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Qualification Testing and Inspection of High Alloy Cast products – High Specification Requirements

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Abstract: Cast products that require a high level of customer order specifications in the nuclear, naval, petrochemical, and defense industries go through rigorous evaluation, inspection, and testing procedures that verify all identifying criteria have been met. These procedures are developed based on standardized documentation from organizing bodies such as ASTM, ASME, ISO/EN, FAR/DFAR, CFR, and others. The agreements made between the producer and customer are finalized in the certificate of conformance and are the guidelines to which high specification castings are to be manufactured to. It is these requirements that demand extensive attention to detail during the contract review, inspection, and material testing of all high specification castings. The general process in which a highly specified casting is produced and certified has been outlined in detail throughout this paper.

Executive Summary: Following all the rules and regulations required to cast, process, and eventually certify high specification castings, there must be an astute and detail orientated team of individuals that understand all aspects of the foundry and customer base serviced. Dedicated Metallurgists, Process Engineers, Foundry Engineers, and QM/QA personnel are a mandatory element for success. The customers final product demands that all codes and specifications must be followed prudently and treated with respect. This is accomplished by applying manufacturing methods that have been proven over decades of foundry practices.

Introduction:

When foundries are contracted to make high specification castings in the nuclear, naval, petrochemical, defense and other industries, there are unique sets of rules and guidelines that must be followed to ensure all identifying criteria are met during production. In general, a high specification casting is one that requires an immense amount of scrutiny paid attention to it during the contract review, inspection, and material testing phases of the manufacturing contact. The casting may require various nondestructive tests (NDT), government obligations, customer specific mandates, dimensional tests, metallurgical tests, and other highly specific agreements that make producing the casting a cumbersome and tedious process. These products are set at such high standards as they typically are used in highly vulnerable situations. For example, pressure valves on a nuclear naval submarine may be produced in a foundry that casts high specification castings. To ensure that all the criteria of the pressure valve that was included in the design of the submarine makes it into the field, the foundry which produces the casting must be able to follow many rules, regulations, and guidelines to meet these standards. The progression in which a casting can be certified as a highly specified product varies from foundry to foundry. The general process in which a highly specified casting is produced in a stainless-steel foundry is outlined and described in detail throughout this paper.

Contract Review:

Contract review is the first step in inspection of high specification castings. The purchase order that a customer provides gives details on the contract for terms of operation of the requested product. Personnel review the customer orders and scan for things that may be a standard requirement when processing high specification castings. The manufacturing routing is created by a methods group or an Industrial Engineer who will order the operations in a logical metallurgical sequence. Next, verifications on previously completed jobs such as pattern and part number verifications, drawing revision verifications, and material specifications are added. Once the sequencing of manufacturing operations is established in the routing, inspection and testing procedures are developed.

The customer will specify the level of criticality during testing and inspection that is required by their internally developed standards. The purchase order will callout all operations that are to be completed before certification. The process in detailing all necessary requirements demands action from both the supplier and customer during the contract review portion of any transaction. If a job has multiple NDT operations such as radiography, magnetic particle, and visual inspection the level of scrutiny that is necessary to ensure a proper product is produced is enhanced and must be taken into consideration during this phase. The length of time in which a product can get through contract review varies greatly from product to product. Depending on how much inspection and testing must be done prior to certification the process for contract review can take weeks to months.

Before specific inspection and testing operations can be put into place, necessary controls for material related issues such as weld repair, test material to be poured, heat treatment, pickling and passivation must be reviewed by a contract specialist. The material specification or base inspection document will tell the specialist many details to the requirements of the inspection and testing acceptance criteria. Things like visual requirements, radiographic levels of soundness, magnetic and liquid penetrants, and other materials tests and inspections must be specified by the customer before order placement is agreed upon to be certified later on the CMTR.

Contract review must consider all the ancillary requirements that don't necessarily specify the following items:

- Governmental regulations – Federal Acquisition Requirements and Defense Federal Acquisition Requirements (FAR / DFAR) for the purchasing of military and naval warfare type products.

- Federal Codes – 10 CFR Part 21 whistle blowing requirements, 10 CFR Part 50, Appendix B (Nuclear casting procurement and requirements), 15 CFR 700 (production control terms to be complied with), 22 CFR Part 120 through 130 (ITAR) and many others.

- Customer specific requirements – Customers create at times very technical and internally specific necessities that are passed down as clauses.

- Standard statements – Declarations such as "castings must be free from the substance of Mercury and other low melting point metals" or Conflict Minerals callouts need to be applied.

Once all the required inspection and testing operations are reviewed, NDE/NDT technicians and level III professionals must submit their technical procedures and time personnel records to numerous agencies for approval. These documents are submitted sequentially and can vary greatly in length on gaining approvals for the testing and inspection operations. Typically, this process can take days to months. But, in more complex circumstances, the process can take as long as 18 months. The necessity for clear compliancy of the codes agreed upon is crucial in ensuring a smooth approval process.

Material specifications:

Material specifications contain terms and conditions including metallurgical, processing, and inspection requirements.

Metallurgical specifications contain chemical ranges, mechanical properties such as tensile strength, yield strength, percent elongation, and percent of area reduction. These properties ensure that the produced material and the heat treatment applied to them meet the minimum properties of that specification. Other metallurgical items that are useful in high alloy work are hardness measurements to verify the heat treatment process was effective. This is a measurement of a materials resistance to permanent indentation and can be a corrosion potential indicator. Impact testing is a very common metallurgical method for high alloy, high specification applications. More specific details are expanded upon for metallurgical material testing in later sections.

