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M. M. Voelker[1] and F. E. Peters[2]

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M. M. Voelker[1] and F. E. Peters[2]

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[1] Industrial and Manufacturing Systems Engineering, Iowa State Univ., Ames, IA 50011 (Corresponding author), e-mail: mvoelker@iastate.edu

[2] Industrial and Manufacturing Systems Engineering, Iowa State Univ., Ames, IA 50011, e-mail: fpeters@iastate.edu

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ABSTRACT

Communication of specifications between a customer and a manufacturer is important for meeting form, fit, and functional requirements of any part. Current standards for the requirements of cast metal surfaces use qualitative methods, including comparator plates and images of surfaces, to specify the surface quality allowing ample room for variation in interpretation of the standard. The length scale of existing contact surface measurements is too small for most casting surfaces. This paper covered a proposed digital standard for specifying cast metal surfaces. The proposed digital standard used point cloud data of a cast surface, likely attained using a non-contact capture method, in order to identify roughness properties and anomalies caused by the casting process. Unlike current qualitative methods, this standard does not specify the potential causes of surface issues, such as porosity or inclusions. This standard was developed in order to reduce measurement variation and eliminate confusion between the customer and manufacturer. Assigning quantitative criterion to the surface allows the customer to specify exactly what is needed as opposed to limiting them to a subjective comparator or image to base their requirements. Additionally, this quantitative method could be used to verify visual inspection results among the inspectors within a production facility to reduce their measurement error and improve productivity.

Keywords
surface inspection, digital surface inspection, surface finish, castings, digital standard

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. These methods show large variation in measurement error for both repeatability and reproducibility due to inconsistencies in the subjective decision making for a single inspector between parts and between inspectors on the same part as demonstrated in studies by Daricilar and Peters [1,2] and Schorn [3], in addition to increased risk of Type I and II errors as demonstrated by Voelker and Peters [4]. A digital surface standard to provide a quantitative method of inspecting cast metal surfaces would reduce the subjectivity and variability of visual inspection.

Research in the area of cast metal surface inspection is limited; however, machined surfaces have been explored in depth. Due to the repetitive nature of the roughness on machined surfaces, stylus profilometers are typically employed to measure a two-dimensional data profile on the surface [5]. Alternative research methods use non-contact methods such as optoelectric profilometers [6], angular speckle-correlation [7], reflectivity [8,9], or image pattern recognition [9]. A non-contact method was also explored by Nwaogu et al. [10] to evaluate the surface roughness of castings. Non-contact methods are not sensitive to vibration, do not damage the inspected surface, and can acquire data over the entire surface more quickly than stylus profilometry, which makes it ideal for use in industry over contact methods, such as stylus profilometry [11]. Various surface parameters to characterize the surface roughness were also studied including the roughness average [6–8,11,12], areal roughness average [11], root mean square roughness [7], and mean roughness depth [12]. The areal roughness was also explored by Nwaogu et al. 10, which determined areal characterization parameters were ideal to classify surface texture of castings due to the random variation in surface characteristics. The concepts for evaluating machined surfaces were taken into consideration for the digital casting standard and modified to accommodate for the random variation in roughness and presence of abnormalities in cast metal surfaces.

The main goal of the proposed digital standard that quantifies acceptance criteria is to improve communication between manufacturers and customers in the interpretation of surface requirements. For the customer, a quantitative, or digital, standard will allow them to be able to communicate to the manufacturer exactly what they need or want. It does not limit the customer to a specific set of surface finishes like other standards that use a set of comparators or images to specify requirements. For the manufacturer, the digital standard will act as a referee to verify results from a visual method and to calibrate or train inspectors in the visual inspection process. Currently, the digital standard is not intended to replace the visual inspection process but enhance it due to the overall speed of visual inspection for large surface anomalies. The scope of this standard is intended for use with all mold types within metal casting including, but not limited to green sand, lost foam, and die casting. The development of the standard for Quantitative Inspection Acceptance Criteria for Cast Metal Surfaces is discussed in this article.

