

_____________________________On ________________

For more information or to set up an appointment contact Kurt Hayden at (269) 276-3385.
APPENDIX F

Scripts
Script #1

Text to be read by the interviewer to potential subjects during the informed consent process. This must be read to the potential subject before they sign the informed content form.

You have been invited to participate in a research project entitled “Determination of the Probability of Visual Sink Mark Detection.” This research is intended to study how surface textures affect the visual perception of an injection molding defect called a sink mark. A sink mark is a shallow depression or dimple on the surface of a finished plastic part due to shrinkage or low fill of the mold cavity. This research will be used to predict the probability of perceiving sink marks in various textured surfaces, a component of Mr. Hayden's dissertation. The benefits of the research will be used to improve product design tools and reduce the probability of customer rejected products.

You will be required to attend two separate, private sessions with Kurt Hayden. The sessions will each last approximately sixty minutes. During the first session, you will be issued a subject number that will be used to identify you for the second session. After the second session, the reference between your name and the subject number will be destroyed. Your participation is not required or compulsory, nor will you receive any special compensation. As your involvement is voluntary, you may withdraw from the survey at any time without reprisal, punishment or penalty.

This research requires subjects between the ages of 18 and 40 years of age with vision correctable to 20/20. If, during the vision test, your vision is found to be less than 20/20 (corrected) you will not be asked to continue the sink mark detection portion of the study. You will be asked to provide general information about yourself such as your age, level of education and the quality of your vision. Each session will involve completing one questionnaire, performing a visual acuity and a contrast sensitivity test and viewing several pairs of plastic parts with different sink marks and textures.

While risk in this research is minimal, there may be unforeseen risks to the participant. If an accidental injury occurs, appropriate emergency measures will be taken; however, no compensation or treatment will be made available to you except as otherwise stated to you during this informed consent process. A potential risk of participation may involve fatigue and discomfort to the eyes from viewing a number of plastic parts. The researcher is prepared to provide an opportunity for you to stop and rest your eyes at any time during the session.

All the information collected from during the research is confidential. That
means that your name will not appear on any document in which your responses are recorded. Except as stated, no information will be collected that can be used to personally identify you. Information that can identify you personally will be destroyed after the second interview session. All information collected and use for analysis will be retained in a lock file for at least three years by the principal investigator.

If you are interested in participating in the project, you may quit at any time without penalty. If you have questions or concerns about this study, you may contact either Dr. Paul V. Engelmann at 269-276-3350 or Kurt Hayden at 269-276-3385. You may also contact Western Michigan University and speak with the Chair of Human Subjects Institutional Review Board at 269-387-8293 or the Vice President for Research at 269-387-8298 with any concerns that you have.
Script #2

The interviewer will read this text to potential subjects after script #1 has been read and if the subject wishes to continue. This script describes in more detail how the testing procedure will be conducted, include appropriate responses to survey questions. The script will be read to the potential subject before they sign the informed content form and can be reviewed during the training process to refresh the subject memory of the process.

Each pair of sample parts will be shown to you with the use of a viewing fixture. The sample parts will be held next to each other in the fixture and will be identified as "Left" and "Right". The parts will remain in the fixture during the observations, you will not be allowed to touch or move your eyes closer than 24 inches to the parts.

Human vision can more easily detect changes in depth if motion is involved in the viewing experience. Therefore, the tabletop of the viewing fixture has been designed to pivot. The researcher will index the fixture to display a specific pair of parts. The researcher will then indicate that you should make your observations. At that time you will be able to reach into the surround of the fixture and move the tabletop to pivot the parts. Pivoting the parts allows the shadows and reflections to change on the part affecting the way you will see the sink mark.

After you have moved the parts, you will be asked if you see the sink mark on the parts. The appropriate answers include:

- "I see don't see any sink marks."
- "I see the sink mark on the {left or right} part and I don't see the sink mark on the {right or left} part."
- "I see sink marks on both parts."

Please indicate if you see sink on both parts. In other words, if you see sink on the right part, but not on the left part please respond "I see the sink mark on the right part, but not on the left part" rather than just "I see the sink mark on the right part."

