Utilizing NDE Methods for Steel Casting Performance

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Abstract

Non-Destructive Examination (NDE) is a valuable tool for ensuring manufacturing quality and part performance in steel castings. The existing methods are workmanship standards and do not include performance. The current standards require large factors of safety and significant testing of a part to failure. The inspection level is set conservatively to ensure no failures in the field. Understanding the advantages and limitations of NDE methods is important.

Research has shown that simulation is a good way to predict part quality and know how they will perform. Simulation also has the advantage of minimizing testing costs and reducing development time. SFSA's on-going and future R&D projects are investigating surface roughness inspection, variability, and correlating solidification analysis with structural analysis to improve reliability.

Introduction

Quality is a primary concern for casting designers and users. The casting process is more poorly understood and variable than many alternate manufacturing methods. As indicated by the title of this symposium, solidification introduces features in manufacturing that may limit component performance. Even with these limits on understanding and confidence, castings are used in the most demanding and critical applications. From the production of prosthetic hip and knee replacements, to single crystal jet engine turbine blades to crane hooks for lifting offshore platforms, castings are used in the most difficult and demanding applications.

From the producers' point of view, many designers and users are incorrectly designing and specifying castings due to fundamental misconceptions about castings and their performance. For steel castings, many of these misunderstandings can be resolved by utilizing industry practices that achieve high performance with high reliability. As designers and users better grasp casting process technology and specification, better cast components can be developed. This paper provides a context and a basis from the producer's standpoint for design and specification that adds value.

First it will be useful to clarify the language used for quality of castings. The title of the symposium contains a troublesome word, "defects". According to ASTM E1316-2005 "Standard Terminology for Nondestructive Testing", components have defects only when they fail to meet the specification requirements (see Table I). No matter how big of a crack a part contains, from a specification and technical point of view, it is does not have a defect unless an inspection for cracks is specified and the crack exceeds the required acceptance criteria.

All real parts do not have flat surfaces, square corners, and features of the correct size or location. We recognize this by the application of tolerances for geometric features. All real parts have mechanical properties that are measurably different than the typical or specified minimum values for the grade. We use conservative design approaches to ensure adequate performance. All real parts have imperfections and discontinuities. Material production processes deliver materials that contain non-uniform properties and other variations. Forming the part introduces other imperfections and discontinuities. Testing is used to ensure that the part will meet the performance requirements demanded. For each performance attribute to be evaluated a test method should be identified and an acceptance criteria imposed. A part contains defects only when the part fails to meet the specified requirements.

Table I. Definitions from ASTM E1316-2005

Defect (noun) - one or more flaws whose aggregate size, shape, orientation, location, or properties do not meet specified acceptance criteria and are rejectable.
Flaw (noun) - an imperfection or discontinuity that may be detectable by nondestructive testing and is not necessarily rejectable.
Imperfection (noun) - a departure of a quality characteristic from its intended condition.
Discontinuity (noun) - a lack of continuity or cohesion: an intentional or unintentional interruption in the physical structure or configuration of a material or component.

Much of our common discussion of defects in castings treats ordinary features of solidification like shrinkage as a defect. Shrinkage is a feature of solidification and is only a defect if soundness is specified and the shrinkage exceeds the imposed acceptance requirement.

This inexact terminology confuses the user of castings by implying that castings are full of “defects” when in fact proper design and specification can easily produce a defect free casting. Defect free does not mean perfect, whatever perfect would mean. This situation is made worse by poor failure analysis where cause of failure is reported as the part feature that initiated the final fracture. Most failures in new designs are due to inadequate design not poor quality part production. Most field failures are due to product misuse and not poor quality component manufacture. When a part is subjected to unsurvivable loads, it will fail through the most heavily loaded section and the failure will initiate at the largest performance-limiting feature in the heavily loaded section. In both cases, it is possible to find the fracture-initiating feature but it is fundamentally incorrect to report that it “caused” the failure and was therefore a “defect”. A discontinuity in properties or NDE indication does not necessarily cause a part to fail. If the discontinuity is less than the critical size, has a certain orientation, or whose design stress is less than the critical level, then the feature will not affect the suitability for service of the part.

A more helpful approach is to recognize that all real parts have performance limitations. The performance limiting features of the part might be a material property, physical property, or even a geometric feature. All manufacturing processes can limit part performance. The challenge is to use the characteristics of the manufacturing process to enhance the performance of cleverly designed parts. Quality is not freedom from defects but desired performance. This is not limited to the fitness for service but might also include aesthetics or manufacturability.