Processing specifications include but are not limited to different types of heat treatment, cleaning methods, machining, and welding. Tables or declarations as to what heat treatment is allowed for each individual alloy. Very specialized welding programs are indicated in the material specifications that are required for staying compliant to the needs of the high specification contracts. Control of filler materials, welder qualifications, equipment calibration, development of welding procedures and many other elements are required to be compliant to the relevant standards.

Lastly, the inspection practices and acceptance criteria that are covered in the material specifications must be detailed in all high specification work. It is not uncommon for visual inspection requirements to be called out. Referencing generally common industry specification like MSS SP-55 or ASTM A802 are both common visual specifications that are called out for acceptance of parts. Other NDE / NDT methods such as radiography, magnetic particle, liquid penetrant, or ultrasonic testing are often used to offer additional assurances that the parts meet the acceptance criteria that have been specified.

The below table summarizes a sampling of the common specifications used in many industries:

Specification	Relevant industry	Purpose
ASTM A703	Steel pressure service for steam and other accumulations where safety and performance could be compromised	Pressure retaining regulations and practices following ASTM conventions
ASTM A351	Oil and gas, fluid power industries, flow control, corrosion resistant necessity for many different industries	To have a collection of material grades where service to relevant industries
ASTM B148	Maritime brass and bronze pressure service	To offer sea water and other high corrosion applications
ASTM A802	Steel production for both pressure retaining as well as non-pressure retaining industries where valves, casings, metering, and flow control items are monitored	To offer numerous classifications of different visual inspections criteria
ASME BPVC, Section IIa	Steel and Nickel based pressure and non-pressure industries	To have pressure capable ferrous alloys to handle many metallurgical situations
ASME BPVC, Section IIb	Numerous industries such as maritime and power generation applications in or near sea water	To have pressure capable non-ferrous alloys to handle many metallurgical situations
NAVSEA Technical Publications	Naval ship and boat production standards covering welding inspection	To have a standardized method for inspection and welding for all systems of Naval war and supply vessels
SAE AMS-STD-2175A	Department of Defense (DoD) including NAVSEA and military projects	The purpose of this military standard is to prescribe the non-destructive testing acceptance criteria for the inspection of metal castings that are classified in accordance with this standard
NORSOK M-630	Offshore oil platform operations	A series of approved material data sheets with industry specific inspections and tests

Customer Derived Technical Specification Documents:

The project or industry specific requirements document has become a common aspect of customer orders. Often these types of documents are proprietary in nature containing protected physical and metallurgical attributes. These situations always come with non-disclosure or secrecy agreements. This is for a specific project where a customer has combined all the relevant requirements to one document. Each line and paragraph of these documents are pertinent to your process during production. Chemistry, mechanical properties, cast hardness, non-destructive testing, and many other factors must be understood, and the interpretations of the base specification should be finalized between the customer and foundry.

EN / ISO Pressure Equipment Directives and Regulations:

Since 1997 the European Union (EU) has been developing new directives to regulate pressure vessel activities and certification of designs, components, and source materials like castings and forgings. In January of 2022 the United Kingdom has had a Pressure Equipment (Safety) Regulation following the same types of alignment and rules. The BREXIT UK Pressure Directive is in force for England, Northern Ireland, Wales, and Scotland. Producing castings for these standards has many complexities. These two directives have provisions where ASTM and ASME materials can be used for supplied projects using a completed and endorsed notified body with a document called a Particular Material Appraisal (PMA). This PMA document has specific design conditions such as temperature (lowest operating temperature), pressure for usage, and other design considerations. It will also list a material for use which could be an American cast grade.

The below table deciphers some of the EU/UK vs. US material and testing specifications:

Special process or testing technique	ISO or EN test method specification required	ASME or ASTM test method specifications required for PMA PED / UK PESR orders
Welding	EN ISO 9606 – 1 thru 5 assorted welding activities EN ISO 15164 – Welder personnel qualification	ASME BPVC, Section IX welding code ASTM A488 – Foundry welding code
Chemical analysis	EN ISO 15350 – Determining C & S EN ISO 10720 – Determining N & O EN ISO 10200 – Chemical analysis of ferrous materials	ASTM A751 – Test methods chemical analysis
Tensile testing	EN ISO 6892-1Tension testing EN895 Destructive weld tensile test	ASTM E8 – Standard method of tension testing
Impact testing	EN ISO 148-1	ASTM E23 – Notched bar impact testing
Hardness testing	ISO 6506 – Brinell testing ISO 6508 Rockwell testing	ASTM E10 – Brinell testing ASTM E18 – Rockwell testing
NDE / NDT personnel Qualification	EN ISO 9712 – Qualification and certification of testing personnel	ASNT SNT-TC-1A for personnel qualification
NDT – X-Ray (RT)	EN ISO 5579 – Radiographic testing of metallic materials	ASTM E94 – Standard RT film methods ASTM E2035 – Computed radiographic method
NDT – Liquid penetrant (PT)	ISO 3452 – Liquid penetrant, general principals	ASTM E165 – General industrial method ASTM E1209- Fluorescent method
NDT – Magnetic particle (MT)	EN ISO 9934 – Magnetic particle testing ISO 17638 – Magnetic particle testing of welds	ASTM E1444 – Standard practice for MT
NDT – Ultrasonic (UT)	ISO 4992-1 – Ultrasonic testing of castings EN ISO 17640 – NDT of welds	ASTM A609 – Casting inspection
NDT – Visual (VT)	EN13018 – Visual testing, general concepts ISO 17637 – Visual testing of weld joints	ASTM A802 – Visual 'MSS sp-55
Material certification	EN 10205 – Metallic inspection documents EN 764-5 – Inspection documentation of metallic materials and compliance with the material specifications	ASTM A703 – Pressure containing parts

Inspection personnel qualification:

All non-destructive testing methods require highly trained, evaluated, and certified personnel to perform these types of tests and evaluations. Each NDE / NDT method has rigorous classroom and hands on training that needs to be documented prior to certification.