CURRENT INSPECTION STANDARDS

The Alloy Casting Institute (ACI) Surface Indicator Scale, Manufacturer Standardization Society (MSS) SP-55 Visual Method [13], ASTM A802-95(2015) [14] that references the Steel Castings Research and Trade Association (SCRATA) comparator plates, and its French equivalent, BNIF 359 [15], continue to be the leading standards used to specify metal casting surfaces. In addition, the GAR Electroforming Cast Comparator C9 is used in some surface roughness inspection processes.

ACI SURFACE INDICATOR SCALE

The ACI Surface Indicator method uses a metal plate with four surface variations, as seen in **Fig. 1**. The method evaluates "general smoothness, height and depth of irregularities extending beyond the range of general variations, and frequency and distribution of such irregularities [16]." The comparator swatches are designated SIS-1 through SIS-4 and correspond to the root mean square (RMS) average deviation in micro-inches. Additionally, the standard specifies criteria for the height and frequency of surface abnormalities through a series of grids of a "controlling square inch."

MSS SP-55 VISUAL METHOD

The MSS SP-55 method uses images as a means to specify surfaces. Twelve different types of abnormalities ranging from porosity to weld repair areas are pictured with examples of both acceptable and non-acceptable cast surfaces [13]. An example of the standard is shown in **Fig. 2**.

ASTM A802-95

The SCRATA method uses plastic plates replicated from actual steel casting surfaces for comparison to the finished part. Nine different abnormalities are represented by lettered plates, each with either two or four levels of severity of the abnormality labeled Level I to Level IV as seen in **Table 1**. The roughness nor abnormalities are

FIG. 1
ACI surface indicator scale [16].

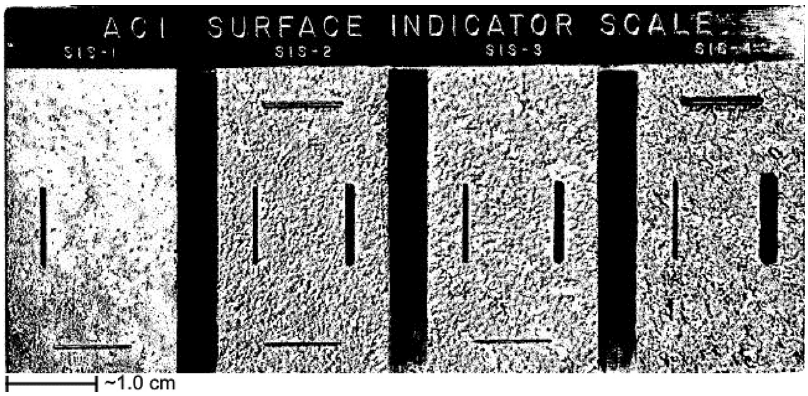
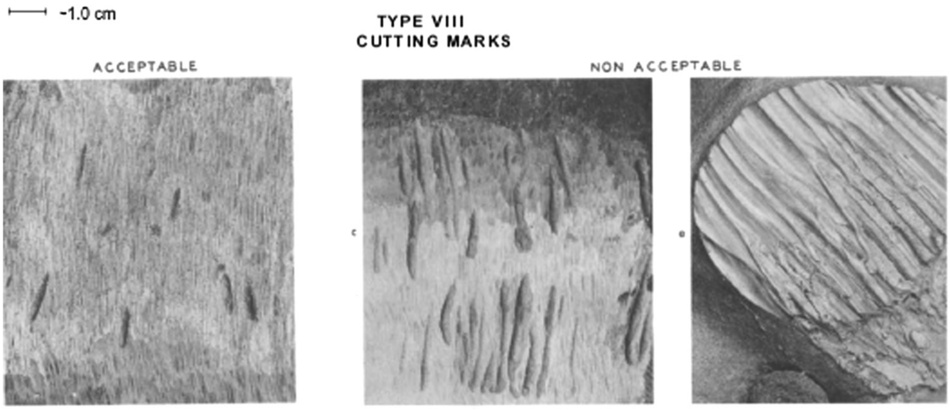


FIG. 2 MSS method example of acceptable (left) and non-acceptable (right) cutting marks [13].



quantified. These abnormalities are similar to the MSS method with a slight variation in how they are grouped. This method is most commonly used in the U.S. steel casting industry.