Non-Destructive Examination

Testing of parts can either be destructive or non-destructive. For example, a part can be loaded to failure giving a measurement of its actual load carrying capacity but after testing the part is no longer usable. Non-Destructive Testing (NDT) is used to evaluate parts without destroying their ability to be used. Since the term, test, often implies the determination of a property on a specimen of material, many prefer not to use it for nondestructive methods. While the name of the ASTM Standard uses the term, “Non-Destructive Testing,” the standard indicates that Non-Destructive Examination, Non-Destructive

Evaluation, and Non-Destructive Inspection are equivalent. In the Standard, under the definition of test and inspection, it is indicated that examination is the preferred term. We follow this practice calling the techniques Non-Destructive Examination. A summary of NDE methods and specifications are available in the SFSA Handbook [1] and Handbook Supplement 2 [2] (see also Appendix A).

Unfortunately for designers and users as well as the producer, NDE standards are all workmanship standards. Workmanship standards specify a level of acceptance based on the general capability of the process and not on the performance of the part. They are set not on an engineering evaluation of the impact on part performance but on the subjective judgment of standards writers. Acceptance levels are not chosen based on application requirements but are arbitrary. The inherent subjectivity of NDE standards limits their usefulness.

Visual Inspection

Casting specifications may contain ambiguous wording in regard to visual inspection, such as "castings are to be clean and free from injurious defects". There is no definition for "defect" and no basis for judgment as to what was "injurious". If the purchaser said, "a surface condition was injurious, it had to be removed and welded", this would also be problematic. Or, if the "injurious defect" had to be "completely removed to sound metal", then there is no definition for "sound metal" and no basis for judging "completely". Requirements of this type can easily be misunderstood, and misapplied; they can cause no end of grief for the designer, user, and producer.

ASTM A703 and A781 specifications have replaced such ambiguous wording with the requirement, "The surface of the casting shall be examined visually and shall be free of adhering sand, scale, cracks, and hot tears". This preferred wording goes on to clarify the extent of removal required, "unacceptable visual surface discontinuities shall be removed and their removal verified by visual examination of the resultant cavities".

Unfortunately, visual standards are subjective and producers commonly over finish the casting grinding and welding without improving the surface or adding value for the customer. The designer and user can specify any surface they like, even for aesthetic reasons. Frequently slight changes in the casting process alters the texture of the surface and this change triggers concern for the user.

Table II. Visual Inspection R&D Study

Casting Inspected	Inspector 1	Inspector 2
One- first time	13	1
One- second time	24	0
Two- first time	45	20
Two- second time	45	0

Recent studies show that visual inspection in the producer's operations is costly and variable. In a repeatability and reproducibility study, two small castings were given to two inspectors twice [3]. After they were marked for additional grinding and welding they were cleaned and returned for a second inspection (see Table II). After each inspection the marks were cover by white dots and the dots counted. The same casting could have 45 dots of work or 0 depending on the visual inspection. In one case an engineer, to avoid any unnecessary finishing, walked a single large casting through the process and that casting had one third the normal grinding and welding. In a similar study, the time spent grinding castings was evaluated [4]. Typically 80% of the grinding was not required to process the part but to meet the surface quality requirements. Unnecessary finishing increases cost and stretches out production times.

Traditional measures of surface roughness are not normally useful in casting surface inspection since the texture of the casting is more severe and long range than machined surfaces. New surface inspection techniques using laser topography or other optical means may be useful for visual inspection. It may be possible to use these data intensive surface measurements to develop a less subjective standard. Fundamentally, it is not clear what role surface roughness may play in performance.

Current best industry practices are to communicate clearly the need and expectation for surface finish. Avoid any finishing or inspection of surfaces to be machined. Do not do any finishing on surfaces used as datum targets. Acceptance of the normal shot-blasted cast surface unless otherwise required. In highly loaded areas of the casting where bending and fatigue limit performance capability, more stringent standards may be required. In this case it is common to apply magnetic particle or liquid penetrant inspection techniques.

Magnetic Particle Inspection

Magnetic particle inspection is used to detect surface features that disrupt the magnetic field in a magnetized part. Nonmagnetic materials cannot be inspected with this technique. For iron and steel castings, magnetic particle inspection is a valuable way of identifying cracks that are so tight or fine to escape visual inspection. It also picks up surface and slightly subsurface inclusions and porosity that typically are shallow and have little effect on performance. Magnetic particle methods for dry powder and wet inspection are set forth in ASTM E109 and E138.

