FINAL TECHNICAL REPORT

Energy Saving Melting and Revert Reduction Technology ("Energy SMARRT")
Program

Task 5.10: Surface/Near Surface Indication - Characterization of Surface Anomalies from Magnetic
Particle and Liquid Penetrant Indications

DOE Award Number: DE-FC36-04GO14230

Project Period: May 1, 2004 to September 30, 2013

Principal Investigator:

John A. Griffin

The University of Alabama at Birmingham
Material Science & Engineering Department
1720 2nd Avenue South
501 BLDG/ Room 102
Birmingham, AL 35294-4450
Tel: 205-975-8461
E-mail: jagrif@uab.edu

Recipient Organization:

The University of Alabama at Birmingham
Material Science & Engineering Department
501 12th Street South
501 Building, Room 102
Birmingham, AL 35294-4450

Date: February 20, 2014

Acknowledgment: This report is based upon work supported by the U.S. Department of Energy under Award No. DE-FC36-04GO14230.

Disclaimer: Any findings, opinions, and conclusions or recommendations expressed in this report are those of the author and do not necessarily reflect the views of the Department of Energy.

Proprietary Data Notice: No proprietary data is contained in this report.

TABLE OF CONTENTS

EXECUTIVE SUMMARY	7
INTRODUCTION	9
BACKGROUND	10
RESULTS AND DISCUSSION	14
Inspection Criteria Survey	14
Surface Indication Characterization	18
Inspection Technique Survey.....	47
Indication Size to Performance.....	75
BENEFITS ASSESSMENT	87
COMMERCIALIZATION.....	88
ACCOMPLISHMENTS	89
CONCLUSIONS	90
RECOMMENDATIONS.....	91
REFERENCES	92
APPENDICES	94

List of Acronyms

ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
EN	European Standard
MT	Magnetic particle testing
NDE	Non-Destructive Evaluation
PT	Liquid penetrant testing
R&R	Repeatability and Reproducibility
SFSA	Steel Founders' Society of America
UTS	Ultimate tensile strength
UAB	University of Alabama – Birmingham
YS	Yield Strength

List of Figures

Figure 1. Type of Inspection Method used by Responding Foundries.	16
Figure 2. Type of Criteria for Visual Inspection used by Responding Foundries.	17
Figure 3. Type of Inspection Method and Criteria for Dry Magnetic Particle.	19
Figure 4. Type of Inspection Method and Criteria for Wet Magnetic Particle.	19
Figure 5. Type of Inspection Method and Criteria for Visible Liquid Penetrant.....	20
Figure 6. Type of Inspection Method and Criteria for Fluorescent Liquid Penetrant.....	20
Figure 7. Plate 1 after removal of 0.050" from Cope surface.....	22
Figure 8. Histogram of Feret Length after 0.050" – Plate 1.....	22
Figure 9. Histogram of Feret Length/Thickness Ratio after 0.050" – Plate 1.	23
Figure 10. Plate 1 after Removal of 0.090" from Cope Surface.....	23
Figure 11. Histogram of Feret Length after 0.090" – Plate 1.....	24
Figure 12. Histogram of Feret Length/Thickness Ratio after 0.090" – Plate 1.	24
Figure 13. Histogram of Feret Length after 0.050" – All Plates	25

Figure 14. Histogram of Feret Length/Thickness Ratio after 0.050" – All Plates.....	25
Figure 15. Histogram of Feret Length after 0.090" – All Plates	26
Figure 16. Macro-photograph of a Non-Linear Set 1 Casting.....	27
Figure 17. Macro-photograph of Non-Linear Set 2 Casting.....	28
Figure 18. Macro-photograph of Non-Linear Set 3 Casting.....	28
Figure 19. Macro-photograph of Linear Set 1 Casting.....	29
Figure 20. Macro-photograph of Linear Set 2 Casting.....	29
Figure 21. Number of Indications vs. Distance from Cast Surface for Non-Linear Casting Set 1.....	32
Figure 22. Average and Maximum Indication Length vs. Distance from Cast Surface for Non-Linear Casting Set 1.	32
Figure 23. Indication Length Histogram for Non-Linear Casting Set 1.	33
Figure 24. Average and Maximum Length to Width Ratio vs. Distance from Cast Surface for Non-Linear Casting Set 1.	33
Figure 25. Length to Width Ratio Histogram for Non-Linear Casting Set 1.....	34
Figure 26. Number of Indications vs. Distance from Cast Surface for Non-Linear Casting Set 2.....	36
Figure 27. Average and Maximum Indication Length vs. Distance from Cast Surface for Non-Linear Casting Set 2.	36
Figure 28. Indication Length Histogram for Linear Casting Set 2.	37
Figure 29. Average and Maximum Length to Width Ratio vs. Distance from Cast Surface for Non-Linear Casting Set 2.	37
Figure 30. Length to Width Ratio Histogram for Non-Linear Casting Set 2.....	38
Figure 31. Number of Indications vs. Distance from Cast Surface for Non-Linear Casting Set 3.....	39
Figure 32. Average and Maximum Indication Length vs. Distance from Cast Surface for Non-Linear Casting Set 3	40
Figure 33. Indication Length Histogram for Linear Casting Set 3	41
Figure 34. Average and Maximum Length to Width Ratio vs. Distance from Cast Surface for Non-Linear Casting Set 3.	41
Figure 35. Number of Linear Indications vs. Distance from As-Received Surface.....	43
Figure 36. Average and Maximum Linear Indication Length vs. Distance from As-Received Surface.....	44
Figure 37. Linear Indication Length Histogram.....	45
Figure 38. Average and Maximum Length to Width Ratio for Linear Indications vs. Distance from Cast Surface.....	45
Figure 39. Length to Width Ratio Histogram for Linear Indications	46
Figure 40. The effect of inspector familiarity with part geometry on the total length of indications – Foundry 1.	49
Figure 41. Time required for each inspection for each inspector for one casting – Foundry 1.	50
Figure 42. The average repeatability for each casting inspected – Foundry 1.....	50
Figure 43. The average reproducibility for each casting inspected – Foundry 1.....	52
Figure 44. The average repeatability for all casting for each inspector – Foundry 1.	52
Figure 45. The average reproducibility for all inspectors and all castings – Foundry 1.	53
Figure 46. The average repeatability for each casting type inspected – Foundry 2.....	53
Figure 47. The average reproducibility for each casting type inspected – Foundry 2.....	55
Figure 48. The average repeatability for all casting for each inspector – Foundry 2.	55

Figure 49. The average reproducibility for all inspectors and all castings – Foundry 2.	56
Figure 50. Average repeatability for all castings and inspectors for LP R&R Foundry 3.....	58
Figure 51. Average reproducibility for all castings and for all inspectors for LP R&R Foundry 3.	58
Figure 52. Average repeatability for all castings and inspectors for MP R&R Foundry 4.....	59
Figure 53. Average reproducibility for all castings and for all inspectors for MP R&R Foundry 4.	59
Figure 54. Average indication length and standard deviation for all indications detected over 50% of the time.....	60
Figure 55. Box and whisker plots for Casting Geometry 1 from Foundry 1.....	66
Figure 56. Box and whisker plots for Casting Geometry 2 from Foundry 1.....	66
Figure 57. Box and whisker plots for Casting Geometry 1 from Foundry 2.....	67
Figure 58. Box and whisker plots for Casting Geometry 2 from Foundry 2.....	67
Figure 59. Box and whisker plots for Casting Geometry 3 from Foundry 2.....	69
Figure 60. Box and whisker plots for Casting Geometry 1 from Foundry 3.....	69
Figure 61. Box and whisker plots and histograms for Casting Geometry 1 from Foundry 4.	70
Figure 62. The average reproducibility for all inspectors and castings. Foundry 5	70
Figure 63. The average reproducibility for all inspectors and all castings. Foundry 6.	73
Figure 64. The average reproducibility for all inspectors and all castings. Foundry 7	74
Figure 65. The average reproducibility for all inspectors and all castings. Foundry 8.	75
Figure 66. Configuration of the flat plate and riser, which was cast to create surface indications for testing.	76
Figure 67. Example of tensile specimen geometry and PT showing severe indications in the gauge section is shown.	77
Figure 68. Stress strain curves from the ES1 material with no indications and artificial indications demonstrating the reduction in properties with increasing indication size.	78
Figure 69. Effect of indication length percentage on elongation for 165-135 steel.....	79
Figure 70. Effect of indication length percentage on elongation for 110-80 steel.....	80
Figure 71. Effect of indication length percentage on elongation for CF8M steel.	80
Figure 72. Effect of indication length percentage on elongation for ES1 steel.	81
Figure 73. Effect of indication length percentage on yield and ultimate strength for 165-135 steel.	82
Figure 74. Effect of indication length percentage on yield and ultimate strength for 110-80 steel.	82
Figure 75. Effect of indication length percentage on yield and ultimate strength for CF8M steel	83
Figure 76. Effect of indication length percentage on yield and ultimate strength for ES1 steel.....	83
Figure 77. Factor of safety of the ultimate stress as a function of indication length for all tested materials is shown.	85
Figure 78. Factor of safety of the yield stress as a function of indication length for all tested materials is shown.	86

List of Tables

Table I. All Methods and Acceptance Criteria submitted for Visual Inspection.	17
Table II. All Methods and Acceptance Criteria submitted for Magnetic Particle	

Inspection.....	17
Table III. All Methods and Acceptance Criteria for Liquid Penetrant Inspection.	19
Table IV. Summary of Castings Submitted with Non-Linear and Linear Indications.	27
Table V. Non-Linear Indication Measurement Results from Non-Linear Casting Set 1.....	31
Table VI. Non-Linear Indication Measurement Results from Non-Linear Casting Set 2.	35
Table VII. Non-Linear Indication Measurement Results from Non-Linear Casting Set 3.	39
Table VIII. Linear Indication Measurement Results.....	42
Table IX. Summary of a Typical Dataset.	49
Table X. Steel Castings Surface Acceptance Standards for Magnetic Particle and Liquid Penetrant Inspection (ASTM A903).	62
Table XI. Steel Castings Surface Acceptance Standards for Magnetic Particle Inspection (EN 1369).....	62
Table XII. Example of indication measurements and calculations from one commercial casting from one foundry.....	64
Table XIII. Tabulated list of standard deviation values from three inspectors on one casting geometry from one foundry.....	64

EXECUTIVE SUMMARY

The systematic study and characterization of surface indications has never been conducted. Producers and users of castings do not have any data on which they can reliably communicate the nature of these indications or their effect on the performance of parts. Clearly, the ultimate intent of any work in this area is to eliminate indications that do in fact degrade properties. However, it may be impractical physically and/or financially to eliminate all surface imperfections. This project focused on the ones that actually degrade properties. The initial work was to identify those that degrade properties.

Accurate numerical simulations of casting service performance allow designers to use the geometric flexibility of castings and the superior properties of steel to produce lighter weight and more energy efficient components for transportation systems (cars and trucks), construction, and mining. Accurate simulations increase the net melting energy efficiency by improving casting yield and reducing rework and scrap. Conservatively assuming a 10% improvement in yield, approximately 1.33×10^{12} BTU/year can be saved with this technology. In addition, CO₂ emissions will be reduced by approximately 117,050 tons per year.

Castings were produced by SFSA member foundries and a variety of surface discontinuities were collected. These indications were removed to provide a population for each degree of severity and anomaly type, and these anomalies were characterized for size, shape, depth, and sharpness.

Commercial castings were also collected from member foundries for surface indication characterization. This information provided some verification that the population of discontinuities taken from the test castings reflects actual discontinuities observed in normal foundry practice.

Selected anomalies were sent to participating foundries for surface inspection and grading. This provided information on the variability of the inspection technique and the effectiveness of the ASTM, ANSI (MSS), ASME, Mil, etc., standards in discriminating the types and levels of anomalies. The first cut effects of surface anomalies on properties were made with tensile property measurements. Ultimate strength, elongation before failure, and fracture surface information can provide general information about other dynamic mechanical properties.

Historical data and this research indicate that just finding an indication of reasonable length (1/4") with one inspection is at best a 50/50 proposition. It is also unlikely that an inspector can discriminate an indication length to a 1/16", perhaps 1/8". Removing false positives increased repeatability and reproducibility by 10% or more.

Steel foundry Non-Destructive Evaluation (NDE) capability does not appear to be any better or worse when compared to other industrial NDE capabilities. The shortcomings of NDE techniques and/or requirements from a customer can be overcome by multiple inspections and intensive inspection.

Artificial indications using a 1/16 inch, 1/8 inch, or 1/4 inch flat-bottomed hole drilled through half the thickness mimicked a similar nonlinear natural indication. A method is proposed to predict a required safety factor during the design of geometry based on elongation and inspection length. Further testing and research is required to validate this approach in general, however this methodology brings us closer to a new era of performance-based inspection and lighter weight and advanced structures.

Numerous presentations and papers of this work have been presented at the annual Steel Founders' Society of America's (SFSA) Technical & Operating Conferences. SFSA is the largest trade association representing steel foundries in North America and has specific committees for ASTM, NACE, ISO and interface with the US Government.

The ultimate goal will be to begin a conversation with designers on the effect of surface indications on steel casting performance. While this project provides limited data on mechanical properties and range of steel alloys, the results are in line with commonly used design data for wrought products. SFSA's interaction with specification committees provide a conduit to rework steel casting specifications to more closely match actual performance instead of overly conservative estimates.

Further testing and research is required to validate the method correlating safety factor, elongation, and indication length. In addition, the relationship between fatigue properties and surface indications in steel castings need to be further developed.