BNIF 359

The BNIF method is a French standard similar to the SCRATA method in that it uses plastic replicas of cast metal surfaces. A comparison of these comparators can be seen in **Fig. 3**. Each comparator is an example of a specific casting process and is classified by the type and amount of finishing required. The three finishing classifications consist of the following: Series No. 1: No or limited finishing, Series No. 2: Particular finishing, and Series No. 3: Special finishing. Suggested values for steel, iron, aluminum, and copper are given based on the molding process. A general scale of the roughness average is provided as a general guideline for each suggested process as seen in **Fig. 4** [15].

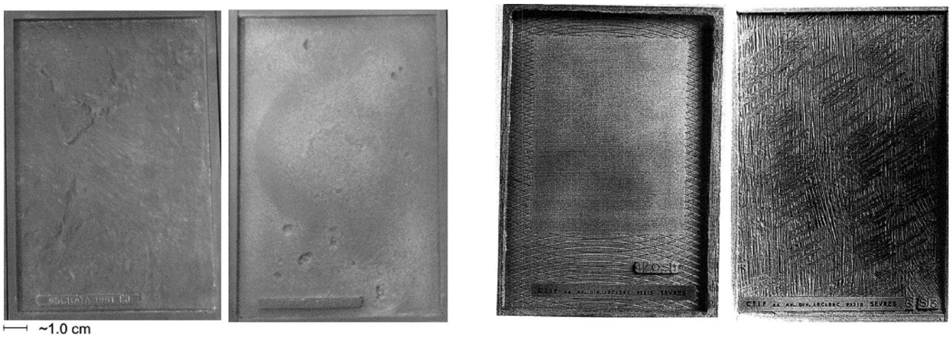
TABLE 1

Visual inspection acceptance criteria of ASTM A802-95 [14].

Surface Feature	Level I	Level II	Level III	Level IV
Surface texture	A1	A2	A3	A4
Nonmetallic inclusions	B1	B2	B4	B5
Gas porosity	C2	C1	C3	C4
Fusion discontinuities	... [a]	D1	D2	D5
Expansion discontinuities	... [a]	... [a]	E3	E5
Inserts	... [a]	... [a]	F1	F3
Metal removal marks:				
Thermal	G1	G2	G3	G5
Mechanical	H1	H3	H4	H5
Welds	J1	J2	J3	J5

[a]No reference comparator plate is available for this surface feature and level.

FIG. 3 Comparison of SCRATA (left- E3, C3) and BNIF comparators (right- 4 OS1, S3) [14,15].



GAR ELECTROFORMING CAST MICROFINISH COMPARATOR C9

The GAR C9 Comparator, seen in **Fig. 5**, is not as widely used as the aforementioned methods. Each comparator swatch represents the surface texture based on root mean square (RMS) values in micro-inches. This standard provides additional clarity compared to the ACI Surface Indicator Scale, MSS SP-55, and ASTM A805-92 for interpretation of the standard; however, it does not define any abnormalities. In addition, inspectors use this comparator qualitatively with little regard for the measurement assignment. Instructed use of this comparator includes "drawing the tip of the fingernail across each surface at right angles" to match the texture of the inspected part [17].

FIG. 4 BNIF suggestion table for steel castings [5].

