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A probabilistic model to estimate visual inspection error for metalcastings given different training and judgment types, environmental and human factors, and percent of defects

Michelle M. Stallard (Voelker)*, Cameron A. MacKenzie, Frank E. Peters

Industrial and Manufacturing Systems Engineering at Iowa State University, Ames, IA, 50011, United States

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ABSTRACT

Current methods for visual inspection of cast metal surfaces are variable in both terms of repeatability and reproducibility. Because of this variation in the inspection methods, extra finishing operations are often prescribed; much of this is over processing in attempt to avoid rework or customer rejection. Additionally, defective castings may pass inspection and be delivered to the customer. Given the importance of ensuring that customers receive high-quality castings, this article analyzes and quantifies the probability of Type I and II errors, where a Type I error is a false alarm, and a Type II error misses a present defect. A probabilistic model frequently used in risk analysis, called an influence diagram, is developed to incorporate different factors impacting the chances of Type I and II errors. These factors include: training for inspectors, the type of judgment used during the inspection process, the percentage of defective castings, environmental conditions, and the inspectors' capabilities. The model is populated with inputs based on prior experimentation and the authors' expertise. The influence diagram calculates the probability of a Type I error at 0.35 and the probability of a Type II error at 0.40. These results are compared to a naïve Bayes model. A manufacturer can use this analysis to identify factors in its foundry that could reduce the probability of errors. Even under the best-case scenario, the probability of Type I error is 0.18 and the probability of Type II error is 0.30 for visual inspection. This indicates improvements to the inspection process for cast metal surfaces is required.

1. Introduction

Inspecting parts to meet quality standards is important for meeting customer needs. In metal casting, current standards use qualitative methods to determine acceptability of surface quality. The inspection process involves one or more trained operators to visually examine the surface to determine if the part is acceptable. Variation exists among interpretation of the standard not only in relation to the repeatability and reproducibility of the inspection process, but also in regards to interpretations between the manufacturer and the customer. The variability in the casting process itself is often less than that of the visual inspection process [1]. This stack-up in variation results in inconsistencies in acceptance criteria and increases the occurrence of Type I and II errors. A Type I error, also known as a false alarm, occurs when a defect is identified on the casting although no defect is present. Type II errors, or misses, occur when a casting passes inspection with a defect present. Although the determination of Type I and II errors is in itself subjective, these errors could be detrimental to the performance of the parts and could lead to disagreements between the manufacturer and customer if not interpreted as intended.

As a labor-intensive process, visual inspection requires the utmost attention to detail by the operator to minimize Type I and II errors. If at any time operators are not focused on their jobs or not physically and mentally alert, the risk of scrap or nonconformance increases. For instance, foundry environments where inspection takes place may be noisy and have poor lighting or extreme temperatures, which may be a distraction and impede the inspector's judgment. Assuring environmental and human factors are optimal will allow operators to perform at their best. Additionally, training operators on best practices to identify defects, such as rastering or using a visual aid, will improve consistency in identifying defects between operators resulting in a more stable process. These factors influencing Type I and II errors are not exhaustive; however, they do play a major role on casting inspection. Megaw [2] provides an extensive list of sources that can affect the accuracy of visual inspection.

The unique contribution of this article is the combination of various

* Corresponding author.
E-mail address: mvoelker@iastate.edu (M.M. Stallard (Voelker)).

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sources that impact the accuracy of visual inspection, as measured by Type I and II errors, to model the effectiveness of cast metal surface visual inspection. This article develops an influence diagram to calculate the probability of a Type I or Type II error. Although influence diagrams have frequently been used to assess risks and identify the optimal alternatives in business and public policy decisions, they have only rarely been applied to manufacturing decisions. Additionally, previous work exploring Type I and Type II errors in the casting industry only examines a single factor's impact.

This article incorporates and predicts the impact of several factors that contribute to Type I and II errors. Management at a manufacturing company can use this type of model to identify factors to focus improvement efforts on to decrease the number of Type I and II errors. The article presents a methodology for using influence diagrams to probabilistically assess the effect of different factors on the visual inspection process. An illustrative example for foundries in general, using results from previous research, is provided to demonstrate how this methodology can be applied. Foundries are encouraged to use their own data and expertise to reassess the probabilities given in this paper and determine likelihood of Type I and II errors for their own inspection processes. Although this article describes how the probabilities have been assessed for this illustrative example, the purpose of the article is not to describe the specific methodology for assessing probabilities either from data or from experts. Readers interested in learning more about how to assess the influence among factors and the likelihood of events are referred to [3–9].