Each NDE / NDT candidate needs to pass a vision screening requiring them to read a Jaeger card and meet a J-1 rating with at least one eye. The Jaeger card is an industry accepted method endorsed by the NAVSEA Technical Publication TP-271 and ASME BPVC that verifies the level of fine print that can be read at a distance of 15 feet. If this cannot be read the employee needs to be sent to an Optometrist for corrective eyewear or contact lenses prior to resuming inspection activities. Additionally, color discrimination testing needs to be performed using an Ishihara color discrimination evaluation. This is a series of test plates that are evaluated by the subject and proof is offered that there is differentiation between colors. If a person is color blind the employee can be accepted for continuation of inspection duties if contract can be demonstrated.

After the passing of the employee through visual acuity and color discrimination formal training in the relevant discipline needs to be performed by a Level II for Level I certification or a Level III for Level II certification. There are multiple different examinations that need to be taken in the method, specification evaluations and hands on practical. Passing all of these earns personnel a Level I, Level II, or Level III. Once certified these personnel, each with limitations, can perform the below inspections.

Inspection:

High specification products require qualification of the physical condition of the casting both on the surface and volumetrically. The use of different types of NDE/NDT methods verify conformance to the standards that are agreed upon with the customer. Common foundry techniques to verify the level of quality on the surface, sub-surface, and volumetric analysis are detailed below. All these methods can be added to the customers purchase order to fulfil the requirements of their project as specified by their specifications and or code callouts.

Visual Testing (VT):

Type of evaluation method – surface analysis

Visual inspection and testing are always the first step in the evaluation of a casting. The appearance of the general condition is the first thing to look at. Does the casting have visual defects and if so, what size are they? Do they meet the general criteria needed that are called out on the castings VT acceptance criteria? Visual testing is often performed using only one's eyes. Magnifiers, bore scopes, and mirrors all can assist. Where high specification work is being inspected, the report form and the endorsements contained on it are key.

One of the most common standards to perform visual testing on sand castings is MSS SP-55. This is a series of photographic plates with some acceptable and some unacceptable images. These are used for qualifying the part. It is a simple inspection practice. Another technique is ASTM A802. This standard has four quality levels to work within. Each of these levels work with a set of tactile plates with different defect classifications and severity of those defects.

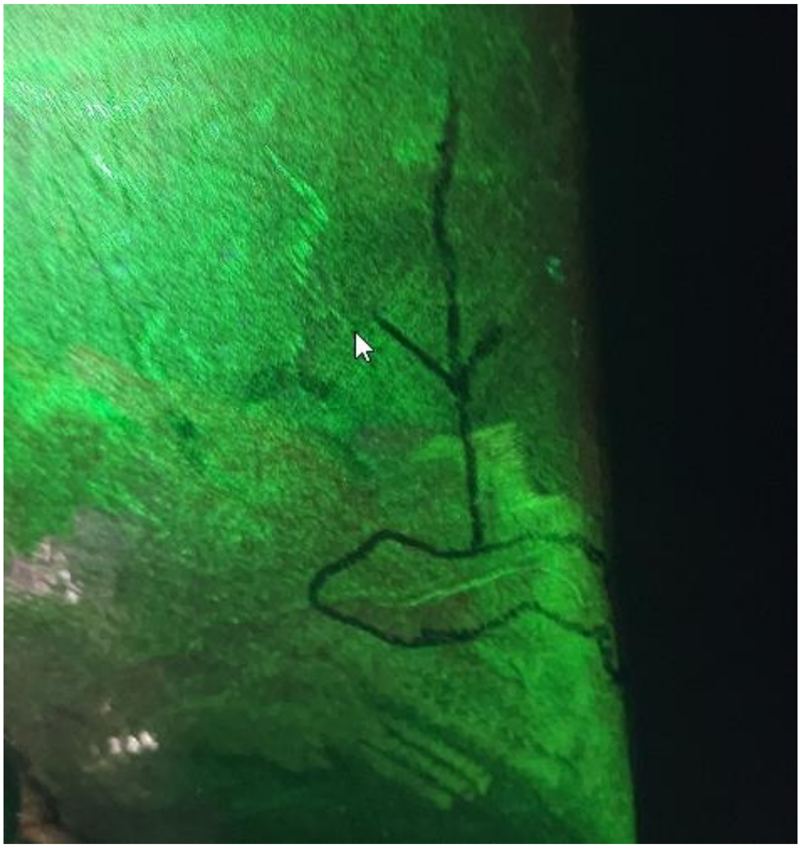
Investment castings have higher requirements to comply with. Specifications such as ASTM A997 which has numerous levels of acceptance from many categories of allowable defects. Some of the categories are positives, negatives, and shrinkage. Having a thorough VT process for both sand and investment castings is crucial. With many inspections in line to qualify the part, the level of stringent evaluations is of high concern during all high specification work.

Magnetic Particle Testing (MT):

Type of evaluation method - surface technique and slight sub-surface technique

Magnetic particle testing is extremely common to apply to high specification projects. It is an extremely sensitive method of NDT which can be done both wet and dry. It is a method that can only be performed on ferro-magnetic materials. It shows the location of linear defects very well. Rounded defects do not show up as easily due to how the magnetic field travels past the indications. A side benefit of MT is that if there are slightly sub-surface defects, they will show up during examination.