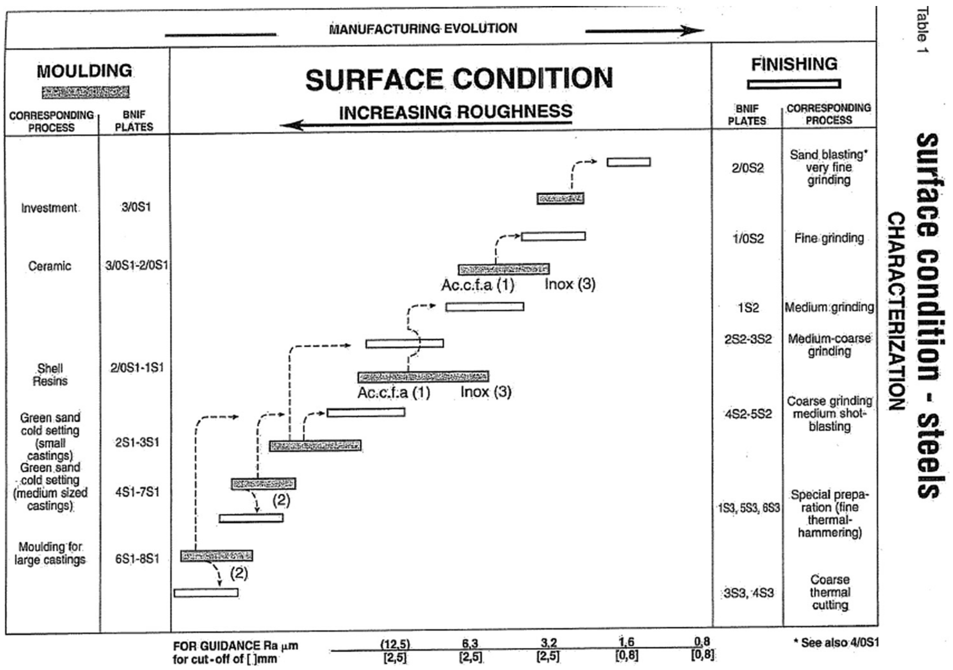


FIG. 5
C9 Microfinish Comparator [17].

OTHER

In addition to these four standards, many company and industry specific standards exist today. These include ISO 11971 [18] and BS EN 1370 [19], which overviews the SCRATA and BNIF, and ASTM A997-08(2012) [20] for investment castings.

SUMMARY OF CURRENT STANDARDS

These standards for metal casting specification and inspection have several disadvantages. These disadvantages include the need for subjective interpretation of the standard, expectations of labor, definition of abnormalities, and distribution of abnormalities.

STANDARD INTERPRETATION

Variation exists between the manufacturer's and customer's interpretation of the standards due to the complexity of the evaluation criteria and variation in qualitative inspection. A definitive cut off point in which the part can be deemed as acceptable currently does not exist or is unclear in the written standards.

LABOR EXPECTATIONS

Personnel must be trained on the standard and should have the standard documentation in hand in order to make the determination of whether or not the part is acceptable. These methods rely solely on the individual's sensory (visual and possibly tactile) capability as opposed to hard data. Due to the subjectivity of the decision, the cutoff point can move out over time or among people. Research has shown that training must be ongoing to keep personnel "calibrated" [9].

UNDEFINED ABNORMALITIES

Surface abnormalities not contained within the given standard make it difficult to assign a value to the finished part. Furthermore, many abnormalities cannot be determined via visual inspection and rather require metallurgical analysis.

Furthermore, the origin of the abnormality is quite irrelevant to the final casting use in most cases.

ABNORMALITY DISTRIBUTION

The distribution of abnormalities versus size over the entire part is not clearly specified. For example, if one large crater is acceptable on a part, there is no reasoning behind why multiple craters of smaller size are not acceptable. Or, if the area under question is smaller than a SCRATA comparator plate, the single larger crater could now not be acceptable.

With the decreasing cost of non-contact technologies, such as white light and laser scanning, a quantitative method can be introduced to increase reliability and repeatability of the casting inspection process.

OVERVIEW OF QUANTITATIVE STANDARD

The quantitative standard uses data obtained from three-dimensional scans of a portion of a casting in order to objectively inspect a surface. From this data, the three main parameters specified by the customer are verified, including the baseline roughness, abnormality level, and abnormality percentage.

The baseline roughness, measured in millimeters, is the roughness average, denoted S_a for areal roughness or R_a for a profile, of the cast surface disregarding abnormalities. This parameter is the minimum requirement to be specified by the customer. Default values will be assigned to other parameters if none are specified.

Abnormalities are any surface anomaly present that is not part of random variation due to the actual baseline roughness and are greater than, arbitrarily, twice the specified baseline roughness. Therefore, there is no need for the customer to specify every type of abnormality that could possibly occur, as with the SCRATA standard; all abnormality types are encompassed under the abnormality level parameter. These include, but are not limited to, porosity, inclusions, and expansion. Abnormalities are considered any point exceeding twice the specified baseline roughness. The abnormality level is specified in millimeters and is represented by the absolute distance of the data point from the underlying geometry. If an abnormality level is not specified, the default level assigned where no abnormalities are acceptable, or twice the specified baseline roughness (as discussed later, the designer could specify a surface with no allowable abnormalities; however, this could come at a higher acquisition cost).