INTRODUCTION

Accurate numerical simulations of casting service performance allow designers to use the geometric flexibility of castings and the superior properties of steel to produce lighter weight and more energy efficient components for transportation systems (cars and trucks), construction, and mining. Accurate simulations increase the net melting energy efficiency by improving casting yield and reducing rework and scrap. Approximately 1.33×10^{12} BTU/year can be saved with this technology (see Attachment A).

Accurate simulations require an engineering understanding of surface and near surface anomalies. Many steel castings are used in dynamic applications where fatigue properties are important. The most common mode of failure for ground based vehicles is fatigue, and fatigue causes about 60% of construction equipment failures. Fatigue failures almost always initiate at or near the surface so surface quality has an important effect on the number of stress cycles that occur before failure.

In addition, questions have arisen about whether the current surface acceptance standard (ASTM A-903) is excessively restrictive. Parts may be scrapped or reworked as a result of surface indications that do not affect the part performance. Quantitative data on the shape, size, and source of surface discontinuities indicated by ASTM A-903 would be extremely valuable for estimating anomaly effects on dynamic properties.

Castings were produced by SFSA member foundries and a variety of surface discontinuities were collected. These indications were removed to provide a population for each degree of severity and anomaly type, and these anomalies were characterized for size, shape, depth, and sharpness.

Commercial castings were also collected from member foundries for surface indication characterization. This information provided some verification that the population of discontinuities taken from the test castings reflects actual discontinuities observed in normal foundry practice.

Selected anomalies were sent to participating foundries for surface inspection and grading. This provided information on the variability of the inspection technique and the effectiveness of the ASTM standard in discriminating the types and levels of anomalies. The first cut effects of surface anomalies on properties were made with tensile property measurements. Ultimate strength, elongation before failure, and fracture surface information can provide general information about other dynamic mechanical properties. Reductions in tensile elongation are a good indication of the effects on fatigue.

BACKGROUND

Every global industry strives to improve its processes and thus improve its product. This statement is especially true in today's quality driven market. As a competitor in the global market, the cast steel industry has continuously improved its process and products to manufacture higher quality parts while minimizing costs and production time.

Some of this improvement can be accredited to the many standards that have been written to help designers define acceptable product limits to produce required performance. However, some of these standards are workmanship standards and are not directly related to part performance. An example of a workmanship standard for steel castings is the radiographic standard ASTM E-186 [1]. This standard consists of reference radiographs that show examples of discontinuities categorized into severity levels, which allows considerable flexibility for the producer and buyer on how to interpret the radiographic grade of a part. This flexibility is necessary since stricter requirements would demand more information on the service environment of the part. Steel castings are used in an almost infinite variety of service conditions. In essence, the radiographic standards are a yardstick and it is up to the producer and buyer on how to use the yardstick.

Other standards such as ASTM A-903 provide quantitative values but were developed from other manufacturing processes and may be overly conservative [2]. This standard specifies levels of acceptance criteria on the surface of castings using measured lengths and geometries of indications. As the cast steel industry has grown more sophisticated in the use of numerical modeling to predict process quality and part performance, design requirements should be reexamined to see if they actually affect part performance. In an attempt to refine designer standards, this study focused on characterizing the effect of surface/near surface indications on tensile properties using the backdrop of current acceptance standards such as ASTM A-903 [2].

Design engineers often base the importance of surface anomalies as revealed by non-destructive inspection by their familiarity with the various classes of severity revealed by reference radiographs or photographs resulting from radiographic or surface inspection, not on correlative testing. Vishnevsky, Bertolino, and Wallace have shown that severe surface discontinuities, well beyond any commercially acceptable standard such as ASTM E125, will not reduce the endurance strength as much as a standard notched fatigue (R.R. Moore) test specimen (8-20% vs. 35%)[3]. This coupled with the tendency of design engineers to use the lowest material properties and large safety factors often result in over designed castings. While the steel casting industry desires to produce a quality product, the inspection and removal of surface indications that do not affect part performance is costly and unnecessary. (SFRF Report "The Effects of Surface Discontinuities on the Fatigue Properties of Cast Steel Sections", 1966)

Surface anomalies can degrade the dynamic response of metal parts. The extent of the degradation depends on four factors: 1) the size, shape, and sharpness of the anomaly, 2) the location and orientation of the anomaly in the stress field, 3) the stress intensity, and 4) the type of loading (dynamic or static bending, torsion, or tensile stress field).

Many steel castings are used in dynamic applications where fatigue properties are important. The most common mode of failure for ground based vehicles is fatigue. A study by a construction equipment manufacturer showed that about 60% of their field failures were caused by fatigue.

Fatigue failures almost always initiate at or near a free surface so surface quality has an important effect on the number of stress cycles that occur before failure. Surface discontinuities and stress risers caused by reoxidation products, entrapped sand, or weld defects are of concern especially if they occur in highly stressed regions.

Bending fatigue is affected by internal shrinkage, but the decrease in properties is small unless the shrinkage extends to near the part surface. The presence of Class 2 and Class 6 (ASTM E-446) shrinkage has been found to reduce torsion fatigue strength by 17% and 32%, respectively in a quenched and tempered product.

Impact ductility and fracture energy can also be degraded by surface discontinuities, and the degree of the degradation is related to discontinuity severity. Surface hot tears have the worst effect on impact/fatigue properties. The sharp surface notch created by hot tears provides a site for both fatigue and impact crack initiation. Severe notches having a radius on the order of 0.001" can reduce the endurance limit by 50% compared to un-notched material. Other discontinuities including gas cavities, weld undercuts, slag inclusions, and re-oxidation products usually have a more rounded surface which reduces the notch severity.

Most prior research on surface quality effects on dynamic properties was performed using specimens containing discontinuities beyond the acceptance standards for most commercial steel castings. A question has arisen regarding whether the current surface acceptance standard (ASTM A-903) for steel castings is too restrictive. Quantitative data on the shape, size, and source of surface discontinuities indicated by ASTM A-903 would provide information for estimating anomaly effects on dynamic properties.

While surface anomalies can degrade the performance of castings, the question is whether the current inspection practices can discriminate between types and degrees of anomaly severity. How significant are magnetic particle (MP) and liquid penetrant (LP) indications, and is there some indicator limit below which no effect on properties would be expected?

The University of Alabama – Birmingham (UAB) proposed to conduct a series of casting trials at participating SFSA member foundries to produce a variety of surface discontinuities. The test casting was similar to the SFSA L-shaped plate which has a large cope surface. A surface inspection was conducted, indications marked, and the surface quality evaluated by the producing foundry. The level and type of each indication according to ASTM A-903 was recorded.

Indications were removed to provide a reasonable population for each degree of severity and anomaly type, and these anomalies metallurgically examined to determine size, shape, and depth, and sharpness. An inspection and analysis protocol was developed to provide data to answer the following questions:

1. What is the root cause of the indications? Possibilities include re-oxidation, cracks, sand, slag, etc.
2. How deep do the anomalies extend into the casting? (Histogram)
3. How detrimental are the anomalies to properties? (Use depth, sharpness, and fracture mechanics to estimate).
4. How sensitive is the inspection technique to small indications (in terms of indication size)?
5. To what extent do anomalies affect product performance. Is there a size limit or indicator limit below which the anomalies have no effect?
6. Can data be developed to that will relate indication size to performance in safety critical applications?

Selected anomalies were also sent to participating foundries for surface inspection and grading. This provided information on the variability of the inspection technique and the effectiveness of the ASTM standard in discriminating of types and levels anomalies.

Some consideration was given to other NDE techniques that might be used to provide information about the nature of surface anomalies. For example Harry Mouat Company in Birmingham is working to develop a resonance unit that creates friction between adjacent surfaces of anomalies (assuming the surfaces contact each other) and the local temperature rise can be seen with an IR scanner. Such a device might discriminate between shallow, rounded indications such as might be caused by superficial re-oxidation products and cracks that would have surfaces that rub and produce a thermal signature. A small portion of the effort (<5%) was used to explore such unconventional techniques for discriminating between anomalies.

In order to meet demands of buyers, the steel casting industry has used several recordable destructive tests to qualify the material properties. The two most prevalent tests are a cyclical loaded tensile test, also known as fatigue, and a monotonic loaded tensile test. The monotonic tensile test is performed by applying an increasing load until failure, whereas the cyclical test applies an oscillating tensile load until failure. These two methods both result in quantifiable material properties. The monotonic tensile test was chosen for this study because of this industrial prevalence.

The first cut effects of anomalies on properties was made with tensile property measurements. Ultimate strength, elongation before failure, and fracture surface information provide a substantial

amount of information about other dynamic mechanical properties. Reductions in tensile elongation are a good indication of expected effects on fatigue.

To date, there has not been a study to determine the quantitative effect of surface indications on the monotonic tensile properties of steel castings. However, there have been studies of the effect of internal indications on mechanical properties. The majority of these studies related fatigue performance to internal radiographic indications. A few studies related internal shrinkage, macro-porosity, and micro-porosity to tensile mechanical properties. In general, reasonable concentrations of internal shrinkage had little effect on 0.2% offset yield strength (YS), ultimate tensile strength (UTS), and elastic modulus, but produced a significantly reduced percent elongation when monotonically tested [4]. It was also observed that monotonically tested specimens with micro-porosity repeated the trend of having little effect on strength but did affect ductility [5]. However, cyclically loaded fatigue specimens with macro-porosity showed elastic modulus varying as a function of porosity volume [5]. Hardin and Beckermann found that the elastic modulus decreased nonlinearly with porosity when cyclically loaded, and this relationship was dependent on the characteristics of the porosity [6]. These studies revealed that indications can potentially affect all mechanical properties, having the greatest effect on elongation.

In order for this study to benefit from these past surface indication studies, a relationship between fatigue and monotonic tensile test must be formed. A comparison of the fatigue and monotonic tensile test is seen in Svoboda's study of fatigue and fracture toughness of five different steels. The study revealed that the YS was lower in fatigue tests than in monotonic tests; however, the UTS was higher in fatigue versus monotonic in four of the five steels [7]. These results reveal that fatigue and monotonic tests are not directly relatable, but they do reveal which material properties will be affected most by surface indications. Thus, only general trends can be carried between surface indication studies using fatigue and studies using monotonic tensile tests.

In order to quantitatively define the effect of surface indications on mechanical properties, the term "surface indication" must first be defined. "Surface indication" has historically been used to describe any visible inconsistency observed on the casting surface. An example of the current nomenclature, ASTM A903 conveys general acceptance guidelines, but does not reveal a quantitative relationship between the size of the indication and the mechanical properties [2]. With quantitative data, a more defined relationship between surface indications and properties can be developed. This relationship will give designers the ability to properly size a part and produce acceptable performance with a reasonable safety factor.

Due to the random nature of surface indications, development of a machinable indication that mimics the effect of naturally occurring indications would be useful for experimental and numerical simulation testing. This technique has been used before by Rudy and Rupert in their study of the mechanical properties of aluminum and its relationship to porosity [8]. This study determined that fine porosity can be as detrimental to a weld as large porosity if the total area of the micro-pores were comparable to the single large pore. Thus, the machined indication replicated a natural indication.

These results lead to a second goal of this study, which is to improve testing repeatability in steel castings by using machined notches to mimic naturally occurring indications.

The standard means of detecting a surface indication is by visual inspection. In order to improve this inspection, techniques such as magnetic particle testing also known as “MT” or liquid penetrant testing also known as “PT” have been developed, which aid the eye in the detection of hard-to-see indications on as cast surfaces. These tools greatly enhance detection, but classification and indication effect on properties are left up to operator interpretation. This study only contains linear and non-linear indication, not cracks from quenching or hot tears. Previous work has shown that linear and non-linear indications typically extend less than 13 mm beneath the surface while cracks developed from quenching or hot tears can run much deeper.

By virtue of studying commonly used steels, the effects of the surface indications will be able to directly contribute to real world safety applications. The less common Eglin steel was selected due to its extremely high tensile properties, thus broadening the data range for the study. A long-term use of this study will be the improvement of the quantification of surface indication effects on other mechanical properties, such as bending fatigue.

Most of the steels used in this study, ASTM A-958 Grade 110-80, ASTM A-958 Grade 165-135, ASTM A-351 Grade CF8M, are widely produced and normally used for valves, flanges, fittings, and other pressure containing parts. The only uncommon steel used was Eglin steel, which is a low cost replacement for super alloy steels such as HY-180 and finds much of its use in military applications. The 110-80, 165-135, and Eglin steel are all low carbon or low alloy steels, the only exception being CF8M. In general, CF8M contains a high percentage of Cr and Ni and is essentially the cast equivalent of 304 type wrought alloys. CF8 may be fully austenitic but it more commonly contains some residual ferrite (3-30%) in an austenitic matrix. CF8M is a version of CF8 alloy with an addition of 2-3% molybdenum, which increases resistance to corrosion by seawater and improves resistance. These molybdenum-bearing alloys are generally the superior choice for weakly oxidizing environments [9] (p. 20-16).

RESULTS AND DISCUSSION

Inspection Criteria Survey

Initially, ASTM A-903 was suggested as the standard by which customers require steel foundries to rate the acceptability of a casting surface. However, other surface quality standards are being used by member foundries. A survey was sent out to all SFSA members requesting information on the methods and acceptance criteria for visual, magnetic particle, and liquid penetrant inspection. The objective of this survey is to identify the most common standard(s) used to rate surface quality and the most common methods used to detect surface anomalies.

The survey was segmented into five different categories:

1. Visual Inspection
2. Wet Magnetic Particle

3. Dry Magnetic Particle
4. Visible Liquid Penetrant
5. Fluorescent Liquid Penetrant

A total of eighteen foundries responded to the survey.