If you see sink on both parts, you will be asked on which part the sink mark is more obvious. Another way of asking this question is "which part do you prefer the least" or "which part is more defective." You may find that by moving the table you can make a sink mark on one part become less obvious or even disappear. However, in most angles, the same sink mark may be much more obvious than that of the other part. You should consider how the sink marks
compare through all angles and then decide which sink mark is worst overall.

This procedure will be repeated for all pairs of sample parts. If at any time you feel fatigued or experience vision difficulties, indicate to the researcher that you require a break. If the research feels that you are experience fatigue, a break will automatically be given. Breaks will be a minimum of one minute in duration and the research will ask if you are ready to begin again before observations recommence. To reduce the possibility of visual fatigue and allow for better judgment when making observation, please look away from the parts while the researcher is indexing to the next pair.
APPENDIX G

HSIRB-Approved Consent Forms
Approved Consent Form for the Pilot Study

Western Michigan University
Department of Industrial and Manufacturing Engineering

Principal Investigator: Dr. Paul V. Engelmann
Research Associate: Kurt Hayden

Determination of the Probability of Visual Sink Mark Detection

This is an invitation to participate in the research project entitled "Determination of the Probability of Visual Sink Mark Detection." This research is intended to study how surface texture affects the visual detection of an injection-molding defect called a sink mark. A sink mark is shallow depression or dimple on the surface of a finished plastic part due to shrinkage or low fill of the mold cavity. This research is a component of Kurt Hayden's dissertation.

You will be asked to attend a private session with Kurt Hayden. This session will last approximately sixty minutes. You will meet with Kurt Hayden at the Plastics Processing Lab (room E-101) on Western Michigan University's Parkview Campus. This session will involve completing one questionnaire; a contrast sensitivity test and the viewing of plastic parts with different levels of sink marks and textures. You will also be asked to provide general information about yourself such as your age, level of education and the quality of your vision. This research requires subjects between the ages of 18 and 40 years of age with vision correctable to 20/20. If, during the vision test, your vision is found to be less than 20/20 (corrected) you will not be asked to continue the sink mark detection portion of the study.

As in all research, there may be unforeseen risks to the participant. If an accidental injury occurs, appropriate emergency measures will be taken; however, no compensation or treatment will be made available to you except as otherwise stated in this consent form. A potential risk of participation may involve fatigue and discomfort to the eyes from viewing a number of plastic parts. The researcher is prepared to provide an opportunity for you to stop and rest your eyes at any time during the session. All the information collected from during the research is confidential. That means that your name will not appear on any papers on which this information is recorded. No information will be collected that can be used to personally identify you. All information collected will be retained in a lock file for at least three years by the principal investigator.

You may refuse to participate or quit at any time during the study without prejudice or penalty. Questions or concerns about this study may be answered by contacting either Dr. Paul V. Engelmann at 269-276-3350 or Kurt Hayden at 269-276-3385. You may also contact the Chair of Human Subjects Institutional Review Board at 269-387-8293 or the Vice President for Research at 269-387-8298 with any concerns that you may have.

This consent document has been approved for use for one year by the Human Subjects Institutional Review Board (HSIRB) as indicated by the stamped date and signature of the board chair in the upper right corner. Do not participate in this study if the stamped date is older than one year.

Your signature below indicates that you have read and/or had explained to you the purpose and requirements of the study and that you agree to participate.

Signature: __________________________ Date: _______________
Consent obtained by: __________________ Date: _______________
Approved Consent Form for the Primary Study

This is an invitation to participate in the research project entitled "Determination of the Probability of Visual Sink Mark Detection." This research is intended to study how surface texture affects the visual detection of an injection-molding defect called a sink mark. A sink mark is a shallow depression or dimple on the surface of a finished plastic part due to shrinkage or low fill of the mold cavity. This research will be used to predict the probability of perceiving sink marks in various textured surfaces, a component of Mr. Hayden's dissertation.