Acceptance criteria can be selected from a set of reference photographs in ASTM E125 that depict the appearance of casting surface conditions revealed by the dry power magnetic particle technique. Different types of discontinuities do not have equal effects on performance and an effort should be made to assign different acceptance levels to areas of the casting, based upon the stresses to which each area is subjected to in service.

Purchasers can specify ASTM A903. Instead of picture and subjective comparisons, this standard sets out dimensions and frequencies of indications for acceptance criteria when using magnetic particle and liquid penetrant inspections. A new project has been started at the University of Alabama – Birmingham to characterize the normal incident rate of indications in steel castings, the reproducibility and repeatability of the measurements, and the extent of each condition. It is anticipated that new standards with meaningful levels related to service performance can be developed. At least some better application of the existing standards for service requirements should be possible. All the existing standards are workmanship standards and have no engineering rationale and do not correlate with performance.

A misuse of the standard is to tighten the acceptance criteria on a casting when inclusions or porosity are found on a machined surface. Since the inspection is unable to "see" below the surface, it does not detect porosity or inclusions at the machined surface. Worse, the tighter standard requires the producer to grind and weld a surface that will be removed by machining. This adds cost and delays production. When a producer is responsible for machining and finds a problem at the machined surface, no magnetic particle inspection is imposed. No NDE technique can routinely detect this undesirable condition. Ultrasonic examination might be able to detect this condition but the casting surface would need to be machined in order to prepare it for examination. The producer makes changes in the casting process or adds a larger machine stock allowance to solve the problem. In fact, many users avoid this problem by purchasing a rough machined casting from the producer.

Magnetic particle inspection is valuable for first article inspection to ensure that the casting design and rigging do not allow cracking in production. If cracks are found, magnetic particle inspection is used to identify the castings to be welded. Magnetic particle inspection is also used on heavily loaded casting surfaces to ensure surface integrity. Magnetic particle inspection is used to audit the process by inspecting samples of normal production.

Liquid Penetrant Inspection

Liquid penetrant inspection is another surface feature detection method. It is not generally used on the "as-cast" or shot blasted surfaces because of the likelihood of obtaining false indications. Penetrant may be retained in surface roughness and give indications unrelated to actual surface conditions. The penetrant method is best suited for use on machined, ground, or very smooth "as-cast" surfaces.

Liquid penetrant inspection is of particular importance for austenitic alloys because they are non-magnetic and therefore their surfaces cannot be examined by magnetic particle inspection. ASTM E 165 describes the standard method for conducting this test. A set of reference photographs for acceptance or rejection is contained in ASTM E433. Acceptance criteria are found in ASTM E125 for the dry powder magnetic particle technique. Each of the documents must specify actual dimensions including maximum length of indications and number of indications per unit area.

Liquid penetrant inspection is subject to many of the limits and misuse cited in magnetic particle testing in addition to false indications. It is included in ASTM A903 and this provides workmanship levels. All the specifications for surfaces must recognize the scale of the part. Frequently the highest level with the smallest allowable features is specified for large castings. This is unrealistic, adds cost and becomes the subjective standard of the customer's inspector. Liquid penetrant inspection like magnetic particle should be used for first article inspection, process auditing, crack detection and to monitor heavily loaded areas on critical castings.

Radiographic Inspection

Customers commonly see radiography or x-ray inspection as essential to the production of high quality steel castings. This creates a permanent record for liability defense especially on critical castings. Unfortunately radiography as a technique over promises and under delivers. The subjective and non-reproducible application of radiography with the limits on resolution and indication location severely impede its usefulness in performance evaluation.

There are three basic groups of reference radiographs issued by ASTM for evaluation of steel castings; E446 applies to castings up to 2 in. in thickness (51 mm), E186 to 2 to 4-1/2 in. (51-114 mm) thick sections, and E280 to wall thickness of 4-1/2 in. to 12 in. (114-305 mm). Currently, reference radiographs become standards for acceptance and rejection after the purchaser and the producer have agreed, in the purchase order or contract, to the acceptable severity level for each individual type of discontinuity. The choice of discontinuity severity level should ideally be based upon realistic evaluation of design and stress analysis criteria under anticipated service conditions. Generally, low severity levels are specified for pressure-containing castings with high-pressure rating and wall sections of 1 in. (25 mm) or less. Likewise, low severity levels are specified for machinery or dynamically loaded casting subject to high fatigue and impact stresses, and with wall sections of less than 1/2 in. (13 mm). As wall sections increase and as the fatigue and impact stresses are reduced, severity levels become somewhat relaxed. For structural castings, which are not dynamically loaded, moderate severity, levels are usually specified, and again, for heavier sections about 3 in. (76 mm) higher severity levels are usually called for.