Figure 1 illustrates a histogram of the type of inspection method used by the responding foundries. As would be expected, visual inspection was used by all foundries, being the most efficient and least expensive method. Seventy-eight percent of the foundries used both wet and dry magnetic particle inspection. Magnetic particle is a robust method for detecting and locating surface and near surface discontinuities. Indications are produced directly on the part surface and produce a picture of actual discontinuities. The principle of the magnetic particle method is based on the distortion of magnetic field lines by a change in material continuity. If the discontinuity is close or open to the surface, the magnetic flux lines will be distorted at the surface. This flux leakage will attract and fix magnetic particles, depending on the strength of the distortion. An experienced operator can often estimate crack depth from the intensity of the indication. Magnetic particle cannot be used on non-ferromagnetic materials such as austenitic stainless steels.

The dry magnetic particle method uses air to transport fine magnetic particles to the part surface. These particles can be pigmented in a variety of colors or be fluorescent. Dry magnetic particle method is most commonly used on rough casting surfaces and is easily transported to the area of interest. The wet particle method is similar to the dry method except the transport medium is a liquid, most commonly water. Wet particles are better at detecting very fine surface cracks for the liquid medium allows easier mobility of the particle to the leakage field compared to air and produces a more uniform coverage. Wet magnetic particle equipment, however, is not easily transported to a part.

Sixty-seven percent of the responding foundries have visible liquid penetrant capabilities and thirty-three percent use fluorescent LP. The liquid penetrant method is not

Figure 1. Type of Inspection Method used by Responding Foundries.

affected by the ferromagnetic properties of the casting and is more likely to be used by high alloy foundries producing austenitic stainless steels. LP is considered to be more sensitive than magnetic particle inspection but requires the discontinuity to be open to the surface and typically requires more time to perform the inspection. Rough surfaces can also be a problem with LP in producing a high level of background interference.

The visible liquid penetrant method is the fastest and simplest of the LP techniques. The penetrant develops a vivid indication in contrast to background of the developer. No special darkrooms are required, only adequate white light. The fluorescent LP technique can be more sensitive than visible LP but at a cost of slower throughput.

Table I lists all visual inspection methods and acceptance criteria submitted by the responding foundries. A total of 22 separate documents are required by foundry customers. This number is under-reported as customer specifications can include different requirements of different parts for a single customer. A histogram of the most common visual inspection criteria used by the foundries is illustrated in Figure 2. ASTM A802 with SCRATA plates and Manufacturers Standardization Specification (MSS) SP-55 are the most common at 65%. Internal standards and customer specifications are used by about 20% of the foundries followed by ASTM E125/A903 and AMS 2175 at about 10%. Note that ASTM A903 and E125 are acceptance criteria for magnetic particle inspection. The foundries use these acceptance criteria to repair indications that will be detected in future magnetic particle inspection.

Table II lists all methods and acceptance criteria reported for wet and dry magnetic particle inspection. A total of 19 different standards were requested by foundry customers. A histogram of the most commonly identified standards for dry magnetic particle inspection is illustrated in Figure 3. ASTM E709 was listed by 57% of the foundries, followed by ASTM E125 (36%), and ASTM E1444 (29%). Eight other documents were also listed as being used by foundries. Figure 4 lists a similar histogram for

Table I. All Methods and Acceptance Criteria submitted for Visual Inspection.

- ASTM E125
- ASTM A903
- ASTM A997
- ASTM A802/SCRATA Comparator Plates.
- MSS-SP-53
- MSS-SP-54
- MSS-SP-55
- MSS-SP-93
- MSS-SP-94
- MSS-SP-112
- AMS 2175
- ASNT SNT-TC1A
- AMSE Section III
- AMSE Section V
- ASME Section VIII
- Mil Std 248
- Mil Std 271
- Mil Std 278
- ANSI B16.34
- Fowler Casting Surface Scale
- Internal Standards
- Customer Specifications

Figure 2. Type of Criteria for Visual Inspection used by Responding Foundries.

Table II. All Methods and Acceptance Criteria submitted for Magnetic Particle Inspection.

- ASTM E125
- ASTM A903
- ASTM E165
- ASTM E1444
- ASTM E709
- MSS-SP-53
- MSS-SP-93
- MSS-SP-112
- ANSI B16.34
- DIN 1690 Part 2
- AMS 2175/Mil Std 2175
- ASME Section III
- AMSE Section V
- ASME Section VIII
- Mil Std 1907
- Mil Std 2035
- Mil Std 271
- Internal Standards
- Customer Specifications

the acceptance criteria and methods for wet magnetic particle inspection. Similar to the dry particle responses, ASTM E709, ASTM E125, and ASTM E1444 were the most common responses followed by seven other methods.

Table III lists all methods and acceptance criteria reported for visible and fluorescent liquid penetrant inspection. A total of 15 different standards were requested by foundry customers. A histogram of the most commonly identified standards for visible liquid penetrant inspection is illustrated in Figure 5. ASTM E165 and MSS-SP-93 were listed by 42% of the foundries, followed by internal standards (33%), and ASME Section 8 (25%). Five other documents were also listed as being used by foundries. Figure 6 lists a similar histogram for the acceptance criteria and methods for fluorescent liquid penetrant inspection. Similar to the dry particle responses, ASTM E165 and MSS-SP-93 were the most common responses followed by customer specifications, ASME Section III and five other methods.

While steel foundries have numerous specifications required by their customers, ASTM A903 is the most reasonable choice for this project. ASTM A903 can be used for both magnetic particle and liquid penetrant inspection, is commonly required by customers, and provides a quantifiable criteria. Another possible option would be ASTM E125 but these reference images are specific for magnetic particle. In any event, if different criteria are determined to be of more benefit to the industry, the inspected samples can be re-graded.

Surface Indication Characterization

A set of ten test plates were cast two on in phenolic urethane bonded molds by a participating foundry. These plates were 6 inches wide by 9 inches long and 1.25 inches thick and were inspected in the as-cast condition. This pattern design was used by the foundry for testing process variables to improve casting cleanliness since the large cope area tended to collect and expose any non-metallic inclusions. These qualities should be useful in the current study. We wanted to produce castings that contained surface indications that typically occur in steel foundries and not produce atypical indications. The foundry did not use any unusual methods to produce or reduce surface indications.

The castings were inspected using indirect magnetization using a Parker Research DA-400 probe with a dry non-fluorescent powder. Both AC and DC magnetization were used to produce the strongest indications. The casting surface was lightly dusted with white paint to improve the contrast to the red magnetic powder.

The cast surface of the test plates were particularly difficult in discriminating between a true discontinuity and surface roughness caused by the mold surface. Although the as-cast surfaces of each plate was inspected and photographed, no measurements of the photographs were conducted. A 0.050 inch layer was removed from the cast surface using a grinding operation. This depth was selected for two reasons: to removed most of the as-cast skin and because most sand grain sizes used in steel foundries are about 0.050" in diameter.

Figure 3. Type of Inspection Method and Criteria for Dry Magnetic Particle.

Figure 4. Type of Inspection Method and Criteria for Wet Magnetic Particle.

Table III. All Methods and Acceptance Criteria for Liquid Penetrant Inspection.

• ASTM E125	• AMS 2175/Mil Std 2175
• ASTM A903	• ASME Section III
• ASTM E165	• AMSE Section V
• ASTM A788	• ASME Section VIII
• ASTM E1417	• Mil Std 2035
• MSS-SP-53	• Customer Specifications
• MSS-SP-93	• Internal Standards
• ANSI B16.34	

Acceptance Criteria and Methods for Visible Liquid Penetrant

Figure 5. Type of Inspection Method and Criteria for Visible Liquid Penetrant.

Acceptance Criteria and Methods for Fluorescent Liquid Penetrant

Figure 6. Type of Inspection Method and Criteria for Fluorescent Liquid Penetrant.

Figure 7 illustrates an 8630 test plate after the removal of 0.050" from the cope surface. This figure shows all indications, including those that are less than 0.0625" in length. After inspection, the plate was digitally photographed to document the surface and near surface indications. An image processing program was used to identify areas containing indications and to measure various dimensions. Following ASTM A903 protocol, all indications with a Feret length dimension less than 0.0625" in length were not counted. The test plates were used to produce primarily non-linear indications. ASTM A903 defines non-linear indications as having a length to width ratio of 3 and greater. To separate between linear and non-linear indications, the Feret length was divided by the Feret width to provide the best approximation of the ASTM length to width requirement. Figure 8 illustrates a histogram of the maximum (Feret) length of indications observed on Plate 1 after removal of 0.050" from the cope surface. The vast majority of the indications were less than 0.25 inches in maximum length. A histogram of the length to width ratio for Plate 1 is illustrated in Figure 9. About two of the thirty indications would be considered to be linear.

Plate 1 was sent back to a local machine shop and an additional 0.040" was removed from the cope surface for a total 0.090". The plate was re-inspected as before and is illustrated in Figure 10. In most cases, the number of indications remained about the same and increased in maximum length slightly (Figure 11) while the L/T ratio remained about the same (Figure 12). This was for the most part atypical from the reaction of most plates to the removal on the as-cast surface.

The remaining eight plates were inspected, documented and measured using the same procedure as described previously. Histograms were plotted for both maximum length and L/T ratio. Figure 13 illustrates a histogram of the maximum length of all indications after removal of 0.050" of cope surface. The majority of the indications were less than 0.125" in length. Most of the indications had an L/T ratio less than 3 and were non-linear (Figure 14). After the removal of 0.090" from the cope surface, the number of indications dropped from around 650 to 275, as shown in Figure 15. It is interesting to note that while the number of changes changed after stock removal, the distribution of sizes did not. Again, the vast majority of indications are non-linear with only a few being linear.

The results so far from these ten 8630 plates indicate that the surface indications were roughly conical shaped and non-linear.

Figure 7. Plate 1 after removal of 0.050" from Cope surface.

Figure 8. Histogram of Feret Length after 0.050" – Plate 1.

Figure 9. Histogram of Feret Length/Thickness Ratio after 0.050" – Plate 1.

Figure 10. Plate 1 after Removal of 0.090" from Cope Surface.

Figure 11. Histogram of Feret Length after 0.090" – Plate 1.

Figure 12. Histogram of Feret Length/Thickness Ratio after 0.090" – Plate 1.

Figure 13. Histogram of Feret Length after 0.050" – All Plates

Figure 14. Histogram of Feret Length/Thickness Ratio after 0.050" – All Plates

Figure 15. Histogram of Feret Length after 0.090" – All Plates

Three additional sets of steel plate castings were submitted from commercial foundries that were suspected to contain non-linear indications. A summary of the castings produced, their size, alloy type, production method and depth of grinding are summarized in Table IV. The first foundry (designated Non-Linear Set 1) submitted ten low alloy 6" x 9" steel plate castings. The Non-Linear Set 1 castings were produced using a pattern that was developed to test sand/binder systems and gating arrangements. No-bake molding was used to produce the castings and a representative photograph of an as-received cope surface is illustrated in Figure 16. Sixteen low alloy 12" x 12" plate castings produced with no-bake molding were also submitted and were designated Non-Linear Set 2. A representative as-received macro-photograph of a cope surface is illustrated in Figure 17. The third foundry (designated Non-Linear Set 3) produced four CF8M and four carbon steel 4" x 8" plate castings using a green sand mold and a representative macro-photograph of a cope surface is shown in Figure 18.

Two sets of commercial castings with linear indications were also submitted and included four low alloy no bake commercial castings (designated Linear Set 1) and two low alloy no-bake commercial castings (designated Linear Set 2). A summary of these castings is included in Table IV and representative macro-photographs of the castings are illustrated in Figures 19 and 20.

Table IV. Summary of Castings Submitted with Non-Linear and Linear Indications

Designation	Casting Type	Alloy Type	Number Analyzed	As-Received Surface Condition	Mold
Non-Linear Set 1	6"x 9" Plate Castings	Low Alloy	10	As-Cast	No-Bake
Non-Linear Set 2	12" x 12" Plate Castings	Low Alloy	16	As-Cast	No-Bake
Non-Linear Set 3	4" x 8" Plate Castings	Carbon Steel and CF8M	8	As-Cast	Green Sand
Linear Set 1	Commercial Casting	Low Alloy	4	Cracked surface was ground	No-Bake
Linear Set 2	Commercial Casting	Low Alloy	2	Cracked surface was ground	No-Bake

Figure 16. Macro-photograph of a Non-Linear Set 1 Casting.

Figure 17. Macro-photograph of Non-Linear Set 2 Casting.

Figure 18. Macro-photograph of Non-Linear Set 3 Casting.

Figure 19. Macro-photograph of Linear Set 1 Casting.

Figure 20. Macro-photograph of Linear Set 2 Casting.

The castings were dry magnetic particle tested using a Parker Research DA-400 Contour Yoke with either red or black magnetic inspection powder. The inspection procedure followed the practices described in ASTM E709/E1444. A magnetic particle pie gauge field strength indicator was used to ensure adequate field strength. Selected plates were taken to a participating steel foundry and inspected using a direct magnetization technique that produced a much stronger magnetic field strength (greater than 1000 amps). Back to back comparison of indications showed no increase in indication number or size with the stronger field strength compared to UAB's probe.

After inspection, each surface was photographed for analysis of the indication size and shape. The samples were successively surface ground to remove either 0.05" or 0.10" from the surface. After each grinding stage, the samples were re-inspected and re-photographed.