You will be required to attend two separate, private sessions with Kurt Hayden. The sessions will each last approximately sixty minutes. During the first session, you will be issued a subject number which will be used to identify you for the second session. After the second session, the reference between your name and the subject number will be destroyed. Each session will involve completing one questionnaire, performing a visual acuity and contrast sensitivity test and the viewing of plastic parts with different sink marks and textures. You will also be asked to provide general information about yourself such as your age, level of education and the quality of your vision. This research requires subjects between the ages of 18 and 40 years of age with vision correctable to 20/20. If, during the vision test, your vision is found to be less than 20/20 (corrected) you will not be asked to continue the sink mark detection portion of the study.

As in all research, there may be unforeseen risks to the participant. If an accidental injury occurs, appropriate emergency measures will be taken; however, no compensation or treatment will be made available to you except as otherwise stated in this consent form. A potential risk of participation may involve fatigue and discomfort to the eyes from viewing a number of plastic parts. The researcher is prepared to provide an opportunity for you to stop and rest your eyes at any time during the session. All the information collected from the research is confidential. That means that your name will not appear on any document in which your responses are recorded. Except as stated, no information will be collected that can be used to personally identify you. All information collected will be retained in a lock file for at least three years by the principal investigator.

You may refuse to participate or quit at any time during the study without prejudice or penalty. Questions or concerns about this study may be answered by contacting either Dr. Paul V. Engelmann at 269-276-3350 or Kurt Hayden at 269-276-3385. You may also contact the Chair of Human Subjects Institutional Review Board at 269-387-8293 or the Vice President for Research at 269-387-8298 with any concerns that you may have.

This consent document has been approved for use for one year by the Human Subjects Institutional Review Board (HSIRB) as indicated by the stamped date and signature of the board chair in the upper right corner. Do not participate in this study if the stamped date is older than one year.

Your signature below indicates that you have read and/or had explained to you the purpose and requirements of the study and that you agree to participate.

Signature: _____________________________ Date: ______________

Consent obtained by: __________________ Date: ______________
APPENDIX H

Questionnaire
Determination of the Probability of Visual Sink Mark Detection.

1. Sex of the participant (circle one):  
   Male  Female

2. What is your age range? (circle one)
   18-25yrs.  26-35yrs.  36-40yrs.

3. Indicate your level of education: (circle one)
   Did not complete  High School or GED  Bachelors Degree  Graduate Degree

4. Do you wear corrective lenses? (circle one)
   No  Yes

5. If yes to #3, do you wear contacts, glasses or both? (circle one)
   Contacts  Glasses  Both

6. If yes to #3, what type of corrective lenses do you wear most often? (circle one)
   Contacts  Glasses

7. If yes to #3, are you near-sighted or far-sighted? (circle one)
   Near-sighted  Farsighted

8. Have you had corrective eye surgery? (If yes, which procedure)
   No  Yes: _________________________________

9. Do you have color blindness? (circle one)
   No  Yes

FrACT Visual Acuity and Contract Sensitivity Score

VA Score: __________________________  CS Score: __________________________
APPENDIX I

Data Collection Form
APPENDIX J

Research Protocol Approval
Protocol Approval for the Pilot Study

Date: April 26, 2006

To: Paul Engelmann, Principal Investigator
   Kurt Hayden, Student Investigator for dissertation

From: Mary Lagerwey, Ph.D., Chair

Re: HSIRB Project Number: 05-08-07

This letter will serve as confirmation that your research project entitled "Determination of the Probability of Visual Sink Mark Detection" has been approved under the expedited category of review by the Human Subjects Institutional Review Board. The conditions and duration of this approval are specified in the Policies of Western Michigan University. You may now begin to implement the research as described in the application.

Please note that you may only conduct this research exactly in the form it was approved. You must seek specific board approval for any changes in this project. You must also seek reapproval if the project extends beyond the termination date noted below. In addition if there are any unanticipated adverse reactions or unanticipated events associated with the conduct of this research, you should immediately suspend the project and contact the Chair of the HSIRB for consultation.

The Board wishes you success in the pursuit of your research goals.

Approval Termination: April 26, 2007
Protocol Approval for the Primary Study

Western Michigan University

Human Subjects Institutional Review Board

Date: June 27, 2006

To: Paul Engelmann, Principal Investigator
    Kurt Hayden, Student Investigator for dissertation

From: Amy Naugle, Ph.D., Chair

Re: HSIRB Project Number: 05-08-07

This letter will serve as confirmation that the changes to your research project “Determination of the Probability of Visual Sink Mark Detection” requested in your memo dated 6/26/2006 (expand pilot project to gather dissertation data; increase total subjects to 100; test at area companies (after site approval letters have been submitted to HSIRB)) have been approved by the Human Subjects Institutional Review Board.