MT is only useful for linear defects. Most of the standards and codes will also contain criteria for rounded indications also. MT has a hard time highlighting these shaped defects and surface conditions. Therefore, many times customer purchase orders call out for PT to be applied and criteria to inspect. If PT were not to be performed there would be incomplete inspection in many cases for high specification work.



Magnetic Particle linear indication on ASTM A487, Grade CA6NM, Class A impeller

Liquid Penetrant Testing (PT):

Type of evaluation method - surface technique

The flexibility of liquid penetrant makes it a versatile technique. It can be applied in the lab or in the field easily. It is a simple NDT method but very powerful. It can be performed as a water washable format or an extremely sensitive solvent method. There is a fluorescent technique that is also very sensitive that is inspected in the dark with a black light. Liquid penetrant is generally used for testing on non-magnetic materials.

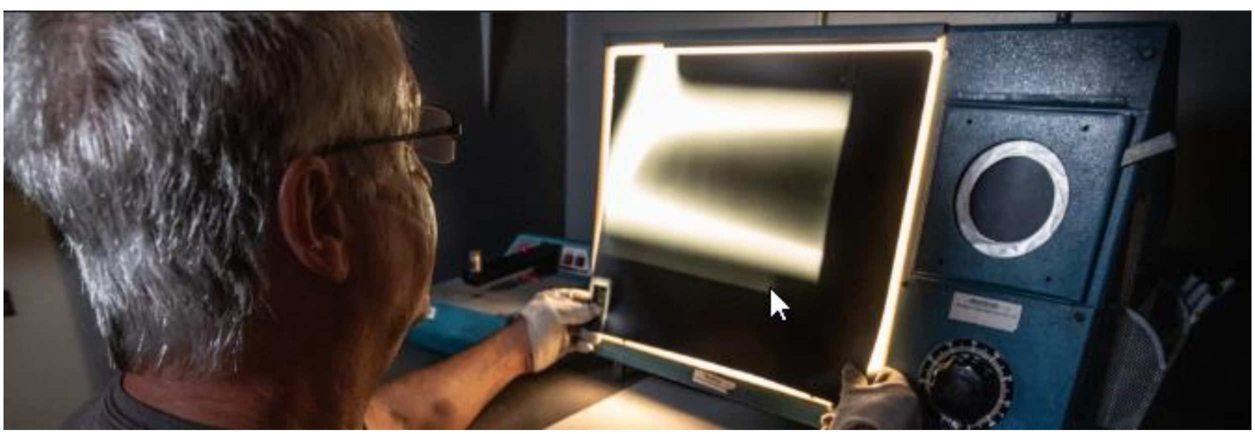
A word of caution when processing high alloy castings with PT is there is an opportunity that with specifically nickel based alloys, grain boundary effects and false indications can be present. When in the presence of inexperienced source inspection personnel these issues might be determined to be rejectable. Also, broad areas of pigmentation where there is a haze of penetrant that may not have been completely washed off requires that the process be cleaned and repeated. Specifications such as ASME Boiler and Pressure Vessel Code Section III, Division1 requires reevaluation when excessive pigmentation appears.

Radiographic Testing (RT):

Type of evaluation method - volumetric technique

Radiographic testing is a well-accepted method. It directs source radiation through the casting of interest and images are exposed on the film. The film has many quality indicators (IQI's) to ensure that the x-ray films meet all the appropriate specifications. Radiography has numerous different standards made of reference radiographs with many different defects and conditions highlighted for acceptance. Most of these standards have levels of acceptance that are used to depict porosity such as shrinkage categories, tears and cracks, and other anomalies.

Reference radiographs which are put out by many agencies such as ASTM and AMS offer at times subjectivity due to many of the defects that are exposed. These need a second party who is typically a NDE Level III to challenge any issues that may come up. Other conditions that can be evaluated in RT is film mottling or grain diffraction. These conditions will cause films are disqualified and need to be reshot and processed.



Radiograph film interpretation by a Level III Radiographer – InspecTech Corp., Milwaukee, WI

Ultrasonic evaluation (UT):

Type of evaluation method – volumetric technique

Being a volumetric method, UT offers a strong and accurate technique to see defects and items of interest within the casting. There are many engineering firms and OEMs that specify UT over RT as they feel it is more accurate and reliable. UT is also capable of measuring material thickness. UT offers the flexibility of being a portable method. It can be done on-site and brought to the field where parts may be located. Radiography is more cumbersome and inconvenient for portable field work.

High specification work employing UT can be performed on a specific surface of the castings. Areas such as flanges and high-pressure locations on the casting often are verified using UT if the material tolerates the UT and doesn't offer false indications. Certain alloys due to grain size and heat treatment conditions can cause these false indications.

NDE / NDT Overview:

These are just some of the more common tests that may be performed on high specification work. Accomplishing the below activities together at the correct cadence requires a skilled team to complete the NDE / NDT of any project.