Unfortunately, the workmanship basis of radiography and the subjective application of the acceptance criteria do not support any particular application of radiography for performance. None of the reference radiographs are based on any kind of test data, and the severity levels are not graded to any basis of acceptability as to service performance. Since the radiograph does not indicate where in the cross section the indication may be, it is inherently unable to predict performance.

The radiographic standards are used as a reference point in communicating the purchaser's requirements. Because the standards are subjective, they are not reproducible. The radiographic images are not to be evaluated based on gray scale and most importantly the reference radiographs are to be prorated to the actual casting image size. No standard method or approach is suggested for this prorating. This prorating allows the standard to have the appearance of objectivity while being completely subjective. A recent study applying gage repeatability and reproducibility to only the reading of existing plate casting radiographs demonstrate the subjective nature of this technique [5]. 128 x-rays were rated seven times for shrinkage type and level. Unanimous agreement was 37% of the x-rays on shrinkage type, 17% on shrinkage level, and 12.5% on both type and level. Agreement was higher if the castings were completely sound or very unsound. Two of the radiographers rated the x-rays twice. Comparing each radiographer's second rating to their first, both radiographers gave different type ratings for at least 19% of the x-rays and different level ratings for at least 34% of the x-rays. Both radiographers also reversed accept/reject decisions for 10-15% of the x-rays. Thus, showing the subjectivity of radiographic examination.

For this reason most market sectors select some radiography for the first article evaluation. This allows the adequacy of the rigging and solidification soundness to be evaluated. In critical parts, radiography may be needed on each part. The casting process is frequently audited with occasional radiography for non-critical parts.

For many applications the imposition of level three communicates the desire for a reasonable soundness that is ordinarily achievable in structural castings. For critical areas a radiographic level of one may be required. To require quality levels in excess of those justified by actual service conditions adds needlessly to the cost of the casting. It should also be kept in mind that the entire casting need not necessarily require radiographic inspection and that the same severity levels need not apply to all areas of the casting. Careful analysis or, at least, good judgment can affect sizable cost savings. In any case, the areas to be radiographed with the required severity level should be indicated on the casting drawing.

Ultrasonic Inspection

Although the ultrasonic method of inspection has not been in common use for as long as radiographic methods, it nevertheless is a valuable tool for examining heavy wall castings for internal discontinuities. The first ASTM specification for ultrasonic inspection of steel castings was issued in 1970 and is for longitudinal-beam ultrasonic inspection of heat treated carbon and low alloy steel castings. This inspection method is in general not useful for austenitic steel castings due to large grain size of these castings.

It is well recognized that ultrasonic inspection and radiography are not directly comparable. However, the technique is invaluable in detecting discontinuities in heavy sections, where radiographic methods would be considerably slower. Since no image of the discontinuity is obtained, considerable judgment must be exercised in the interpretation of results.

The addition of computer analysis allows a wider application of ultrasonic inspection. It is more quantitative (digital) than most of the other NDE techniques. This should allow the enhanced use of ultrasonic especially to develop standards that ensure performance. At the least, ultrasonic inspection can assess the amount of sound wall that exists to carry the design load. It can also pick up areas of microporosity too fine to be detected by radiography.

One approach in the examination of large, heavy wall castings when ultrasonic evaluation may not be acceptable to the purchaser is to first inspect with ultrasonic to identify areas with indications and then check these areas with radiography. Another possibility, since radiography does not reveal the depth of a discontinuity, is to follow radiography with ultrasonic in order to determine and evaluate the depth of the discontinuity.

Eddy Current Testing

Eddy current testing presents special challenges in steel castings that are ferromagnetic due to the non-linearity of magnetic permeability. However, one traditional method of handling this is to apply a field of magnetic saturation. This makes discontinuities easily detectable. One other challenge for castings is the geometric effects of steps and edges that make certain areas of a casting not suitable for eddy current testing. There have also been some development of transducers for eddy current testing that are better for low frequency testing of ferromagnetic materials.