The conditions and the duration of this approval are specified in the Policies of Western Michigan University.

Please note that you may only conduct this research exactly in the form it was approved. You must seek specific board approval for any changes in this project. You must also seek reapproval if the project extends beyond the termination date noted below. In addition if there are any unanticipated adverse reactions or unanticipated events associated with the conduct of this research, you should immediately suspend the project and contact the Chair of the HSIRB for consultation.

The Board wishes you success in the pursuit of your research goals.

Approval Termination: April 26, 2007
APPENDIX K

HSIRB Site Approval Documents
Access Granting Letter for Lear Corporation

Kurt Hayden
Doctoral Associate
Department of Industrial & Manufacturing Engineering Western Michigan
University Parkview Campus Room 9232
4601 Campus Drive
Kalamazoo, MI 49008-5336

Dear Mr. Hayden,

Per our phone conversations and e-mail communications we are granting you access to our employees for use in your research entitled "Determination of the Probability of Visual Sink Mark Detection". We understand that this is senior-level research that will be conducted at our facilities as part of your dissertation research. We will provide a room for you to use at our facility.

We further understand that human subject research can have ethical implications and understand that coercive methods shall not be used in obtaining the consent of potential subjects and that there are no penalties for withdrawal from the survey. It is understood that the identity of the subjects shall be kept confidential by the researchers and the responses given by a subject shall not be personally identifiable to the subject.

Please arrange dates for the interviews with me when you contact our company.

Regards,

Kevin Smelter
Process Engineer
Lear Corporation
Hendon, MI 49072
Date: July 6, 2006

To:  Carl Engelmann, Principal Investigator
     Kurt Hayden, Student Investigator for dissertation

From: Mary Lagerwey, Ph.D., Chair

Re:  HSIRB Project Number: 05-08-07

This letter will serve as confirmation that HSIRB has received a site approval letter from Lear Corporation and you are approved to collect data there for your research project “Determination of the Probability of Visual Sink Mark Detection.”

The conditions and the duration of HSIRB approval are specified in the Policies of Western Michigan University.

Please note that you may only conduct this research exactly in the form it was approved. You must seek specific board approval for any changes in this project. You must also seek reapproval if the project extends beyond the termination date noted below. In addition if there are any unanticipated adverse reactions or unanticipated events associated with the conduct of this research, you should immediately suspend the project and contact the Chair of the HSIRB for consultation.

The Board wishes you success in the pursuit of your research goals.

Approval Termination: April 26, 2007
Dear Mr. Hayden,

Based on our phone conversations last week we are granting you access to our employees for use in your research study entitled "Determination of the Probability of Visual Sink Mark Detection". We understand that this is senior-level research that will be conducted at our facilities as part of your dissertation research. We will provide the necessary facilities for you to use for the purpose of your research.

We understand that human subjects research can have ethical implications and understand that coercive methods shall not be used in obtaining the consent of potential subjects and that there are no penalties for withdrawal for the survey. It is understood that the identity of the subjects shall be kept confidential by the researchers and the responses given by a subject shall not be personally identifiable to the subject.

Please call me to arrange dates for the interviews with our company.

Regards,

Marc VanderKooi
Technical Manager

ROYAL PLASTICS, INC.
3785 Quincy Street
Holland, MI 49426
Phone: 616.699.5393
Fax: 616.690.0290

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Date: July 14, 2006
To: Paul Engelmann, Principal Investigator
    Kurt Hayden, Student Investigator for dissertation
From: Mary Lagerwey, Ph.D., Chair
Re: HSIRB Project Number: 05-08-07

This letter will serve as confirmation that HSIRB has received a site approval letter from Royal
Plastics Inc. and you are approved to collect data there for your research project “Determination
of the Probability of Visual Sink Mark Detection.”

The conditions and the duration of HSIRB approval are specified in the Policies of Western
Michigan University.