Automated image analysis of the images was performed using Image Pro Plus® image analysis software. Indications were not measured if their size was less than 1/16" in length which is the minimum length for a relevant indication in most inspection criteria. Measurements included the Feret length and width of each indication. Analysis was performed on the Feret length and the ratio of the Feret length to width of each indication. In this initial analysis, no effort was made to group closely spaced indications. On the castings containing linear indications, some of the cracks were traced prior to measurement. Because of the small number of castings analyzed with linear indications, all the results from these castings will be combined for analysis.

The automated image analysis results from the Non-Linear Casting Set 1 are listed in Table V. The surface was quite rough on these castings making automated image analysis unrealistic as a large fraction of the surface gave indications. Because of this, results are presented at depths from the cast surface ranging from 0.05" up to 0.40".

The number of indications dropped sharply between the removal of 0.05" and 0.10" of material as illustrated in Figure 21. The large number of indications at a depth of 0.05" was partly due to the contribution of surface roughness as some of the as-cast surface was still present at this depth on a few of the castings. At a depth of 0.1" no as-cast surface remained on any of the castings. At depths between 0.1 and 0.4" the number of indications remained fairly constant.

The results for the maximum and average indication length in the Non-Linear Casting Set 1 are illustrated in Figure 22. Error bars represent the 95% confidence intervals about the average. The largest indication was seen at a depth of 0.05" with a size of 2.588". A number of the largest indications at this depth were surface defects due to a rough cast surface that was not fully removed with the first 0.05" grinding and disappeared at a depth of 0.10". At depths of 0.10" and higher, the maximum indication size leveled out and ranged from 0.345 to 0.545" in length with no significant reduction in size at depths up to 0.4". The average indication length dropped from 0.156 to 0.115" between depths of

0.05 and 0.15". At depths of 0.15" and deeper, the average indication size remained about constant near 0.12".

Figure 23 shows the indication length histogram for the Non-Linear Casting Set 1. At all depths, the majority of the indications ranged between $\frac{1}{8}$ and $\frac{1}{4}$ " in size. At a depth equal to or exceeding 0.15" the number of indications ranging in length from $\frac{1}{8}$ and $\frac{1}{4}$ " increased from about 55% to about 70% and the range in indication size narrowed and shifted to somewhat to smaller sizes.

The length to width ratio of the non-linear defects is illustrated in Figure 24. The average length to width ratio dropped from about 2 at a depth of 0.05" to 1.7 at a depth of 0.1" and remained fairly constant at greater depths. Surprisingly, the maximum length to width ratio was above three at all depths measured even though none of the indications were cracks. Between grindings of 0.05" to 0.1" the maximum ratio dropped from greater than 9 to about 4 and stayed near 4 up to 0.4" into the casting.

The length to width ratio histogram for the non-linear defects in Non-Linear Casting Set 1 is illustrated in Figure 25. At all depths, the majority of the defects had length to width ratios between 1 and 3 and there were a number of indications with length to width ratios greater than 3. The greatest number with ratios greater than 3 was seen in the samples ground only to a depth of 0.05".

Table V. Non-Linear Indication Measurement Results from Non-Linear Casting Set 1.

Depth of Grinding (in)	0.05	0.1	0.15	0.2	0.25	0.3	0.4
Number Measured	493	216	176	246	263	231	236
Average Indication Length (in)	0.1557	0.140	0.115	0.115	0.115	0.122	0.118
Std. Dev. Length (in)	0.181	0.085	0.050	0.0558	0.0512	0.0543	0.055
Max. Length (in)	2.588	0.545	0.412	0.424	0.352	0.345	0.394
Average Length to Width Ratio	2.019	1.73419	1.734763	1.729382	1.718578	1.675522	1.659408
Std. Dev. Length to Width Ratio	0.831	0.494	0.449	0.574	0.518	0.448	0.489
Max. Length to Width Ratio	9.661	4.008	3.465	4.746	4.141	3.757	4.048

Figure 21. Number of Indications vs. Distance from Cast Surface for Non-Linear Casting Set 1.

Figure 22. Average and Maximum Indication Length vs. Distance from Cast Surface for Non-Linear Casting Set 1.

Figure 23. Indication Length Histogram for Non-Linear Casting Set 1.

Figure 24. Average and Maximum Length to Width Ratio vs. Distance from Cast Surface for Non-Linear Casting Set 1.

Figure 25. Length to Width Ratio Histogram for Non-Linear Casting Set 1.

Image analysis results from the second set of non-linear castings are illustrated in Table VI. Surface roughness still prevented automated measurement of the as-cast surface in these castings and measurements were obtained at depths of 0.05 and 0.15 inches only. Although the cast surface made automated measurements in these castings difficult, the as-cast surface was completely removed at a depth of 0.05" unlike the first non-linear set.

The number of indications measured at the two depths is shown in Figure 26. The density of indications in these castings was lower than was seen in the first non-linear casting set but in both situations there was a significant reduction in the number of indications between the first and second surface grindings. In this set the number of indications dropped from a high of 174 at a depth of 0.05" down to 83 at a depth of 0.15".

The average and maximum indication length for the second non-linear casting set are illustrated in Figure 27 and the results were about the same at both depths tested. The maximum indication length was near 0.75" and the average was about 0.17". In Figure 28, the indication length histogram is illustrated. There was little discernable difference in the indication size at the two depths tested.

The average length to width ratio for the second non-linear casting set stayed fairly constant at the two depths tested with an average value close to 2 as illustrated in Figure 29. Again, although no cracks were present, the maximum length to width ratio was above 3 at both depths and had a value of 3.714 at 0.05" and 5.348 at a depth of 0.15". The indication histogram for Casting Set 2 is shown in Figure 30. Both depths had at least 90% of the indications with a length to width ratio of 3 or less. The 0.15" depth grind had a few more indications with a larger ratio of length to width compared to the 0.05" grind.

Table VI. Non-Linear Indication Measurement Results from Non-Linear Casting Set 2.

Depth of Grinding (in)	0.05	0.15
Number Measured	174	83
Average Indication Length (in)	0.174	0.192
Std. Dev. Length (in)	0.125	0.142
Max. Length (in)	0.736	0.776
Average Length to Width Ratio	1.892	2.018
Std. Dev. Length to Width Ratio	0.563	0.835
Max. Length to Width Ratio	3.714	5.348

Figure 26. Number of Indications vs. Distance from Cast Surface for Non-Linear Casting Set 2.

Figure 27. Average and Maximum Indication Length vs. Distance from Cast Surface for Non-Linear Casting Set 2.

Figure 28. Indication Length Histogram for Linear Casting Set 2.

Figure 29. Average and Maximum Length to Width Ratio vs. Distance from Cast Surface for Non-Linear Casting Set 2.

Figure 30. Length to Width Ratio Histogram for Non-Linear Casting Set 2.

The as-cast surface roughness of the third set of steel plates with non-linear indications allowed for automated image analysis of the indications on the as-cast surface. Three depths were analyzed and included the as-cast surface and depths of 0.05 and 0.15". The results are summarized in Table VII.

The number of indications dropped rapidly as the distance from the cast surface increased and these results are shown in Figure 31. Grinding to 0.05" reduced the indications from 348 to 126 and further grinding to 0.15" reduced the number to 57.

Table VII. Non-Linear Indication Measurement Results from Non-Linear Casting Set 3.

Depth of Grinding (in)	0	0.05	0.15
Number Measured	348	126	57
Average Indication Length (in)	0.118	0.146	0.131
Std. Dev. Length (in)	0.094	0.151	0.079
Max. Length (in)	0.834	1.5	0.399
Average Length to Width Ratio	1.288	1.241	1.232
Std. Dev. Length to Width Ratio	0.107	0.108	0.105
Max. Length to Width Ratio	1.544	1.561	1.511

**Number of Indications Vs. Distance from Cast Surface
Non-Linear Set 3**

Figure 31. Number of Indications vs. Distance from Cast Surface for Non-Linear Casting Set 3.

In Figure 32, it is shown that the average indication length stayed about constant up to depths of 0.15" while the maximum length did not correlate with depth. The largest indication was 1.5 inches in length and was seen at a depth of 0.05".

Figure 32. Average and Maximum Indication Length vs. Distance from Cast Surface for Non-Linear Casting Set 3

The cast surface had a greater proportion of smaller indications as illustrated in Figure 33. Over 70% of the indications were less than $\frac{1}{4}$ inch in length at the cast surface and this number dropped to between 55 and 65% at depths of 0.05 and 0.15".

The average and maximum length to width ratios were smaller in the third non-linear casting set than was seen in the first two and the results for the third set are shown in Figure 34. The difference between the average and maximum values was small in this casting set and no indication reached the critical non-linear ratio of three. All indications had ratios less than 1.6. The maximum length to width ratio stayed fairly constant at all three depths tested while there was a small reduction in the average ratio at greater depths.

Figure 33. Indication Length Histogram for Linear Casting Set 3

Figure 34. Average and Maximum Length to Width Ratio vs. Distance from Cast Surface for Non-Linear Casting Set 3.

The results from the two linear indication casting sets submitted are listed in Table VIII. Cracks that appeared to be the same crack that disappeared and reappeared on the surface were counted separately. The number of linear indications dropped from 175 on the machined as-received casting surfaces down to close to 100 at all other depths examined as shown in Figure 35.

Table VIII. Linear Indication Measurement Results.

Depth of Grinding (in)	0	0.05	0.1	0.2
Number Measured	175	105	101	101
Average Indication Length (in)	0.326	0.303	0.356	0.321
Std. Dev. Length (in)	0.328	0.228	0.335	0.351
Max. Length (in)	2.355	0.910	2.135	2.482
Average Length to Width Ratio	5.784	6.987	5.825	5.737
Std. Dev. Length to Width Ratio	3.441	3.763	3.172	2.799
Max. Length to Width Ratio	1.340	1.211	1.414	1.77
Min. Length to Width Ratio	1.340	1.211	1.414	1.770

Figure 35. Number of Linear Indications vs. Distance from As-Received Surface.

The average linear indication length was around 0.3" at all depths tested as illustrated in Figure 36. The maximum indication length did not correlate with grinding depth and ranged from about 0.9 to 2.5". No relationship between the depth and the indication length distribution was seen in the cracked castings as shown in Figure 37.

Figure 36. Average and Maximum Linear Indication Length vs. Distance from As-Received Surface.

The average and minimum indication length to width ratio stayed about the same at all depths tested. These measurement results are illustrated in Figure 38. The average length to width ratio ranged from 5.7 to 7 and the minimum ratio was between 1 and 2 at all depths. The maximum indication length to width ratio was above 15 at all four depths tested. At all four depths there were a number of indications with a length to width ratio less than three and the distribution for this measurement is illustrated in Figure 39. The number of indications with a ratio less than three would decrease if the cracks that disappeared and reappeared on the surface of the castings were connected. This measurement will be performed in the future.

Figure 37. Linear Indication Length Histogram.

Figure 38. Average and Maximum Length to Width Ratio for Linear Indications vs. Distance from Cast Surface.

Figure 39. Length to Width Ratio Histogram for Linear Indications.

Three sets of steel castings with non-linear indications were analyzed using automatic image analysis. The third set of castings with non-linear indications had a surface finish that allowed for indication identification on the as-cast surface. However, the first set was quite rough, while the second set was much smoother but was irregular due to remnants of a riser on all the castings and deep grinding marks from the riser removal. Automated image analysis from the dry-mag. analyzed as-cast surfaces of these two casting sets was performed but was not presented in this paper because the results were complicated by numerous indications from machined surface irregularities and rough as – cast surfaces. Similar inaccurate results could be obtained with manual rating of the casting with either over or underestimation of the defects on the cast surface possible. Overestimation could be caused by identification of indications that are present only on the surface. Under counting of defects might also occur as indications from defects that extend into the casting might be hidden by surface roughness.

In all three non-linear casting sets, the number of indications greater than 1/16" in length dropped off steeply up to distances of 0.15" below the cast surface. Between 0.15 and 0.4" the number of indications remained fairly constant. The indication size showed similar results in the first non-linear casting set which also had the worst as-cast surface roughness. The indication size dropped steeply up to depths of 0.15" and then leveled out between 0.15 and 0.40". In Sets 3 and 2 with a smoother as-cast surface, the average indication size remained constant across the depths examined.

The indication length to width ratio in the castings from Non-Linear Set 3 was less than three for all indications measured at all depths. In the first and second non-linear casting sets, the average length to width indication ratio was below three and the majority of the indications also had ratios below three. However, at all depths examined, these two sets also contained a number of indications with larger length to width ratios. The largest ratios and greatest percentages were found in the first casting set with the worst surface finish. These indications were clearly not cracks. These results may indicate that the cut-off value of length to width ratio of three between linear and non-linear indications may need further evaluation. Another criterion might be added to distinguish these indication types.

Castings with linear indications were also examined and the surface of these castings had been ground prior to examination. The number of indications dropped from the as-received castings up to depths of 0.05" and then leveled off. The average size of the indications remained constant up to the maximum depth examined of 0.2". The average length to width ratio of the indications was above five for all depths examined and at all depths some cracks were present with ratios below three. It is believed that many of these low ratio indications will disappear when discontinuous cracks are connected and measured as one crack.

Inspection Technique Survey

Four foundries are initially involved in this study. In an initial visit to one of the foundries, a production casting that has been historically shown to contain surface indications was selected. A population of castings was collected for the trial. The population size depended on the availability and size of the casting. The method by which the foundry normally inspects for indications was reviewed to develop a system to collect and record the casting ID, inspector name, indication location, and indication size. A summary of typical dataset is illustrated in Table IX. In one instance, the foundry photographed the indication with a scale to provide length and location information. In another instance, when photography of fluorescent dyes was impractical, the inspector marked the length and location on a schematic of the part. In all cases, the typical procedure used to inspect the part was followed as closely as possible to reduce any experimental bias.