Below is a table that lists common NDE / NDT activities with some positive attributes and some of the limitations that come with the technique:

NDE / NDT method	General applications and positive attributes	Limitations
Radiography (RT)	Can be used for ferrous and non-ferrous materials. Has a great reference library from ASTM (E192, E186, E280, E446) for steels. Many different classifications of defects are showcased in the above reference radiographs	Casting wall thickness vs. thinness and the ability to maintain proper levels of sensitivity. Is not reliable to exhibit cracking and linear indications.
Magnetic Particle (MT)	Used for ferro-magnetic materials with being extremely sensitive to cracks and does well highlighting larger rounded indications.	Smaller (0.062" diameter and smaller indications) are hard to ascertain. Relies on being able to magnetize with coil or cabling.
Liquid Penetrant (PT)	Used on non-magnetic materials highlighting cracks of all sizes but is more sensitive when used as a fluorescent method. Does very well with all sizes of rounded indications.	Can leave many false indications on the surface of certain alloys. Method is limited to surface evaluation only.
Ultrasonic Testing (UT)	Must be used on fine grained materials. Larger grained microstructures like austenitic materials and nickel-based alloys lose the back reflections.	Needs very experienced technician to be able to ascertain reflections from the material being tested.
Visual Testing (VT)	Used to verify cast external and internal surfaces using reference photographs or tactile plates. Easy to use magnification to assist in evaluation.	Can be very subjective to determine conformance to specifications, difficult to find readily available Level III personnel

NDE / NDT Summary:

The use of non-destructive testing to determine if the cast part conforms to the ordered requirements is necessary to be able to declare conformance for high specification customer orders. Many of the materials that require NDE / NDT do not respond properly to the callouts from specifications. An example would be that a carbon steel such as ASTM A216 grade WCB is required to meet liquid penetrant requirements when a more appropriate callout would be magnetic particle. Magnetic particle testing works great for magnetic alloys such as WCB where liquid penetrant is not sensitive enough to do the job properly as it is made for larger grained material like cast austenitic stainless steels like CF8M.

Dimensional testing:

Customer orders often require the produced parts be measured to verify conformance to the customers drawings. Performing dimensional inspection of the castings produced requires like all other inspection techniques very skilled and high-performance operators. They are expected to be able to measure with electronic devices such as coordinate measuring machines (CMM's), dimensional scanners, and other electronic hand tools that download measured readings to a PC or other storage device. Standard hand tools such as calipers and micrometers are useful but many times a calibrated steel scale is the most useful and appropriate for the job. A final useful device specifically for investment cast products are plug gages. These are quick go/no-go gages allowing fast and accurate comparisons. All the above techniques may be applied to a specific casting. These measurements are always recorded in a log. Documents and reports that can be sent with the CMTR package pertaining conformance to the customers specifications and drawings offers to the project or purchase order completion.

Positive Material Identification (PMI):

Monitoring incoming materials as melt stock, qualifying outgoing foundry returns sales, as well as fulfilling contract or specification requirements makes PMI an extremely useful and operator dependent procedure. PMI is a portable chemical analysis using a hand-held analyzer. This type of analyzer uses an x-ray tube which is like the full sized XRF chemical analyzer. When properly employed it can reach some of the same levels of accuracy as a traditional XRF. It should be noted that there are no current provisions through ASTM method specifications that can use results provided from a PMI analyzer to certify products.

Since you cannot use a PMI analyzer to perform certification activities, you can use an analyzer to screen products. Many industries such as oil and gas, pressure service, and some highly engineered products demand that their product is verified on a pallet prior to shipment. This offers assurance to within a percentage value to the certifiable chemistry from your metal laboratory. This activity is often useful for high specification work call outs in the material or project specification. Companies like Exxon or Mobil Gas and Oil create very complicated specifications. There will be materials listed as CF8M/cast 316 stainless steel that by specification if chromium for example can be 16.0% to 23.0% per the Exxon PMI specification and the orders requirement needs to meet ASTM A351, Grade CF8M requires 18.0% to 21.0% chromium. PMI even though it may have a well-prepared sample that has been ground prior to analysis and tests conducted by qualified operators using proper certified reference materials, it needs to show that the material meets the PMI specification and is close to the certified chemistry that will be on the CMTR document.

The limitation of a PMI analyzer is that in most instances light elements like Carbon, Silicon, and Sulfur cannot be analyzed due to their low atomic weight. XRF technology has this limitation with these light elements but new technologies such as LIBS (Laser Induced Breakdown Spectroscopy) can do so. LIBS technology uses a restoring laser pattern for checking chemistry, but this technology has not proven itself to the ASTM community to have it listed as a certifiable technique. PMI is a powerful tool to verify product but not a certifiable technique.

Material Properties Testing:

Optical Emission Spectrometry (OES):

Optical emission spectrometry has been widely used as a method to control the production of steel and other alloys in primary producing manufacturers such as foundries due to its speed, accuracy, and efficiency. The technology is well understood and has been enhanced with modern day analytical methods to produce chemical specifications for a wide range of alloys. In the case of highly specified cast alloys, OES analysis is a common technique to confirm the chemical composition of a metallic sample.

The chemistry of cast materials are verified by calibrating the OES equipment with certified reference materials (CRM) of a known chemical compositon. Governing bodies such as ASTM, ASME, ISO/EN, FAR/DFAR, CFR, and others have specific chemical designations for all alloys produced in manufacturing industries. These designations require that specific rules and techniques are followed to maintain repeatability and accuracy.

The most used OES technologies for primary producing manufacturers in high specification work are arc spark excitation, glow discharge, combustion methods for carbon and sulfur measurements, X-Ray diffraction, and gas fusion methods for nitrogen and oxygen levels. In all OES technologies, an emission line is produced by exciting the atoms on the surface of a sample. These excited atoms emit radiation which is then reflected and reproduced into narrow slits that disperses the radiation into individual spectral lines that are unique to the element of the atoms that emitted them. These spectral lines are then amplified and collected to determine the present quantity of primary, secondary, and tertiary elements in a solid sample based on a relative method. This is a relative method and is standardized through calibration with a CRM.