2. Background Information

Since this article draws from two distinct fields (manufacturing inspection and probabilistic risk analysis), it is necessary to provide background and cite the relevant literature for both fields. The first part of this section introduces the visual inspection standards and reviews the relevant literature on the inspection process. The second part of this section presents the influence diagram model, which will be used to assess the uncertainty in Type I and II errors. This brief review of both fields will provide the foundation to understand the model in Section III.

2.1. Current visual inspection standards

Visual inspection of castings often occurs several times during their production and often is the final processing step before they are shipped. The workstation varies widely depending on many factors including the shop layout and size of castings. In almost all cases, the castings are delivered to the inspection station via a fork truck, overhead crane with a magnet, or via a roller crane. Depending on the size of the castings, they could be delivered individually or as a group of castings. For those that can be safely handled, they are often inspected as the inspector manipulates the part on a steel workbench. Medium sized castings are picked up via a jib crane operated by the inspector to safely access all sides of the castings. Very large castings are inspected on the floor, and then moved by the overhead crane to access the other sides. The environmental conditions of the inspection workstation will vary in these scenarios, but they are essentially always in a shop environment in the midst of the other processing steps. As with the casting size, the production volumes vary greatly where an inspector could be inspecting a few dozen or maybe a couple thousand castings in a day, which often consists of a variety of geometries. Any problem areas that need additional attention are highlighted with chalk or a special marking pen directly on the casting surface.

Many qualitative standards exist for the surface inspection of cast metal including company and industry specific standards. The Manufacturer Standardization Society (MSS) SP-55 Visual Method, American Society for Testing and Materials (ASTM) A802 which references the use of comparator from the Steel Castings Research and Trade Association (SCRATA), Alloy Casting Institute (ACI) Surface Indicator Scale, and GAR Electroforming Cast Comparator C9 are the most commonly used metal casting standards in industry. Inspectors use comparators and images in these methods to visually classify the surface roughness and abnormalities on an actual casting. The methods are primarily qualitative and based on a discretized scale, as opposed to a continuous scale, of classification.

In the MSS SP-55 method, images are used for comparison to cast surfaces. Twelve abnormality types, ranging from porosity to weld repair areas, are identified and images of acceptable and non-acceptable surfaces are provided for each [10]. Plastic replications of actual metal castings are used for comparison in the SCRATA method and adopted by ASTM [11]. Lettered plates representing one of nine abnormalities are used, each with various severity levels. The abnormalities represented are similar to the MSS method. This standard is the most widely used standard in the U.S. steel casting industry. For the surface inspection process, inspectors compare the image or comparator associated with the surface specification to surface characteristics (abnormalities and roughness) of the casting. They then judge whether the surface characteristics fall below the threshold established by the plates. If the surface characteristics exceed the threshold, the part is rejected.

The ACI Surface Indicator evaluates "general smoothness, height and depth of irregularities extending beyond the range of general variations, and frequency and distribution of such irregularities" [12]. Designations SIS-1 through SIS-4 correspond to the root mean square (RMS) average deviation in micro-inches. The standard also specifies criteria for the height and frequency of surface abnormalities. Inspection is executed similarly to the two standards mentioned previously.

Less widely used than the other methods is the GAR C9 Comparator. Comparator swatches (each 12 x 36 mm) quantify the surface roughness based on root mean square (RMS) values in micro-inches. No abnormalities are defined in this standard. In addition to a visual examination, inspectors are instructed to "draw the tip of the fingernail across each surface at right angles" to match the texture of the inspected part [13].

Inspectors compare the surface of the casting to the appropriate standard in order to make the determination of whether or not the surface is acceptable. Regardless of the standard, inspectors should be trained in the applicable standard and have access to documentation to determine the acceptability of a part. Training should be ongoing to ensure inspectors remain calibrated [14]. Additionally, any errors identified downstream should be fed back to the inspector as soon as possible to reduce the likelihood of future occurrences [15]. Although these measures are in place to combat errors, the current standards lack robustness as they can be interpreted differently between people, rely on inspectors' sensory capabilities, and lack definition regarding rarely occurring abnormalities and their distribution over the surface. As long as there is a human element involved in the inspection process, various factors can affect their performance, which risk inaccurately determining whether or not a surface is acceptable. A digital standard is under development, which can be used to verify inspectors' judgments per customer requirements [16]. This will also lay the groundwork for more quantitative specifications for cast metal surfaces in the future, which would be an ideal method by reducing the human element and subjectivity of inspection.

While machine vision is readily applied for some casting surface inspection tasks, it is limited to a range of defects in certain areas. For example, online vision systems are used to detect defects on flat surfaces [17] and to match morphological features on a part surface to a database of similar geometrical defects [18]. However, this is not feasible for many castings as their geometries are complex and their defects are inconsistently shaped or located. A vision system would require that the orientation of the component is known, which would be time consuming and costly for the large variety of shapes produced in small quantities. Additionally, cleaning and maintenance of vision