Probability of detection (POD) is considered to be standard method for quantitative NDT process capabilities assessment. However, generation of POD statistics requires a large number of known indications. Iowa State developed a methodology for determining measurement error in their work on visual inspection techniques (Measurement Error of Visual Casting Surface Inspection – 2005 SFSA T&O) and this method was used in the analysis.

The trial at Foundry 1 included two casting geometries with weights ranging from 3000 to 4000 lbs net. One casting geometry had a high incidence of indications while the second geometry had a lower incidence. The castings were inspected using direct magnetization and dry visible magnetic particles. Four inspectors were used in the trial with a mixture of day shift/night shift inspectors and inspectors who were familiar and unfamiliar with the casting geometry. Each indication was

photographed with a scale and marked on a schematic of the part. A total of six castings were involved in this trial and 92 inspections were made.

The effect of inspector familiarity with part geometry on the total length of indications is illustrated in Figure 40. This histogram plots the total indication length for all four inspectors on a single casting that was inspected by each inspector 3-4 times. Inspector 1 and 2 were normally used to inspect this casting geometry and their total length did not change significantly, ranging from 4 to 8 inches. Inspectors 3 and 4 were not normally used to inspect this part and their total indication lengths were initially 2-3 times higher than the experienced inspectors but decreased after 3-4 inspections to more closely match the results from Inspectors 1 and 2. The time required for each inspection for a single casting is illustrated in Figure 41. In this case, there was not a significant trend in inspection time with inspector experience.

The average repeatability for each casting inspected is illustrated in Figure 42. The two different casting geometries are indicated on the graph as is an error bar indicating ± 1 standard deviation from the mean. The blue colored bars are the repeatability of the inspectors' indication length. For this foundry, if the measured lengths were within one inch, it was considered a match. The red colored bars are the repeatability of the inspectors' indication areas. We consider repeatability of the area to be more important than indication length for it

Table IX. Summary of a typical dataset.

Order	Date	Inspector	Pattern	Serial #	No.	Location	Minutes	Inches
2	11/13/2006	Inspector 1	N/A	N/A	1	2N	11	59
3	11/13/2006	Inspector 2	N/A	N/A	1	2N	75	363
4	11/13/2006	Inspector 1	N/A	N/A	1	5S	50	97
7	11/15/2006	Inspector 3	N/A	N/A	1	2S	13	52
13	11/17/2006	Inspector 3	N/A	N/A	1	2S	14	50
16	11/20/2006	Inspector 4	N/A	N/A	1	5S	16	57
17	11/21/2006	Inspector 2	N/A	N/A	1	2N	35	156
20	11/27/2006	Inspector 4	N/A	N/A	1	5S	14	36
21	11/28/2006	Inspector 1	N/A	N/A	2	5S	30	94
22	11/29/2006	Inspector 3	N/A	N/A	2	2S	20	45
25	11/30/2006	Inspector 2	N/A	N/A	2	2N	20	57
28	12/6/2006	Inspector 2	N/A	N/A	2	2N	20	199
30	12/7/2006	Inspector 4	N/A	N/A	2	5S	10	43
32	12/11/2006	Inspector 1	N/A	N/A	2	5S	20	76
33	12/12/2006	Inspector 1	N/A	N/A	3	5S	25	66
34	12/12/2006	Inspector 1	N/A	N/A	3	5S	15	101
36	12/13/2006	Inspector 2	N/A	N/A	3	2N	22	124
37	12/20/2006	Inspector 4	N/A	N/A	2	5S	10	36

Figure 40. The effect of inspector familiarity with part geometry on the total length of indications – Foundry 1.

Figure 41. Time required for each inspection for each inspector for one casting – Foundry 1.

Figure 42. The average repeatability for each casting inspected – Foundry 1.

is the indications you do not find that will give the most problems. Also included in the graph is the total number of indication areas found by all inspectors which we assume to be the true number of indications in the part. The repeatability ranged from 12 to 100% and was influenced by the total number of indications in the part. The more indications contained in the part, the lower the repeatability.

The average reproducibility for each casting inspected is illustrated in Figure 43. The two different casting geometries are indicated on the graph as is an error bar indicating ± 1 standard deviation from the mean. The blue colored bars are the reproducibility of the inspectors' indication length. The red colored bars are the reproducibility of the inspectors' indication areas. Again, we consider reproducibility of the area to be more important than indication length for it is the indications you do not find that will give the most problems. The reproducibility ranged from 13 to 100% and was influenced by the total number of indications in the part. The more indications contained in the part, the lower the reproducibility.

The average repeatability for all casting for each inspector is illustrated in Figure 44. The number of inspections for each inspector is also listed in the graph. The average repeatability for the inspectors averaged about 45% with the exception of Inspector 4 which had about half the number of inspections compared to the three other inspectors. Figure 45 plots the average reproducibility for all inspectors and all castings. Again the reproducibility averaged about 45%.

The trial at Foundry 2 included three casting geometries with weights ranging from 10 to 15 lbs net. The castings were inspected using direct magnetization and wet fluorescent magnetic particles. Four inspectors were used in the trial with ten casting per part geometry with each inspector inspecting each part five times. Indication length and location was marked on a part schematic since photography of the indication was impractical. A total of thirty castings were involved in this trial and 600 inspections were made.

The average repeatability for each casting type inspected is illustrated in Figure 46. An error bar indicating ± 1 standard deviation from the mean is indicated on the graph. The blue colored bars are the repeatability of the inspectors' indication length. For this foundry, if the measured lengths were within $1/16''$, it was considered a match. The red colored bars are the repeatability of the inspectors' indication areas. Also included in the graph is the total number of indication areas found by all inspectors which we assume to be the true number of indications in the part. The repeatability for the different geometries ranged from 42 to 78%. These casting having less surface area averaged fewer indications compared to Foundry 1. Even so, castings that contained 2-3 indications areas produced about the same range of repeatability values as Foundry 2.

The average reproducibility for each casting type inspected is illustrated in Figure 47. The blue colored bars are the reproducibility of the inspectors' indication length. The red colored bars are the reproducibility of the inspectors' indication areas. The reproducibility ranged from 20 to 50%.

Figure 43. The average reproducibility for each casting inspected – Foundry 1.

Figure 44. The average repeatability for all casting for each inspector – Foundry 1.

Figure 45. The average reproducibility for all inspectors and all castings – Foundry 1.

Figure 46. The average repeatability for each casting type inspected – Foundry 2.

The average repeatability for all casting for each inspector is illustrated in Figure 48. The average repeatability for the inspectors averaged about 60%. Figure 49 shows the average reproducibility for all inspectors and all castings. Again the reproducibility averaged about 30%.

Figure 47. The average reproducibility for each casting type inspected – Foundry 2.

Figure 48. The average repeatability for all casting for each inspector – Foundry 2.

Figure 49. The average reproducibility for all inspectors and all castings – Foundry 2.

The trial at Foundry 3 included a high alloy casting geometry with a weight of about 10 - 15 lbs net. The castings were inspected using visible liquid penetrant. Three inspectors were involved in the trial with each inspector inspecting each part three times. Indication length and location was marked on a part schematic since photography of the indication was impractical. A total of twenty-four castings were involved in this trial and 216 inspections were made. False positive indications were removed from the data set before analysis. A false positive is an indication being marked only once for all inspections.

The average repeatability for all casting for each inspector is illustrated in Figure 50. The average repeatability for the inspectors for indication length match and master indication area match averaged about 80%. Figure 51 shows the average reproducibility for all inspectors and all castings. Again the reproducibility for master indication area match averaged about 70% and averaged about 60% for indication length match.

The trial at Foundry 4 included a low alloy steel casting geometry with a weight of about 500 lbs net. The castings were inspected using direct magnetization and dry visible magnetic particles. Three inspectors were involved in the trial with each inspector inspecting each part three times. Indication length and location was marked on a part schematic since photography of the indication was impractical. A total of ten castings were involved in this trial and 90 inspections were made. False positive indications were removed from the data set before analysis.

The average repeatability for all casting for each inspector is illustrated in Figure 52. The average repeatability for the inspectors for indication length match and master indication area match averaged about 60-70%. Figure 53 shows the average reproducibility for all inspectors and all castings. Again the reproducibility for master indication area match averaged about 40% and averaged about 30% for indication length match.

The average indication length and standard deviation for every indication that was detected in at least 50% of the time is illustrated in Figure 54. For indications less than an inch in length, the standard deviation was typically around 1/4". Larger indication lengths produced a larger standard deviation. Since one standard deviation about the mean encompasses about 67% of the population, these results indicate the limit to the resolution of the method. The current standards have discrimination limits at 1/16". However, it is unlikely that an inspector can discriminate to that resolution.

Figure 50. Average repeatability for all castings and inspectors for LP R&R Foundry 3.

Figure 51. Average reproducibility for all castings and for all inspectors for LP R&R Foundry 3.

Figure 52. Average repeatability for all castings and inspectors for MP R&R Foundry 4.

Figure 53. Average reproducibility for all castings and for all inspectors for MP R&R Foundry 4.

Figure 54. Average indication length and standard deviation for all indications detected over 50% of the time.

The Gage R&R study did not directly answer a fundamental question about non-destructive examination – what is the precision of the NDE technique? An indication with a length less than $1/16^{\text{th}}$ of an inch (1.5 mm) is considered non-relevant by most acceptance standards. In other words, the measurement must be precise to a $1/16^{\text{th}}$ of an inch. The precision of a system can never exceed its resolution and in most cases, resolution must be 3-5 times better than the precision. So according to the standards, the operator must use a measuring device with a resolution 3-5 times better than $1/16^{\text{th}}$ of an inch. Of course, accuracy is also important but the type of data and method of collection precludes any estimation of accuracy.

Precision is “the ability of an estimator to give repeated estimates which are very close together.”[10] “The precision of an estimator is a measure of the repeatability of the estimator. Therefore, precision may be expressed in terms of the variance of an estimator.”[11] Standard deviation is the most useful and informative measure of variability.[12] Sample standard deviation as a measure of precision and the limited data gathered from the Gage R&R study will be used to estimate the precision of surface indication NDE techniques.

Repeatability and reproducibility are both directly related to precision [13]. Repeatability as defined by ASTM E-177-71 is “the precision associated with the most restrictive system of causes it is reasonable and useful to consider”. The mean of standard deviations from a single operator on single part geometry is a reasonable measure of repeatability, including the random error caused by the operator and method while excluding the bias (systematic error) for other operators. Reproducibility is

defined by ASTM E-177 as “precision associated with a broader system of causes of variability. The mean of standard deviations from all operators on a single part geometry is a reasonable measure of reproducibility, including the random error caused by the operators and method and the bias (systematic error).

Table X illustrates the indication lengths for ASTM A903 (Standard Specification for Steel Castings, Surface Acceptance Standards, Magnetic Particle and Liquid Penetrant Inspection). Differences between the levels vary only by $1/16^{\text{th}}$ of an inch for all the linear indications and for some of the non-linear indications. This would require a precision of $1/16^{\text{th}}$ of an inch in indication length measurements which in turn requires a resolution higher than $1/16^{\text{th}}$.

The precision requirements from European Standard EN 1369 (Founding – Magnetic Particle Inspection) for isolated indications is presented in Table XI. The requirements for EN 1371 (Founding – Liquid Penetrant Inspection) are identical to EN 1369. The maximum precision required for this standard is 0.5mm (0.02”).

These two standards suggest that the precision of the magnetic particle and liquid penetrant inspection methods must have a resolution significantly better than $1/16^{\text{th}}$ of an inch.

The number of foundries included in the study to date from the Gage R&R study is not sufficient to provide a definitive measurement of the precision of the process. However, a methodology was developed to at least estimate the precision.

Sample standard deviation was used as a measure of resolution. Each indication on every casting involved in this study was specifically located, identified and the length measured. A sample standard deviation was calculated from the multiple measurements of a specific indication. We assumed that the indication was not significantly changed between inspections. We also assumed that the range of indication lengths within a casting geometry did not significantly affect variation. A sample standard deviation was calculated for each indication by each individual inspector (repeatability). Also, a standard deviation was calculated for each indication grouping all of the measurements from the inspectors (reproducibility).

To minimize false positive readings and to provide a valid set of data to analyze, only data from a minimum of three inspections per casting for each inspector was used and an indication had to be detected at least 50% of the time. The results were grouped by casting type if multiple geometries were used and by inspector. All of the sample standard deviation values that met these criteria were tabulated for each inspector for a particular casting geometry. The values were statistically analyzed using Statgraphics for normalcy and plotted using a box and whisker plot to illustrate data range and distribution. Confidence intervals for both the mean and median were calculated. Since we do not know the true mean of the standard deviation (precision), the confidence interval provides information on the range of standard deviation means possible.

Table X. Steel Castings Surface Acceptance Standards for Magnetic Particle and Liquid Penetrant Inspection (ASTM A903).

	Level 1	Level 2	Level 3	Level 4	Level 5
Linear	$\leq 1/16"$	$\leq 1/8"$	$\leq 3/16"$	$\leq 1/4"$	$\leq 3/8"$
Non-linear	$\leq 1/8"$	$\leq 3/16"$	$\leq 3/16"$	$\leq 1/4"$	$\leq 3/8"$

Table XI. Steel Castings Surface Acceptance Standards for Magnetic Particle Inspection (EN 1369).