OES allows for the analysis of many elements in a large magnitude of concentrations in a single measurement making it a useful tool to certify high specification cast alloys. Ni, Cr, Cu, Mo, Va are residual elements that can be of concern in certain steel grades for high spec work. ASTM A216 and A487 are common standards in the analysis of these residual elements. They are of concern because some of these elements control weldability, grain refinement, microstructure, and responsiveness to heat treating.

Tensile testing:

When determining the mechanical properties of a cast material, tensile testing is a commonly used technique. The exact type of test material, test equipment, and test parameters vary based on the material being tested and the application it is used for.

Tensile testing consists of applying a pulling force on a test material in two opposite directions. This allows us to determine how strong a material is and how much deformation it can withstand. Ultimate tensile strength, elasticity, yield strength, and strain deformation are typical properties reported but several other characteristics can also be determined. Calculations for yield strength can be affected by the 1.0 or 0.2 offset vs. 0.5 extension under load between different specification orders and alloy combinations.

These tests are generally performed on an electromechanical or universal testing machine and are standardized by ASTM E8, ASTM A370, and ISO 6892. The degree to which a material is tested is governed by the level of specification required by the customer. ASTM E8 is the more widely used method for determining tensile properties of cast materials. It is conducted on a large variety of metals causing system requirements to vary greatly but typically dog bone specimens are used in cast material.

There are several factors to control when performing standardized tensile testing but the most important are stress rate, strain rate, and crosshead displacement control. Additionally, whether proportional or non-proportional grips are used must be taken into consideration. The need for high accuracy in high specification cast material requires the use of an extensometer to determine properties at lower strain values.

ASTM A370 is another broadly used standard for determining tensile properties of metallic samples and contains many of the same characteristics of the E8 standard. This standard differs from the latter as it further defines the specimen characteristics of steels specific to several different product types such as bar, tube, fasteners, and round wires. ISO 6892 is another commonly used standard for testing of tensile properties of metallic materials. The differences that are found between the ASTM and ISO standards are subtle and typically reside in the environmental testing conditions, device and apparatus usage, test specimen dimensions, test rates, calibration methods, and uncertainties of test results.

Hardness testing:

Hardness testing is a way to measure the surface quality of a cast material. It allows for the determination of a materials resistance to permanent indentation of the surface through a nondestructive manner. It can be an indicator on the performance of the material based on its given application and is typically a requirement when certifying any high specification cast alloy.

When determining which hardness test method to use, it is important to understand the material that you are testing as it will dictate the appropriate technique to be used. Any hardness test has several factors that influence the type of load applied, indenter geometry and material, and method of measurement. For example, a Brinell hardness test measures the area of indentation and uses a ball shaped carbide steel indenter. A Rockwell test however measures the depth of indentation and can use a spherical or cone shaped diamond indenter to measure harder materials as well as the traditional carbide steel ball used in other techniques. Additionally, if required in the specification, hardness testing techniques are used to measure hardness on the micro scale. Vickers, Knoop, Berkovich, and instrumented indentation are commonly used methods to measure microhardness.

Rockwell, Brinell, Vickers, Leeb-equotip, tele-Brinell, and file hardness methods are commonly used in the foundry industry to meet high specification requirements. The Brinell method is by far the most widely used method in hardness testing. ASTM E18, E10, and A956 offer guidelines on hardness testing to ensure repeatability and accuracy are maintained through an industry standard.

One of the items that are used in high spec work often is portable testing. ASTM A956 (Leeb testing) is used often in refineries, welding inspections, ship building, etc. Leeb testing is a process in which the rebound of a steel ball is dynamically measured. Additionally, another portable hardness test would be a king Brinell method. The king Brinell works off the same concept of standard Brinell testing in accordance with ASTM E10.

Impact testing:

Impact testing is used to evaluate the amount of work required to rupture a test material in a brittle fashion. The Charpy test is the most used technique in measuring this material property for high specification cast alloys. The Charpy test consists of a pendulum like apparatus that swings a hammer from a rested position into a notched sample. The amount of energy that is absorbed by the sample can be determined by measuring the height of the hammer pendulum after rupture. A notched sample is used as it allows for the examination of brittle behavior in ductile materials.

ASTM E23 and ISO 148-1 are the governing guidelines for Charpy impact testing of V-notch metallic materials. Each guideline has been revised many times over the years to reduce statistical scatter, improve accuracy of results, and to standardize testing procedures in various industries. There are three main characteristics that can be measured by a Charpy Impact Test: total absorbed energy, lateral expansion, and percent shear fracture area. The percent shear fracture area is a qualitative measurement of the fracture surface and is typically determined through comparative measures. It is important as it can be used in conjunction with absorbed energy and lateral expansion measurements to define a ductile-brittle transition temperature. The percent shear is proportional to the height of the brittle fracture and ductile area surrounding it. Brittle fracture can be identified as having a sparkly appearance while shear fracture is defined as dull and rough. The lateral expansion of a sample is a measurement of the ductility of the material. During fracture, the sample plastically deforms before rupture and material is pushed outward laterally on the sides of the notch. The amount of deformation is measured and reported to quantify ductility of the material.

The results obtained via impact testing are looking to verify key properties such as absorbed energy, percent shear, and lateral expansion for high spec work. It is very common for welding procedures to include these measurements.

Corrosion Testing:

Corrosion testing is an important metric when certifying certain high specification cast alloys. It is widely used in the sour gas, oil production, and nuclear industries where there are high vulnerabilities for pressure leaks.