Leak Testing

Fluid handling components are often leak tested to ensure performance. The user frequently does this test. If the casting fails it becomes the responsibility of the producer to replace or rework the casting. Often leaks are due to porosity too fine to be detected by radiography.

Recent work has examined some leaks to determine the solidification patterns that lead to leaks. Some examples of leaking castings suggest that while the castings meet the solidification criteria for radiographic soundness, they are still marginal for microshrinkage. In solidification modeling, a Niyama value of greater than 0.1 ensured radiographic soundness while leak free castings required Niyama values in leaking areas to exceed 0.7.

Thermography

Thermography is not readily used by the metalcasting industry for casting examination. The inspection could occur passively as the castings cool or with flash heating, which is done with a flash bulb. Active thermography has been used in the aerospace and composite industries.

Tests and Castings

ASTM requirements and commercial practices normally result in the producer performing mechanical tests on each heat of steel to verify conformance with specification requirements. Many users misunderstand the significance of these tests and believe that the test bar results for each heat will be the same as the properties of the casting. This is not true in most products, certainly not in steel products and clearly not in castings. The routine mechanical tests that are performed for each heat are to verify the capability of the material not to determine the properties of the product. The properties of bars cut from the product, cut from the casting, depends on the location, section size, heat treatment, and shape of the casting. If verification of mechanical properties of the product is required, a check of hardness in critical area is done. If a large critical casting is produced a large connected test coupon may be added to the casting for properties verification. In this case the properties of the test coupon are not given in the material standard but are subject to agreement between purchaser and producer. If a test bar is removed from a casting and it fails to meet the specification requirements for the material grade, the casting is not "defective." Only if the test bar from the heat fails to meet the properties is the material unacceptable.

Test coupons are typically made from the ASTM double-legged keel block per ASTM A370. Per the *Steel Castings Handbook*, there is good reliability between tensile test data for attached specimens and keel block specimens [6]. There is 95% assurance between the two tests and actual strength is within 1 ksi for UTS and 1.6 ksi for YS with elongation within 3%. Larger castings have a great propensity to form discontinuities and be affected by section size, geometric, and metallurgical effects on material properties. Foundry practices can be utilized to provide optimal properties. Analysis of CA6NM and 105/85 cast steel materials have shown that alloying reduces any impact of section thickness and geometry [7]. This same analysis showed that shrinkage in a casting had little effect on yield strength. In theory, since shrinkage is along the centerline, low stress region, and fatigue failures typically occur from surface defects, the fatigue limit should likewise be minimally affected.

Tests have shown that tensile properties are not greatly affected by different types of discontinuities [6]. There is a mostly direct relationship between the class of defect and the degradation in tensile properties. For instance, gas porosity will reduce the UTS by a little over 3 ksi per class. Out of the different types of porosity, linear shrinkage has the biggest impact on strength. But, even this type of defect only reduces the UTS by a little over 8 ksi per class. Keeping in mind location, usage, and factor of safety, it is easy to see why steel castings with discontinuities can survive well past testing requirements. Testing on a hanger bracket casting have shown that defects do not necessarily lead to part failure [8]. Brackets with class 2 and 5 discontinuities had very little influence on the static and fatigue properties. Only in a few cases, where the defect was at or near the surface, did the location of the failure change. However, even in these cases, the properties of the casting were not impacted.

Future Trends

The steel casting industry is working on a number of projects to develop better NDE standards that are useful in performance assurance. Modeling casting production and solidification in particular is key. The ability to link properties based on solidification patterns, design with these real world properties and craft NDE standards that assure performance promises a new generation of high performance cast steel components.

Rules of Thumb

Testing a section from a part is expensive but provides a data point on properties for the part. Testing a part to failure can likewise provide valuable information but comes at a cost. If a part with known level and type of discontinuity from NDE is tested, then setting the level one step higher for production parts should ensure desired performance characteristics. Working with a quality foundry will help ensure that discontinuities are minimized in the casting through optimized manufacturing techniques. Selecting a source based upon best value versus lowest cost always pays for itself over the long run. As stated earlier, using analysis software is not only cost-effective but a very good means to identify discontinuities. Using zoning to inspect a casting will ensure cost-effective inspection. Areas of the part that see higher performance demands are inspected more frequently and to a higher level then other sections. Thus, sections with greater discontinuities that do not affect the part's performance will not prevent the part from passing inspection. The impact of a discontinuity on performance depends on the casting's size and use.