	SM 1	SM 2	SM 3	SM 4	SM 5
Non-linear	1.5mm >< 3mm	2mm >< 6mm	3mm >< 9mm	5mm >< 14mm	5mm >< 21mm
	LM 1	LM 2	LM 3	LM 4	LM 5
Linear	1.5mm >< 2mm	2mm >< 4mm	3mm >< 6mm	5mm >< 10mm	5mm >< 18mm
t = 16mm					
Linear	1.5mm >< 3mm	2mm >< 6mm	3mm >< 9mm	5mm >< 18mm	5mm >< 27mm
16mm < t = 50mm					
Linear	1.5mm >< 5mm	2mm >< 10mm	3mm >< 15mm	5mm >< 30mm	5mm >< 45mm
t > 50mm					

A box and whisker plot was chosen to illustrate important features of the numeric data. A box was drawn extending from the lower quartile of the sample data to the upper quartile. This is the interval covered by the middle 50% of the standard deviation values when sorted from smallest to largest. A vertical line was used to illustrate the median point while a plus sign was used to locate the sample mean value. Whiskers were drawn to the largest and smallest values less than 1.5 interquartile ranges. If a data point was outside the 1.5 interquartile ranges, the point was indicated by a symbol and considered an outlier. A median notch (95% confidence interval) was used to provide an indication of the potential sampling error in the median, assuming that the data were a random sample from a normal population.

An example of the procedure is illustrated in Tables XII and XIII. Table XII lists the indication lengths found on one commercial casting from a foundry. A total of two potential indications were found after three inspectors examined the casting three times. Inspectors 2 and 3 never detected Indication 1 while Inspector 1 found Indication 1 in all three inspections. All three inspectors found Indication 2. Inspectors 1 and 3 found Indication 2 in all three inspections, while Inspector 2 found it in two of the three inspections. For the individual inspectors, four standard deviation values were calculated out of a possible six since Indication #1 was not detected by Inspectors 2 and 3. For all inspectors, the standard deviation was calculated only for Indication 2 since Indication #1 was detected only three out of nine inspections (less than 50%).

Table XIII lists the standard deviations calculated on one casting geometry from one foundry. The data in this table includes the standard deviations from Table 3 plus any additional values from the remaining castings in that group. A total of 76 individual indications were detected at least one time by at least one inspector after three inspections. However, Inspector 1 only found three of these indications at least twice in the three inspections for that casting. Similarly, Inspector 2 found eight and Inspector 3 found six. The values along a row are not necessarily from measurements of the same indication. Each column simply gives the variation in measured indication length from indications found by an inspector. The column labeled "All" is the variation inclusive of all inspectors for an indication that met the criteria.

The trial at Foundry 1 included two casting geometries with weights ranging from 3000 to 4000 lbs net. One casting geometry had a high incidence of indications while the second geometry had a lower incidence. The castings were inspected using direct magnetization and dry visible magnetic particles. Four inspectors were used in the trial with a mixture of day shift/night shift inspectors and inspectors who were familiar and unfamiliar with the casting geometry. Each indication was photographed with a scale and marked on a schematic of the part. A total of six castings were involved in this trial and 92 inspections were made. It should

Table XII. Example of indication measurements and calculations from one commercial casting from one foundry.

Casting Number	1		
Inspector:	1		
		Indication Length (in)	
Area		1	2
Inspection 1		0.030	0.090
Inspection 2		0.045	0.060
Inspection 3		0.030	0.040
Standard Deviation		0.009	0.025
Inspector:	2		
		Indication Length (in)	
Area		1	2
Inspection 1			0.900
Inspection 2			0.450
Inspection 3			
Standard Deviation			0.318
Inspector:	3		
		Indication Length (in)	
Area		1	2
Inspection 1			0.060
Inspection 2			0.060
Inspection 3			0.060
Standard Deviation			0.000
All			0.309

Table XIII. Tabulated list of standard deviation values from three inspectors on one casting geometry from one foundry.

Inspector1	Inspector 2	Inspector 3	All
0.009	0.318	0	0.309
0.025	0.109	0.009	0.277
0.021	0	0	0.036
	0.141	0.011	0.229
	0	0.023	
	0.212	0.025	
	0.004		
	0		

be noted that the inspectors in this foundry are not required to measure indication length, only to detect and repair the indications. The markers used in this study had a smallest indication length of 0.5" so measurement accuracy is limited.

The box and whisker plots for casting geometry 1 are illustrated in Figure 55. Few inspections were performed on this particular casting geometry which resulted in only two of the four inspectors having enough qualified data to present. Inspector 4 was relatively new in inspecting this casting geometry which resulted in very high indication counts and lengths initially compared to Inspector 2. But after the second or third inspection, both indication count and length was in line with Inspector 2. This variation in standard deviation values along with the relatively few values caused the 95% confidence interval of population mean for all inspectors to be higher than expected and ranged from 0.3 to 7.5 inches.

The box and whisker plots for casting geometry 2 are illustrated in Figure 56. The mean confidence interval for Inspectors 1, 2, and 3 ranged from 0.03 to 1 inch. Inspector 4 again had higher indication lengths and counts in initial inspections but in following examinations matched well with the other inspectors. The mean confidence interval for all inspectors ranged from 0.9 to 1.7 inches or roughly 2-3 times the resolution of the markers used to measure indication length.

The trial at Foundry 2 included three casting geometries with weights ranging from 10 to 15 lbs net. The castings were inspected using direct magnetization and wet fluorescent magnetic particles. Four inspectors were used in the trial with ten casting per part geometry with each inspector inspecting each part five times. Indication length and location was marked on a part schematic since photography of the indication was impractical. A total of thirty castings were involved in this trial and 600 inspections were made.

The box and whisker plots for casting geometry 1 are illustrated in Figure 57. The mean confidence interval for Inspectors 1, 2, and 4 ranged from 0.05 to 0.27 inches and the interval for all inspectors ranged from 0.08 to 0.27 inches. If we assume that the resolution of the gage used to measure the indication length is 0.0625" (1/16th inch) then the precision should be around 0.18 inches which falls within the confidence range.

The box and whisker plots for casting geometry 2 are illustrated in Figure 58. The mean confidence interval for Inspectors 1, 2, 3, and 4 ranged from 0.05 to 0.27 inches and the interval for all inspectors ranged from 0.11 to 0.57 inches. These values are higher than geometry 1 and reflect a more difficult geometry to inspect.

The box and whisker plots for casting geometry 3 are illustrated in Figure 59. The mean confidence interval for Inspectors 1, 2, and 4 ranged from 0.00 to 0.49 inches and the interval for all inspectors ranged from 0.00 to 0.31 inches.

Casting Geometry 1

Figure 55. Box and whisker plots for Casting Geometry 1 from Foundry 1.

Casting Geometry 2

Figure 56. Box and whisker plots for Casting Geometry 2 from Foundry 1.

Casting Geometry 1

Figure 57. Box and whisker plots for Casting Geometry 1 from Foundry 2.

Casting Geometry 2

Figure 58. Box and whisker plots for Casting Geometry 2 from Foundry 2.

The mean precision (standard deviation) from this foundry ranged from very good (0.00) to not so good (0.50"). If we assume that true precision (standard deviation) mean for all inspectors is close to 0.25", it is unlikely that difference of a 1/16th inch will be consistently identified.

The trial at Foundry 3 included a high alloy casting geometry with a weight of about 10 - 15 lbs net. The castings were inspected using visible liquid penetrant. Three inspectors were involved in the trial with each inspector inspecting each part three times. Indication length and location was marked on a part schematic since photography of the indication was impractical. A total of twenty-four castings were involved in this trial and 216 inspections were made.

The box and whisker plots for casting geometry 1 are illustrated in Figure 60. The mean confidence interval for Inspectors 1, 2, and 3 ranged from 0.00 to 0.2 inches and the interval for all inspectors ranged from 0.01 to 0.5 inches. Inspectors 1 and 3 were very consistent in their indication length values which resulted in very low standard deviations. Inspector 2 in some cases matched the values of Inspectors 1 and 3 but in others, exceed their values by a factor of about 10. This also increased the confidence interval for all inspectors as well.

The mean precision (standard deviation) from this foundry was very good (0.00 – 0.04") for two of the inspectors and a 1/16th precision may be reasonable. Inspector 2, however, showed not only variability within his measurements but also varied significantly for the measurements of the other two inspectors.

The trial at Foundry 4 included a low alloy steel casting geometry with a weight of about 500 lbs net. The castings were inspected using direct magnetization and dry visible magnetic particles. Three inspectors were involved in the trial with each inspector inspecting each part three times. Indication length and location was marked on a part schematic since photography of the indication was impractical. A total of ten castings were involved in this trial and 90 inspections were made.

The box and whisker plots for casting geometry 1 are illustrated in Figure 61. The mean confidence interval for Inspectors 1, 2, and 3 ranged from 0.00 to 0.16 inches and the interval for all inspectors ranged from 0.14 to 0.21 inches. All three inspectors were consistent in their indication length values (with the exception of a few outliers) which resulted in low standard deviations. Histograms of the standard deviation values were also plotted for each inspector and for all inspectors. The individual inspector histograms showed a one tail normal distribution while the all inspector histogram was a normal distribution as would be expected. This shows a bias in indication length between inspectors which is to be expected.

Casting Geometry 3

Figure 59. Box and whisker plots for Casting Geometry 3 from Foundry 2.

Casting Geometry 1

Figure 60. Box and whisker plots for Casting Geometry 1 from Foundry 3.

Casting Geometry 1

Figure 61. Box and whisker plots and histograms for Casting Geometry 1 from Foundry 4.

The precision mean (standard deviation) from this foundry ranged from very good (0.00) to good (0.16") for the individual inspectors. The precision mean for all inspectors ranged from 0.14 to 0.21 inches. If we assume that the true precision (standard deviation) mean is close to 0.18", it is unlikely that difference of a 1/16th inch will be consistently identified.

A series of cast steel plates and casting geometries were progressively ground to determine the depth and shape of both non-linear and linear indications. Non-linear indications typically had a subsurface depth of approximately 0.3 inches in the set of casting examined. Linear indications extended deeper than 0.5 inches depending on cause and material properties. Cracks caused by local thermal stress from surface cutting were relatively shallow (> 0.5 inches). However, cracks or tears caused by quenching or solidification stresses sometimes extended thru thickness, especially in highly hardenable alloys.

A Gage Repeatability and Reproducibility study was conducted at four foundries using production parts and in-house magnetic particle and liquid penetrant methods⁵. The average repeatability for indication detection ranged from 50 to 60% for all foundries while the average reproducibility ranged from 20 to 50%. The average repeatability for indication length match ranged from 30 to 80% for all foundries and the average reproducibility ranged from 30 to 60%.

The Gage R&R study did not directly answer a fundamental question about non-destructive examination – what is the precision of the NDE technique? An indication with a length less than 1/16th

of an inch (1.5 mm) is considered non-relevant by most acceptance standards. In other words, the measurement must be precise to a $1/16^{\text{th}}$ of an inch. So according to the standards, the operator must use a measuring device with a resolution 3-5 times better than $1/16^{\text{th}}$ of an inch. Sample standard deviation was used as a measure of precision and the limited data gathered from the Gage R&R study to estimate the precision of surface indication NDE techniques.

From the limited data currently available, discrimination of the difference between a $1/16^{\text{th}}$ and a $1/8^{\text{th}}$ inch indication, while possible, is not likely. Of course, detecting a $1/16^{\text{th}}$ or $1/8^{\text{th}}$ inch indication with a single inspection is also somewhat problematic with a low probability of success. In addition, the repeatability, reproducibility are low. However, the foundry NDE capability does not appear to be any better or worse when compared to other industrial NDE capabilities. The shortcomings of NDE techniques and/or requirements from a customer can be overcome by multiple inspections and intensive inspection which is acceptable if the customer is willing to pay for it.

The trial at Foundry 5 included one casting geometry with a weight of about 200 lbs. The castings were inspected using direct magnetization and wet fluorescent magnetic particles. Five inspectors were used in the trial with a mixture of day shift/night shift inspectors. Each indication was marked on a schematic of the part and the indication length listed. A total of ten castings were involved in this trial and 150 inspections were made. The number of possible indications for a casting ranged from 3 to 14. If an indication was detected twice or less in the fifteen inspections, the indication was considered a false positive. The data was analyzed both with and without any false positives. If indication lengths were within ± 0.125 inches, they were considered a match. All of the graphs shown in this report were from data with the false positives removed.

The average reproducibility for all castings and inspectors is illustrated in Figure 62. The reproducibility was about 60% for indication length match and 40% for indication area match.

The trial at Foundry 6 included one casting geometry with a weight of about 200 lbs. The castings were inspected using visible liquid penetrant. Three inspectors were used in the trial with twelve castings and each inspector inspecting each part three times. Indication location was marked on a part schematic. A total of 108 inspections were made.

This trial is unique for several reasons. The indications in these parts were non-linear which tend to form clusters and do not lend themselves to length measurement. Therefore, only area indication match was calculated from this data. The inspectors differentiated between non-relevant indications (less than $1/16''$), relevant but acceptable, and unacceptable indications (needing rework). For this report, only data containing indications relevant and/or unacceptable was used in the calculations. The number of possible indications for a casting ranged from 1 to 4. All of the graphs shown in this report were from data with the false positives removed.

The average reproducibility for all castings and inspectors is illustrated in Figure 63. The reproducibility was about 70% for indication area match.

The trial at Foundry 7 included one casting geometry with a weight of about 200 lbs. The castings were inspected using wet fluorescent magnetic particles. Two inspectors were used in the trial with thirty-five castings and each inspector inspecting each part two times. Indication location was marked on a part schematic. A total of 140 inspections were made. The number of possible indications for a casting ranged from 1 to 2. All of the graphs shown in this report were from data with the false positives removed.