ASTM A262, A923, and G28 are the three main ASTM standards when choosing appropriate corrosion test methods. ASTM A262 deals with intergranular corrosion which is when a metal becomes sensitized making it more susceptible to corroding effects. Sensitization is when grain boundaries precipitate carbide deposits that are prone to intergranular corrosion. Of the four different test methods, all consist of submerging the metal in a corrosive solution and either visually comparing the results to standards or weighing the samples after sufficient time for the corrosion effects to take place. ASTM A923 is used to detect detrimental intermetallic phases such as sigma and chi. It is important to control the presence of these phases as they reduce the toughness and corrosion resistance of duplex stainless steels.

Stress corrosion cracking (SCC) is a common issue in stainless steels. SCC is when cracks propagate either in a transgranular manner or an intergranular one due to one or a combination of several factors. Tensile stresses in the material, corrosive mediums, and susceptibly prone materials are a few contributing influencers to SCC in stainless steel.

Common corrosion testing methods used listed below verify proper heat treatment, microstructure, and chemical balance of the alloy ensuring customer requests are carried out from purchase order requirements.

ASTM Test Method	Applicable Forms and alloys	Relevant Types of Corrosion
ASTM A262, Method A	Cast and wrought austenitic stainless steel	Detection of Sigma phase
ASTM A262, Method B	Cast and wrought austenitic stainless steel	Intergranular corrosion
ASTM A262, Method C	Cast and wrought austenitic stainless steel	Intergranular corrosion
ASTM A262, Method E	Cast and wrought austenitic stainless steel	Intergranular corrosion
ASTM A923, Method A	Cast and wrought duplex-austenitic / ferritic stainless steel	Detecting detrimental intermetallic phases
ASTM A923, Method B	Cast and wrought duplex-austenitic / ferritic stainless steel	Detecting detrimental intermetallic phases (Utilizing Charpy V-notch impact testing)
ASTM A923, Method C	Cast and wrought duplex-austenitic / ferritic stainless steel	Detecting detrimental intermetallic phases
ASTM G28, Method A	Wrought Nickel-rich Chromium bearing alloys	Intergranular corrosion
ASTM G28, Method B	Wrought Nickel-rich Chromium bearing alloys	Intergranular corrosion
ASTM G36	Wrought, cast, and welded stainless steels and related alloys	Stress Corrosion Cracking (SCC)
ASTM G48, Method A	Stainless steel, Nickel based and Chromium bearing alloys	Pitting corrosion
ASTM G48, Method C	Stainless steel, Nickel based, and Chromium bearing alloys	Pitting corrosion

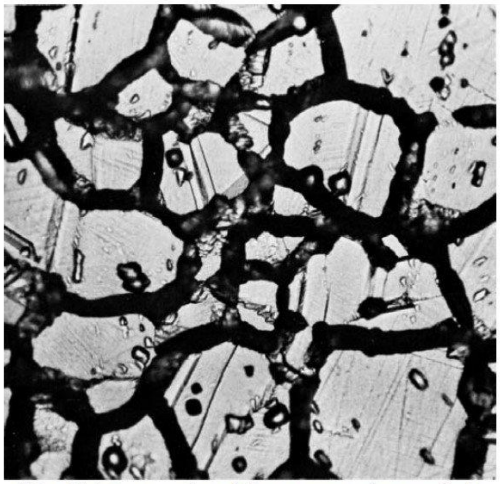


FIG. 3 Ditch Structure (500×) (One or more grains completely surrounded by ditches)

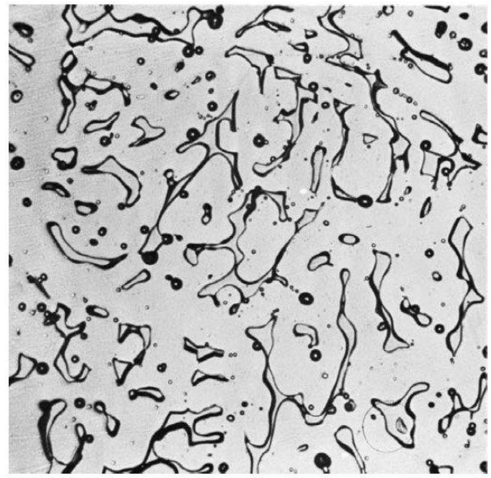


FIG. 4 Isolated Ferrite Pools (250×) (Observed in castings and welds. Steps between austenite matrix and ferrite pools)

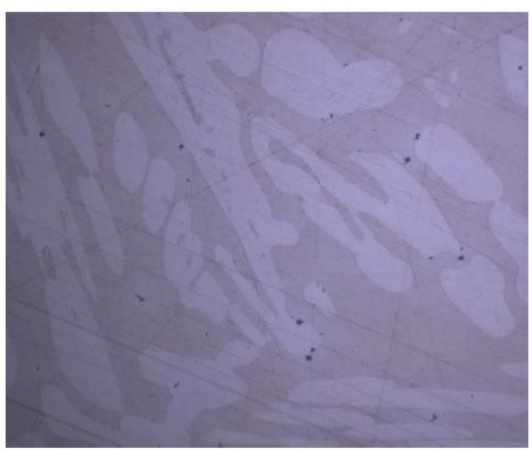
Not acceptable and acceptable microstructures – ASTM A262, Practice A

Metallography:

Metallography is a method in which a metallic sample is cut down to size, mounted by either thermal or mechanical compression of a resin or epoxy material, ground with progressively finer grit sandpaper, polished with various cloths and suspension, and in many cases etched with a wide range of chemicals and other techniques. The sample is then placed under a microscope and an analysis of the metal's microstructure can determine several different material properties.

For steels, the identification of the amount of austenite, ferrite, austenite and ferrite, and martensite phases is necessary in any cast product. In high specification foundry work, this is a very common requirement and requires precise image analysis methods and techniques to be applied.