Please note that you may only conduct this research exactly in the form it was approved. You
must seek specific board approval for any changes in this project. You must also seek reapproval
if the project extends beyond the termination date noted below. In addition if there are any
unanticipated adverse reactions or unanticipated events associated with the conduct of this
research, you should immediately suspend the project and contact the Chair of the HSIRB for
consultation.

The Board wishes you success in the pursuit of your research goals.

Approval Termination: April 26, 2007
Access Granting Letter for Anderson Technologies, Inc.

Dear Ms. Hayden,

Per our phone conversations and e-mail communications we are granting you access to our employees for use in your research entitled "Determination of the Probability of Visual Sink Mark Detection". We understand that this is senior-level research that will be conducted at our facilities as part of your dissertation research. We will provide a room for you to use for the purpose of your research on the dates that you are on-site at our facility.

We further understand that human subjects research can have ethical implications and understand that coercive methods shall not be used in obtaining the consent of potential subjects and that there are no penalties for withdrawal for the survey. It is understood that the identify of the subjects shall be kept confidential by the researchers and the responses given by a subject shall not be personally identifiable to the subject.

Please arrange dates for the interviews with you contact in our company.

Regards,

Brian E. Gruber

14000 172nd Ave. • Grand Haven, MI 49417 • 616.844.2505 • FAX 616.844.2267

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Site Approval Letter for Anderson Technologies, Inc.

WESTERN MICHIGAN UNIVERSITY

Date: July 17, 2006
To: Paul Engelmann, Principal Investigator
Kurt Hayden, Student Investigator for dissertation
From: Mary Lagerwey, Ph.D., Chair
Re: HSIRB Project Number: 05-08-07

This letter will serve as confirmation that HSIRB has received a site approval letter from Anderson Technologies Inc. and you are approved to collect data there for your research project “Determination of the Probability of Visual Sink Mark Detection.”

The conditions and the duration of HSIRB approval are specified in the Policies of Western Michigan University.

Please note that you may only conduct this research exactly in the form it was approved. You must seek specific board approval for any changes in this project. You must also seek reapproval if the project extends beyond the termination date noted below. In addition if there are any unanticipated adverse reactions or unanticipated events associated with the conduct of this research, you should immediately suspend the project and contact the Chair of the HSIRB for consultation.

The Board wishes you success in the pursuit of your research goals.

Approval Termination: April 26, 2007
APPENDIX L

Model Statistics
Statistics on the Parameters of the Model Including Fourth Level Interactions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Logit Transformed Param.</th>
<th>Logit Transformed Std.Err</th>
<th>Logit Transformed t</th>
<th>Logit Transformed p</th>
<th>-95.00% Confidence Limit</th>
<th>+95.00% Confidence Limit</th>
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<tbody>
<tr>
<td>Intercept</td>
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Statistics on the Model Including Fourth Level Interactions

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<th></th>
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<th>Multiple R²</th>
<th>Adjusted R²</th>
<th>SS Model</th>
<th>df Model</th>
<th>MS Model</th>
<th>SS Residual</th>
<th>df Residual</th>
<th>MS Residual</th>
<th>F</th>
<th>p</th>
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</thead>
<tbody>
<tr>
<td>Logit Transformed</td>
<td>0.9615</td>
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<td>0.9205</td>
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Histogram of Raw Residuals
For the Model Including Fourth Level Interactions
Dependent Variable: Logit Transformed Probabilities
(Analysis sample)
Normal Probability Plot of Raw Residuals
For the Model including Fourth Level Interactions
Dependent Variable: Logit Transformed Probabilities
(Analysis sample)

Observed vs. Predicted Values
For the Model including Fourth Level Interactions
Dependent Variable: Logit Transformed Probabilities
(Analysis sample)
Histogram of Observed Values
Logit Transformed Probabilities

Histogram of Raw Predicted Values
For the Model Including Fourth Level Interactions
Dependent Variable: Logit Transformed Probabilities
(Analysis sample)
## Statistics on the Parameters of the Model Including Third Level Interactions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Logit Transformed Param.</th>
<th>Logit Transformed Std.Err</th>
<th>Logit Transformed t</th>
<th>Logit Transformed p</th>
<th>-95.00% Confidence Limit</th>
<th>+95.00% Confidence Limit</th>
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<tbody>
<tr>
<td>Intercept</td>
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<td>Plaque Color<em>Color Level Delta</em>Depth Delta</td>
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### Statistics on the Model Including Third Level Interactions