The third parameter to describe the surface is the abnormality percentage. This is expressed as the total fraction of the surface area that is considered abnormal, or exceeding twice the specified baseline roughness. The default inspection area is 8 by 8 cm, arbitrarily, unless otherwise agreed upon by the customer. The abnormality area is a percentage of this target area. The target area can be any 8 by 8 cm area on the surface, meaning every such area needs to be in specification. This prevents discrepancies between the customer and manufacturer when interpreting the abnormality percentage. If an abnormality percentage is not specified, the default level assigned will be 5 %. This standard does not cover dimensional accuracy, unusual visual conditions, such as casting color, nor chaplets. Chaplets are not included in this specification because they represent a likely performance issue, unlike most other abnormalities on the casting surface.

These three parameters should be specified at their maximum acceptable value for use and annotated using the Voelker Surface Ratio (VSR), which is written numerically with dashes as, "VSR [baseline roughness] – [abnormality level] – [abnormality percentage]." An example of this notation is, "VSR 0.30 – 0.60 – 2," indicating a maximum baseline roughness of 0.30 mm, a maximum abnormality level of 0.60 mm, and the maximum percentage of the inspected surface considered abnormal of 2 %. If the standard only specifies "VSR 0.30," the defaults for abnormality level and abnormality percentage are assigned as twice the specified baseline roughness, or 0.60, and 5, respectively, for any 8 by 8 cm area on the casting.

In order to consistently calculate these parameters due to the complexity of cast surfaces, the underlying geometry must be determined. The underlying geometry is the geometry of the surface in absence of the surface roughness and abnormalities. This geometry may differ from the intended part geometry due to contraction, mold movement, and other dimensional changes during the casting process. To illustrate the use of the proposed standard, the process of finding the underlying geometry to calculate surface deviations and identifying abnormalities for a criterion of VSR 1.85 – 12.00 – 35 is found in **Fig. 6**. After a surface is scanned and the underlying geometry is determined, the deviations from each point to the underlying geometry are calculated. Based on the acceptance criteria from the customer and deviations from the underlying geometry, the actual baseline roughness is calculated, and abnormalities are identified and measured.

FIG. 6 Parameter calculation process (a) determine underlying geometry, (b) calculate deviations from the underlying geometry, (c) identify and measure abnormal points based off of the deviations from the underlying geometry and assigned acceptance criteria.

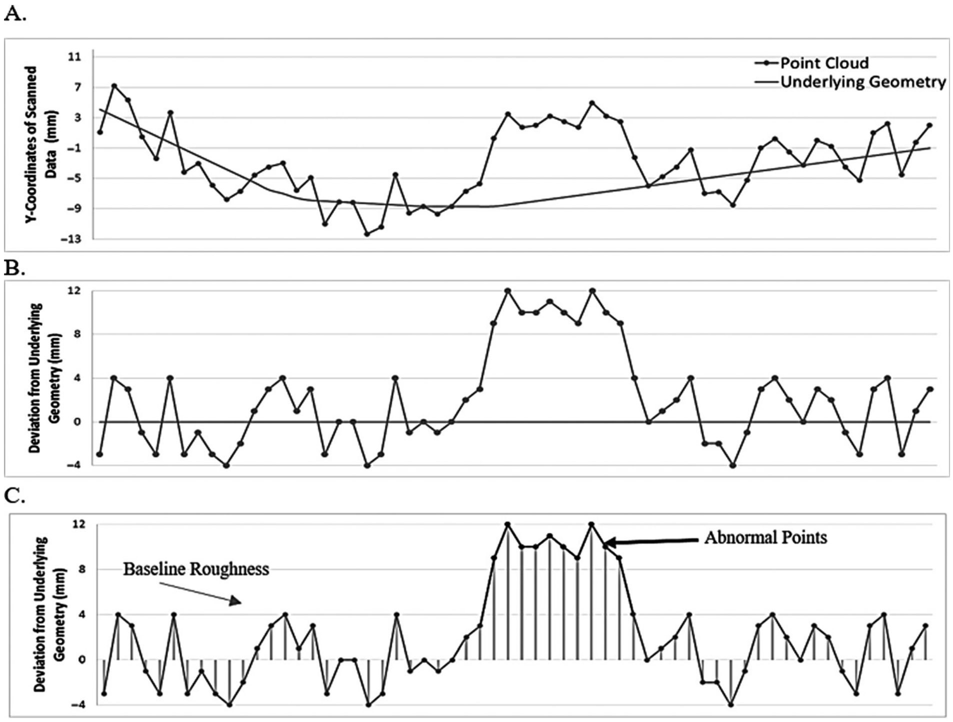
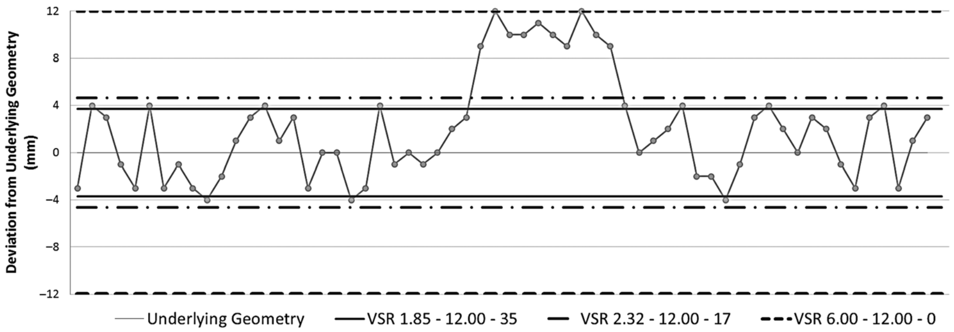