ASTM has maintained documentation on standard metallography methods on how to characterize metals using image analysis techniques. ASTM E4 is an encompassing committee that creates and maintains standards for electron and light microscopy procedures. ASTM E562 is a commonly used standard for volume fraction determinations of steels and other metals using metallographic techniques. E1245 is a standard used for automated image analysis of secondary phases that allow for an overall inclusion rating of steels and stainless steels.



Duplex Stainless Steel – ASTM A995, Grade 4A (CD3MN), 200X, Etched with Villas Reagent

Ferrite prediction:

The use of stainless steel in high specification work is in large part due to its combination of suitable material properties for corrosion resistant applications. These material properties are heavily influenced by the presence of ferrite in the casting. The chemical composition and cooling rate plays an important role in the development of ferrite and empirical methods have been established to predict the amount present in stainless steel castings.

The most accurate methods for ferrite prediction using concentration methods use a nickel/chromium equivalent index in accordance with ASTM A800 (Schoefer diagram). Other calculations used often are the Schaeffler diagram for austenitic stainless steel and calculations such as the Halls equation for duplex stainless steel (austenitic/ferritic). Additionally, a ferrite scope, Severn Gage, and other chemical-based predictors can be used to determine ferrite concentration. Often other ferrite-based tests such as magnetic permeability are used as absolute techniques that relate directly to ferrite levels in castings.

Metallurgical testing summary:

In high specification work, the need to determine the chemical, mechanical, and material properties of cast metal is crucial in ensuring that the customer receives a product that meets their design requirements. OES, tensile, hardness, impact, corrosion, metallography, and ferrite prediction testing are all essential methods to satisfy the stringency of high specification castings. The governing bodies that encompass the standards for these tests are continually audited and revised to ensure that industry repeatability and accuracy is maintained.

Source inspection:

A source inspector is an individual who is hired by a customer or the engineering group overseeing the project to witness milestones in the creation of the casting. Common occurrences are some of the following operations:

- Contract review
- Melt and pouring
- Stamping of heat numbers for traceability – castings and test material
- Heat treatment
- Welding
- Post weld heat treatment
- All the inspection operations – VT, RT, MT, PT, dimensional, etc.
- Endorsement of the certification package
- Shipping operations

Most of the source inspectors commonly will act as expediter on the customers behalf. They typically will supply status reports and make statements how all tests went that day sending the status back to their customer. Often, they will take status photographs or ask for objective evidence to send back in their reports. This evidence can be heat treat charts, welding records, or many different inspection accounts.

QA Material certifications:

Bringing finality to a project ends with documentation that requires precision and attention to detail. Documenting processes and providing them to your customer is dependent upon the requirements that the castings were ordered to and produced to.

There are generally three tiers of documentation that certify the final raw casting. These tiers are as follows:

- Certificate of Conformance (COC) – The certification of conformance generally is a series of statements on a single page document that attests that all the requirements of the purchasing documentation have been applied to and carried out on the castings being sold. This is typically referring to all lines of documentation on the purchase order that need compliance that are not directly affecting the quality of the casting. Such statements of conformance may be FARs (Federal Acquisition Regulations) and DFARS *Defense Federal Acquisition Regulations), purchasing conditions such as Code of Federal Regulations callouts 10CFR Part 21 or 10CFR Part 50, Appendix B conditions and other non-physical, analytical or inspection related activities are certified and attested to. Metallurgical and direct inspections and tests are located on the CMTR.

- Certified Material Test Report (CMTR) – This document consists of traceable events and accountabilities that are unique to the specific part or series of parts. All castings are stamped with traceability identification. Chemistries and physical properties (tensile strength, Yield strength, percent elongation, percent reduction in area, hardness, impact test values and conditions, etc.) unique to this heat and/or lot number potentially heat treat load traceability are certified as to quantity, material specification, alloy grade and other attributes. There will also be many statements that state the heat treat condition of the castings or possibly that they have been passivated and/or pickled. The results of nondestructive testing performed can be stated in addition reference to the certificate of conformance document. Finally, a signature from a Quality Management appointed authorized agent who will endorse the CMTR. In some cases, a Notary Public will additionally endorse witness to the authorized agents signing of the CMTR.

- Supporting Special Process Documentation – There can be many different documents that are attached or enclosed with the CMTR and COC. These include but are not limited to heat treatment charts, many different types of nondestructive testing reports, inspection documentation, dimensional reports and other items that are objective evidence attesting to statements made on the CMTR and COC. All these documents generally reference traceability to heat and lot numbers as well as the customers purchase order number. These documents are key to offering validation that all the details of the process were followed.

Conclusion:

When producing high specification castings for the nuclear, naval, petrochemical, defense, and other industries, there are various regulations and customer specific demands that must be considered. The contract review, inspection, and material testing of the high specification casting is crucial to ensure that all identifying criteria are met during production. Having seasoned and well experienced personnel allows for a smooth process to be followed but intense scrutiny and care must be considered during all phases of the manufacturing practice. These personnel set the operational sequence for all the technical mandates such as the required metallurgical process, validation procedures like inspection, and the certification process. It requires many details to be followed for a high specification casting to be produced right the first time. The potential for economic, environmental, or loss of life puts stress on the foundry to verify the steps and operations are correct, processed by the properly qualified technicians and certification personnel, and are produced to the highest of quality and standards.

Biographies:

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Stainless Foundry & Engineering, Inc.
Servicing and working in the foundry industry since 1980 primarily in Metallurgy, Quality Management, Operations, Sales, and an educator. NDE Level III and ASME NQA-1 Lead Nuclear Auditor. Born and raised in Milwaukee, Wisconsin.

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