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<th>Multiple R</th>
<th>Multiple $R^2$</th>
<th>Adjusted $R^2$</th>
<th>SS Model</th>
<th>df Model</th>
<th>MS Model</th>
<th>SS Residual</th>
<th>df Residual</th>
<th>MS Residual</th>
<th>F</th>
<th>p</th>
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<tbody>
<tr>
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#### Histogram of Raw Residuals

For the Model Including Third Level Interactions

Dependent Variable: Logit Transformed Probabilities

(Analysis sample)
Histogram of Observed Values
Logit Transformed Probabilities

Histogram of Raw Predicted Values
For the Model Including Third Level Interactions
Dependent Variable: Logit Transformed Probabilities
(Analysis sample)
Statistics on the Parameters of the Model Including Second Level Interactions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Logit Transformed Param.</th>
<th>Logit Transformed Std.Err</th>
<th>Logit Transformed t</th>
<th>Logit Transformed p</th>
<th>-95.00% Confidence Limit</th>
<th>+95.00% Confidence Limit</th>
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<tbody>
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Statistics on the Model Including Second Level Interactions

<table>
<thead>
<tr>
<th></th>
<th>Multiple R</th>
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<th>Adjusted $R^2$</th>
<th>SS Model</th>
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<th>SS Residual</th>
<th>df Residual</th>
<th>MS Residual</th>
<th>F</th>
<th>p</th>
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<tr>
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Histogram of Raw Residuals
For the Model Including Second Level Interactions
Dependent Variable: Logit Transformed Probabilities
(Analysis sample)
Normal Probability Plot of Raw Residuals
For the Model including Second Level Interactions
Dependent Variable: Logit Transformed Probabilities
(Analysis sample)

Observed vs. Predicted Values
For the Model including Second Level Interactions
Dependent Variable: Logit Transformed Probabilities
(Analysis sample)

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Histogram of Observed Values
Logit Transformed Probabilities

Histogram of Raw Predicted Values
For the Model Including Second Level Interactions
Dependent Variable: Logit Transformed Probabilities
(Analysis sample)

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<table>
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<th>Logit Transformed t</th>
<th>Logit Transformed P</th>
<th>-95.00% Confidence Limit</th>
<th>+95.00% Confidence Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>-0.41</td>
<td>0.230</td>
<td>-1.7738</td>
<td>0.0771</td>
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<td>Depth Delta</td>
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<td>6.518</td>
<td>2.5062</td>
<td>0.0127</td>
<td>3.51</td>
<td>29.16</td>
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<tr>
<td>Color Delta</td>
<td>POOLED</td>
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<tr>
<td>Texture Delta</td>
<td>POOLED</td>
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</tbody>
</table>
Statistics on the Model Including Main Predictors Only

<table>
<thead>
<tr>
<th>Logit Transformed</th>
<th>Multiple R</th>
<th>Multiple R²</th>
<th>Adjusted R²</th>
<th>SS Model</th>
<th>df Model</th>
<th>MS Model</th>
<th>SS Residual</th>
<th>df Residual</th>
<th>MS Residual</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.8713</td>
<td>0.7592</td>
<td>0.7567</td>
<td>1789.564</td>
<td>5</td>
<td>357.913</td>
<td>567.4789</td>
<td>300</td>
<td>1.8916</td>
<td>189.2120</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Histogram of Raw Residuals
For the Model Including Main Predictors Only
Dependent Variable: Logit Transformed Probabilities
(Analysis sample)
Normal Probability Plot of Raw Residuals
For the Model Including Main Predictors Only
Dependent Variable: Logit Transformed Probabilities
(Analysis sample)

Observed vs. Predicted Values
For the Model Including Main Predictors Only
Dependent Variable: Logit Transformed Probabilities
(Analysis sample)


Shi, L., & Gupta, M., (2000). Modeling of sink mark formation in cross-rib-reinforced injection-molded plastic parts by localized finite element...