FIG. 7 Comparison of control limits where data points are considered abnormal based on the specified baseline roughness of each example specification.



A single surface can be specified in different ways. The sample profile in the previous example shows a surface with an abnormality located in the center. For the purpose of simplifying conceptualization, the total number of abnormal points in the two-dimensional profile divided by the total number of points in the profile will be used to illustrate the abnormality percentage. Given this assumption, the profile could be classified as the following variations: *VSR 1.85 – 12.00 – 35, VSR 2.32 – 12.00 – 17, and VSR 6.00 – 12.00 – 0.* The bounds of each variation where the data points falling outside of the bounds are considered abnormal are shown in **Fig. 7**.

VSR 1.85 – 12.00 – 35

This specification criterion considers the 21 points with a deviation from the underlying geometry greater than 3.7 mm (twice the specified baseline roughness represented by thick, solid line in **Fig. 7**) as abnormal. These points were omitted from the actual baseline roughness parameter calculation; however, they were captured in the abnormality percentage parameter given. The 21 points over the entire inspected area of 60 points, or 35 %, were considered abnormal. This is right at the threshold as presented by the third parameter (twice the specified baseline roughness). The abnormality level sets the maximum deviation from the underlying geometry of the data points to 12. This would mean the part would be rejected if points greater than 12 mm from the underlying geometry were present.

VSR 2.32 – 12.00 – 17

The 10 points with a deviation from the underlying geometry greater than 4.64 mm (represented by alternating dot and dashed line in **Fig. 7**) are considered abnormal for this specification criteria. The same process was used as part A to determine the parameters of the criteria.

VSR 6.00 – 12.00 – 0

In this scenario, all points within ± 12 mm (represented by dashed line in **Fig. 7**) of the underlying geometry are not considered abnormal since the abnormality level is exactly twice the specified baseline roughness. All 60 data points are used in calculation of the actual baseline roughness for this criteria. This particular specification does not allow any point to be abnormal, but it opens up the deviation from the underlying geometry to be considered abnormal.

OTHER VARIATIONS

This surface profile would also be considered acceptable where any of the three parameters are greater than those currently stated, such as VSR 4.12 – 15.00 – 40. This is because the specification notes the maximum acceptable value for use of all parameters. However, one must consider resulting surface variations if specifying values for the baseline roughness and abnormality level greater than their sample surfaces, since a lower quality surface than the sample could be considered acceptable under these increased parameters.