Figure 62. The average reproducibility for all inspectors and castings. Foundry 5

Figure 63. The average reproducibility for all inspectors and all castings. Foundry 6.

The average reproducibility for all castings and inspectors is illustrated in Figure 64. The reproducibility was about 100% for both indication length match and indication area match.

The trial at Foundry 8 included one casting geometry with a weight of about 150 lbs. The castings were inspected using wet fluorescent magnetic particles. Three inspectors were used in the trial with ten castings and each inspector inspecting each part once. Indication location was marked on a part schematic. A total of 30 inspections were made. This trial did not repeat thru the inspector so repeatability was not calculated. The number of possible indications for a casting ranged from 2 to 17. All of the graphs shown in this report were from data with the false positives removed.

The average reproducibility for all castings and inspectors is illustrated in Figure 65. The reproducibility was about 95% for both indication length match and indication area match.

The average repeatability and reproducibility for these foundries ranged from 70 to 90% with the false positives removed. This is about 10-20% higher than the previous work presented at the 2009 SFSA T&O. The current foundries also had on average fewer indications per casting and indication length was shorter. There was a trend with repeatability and reproducibility being inversely proportional to the number of relevant indications found. The number of false positives was also proportional to the number of indications detected.

Figure 64. The average reproducibility for all inspectors and all castings. Foundry 7

Figure 65. The average reproducibility for all inspectors and all castings. Foundry 8.

Indication Size to Performance

The effect of surface and near surface indications on the tensile properties of cast steel was investigated with four steel grades. The steels included three carbon and low alloy steels and one high alloy steel. These steels provided a range of yield strengths (YS) from 40 kilopounds per square inch or “ksi” up to 160 ksi. The carbon and low alloy steels include a 110/80 (minimum YS 80 ksi, minimum UTS 110 ksi), a 165/135 (minimum YS 135 ksi, minimum UTS 165 ksi), and Eglin steel. A high alloy CF8M cast steel was also included to provide different microstructure and modulus but with tensile properties similar to a 70/40 steel.

Plates were cast from the steels yielding approximately 30 potential test bars for each alloy, with the exception of the Eglin steel. The only available supply of Eglin steel was in machined billets with no as cast surface and hence no surface indications. In this case, tensile specimens were removed from the billets and artificial indications were machined into the gauge section. The other cast plates had approximately 0.050 inches or “in.” removed from the cope to remove the as cast surface roughness. Most of the plates were machined to yield 0.500 in. wide standard flat tensile bars as per ASTM E8/E8M from 2009; however, the Eglin steel was machined with a thickness of 0.250 in. as opposed to 0.500 in. This reduced thickness was required for the Eglin steel in order to lower maximum load of the test bars to within the maximum load rating of the tensile test frame. These test bars were machined from the cope of a cast plate to capture any potential surface indications to the desired shape shown in Figure 66.

Figure 66. Configuration of the flat plate and riser, which was cast to create surface indications for testing. Tensile bars were removed from the top surface of the casting.

Once machined, the carbon and low alloy steel specimens were MT inspected using ASTM E709-09 to detect any surface/sub-surface indications present. All specimens were tested with PT by standard ASTM E165/E165M-09 to distinguish surface and sub-surface indications, and reveal any indications running perpendicular to the gauge length. Of course, the CF8M specimens were only tested with PT. Indications found within the 2.25 in. reduced gauge section were photographed and measured using Image Pro Plus Image Processing Software. According to ASTM A903, an indication is considered relevant if it is equal to or greater than 1/16 in. ASTM A903 surface inspection criteria also only considers this 1/16 in. relevant if the length of the indication is greater than 3 times its width i.e. linear. For the purposes of this study, all indications detected via MT and PT will be considered relevant. Since the loading direction was known, indication length was measured as the length perpendicular to the loading direction, which will produce inherently conservative results. A severe indication in an example tensile sample is shown in Figure 67.

Many tensile bars had no indications present and some of these bars were used to provide baseline properties for this study. In addition, some of the bars without indications were notched to simulate a naturally occurring nonlinear surface indication. These notches were machined using different drill bit diameters (1/16 in., 1/8 in., and 1/4 in.) leaving a flat-bottom circular indication in the bar. The created indication falls into the nonlinear class. The depth of drilling was limited to half the thickness of the tensile bar, which results in the surface class of indication as defined by fatigue design of welded joints and components. [14] (p.89) This simulated surface indication was meant to mimic the worst-case scenario nonlinear indications.

Figure 67. Example of tensile specimen geometry and PT showing severe indications in the gauge section is shown. An example of artificial indications using a flat bottom machined hole is also shown.

The bars were tested according to ASTM E8/A370 using a MTS 810 material test system 50 kip frame with FlexTest SE controller and hydraulic grips. The tensile test was displacement controlled, while recording the applied force. Stress was determined using the resulting force over the determined cross-sectional area. The strain was recorded using a 2 in. clip-on extensometer utilizing MTS Flex Test SE software.

After tensile testing, the bars were studied to see if fracture occurred at an indication. The fracture surfaces were then photographed and the defect's projected surface area, if present, was measured using Image Pro Plus. The natural and machined indication properties were then compared to the baseline properties to see if a quantitative effect of the measured indications is observable. The tensile properties studied were 0.2% offset yield strength, ultimate tensile strength (UTS), elongation, and Young's Modulus.

In general, the presence of surface indications has the effect of reducing the cross section area and increasing the stress concentration near the indication. Therefore, the observed properties from a monotonic or static stress-strain curve impacted are the elastic modulus, the elongation, yield stress, and ultimate stress. An example of results is shown below in Figure 68 illustrating the effect of indications (artificial) on the stress-strain performance for the ES1 steel material. As seen from the figure, the ultimate stress follows an expected trend down as the indication size increases. The 1/4"

artificial indication represents 50% reduction of the area of the cross section of the tensile sample. Thus it is not surprising that the ultimate strength decreases dramatically.

Figure 68. Stress strain curves from the ES1 material with no indications and artificial indications demonstrating the reduction in properties with increasing indication size.

Elastic modulus was minimally impacted by the natural and artificial indications. It was expected that indications would affect the modulus in the same way porosity reduced the modulus as shown in the work of Hardin and Beckermann .[15] However this reduction was small or negligible in these samples because the indication generally represented a small portion of the gauge length. For example, the worst artificial indication at 1/4" represents only 12.5% of the 2" gauge length. Therefore, this simple estimate of the influence of surface indications on the modulus is small and uncertainty of the measurement may be on the same order as the measurement. From the measurements, modulus reduction was between 2.9% and 17.5% for all experiments. For this reason, plots discussing modulus have not been included.

The elongation of the material with indications dropped precipitously with indication size as shown in Figures 69 through 72. Surface indication length was normalized by dividing the indication

length by the tensile specimen width (0.50"). This allows a comparison of indication length to "part" size. Elongation reduction varied from 38.5% to 69.9% over the range of indication length percentages, with the majority of the alloys showing an approximate 60 percent loss in elongation. The reduction in elongation also limits the ultimate stress in the material because failure occurs before additional work hardening elevates the ultimate strength.

The elongation of the material without indications may be used to predict notch sensitivity. Generally in design, notch sensitivity is determined by the ultimate strength of the material rather than the elongation. This data suggests that additional research toward using the elongation to define notch sensitivity rather than the ultimate stress may be applicable.

Figure 69. Effect of indication length percentage on elongation for 165-135 steel.

Figure 70. Effect of indication length percentage on elongation for 110-80 steel.

Figure 71. Effect of indication length percentage on elongation for CF8M steel.

Figure 72. Effect of indication length percentage on elongation for ES1 steel.

The reduction in the yield and ultimate stress for both natural and artificial indications in the four steels investigated is shown in Figures 73 through 76. The artificial indications above 1/16", representing ~20% of the gauge width, began to significantly reduce both the yield and ultimate stress. High strength and low elongation materials were more impacted smaller indications. In most cases, the artificial indications were the lowest properties compared to natural indications. The scatter of properties with small or no indications was greatest due to the presence of internal porosity. Work hardening of these materials was limited by the low elongations, which reduced the difference between the yield and ultimate stress in all but the most compliant alloy, CF8M.

Figure 73. Effect of indication length percentage on yield and ultimate strength for 165-135 steel.

Figure 74. Effect of indication length percentage on yield and ultimate strength for 110-80 steel.

Figure 75. Effect of indication length percentage on yield and ultimate strength for CF8M steel.

Figure 76. Effect of indication length percentage on yield and ultimate strength for ES1 steel.

The tensile results from artificial and natural indications confirm that the indications are no worse than an equivalent length geometric feature in the part. Features or notches would reduce elongation depending on the “sharpness” of the notch with sharper notches resulting in higher stresses with low elongation .[16] It appears consistent with other testing confirming the incipient plasticity due to stress concentrations from the geometry. The real challenge with a surface indication is to determine whether or not these indications behave as cracks or as notches. The reality is that it may not matter whether a surface indication is a notch or a crack because the stress strain curve should be the same as any small feature on the surface of the geometry. The net effect is that the elongation goes down and for sharper notches the stress strain path follows the same curve as the curve without indications. The follow on question is to determine how to use this information in the design process to understand setting a specification to bracket the performance of parts for more consistent results. For this purpose either a static factor of safety or a fatigue design using a modified Goodman diagram could be used.

Three things must be determined during the design process including: the load bearing section thickness, the material properties, and the inspection quality. The load bearing thickness is given by the optimal shape and design space of the component. Geometry is normally the starting point for designs. Second, material properties are chosen to satisfy the given load and compliance requirements. If stress exceeds yield, or if displacement is too large, then higher yield strength or modulus materials must be used. At the material property limits, section thickness may be changed to accommodate deficiencies in material properties. When the final geometry and material properties are chosen, then inspection and testing are instituted to guarantee that the design properties are met both with mechanical properties and inspection for surface indications. In addition, due to uncertainties in both the loads and in the material quality, a blanket factor of safety is applied. However, this final step is the compromise of design and purchasing because testing and inspection are expensive and are not value added activities. This description is close to the practice of most modern manufacturers.

An alternate method for determining geometry, material properties, and inspection may be more beneficial. Again, start with geometry but use material properties determined from your common inspection practice. The final stress strain curve is a function of both properties and inspected quality, and is even more conservative if the inspected quality is improved. The final iteration is between the section size and the material properties for a given inspection requirement. Then the need for a given quality is motivated by the stress strain relationship, which impacts the expected life and part performance. In this scenario, the designer and purchaser can truly discuss part requirements and cost given the improved performance guaranteed by the inspection and mechanical behavior.

Currently, elongation and surface indications are both workman standards and mean nothing to part performance or play no role in design. This data suggests that factor of safety for static design or a surface factor on the endurance limit for fatigue analysis could be used actively in design. One proposal for developing such a relationship is shown in Figures 77 and 78. Figure 77 shows the required factor of safety for the ultimate stress given that the allowable stress is taken as the ultimate stress found in materials with indications. Equation 1 and 2 are

$$FoS|_{UTS} = \frac{\sigma_{UTS}}{\sigma_{Allowable}}, \quad \text{Equation 1}$$

$$\sigma_{Allowable} = \sigma_{UTS}|_{Indication}, \quad \text{Equation 2}$$

A similar method is used to determine the factor of safety for the yield stress as shown in Figure 78. From these figures, the highest strength and lowest elongation materials has the largest factor of safety and the lowest strength and highest elongation material has the smallest factor of safety.

Figure 77. Factor of safety of the ultimate stress as a function of indication length for all tested materials is shown.

Figure 78. Factor of safety of the yield stress as a function of indication length for all tested materials is shown.

The above discussion and results of the factor of safety analysis can be converted to a single equation for factor of safety required for a given material with elongation and inspected for indication length. Equation 3 and 4 are

$$FoS_{UTS} = (2.1539 - 3.5315 * El / 100) * L_{Indication} + 1, \quad \text{Equation 3}$$

$$FoS_{YS} = (2.6185 - 3.0705 * El / 100) * L_{Indication} + 1. \quad \text{Equation 4}$$

These equations predict a required safety factor for a given material choice during the design of geometry. They could be used as a target for static loading or recalculated for the surface factor of the Goodman diagram in the case of fatigue. Further testing and research is required to validate this approach in general, however this methodology brings us closer to a new era of performance based inspection and lighter weight and advanced structures.

The results of these tests for artificial and natural indications confirm that the indications are no worse than an equivalent length geometric feature in the part.

In general, the presence of surface indications has the effect of reducing the cross section area and increasing the stress concentration near the indication. Elongation showed the greatest decrease

and modulus showed the smallest decrease with larger indication size. The effect was larger and occurred at smaller indication sizes for less ductile materials.

An alternate method for determining geometry, material properties, and inspection may be more beneficial. Again, start with geometry but use material properties determined from your common inspection practice. The final stress strain curve is a function of both properties and inspected quality, and is even more conservative if the inspected quality is improved. The final iteration is between the section size and the material properties for a given inspection requirement. Then the need for a given quality is motivated by the stress strain relationship, which impacts the expected life and part performance. In this scenario, the designer and purchaser can truly discuss part requirements and cost given the improved performance guaranteed by the inspection and mechanical behavior.

A method is proposed to predict a required safety factor during the design of geometry based on elongation and inspection length. Further testing and research is required to validate this approach in general, however this methodology brings us closer to a new era of performance based inspection and lighter weight and advanced structures.

BENEFITS ASSESSMENT

Accurate simulations require an engineering understanding of surface and near surface anomalies. Many steel castings are used in dynamic applications where fatigue properties are important. The most common mode of failure for ground-based vehicles is fatigue, and fatigue causes about 60% of construction equipment failures. Fatigue failures almost always initiate at or near the surface so surface quality has an important effect on the number of stress cycles that occur before failure.