A good starting point for NDE of steel castings is ASTM A903 with level III. Radiography is good to use in critical sections with level III as a starting point, and a rating per type of discontinuity should be applied. Ultrasonic testing can be used in castings with section sizes over 6 in. A tensile test should be carried out for each heat to ensure the material's properties. Hardness testing should be done on critical sections. A hardness test is relatively low in cost and hardness correlates with other mechanical properties. Since casting and welding are similar processes, the same NDE can be utilized.

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Appendix A: Ordering Steel Castings with NDE

Overview

When making inquiries or ordering parts, all pertinent information must be stated on both the inquiry and order. This information should include all of the following components.

1. Casting shape – either by drawing or pattern. Drawings should include dimensional tolerances, indications of surfaces to be machined, and datum points for locating. If only a pattern is provided, then the dimensions of the casting are as predicted by the pattern.
2. Material specification and grade (e.g. ASTM A 27/A 27M – 95 Grade 60-30 Class 1).
3. Number of parts.
4. Supplementary requirements (e.g. ASTM A 781/A 781M – 95 S2 Radiographic Examination).
    a. Test methods (e.g. ASTM E 94)
    b. Acceptance criteria (e.g. ASTM E 186 severity level 2, or MSS SP-54-1995).
5. Any other information that might contribute to the production and use of the part.

To produce a part by any manufacturing process it is necessary to know the design of the part, the material to be used and the testing required. These three elements are discussed in detail in the following sections.

Background

To obtain the highest quality product, the part should be designed to take advantage of the flexibility of the casting process. The foundry must have either the part drawing or pattern equipment and know the number of parts to be made. To take advantage of the casting process, the foundry should also know which surfaces are to be machined and where datum points are located. Reasonable dimensional tolerances must be indicated where a drawing is provided. Tolerances are normally decided by agreement between the foundry and customer. SFSA Supplement 3 represents a common staring point for such agreements. Supplement 3 is not a specification and care should be taken to reach agreement on what tolerances are required. Close cooperation between the customers' design engineers and the foundry's casting engineers is essential, to optimize the casting design, in terms of cost and performance. Additional guidelines for casting design are given in "Steel Castings Handbook" and Supplement 1,3, and 4 of the "Steel Castings Handbook".

NDE Methods

Nondestructive examination testing is done to verify the mechanical integrity or soundness of the steel casting. It can be separated in to surface examination methods which include visual, liquid penetrant, and magnetic particle and subsurface or internal examination methods which include radiography and ultrasonics. Not only must a test method be chosen, but also an acceptance criterion must be applied. Acceptance criteria should be related to the service requirements because overly stringent criteria add directly to the cost. For critical service both surface and internal examination may be required to assure the attainment of the level of soundness specified.

Visual Examination

Equipment Required	Enables Detection of	Advantages	Limitations	Remarks
Surface comparator Pocket rule Straight Edge Workmanship standards	Surface flaws – cracks, porosity, slag inclusions, adhering sand, scale, etc.	Low cost Can be applied while work is in process, permitting correction of faults	Applicable to surface defects only Provides no permanent record	Should always be the primary method of inspection, no matter what other techniques are required

ASTM A 802/A 802M – 95	Standard Practice for Steel Castings, Surface Acceptance Standards, Visual Examination
SCRATA Comparators	Steel Casting Research and Trade Association (SCRATA) Comparator Plates - for establishing mutually agreeable acceptance criteria for a specific part
ISO DIS 1197(a)	Visual examination of surface quality of steel castings
MSS SP-55-1996	Quality Standard for Steel Castings for Valves, Flanges and Fittings, and Other Piping Components (Visual Method for Evaluation of Surface Irregularities)

Liquid Penetrant Examination

Equipment Required	Enables Detection of	Advantages	Limitations	Remarks

Commercial kits, containing fluorescent or dye penetrants and developers Application equipment for the developer A source of ultraviolet light – if fluorescent method is used	Surface discontinuities not readily visible to the unaided eye	Applicable to magnetic, nonmagnetic materials Easy to use Low cost	Only surface discontinuities are detectable	

ASTM A 903/A 903M – 91 Steel Castings, Surface Acceptance Standards, Magnetic Particle and Liquid Penetrant Inspection