Customers need to be conscientious when specifying cast surfaces as there can be an infinite number of surfaces that would be acceptable for each VSR surface specification. Variations of a surface profile for each criterion assigned in the previous example are seen in **Fig. 8**: VSR 1.85 – 12.00 – 35, VSR 2.32 – 12.00 – 17, and VSR 6.00 – 12.00 – 0. Sample A of **Fig. 8** is identical to the profile found in **Fig. 6**. Based on the number of points exceeding the bounds of twice the specified baseline roughness, as previously demonstrated in **Fig. 7**, Samples A-B of **Fig. 8** would be considered acceptable with all three standards previously mentioned. Samples C-F of **Fig. 8** only correspond to VSR 6.00 – 12.00 – 0 since a greater number of points exceed twice the specified baseline roughness of the other examples. As a general rule, the specified baseline roughness and abnormality percentage are inversely related when assigning different specifications to the same surface. To simplify specification assignment and interpretation, it is suggested the abnormality percentage for an 8 by 8 cm surface area does not exceed 10 %.

Designers must determine the type of surface, which is acceptable for their component, and then write the appropriate VSR specification, keeping in mind that more restrictive specifications will increase the procurement cost. A major advantage of the VSR standard is that the designer can quantify the surface that is acceptable, and not rely on comparative methods which may not result in the surface they were expecting.

All parts deemed acceptable through VSR 1.85 – 12.00 – 35 and VSR 2.32 – 12.00 – 17 will also be considered acceptable under the VSR 6.00 – 12.00 – 0 criteria; however, unlike the other two requirement examples, VSR 6.00 – 12.00 – 0 also can be specified, which increases the number of allowable points located further from the underlying geometry, while maintaining a roughness less than or equal to 6.00 mm. Since an abnormality is defined as greater than twice the specified baseline roughness, any data falling within $\pm$ 12 mm from the underlying geometry would not be considered abnormal. Therefore, since the sample surfaces do not have any data points falling outside of this range, the abnormality percentage is 0 %. This method sets a range on the maximum permissible deviation from the underlying geometry as opposed to calling out any abnormalities and is ideal when specifying no abnormalities can be present on the surface.

In order to begin assigning criteria to their castings, customers can use current castings as a baseline for specifying a standard. To do this, customers can select a part with what they consider the least acceptable surface roughness and abnormality level, or a part that is not of the highest quality but still meets their current surface