Design engineers often base the importance of surface anomalies as revealed by non-destructive inspection by their familiarity with the various classes of severity revealed by reference radiographs or photographs resulting from radiographic or surface inspection, not on correlative testing. Vishnevsky, Bertolino, and Wallace have shown that severe surface discontinuities, well beyond any commercially acceptable standard such as ASTM E125, will not reduce the endurance strength as much as a standard notched fatigue (R.R. Moore) test specimen (8-20% vs. 35%).^[3] This coupled with the tendency of design engineers to use the lowest material properties and large safety factors often result in over designed castings. While the steel casting industry desires to produce a quality product, the inspection and removal of surface indications that do not affect part performance is costly and unnecessary. (SFRF Report "The Effects of Surface Discontinuities on the Fatigue Properties of Cast Steel Sections", 1966)

Therefore, questions have arisen about whether the current surface acceptance standards such as ASTM A-903 are excessively restrictive. Parts may be scrapped or reworked because of surface indications that do not affect the part performance. Is there a meaningful difference in size, shape, and depth between a Level II and a Level III linear or non-linear indication? Can a qualified NDE technician

consistently identify and quantify an indication? Quantitative data on the shape, size, and source of surface discontinuities indicated by ASTM A-903 would be extremely valuable for estimating anomaly effects on dynamic properties. Previous work performed for SFSA on reoxidation products in steel castings indicated that all surface indications, as detected by radiography, are located within the first one-half inch of the cope surface.

The systematic study and characterization of surface indications has never been conducted. Producers and users of castings do not have any data on which they can reliably communicate the nature of these indications or their effect on the performance of parts. Clearly, the ultimate intent of any work in this area is to eliminate indications that do in fact degrade properties. However, it may be impractical physically and/or financially to eliminate all surface imperfections and we want to focus on the ones that actually degrade properties. The initial work was to identify those that indeed do degrade properties.

Accurate numerical simulations of casting service performance allow designers to use the geometric flexibility of castings and the superior properties of steel to produce lighter weight and more energy efficient components for transportation systems (cars and trucks), construction, and mining. Accurate simulations increase the net melting energy efficiency by improving casting yield and reducing rework and scrap. Conservatively assuming a 10% improvement in yield, approximately 1.33×10^{12} BTU/year can be saved with this technology. In addition, CO₂ emissions will be reduced by approximately 117,050 tons per year.

Currently, elongation and surface indications are both workman standards and mean nothing to part performance or play no role in design. This data suggests that factor of safety for static design or a surface factor on the endurance limit for fatigue analysis could be used actively in design. A method is proposed to predict a required safety factor during the design of geometry based on elongation and inspection length. Further testing and research is required to validate this approach in general, however this methodology brings us closer to a new era of performance based inspection and lighter weight and advanced structures.

COMMERCIALIZATION

Numerous presentations and papers of this work have been presented at the annual Steel Founders' Society of America's Technical & Operating Conferences. SFSA is the largest trade association representing steel foundries in North America and has specific committees for ASTM, NACE, ISO and interface with the US Government.

The ultimate goal will be to begin a conversation with designers on the effect of surface indications on steel casting performance. While this project provides limited data on mechanical properties and range of steel alloys, the results are in line with commonly used design data for wrought products. SFSA's interaction with specification committees provide a conduit to rework steel casting specifications to more closely match actual performance instead of overly conservative estimates.

ACCOMPLISHMENTS

Surface Indication Characterization

Linear and non-linear indications did not extend deeper than 0.5" beneath the cope surface. Most of these indications were caused by re-oxidation products and exogenous material. Hot tears or cracks formed during solidification or from heat treatment can extend deeper than 0.5", depending on the severity of the conditions and steel properties.

Inspection Technique Survey

Historical data and this research indicate that just finding an indication of reasonable length (1/4") with one inspection is at best a 50/50 proposition. It is also unlikely that an inspector can discriminate an indication length to a 1/16", perhaps 1/8". Removing false positives increased repeatability and reproducibility by 10% or more.

Steel foundry NDE capability does not appear to be any better or worse when compared to other industrial NDE capabilities. The shortcomings of NDE techniques and/or requirements from a customer can be overcome by multiple inspections and intensive inspection.

Indication Size to Performance

Artificial indications using a 1/16 inch, 1/8 inch, or 1/4 inch flat-bottomed hole drilled through half the thickness mimicked a similar nonlinear natural indication. A method is proposed to predict a required safety factor during the design of geometry based on elongation and inspection length. Further testing and research is required to validate this approach in general, however this methodology brings us closer to a new era of performance based inspection and lighter weight and advanced structures.

Publications

"Surface/Near Surface Indication - Characterization of Surface Anomalies from Magnetic Particle and Liquid Penetrant Indications", J.A. Griffin, R.D. Griffin, Proceedings of the 2005 SFSA Technical and Operating Conference, Chicago, IL, 2005.

"Surface/Near Surface Indications – Shape and Depth of Magnetic Particle-Liquid Penetrant Indications in Steel Castings" J.A. Griffin, R.D. Griffin, Proceedings of the 2006 SFSA Technical and Operating Conference, Chicago, IL, 2006.

"Surface/Near Surface Indications – Magnetic Particle and liquid Penetrant Inspection Gauge R&R" J.A. Griffin, R.D. Griffin, Proceedings of the 2007 SFSA Technical and Operating Conference, Chicago, IL, (2007).

“Surface/Near Surface Indications- Characterization of Surface Indications from Magnetic Particle and Liquid Penetrant Inspection” J.A. Griffin, R.D. Griffin; Proceedings of the 2008 SFSA Technical and Operating Conference, 2008.

“Surface/Near Surface Indications – Variation of Surface Indications from Magnetic Particle and Liquid Penetrant Inspections”, J.A. Griffin, R.D. Foley, Proceedings of the 2009 Steel Founders’ Technical and Operating Conference, 2009.

“Surface/Near Surface Indication – Magnetic Particle and Liquid Penetrant Inspection Gauge R&R”, J.A. Griffin, R.D. Foley, Proceedings of the 2010 Steel Founders’ Technical and Operating Conference, 2010.

“Surface / Near Surface Indications – Tensile Measurements”, C. A. Monroe, J.A. Griffin, R. D. Foley, and Jeff Hamby, Proceedings of the 2013 Steel Founders’ Technical and Operating Conference, 2013.

CONCLUSIONS

Surface Indication Characterization

- The number of non-linear indications rapidly decreased in number after the first 0.010” of metal removal but stabilized to a constant value.
- The non-linear indication length also decreased but not as drastically as the number of indications.
- Linear indications decreased in number after the first 0.010” of metal removal but stabilized to a constant value.
- Linear indication length did not significantly reduce.
- Hot tears and/or cracks typically had length to width ratios greater than 3.
- Non-linear indications extended about 0.4” beneath the cast surface.
- Linear indications can extend deeper than 0.5” beneath the cast surface depending on cause and material properties.

Inspection Technique Survey

- Removing false positives increased repeatability and reproducibility by 10% or more.
- Historical data and this research indicate that just finding an indication of reasonable length (1/4”) with one inspection is at best a 50/50 proposition.

- It is also unlikely that an inspector can discriminate an indication length to a 1/16", perhaps 1/8".
- Foundry NDE capability does not appear to be any better or worse when compared to other industrial NDE capabilities.
- The shortcomings of NDE techniques and/or requirements from a customer can be overcome by multiple inspections and intensive inspection.

Indication Size to Performance

- Artificial indications using a 1/16 inch, 1/8 inch, or 1/4 inch flat-bottomed hole drilled through half the thickness mimicked a similar nonlinear natural indication.
- A method is proposed to predict a required safety factor during the design of geometry based on elongation and inspection length.

RECOMMENDATIONS

Further testing and research is required to validate the method correlating safety factor, elongation, and indication length. In addition, the relationship between fatigue properties and surface indications in steel castings need to be further developed.

REFERENCES

- [1] – ASTM E186-10. “Standard Reference Radiographs for Heavy-Walled Steel Castings.” 2010
- [2] – ASTM A903/A903M. “Standard Specification for Steel Castings, Surface Acceptance Standards, Magnetic Particle and Liquid Penetrant Inspection.” 2009
- [3]- C. Vishnevsky, N.F. Bertolino, J.F. Wallace, “The Effects of Surface Discontinuities on the Fatigue Properties of Cast Steel Sections”, Case Institute of Technology, Steel Foundry Research Foundation, August 1966
- [4] – Hamby, Jeff, John Griffin, and Dr. Robin Foley. “Verification of the New Radiographic Testing (RT) Standard through Mechanical Testing”. UAB. Dec. 2011.
- [5] – Sigl, K.M. et al. “Fatigue of 8630 cast steel in the presence of porosity.” International Journal of Cast Metals Research 2004 Vol. 17 No.3. University of Iowa 2004.
- [6] – Hardin, R. A., & Beckermann, C. “Effect of Porosity on the Stiffness of Cast Steel”. Metallurgical and Materials Transactions A. Vol. 38A(12). 2992–3006. The Minerals, Metals, & Materials Society and ASM International. 2007.
- [7] – Svoboda, John M. Fatigue and Fracture Toughness of Five Carbon Low Alloy Steels at Room and Low Climactic Temperatures (Part II) A. Steel Founders’ Society of America Research Report No. 94A. Carbon and Low Alloy Technical Research Committee Steel Founders’ Society of America. October 1982.
- [8] – Rudy, J. F. and Rupert, E. J. “Effects of Porosity on Mechanical Properties of Aluminum Welds”. Welding Research Supplement. 322-s–335-s. July 1970.
- [9] – Steel Castings Handbook. “Supplement 2: Summary of Standard Specifications for Steel Castings”. Steel Founders’ Society of America. 2009
- [10] - Ostle, B., Statistics in Research, 487 pp, The Iowa State University Press, Ames, Iowa, 1954).
- [11] - Ostle, B. , Statistics in Research, 2nd edition, 585 pp, The Iowa State University Press, Ames, Iowa, 1963.
- [12] - Spatz, C and James O. Johnson, Basic Statistics: Tales of Distribution, 2nd Edition, Brooks/Cole Publishing Company, 1981.
- [13] - McCuen Richard H., Statistical Methods for Engineers, Prentice-Hall, Inc., 99 pp, 1985.

[14] - Hobbacher, A. Fatigue design of welded joints and components. 1996

[15] - Hardin, R. A., & Beckermann, C. "Effect of Porosity on the Stiffness of Cast Steel". Metallurgical and Materials Transactions A. Vol. 38A(12). 2992–3006. The Minerals, Metals, & Materials Society and ASM International. 2007.

[16] - Sachs, G., & Lubahn, J. (1942). Effects of Notching on Strained Metals - Part 1. The Iron Age, 150, 31–38.

APPENDICES

Attachment A

ENERGY BENEFITS TABLE					
ENERGY SOURCE	CURRENT TECHNOLOGY (BTU/YR/UNIT)	PROPOSED TECHNOLOGY (BTU/YR/UNIT)	ENERGY SAVINGS (BTU/YR/UNIT)	NO. OF UNITS IN 10 YEARS	CUMULATIVE ENERGY SAVINGS (BTU/YR)
	(a)	(b)	(c= a -b)	(d)	(e= c* d)
OIL/GASOLINE/ DIESEL	1.76×10^9	1.58×10^9	0.176×10^9	100	17.6×10^9
NATURAL GAS	42.6×10^9	38.3×10^9	4.3×10^9	100	430×10^9
COAL					
ELECTRICITY +	87.7×10^9	78.9×10^9	8.8×10^9	100	880×10^9
OTHER ENERGY					
TOTAL PER UNIT	132.1×10^9	118.8×10^9	13.2×10^9	100	1.33×10^{12}
<p>Data and assumptions used in calculations:</p> <p>300 steel foundries in U.S. (2001)</p> <p>1,056,400 metric of steel produced in U.S. (2001)</p> <p>An average foundry produces 3521 metric ton of steel per year.</p> <p>One ton of steel requires 2.49×10^7 BTU electricity, 1.21×10^7 BTU natural gas, 0.05×10^7 BTU Oil.</p> <p>Assumptions: new technology reduces scrap and increases yield by 10% in 1/3 of all foundries (100)</p> <p>+ Electricity generation sources need not be shown. Use 10,500 Btu/kWh</p> <p>+ Define one unit-year of operation (A typical process unit is an average steel foundry producing 3521 metric tons of steel per year. The typical unit capacity is 3521 metric tons per year.)</p>					

Column 1: is the type of energy

Column 2: (a) is the energy consumed or produced with the current technology.

Column 3: (b) is the energy consumed or produced by the new technology.

Column 4: (c) is the per unit energy savings (derived from 'a - b').

Column 5 (d): is the number of units expected to be in place in 10 years (specify period).

Column 6: (e) is the cumulative savings (derived from 'c * d')

This table should cover all the energy uses, including:

- ENERGY AND PETROLEUM EMBODIED IN THE MANUFACTURE OF PRODUCTS;
- TRANSPORTATION ENERGY FOR HAULING OF WASTE TO DISPOSAL (USE 130,000 BTU/GAL FOR GROUND TRANSPORTATION FUEL);
- ANY COAL OR DERIVED PRODUCT USE;
- ENERGY USED IN WASTE REDEMPTION, TREATMENT OR DISPOSAL;
- ANY PETROLEUM PRODUCT USED;
- ANY NATURAL GAS PRODUCT USED;
- ELECTRICITY (USE A POWER GENERATION RATE OF 10,500 BTU/KILOWATT HOUR)