ASTM E 165 – 95 Standard Test Method for Liquid Penetrant Examination

ASTM E 433 – 71 Standard Reference Photographs for Liquid Penetrant Examination

ISO 3452 Non-destructive testing – Penetrant inspection – General principles

ISO 4987 Steel castings – Penetrant inspection

MSS SP-93-1987(92) Quality Standard for Steel Castings and Forginngs for Valves, Flanges and Fittings, and Other Piping Components (Liquid Penetrant Examination Method)

Magnetic Particle Examination

Equipment Required	Enables Detection of	Advantages	Limitations	Remarks
Special commercial equipment Magnetic powders – dry or wet form; may be fluorescent for viewing under ultraviolet light	Excellent for detecting surface and subsurface discontinuities to approximately ¼" below the surface – especially cracks	Permits controlled sensitivity Relatively low cost method	Applicable to ferromagnetic materials only Requires skill in interpretation of indications and recognition of irrelevant patterns Difficult to use on rough surfaces	Elongated discontinuities parallel to the magnetic field may not give pattern; for this reason the filed should be applied from two directions at or near right angles to each other

ASTM A 903/A 903M – 91 Steel Castings, Surface Acceptance Standards, Magnetic Particle and Liquid Penetrant Inspection

ASTM E 709 – 95 Standard Guide for Magnetic Particle Examination

ASTM E 125 – 63 Standard Reference Photographs for Magnetic Particle Indications on Ferrous Castings

ASTM E 1444 – 94a Standard Practice for Magnetic Particle Examination

ISO 4986 Steel castings – Magnetic particle inspection

MSS SP-53-1995 Quality Standard for Steel Castings and Forgings for Valves, Flanges and Fittings, and Other Piping Components (Magnetic Particle Examination Method)

Radiographic Examination

Equipment Required	Enables Detection of	Advantages	Limitations	Remarks
Commercial x-ray or gamma units, made especially for inspecting welds, castings, and forgings Film and processing facilities	Internal macroscopic flaws – cracks, porosity, blow holes, non-metallic inclusions, shrinkage, etc.	When the indications are recorded on film, gives a permanent record	Requires skill in choosing angles of exposure, operating equipment, and interpreting indications Requires safety precautions Cracks difficult to detect	Radiographic inspection is required by many codes and specifications Useful in qualification of processes Because of cost, its use should be limited to those areas where other methods will not provide the assurance required

ASTM E 94 – 93	Standard Guide for Radiographic Testing
ASTM E 142 – 92	Standard Method for Controlling Quality of Radiographic Testing
ASTM E 446 – 93	Standard Reference Radiographs for Steel Castings up to 2 in. in Thickness (3 Sets; X-rays, Iridium, Cobalt)
ASTM E 186 – 93	Standard Reference Radiographs for Heavy-walled (2 to 4-1/2 in.) Steel Castings (3 Sets; X-ray, Gamma Rays, Betatron)
ASTM E 280 – 93	Standard Reference Radiographs for Heavy-walled (4-1/2 to 12 in.) Steel Castings (2 Sets; X-ray, Betatron)
ASTM E192 – 95	Standard Radiographs of Investment Steel Castings for Aerospace Applications
ISO 4993	Steel castings – Radiographic inspection
ISO 5579	Non-destructive testing – Radiographic examination of metallic materials by X- and gamma rays – Basic rules
MSS SP-54-1995	Quality Standard for Steel Castings for Valves, Flanges and Fittings, and Other Piping Components (Radiographic Examination Method)

Ultrasonic Examination

Equipment Required	Enables Detection of	Advantages	Limitations	Remarks
Special commercial equipment, either of the pulse-echo or transmission type	Sub-surface discontinuities, including those too small to be detected by other methods Especially for detecting subsurface, planar discontinuities	Very sensitive Permits probing of joints inaccessible to radiography	Requires high degree of skill in interpreting pulse-echo patterns Permanent record is not readily obtained	

ASTM A 609/A 609M - 91	Standard Practice for Castings, Carbon, Low-alloy, and Martensitic Stainless Steel, Ultrasonic Examination Thereof
ISO DIS 4992(a)	Steel castings – Ultrasonic inspection
MSS SP-94-1992	Quality Standard for Ferritic and Martensitic Steel Castings for Valves, Flanges and Fittings, and Other Piping Components (Ultrasonic Examination Method)