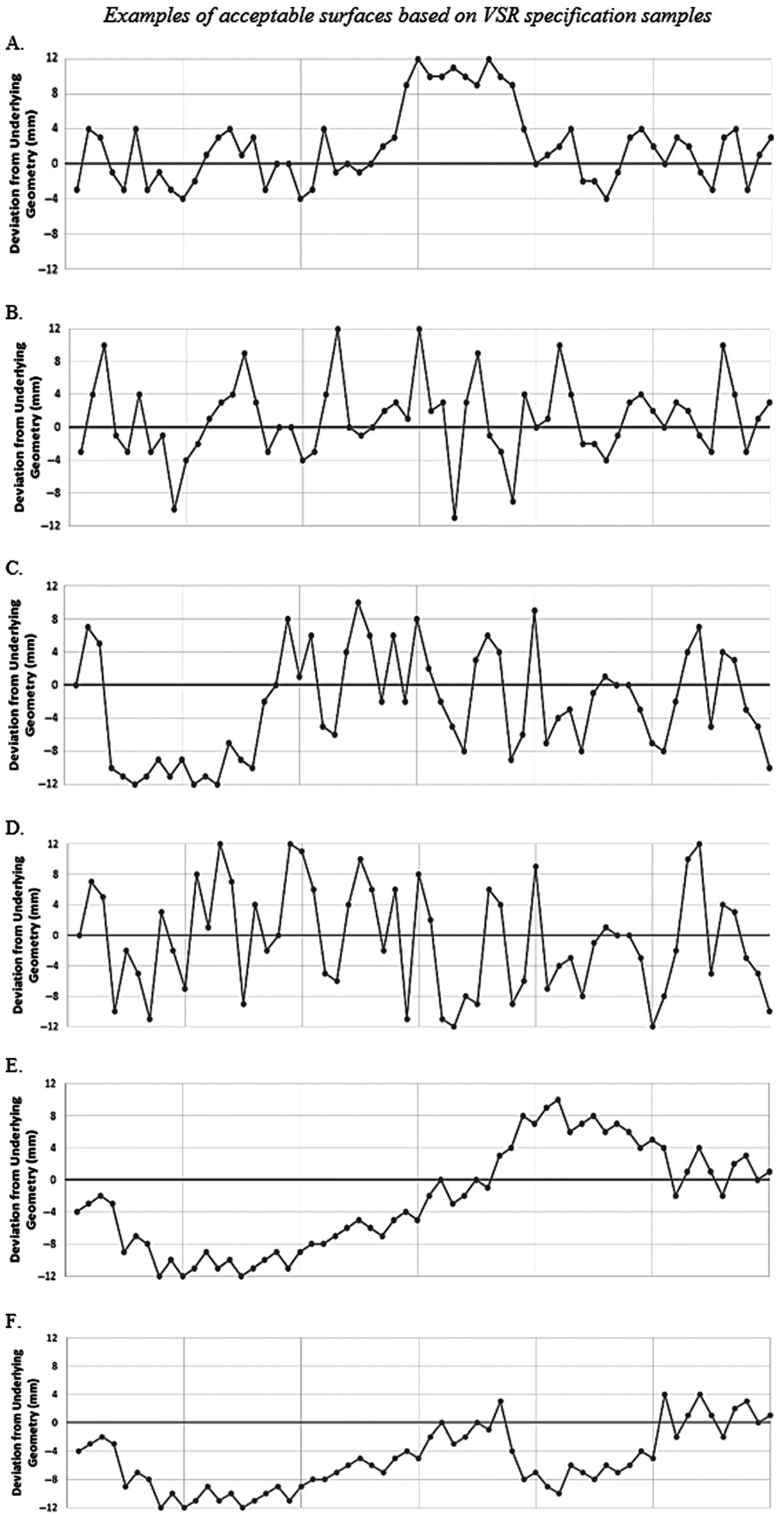


FIG. 8
Surface profiles representing an 8 by 8 cm constant cross-section of acceptable surfaces specified as VSR 1.85 – 12.00 – 35 or VSR 2.32 – 12.00 – 17 (A-B) and VSR 6.00 – 12.00 – 0 (AF) based on the distance of each data point from the underlying geometry.

expectations. After using a non-contact method to collect data points from the surface, the customer can select a criterion for that surface by comparing the data to the underlying geometry. A single acceptance criterion may be specified over the entire cast surface, or multiple criteria may be specified for various areas of the casting in order to reduce the variation of interpretation using the methods discussed in this section.

Discussion

The quantitative standard eliminates the discrepancies between the manufacturer's and customer's interpretation of inspection criteria, as seen in the qualitative standards. The reduced complexity of the evaluation criteria and variation from qualitative inspection allows for a clearer understanding of expectations.

The quantitative standard uses hard data to evaluate whether or not the surface is or is not acceptable and does not rely on an individual's sensory capability. This hard data does not differentiate between the types of abnormality present, which is beneficial if an unexpected abnormality appears on the final part and was not taken into consideration by the customer when specifying the surface. Additionally, the % of the surface that is classified as abnormal, which was specified in only one of the qualitative methods, is specified within the standard and can be modified, if desired, allowing the customer to better relay his or her requirements. These aspects of the quantitative standard allow for a clearer communication of expectations of cast surface specifications between the manufacturer and customer.

Work is ongoing by the authors, with the support of industry sponsors of the Steel Founders Society of America [21], to develop methods to automate the data collection and data analysis. Ultimately, these techniques would be integrated into a portable scanning device that a user could enter the specified VSR values and point the scanner at the 8 by 8 cm surface patch in question. It would also determine if the surface was acceptable. The intent is that this device would be used to assist the manual visual inspection process; however, future efforts could include this methodology in an automated inspection process.

Conclusions

Surface standards for metal cast surfaces help to determine the acceptability of surface quality. Implementation of the quantitative inspection standard will increase the quality of metal cast surfaces by improving communication between manufacturers and customers in the interpretation of requirements. Methods to collect and clean point cloud data for use in this standard are currently being developed to increase repeatability and reproducibility when calculating components of the VSR. This includes the development of algorithms for the underlying geometry of the scanned part. Future work includes exploring the feasibility of an automated inspection process to eliminate the need for human interaction in the process.

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