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Designing High Performance Steel Castings Today

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ABSTRACT

The US Army Armaments Research and Development Engineering Center’s (ARDEC) Benet Laboratories will present an approach and considerations for designing high performance steel cast components. The interdependencies on materials and properties on the casting process will be considered, including part geometry and Geometric Dimensioning & Tolerancing (GD&T), critical performance areas as defined by Finite Element Analysis (FEA), allowable defects for optimal performance in service, as well as inspection and repair criteria.
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INTRODUCTION

There are many approaches to metal component design that can be chosen to result in proper form, fit and function, but when overall system cost and weight considerations are taken, it is essential to consider manufacturing processes to optimize the use of high performance materials. It is well known that as the strength of materials increase, that ductility and fatigue life generally tend to decrease, so materials must be designed with sufficient cleanliness, microstructure and macrostructure to reduce the possibility of detrimental phases or inclusions which can initiate defects or decrease the service life of a finished part. For the purposes of this paper, high performance alloys are defined by the following desired mechanical properties, and may be used in critical safety applications such as pressure vessels.

Yield strength (0.1% offset) – 140/160 ksi
Reduction in Area – 30% min.
Charpy V-Notch resistance @ -40 +/- 20°F – 20 ft-lb

While a designer may often start with yield strength when choosing an appropriate material, the geometric complexity, direction of applied stress during use, and quantity to be manufactured need also be considered when choosing an appropriate manufacturing process. For many high performance, cyclic loaded, complex geometry parts produced in relatively low quantities, castings are ideally suited to meet these requirements.

OBJECTIVE

The primary objective of this paper is to list the considerations when choosing to use a casting for high performance designs, and we will address each of these topic areas for review. The considerations include the following topics: Configuration, Material Composition, Performance, Initial Allowable Defect Criteria, Inspection Methods, Final Allowable Defect Criteria, Inspection Requirements, Casting Repairs, Mechanical Property Testing, Corrosion Protection, and Geometric Dimensioning & Tolerancing.

DISCUSSION

A. CONFIGURATION

Designing a high performance steel casting is significantly easier and more likely to be successful today because of modeling and simulation software. Finite Element Analysis (FEA) will reveal critical (highly stressed) areas which can become significantly less stressed areas by modifying the configuration or adding material. Commercially available solidification modeling software can reveal where shrinkage will occur, which then can be reduced or moved outside the casting configuration with adequate gating and risering.
The more complicated the configuration the more likely a casting process will be the most economical method for producing it. A great benefit of casting processes is there seems to be no limitation as to the configuration that can be produced. Using FEA and casting solidification modeling and simulation software, material can be added and removed to optimize component life and weight. To attain the optimum manufacturing process results, it is desirable to avoid dramatic changes in thickness; i.e. avoiding a thin section connecting to a thick section because of “hot tearing” (separation of metal) that can occur during cooling and solidification from the liquid state. This occurs due to the different cooling rates and the resultant stresses that build within each section. Also determining which features can be left “as-cast”, which is directly related to tolerances and surface requirements, will have a large influence on which casting process is selected.

B. MATERIAL COMPOSITION

Allowable chemistry ranges and residual (tramp) element levels should be specified whenever possible because the resultant properties will dictate the useful life of the designed component. Alloy composition and proper heat treatment will establish the optimum material properties and performance. For the components of interest, the combination of high strength and ductility are essential to meet the applied stresses during service, but it is also important to understand how the component will perform over repeated cycles or in the presence of a defect such as a crack that can develop and grow over time. The fatigue life, or the number of cycles that a structural component will survive under repeatedly applied loads, can be calculated by evaluating the crack propagation growth rate \( \frac{da}{dn} \), where ‘a’ is a crack length and ‘n’ is the number of cycles under an applied load. Fatigue life, crack propagation, and fracture toughness \( K_{IC} \) are all dependent on the material chemistry. Often, these properties are available in material data sheets or handbooks as they require expensive tests. To reduce the testing cost on each component, most often a charpy v-notch specimen per ASTM E23 is required to be tested at -40°F to estimate the fracture toughness of a given part. If the material composition is known the correlation of charpy values to fracture toughness values will be known. The \( \frac{da}{dn} \) test values are typically available in Aerospace Structural Metals Handbook. A commonly used alloy group includes the medium carbon (0.2% - 0.5%), Nickel-Chromium-Molybdenum alloy steels such as Grade 10, Class B per ASTM A487 which require heat treating (austenitizing, liquid quenching, tempering) in order to meet the optimal mechanical properties (yield strength, ductility, fracture toughness). Also, for many applications precipitation hardening stainless steels (e.g., 17-4PH) can be specified for a casting that has small cross sectional thicknesses. This type of alloy remains liquid at lower temperatures than Ni-Cr-Mo steels and can appropriately fill thin sections in a mold. Also it has a good combination of strength-ductility-toughness to achieve the desired high performance requirements.
C. PERFORMANCE

As stated above, FEA can be used to establish dimensional stability, or the maximum compressive and tensile stress levels expected during operation of the component. These applied stresses are must be less than the yield strength to prevent deformation in service. In addition, the component life may be limited by low cycle-high stress fatigue. Once a crack is formed it may or may not grow, depending on the orientation of the applied stresses. Complex configurations require FEA to calculate the stress levels, and show the worst case stresses where a crack may propagate. Typically, we use the Paris Law to predict crack propagation rate:

\[ \text{Paris Law: } \frac{da}{dn} = C x K^m \]

The values for C and m are constants extracted from a plot of the \( \frac{da}{dn} \) vs K (stress intensity) test data. The data is plotted as a straight line when both \( \frac{da}{dn} \) and the K values are converted to log values. The C value is the log \( \frac{da}{dn} \) value where the K value is zero and the m value is the slope of the straight line. K is the stress intensity which equals the stress (S) applied \( \times (\pi x a)^{1/2} \times f \) where a is the crack depth and f is the crack shape factor which is described in the ASTM \( \frac{da}{dn} \) test spec. (ASTM E647).

D. INITIAL ALLOWABLE DEFECT CRITERIA

To establish the required crack propagation life, the applied stress (S) perpendicular to the crack length and the fracture toughness \( K_{1c} \) have to be known. The \( da \) and \( dn \) derivatives in the Paris Law are integrated. The integral of \( dn \) equals the propagation cycles to failure (N_p) and the integral of \( da \) is from the initial crack depth (\( a_i \)) to the final depth at fracture, named critical depth (\( a_c \)). If \( K_{1c} \) is known then \( a_c \) is calculated by letting \( K = K_{1c} \). The shortest propagation life is when the crack shape is a semi-circle which is length (L)/depth (a) equal to 2. Based on experience and experiments with commonly used alloys, a reasonable value for f for a semicircular crack is 0.73. The value of \( a_i \) to provide the propagation life is calculated however \( a_i \) is crack depth but the inspection methods typically measure length. The initial allowable defect length, \( L_i \) of a semicircle would be 2 x \( a_i \). The inspection method that can reveal this length or shorter has to be specified. The final form of the equation after integration is as follows:

\[ N_p = \left\{ \frac{1}{C (S^{1/2} f^m x (m/2 - 1))} \right\} \times \left[ \frac{1}{a_{i}^{m/2 - 1}} - 1/ a_{c}^{m/2 - 1} \right] \]

E. INSPECTION METHODS

Inspection methods can be specified in advance, for example based on availability of existing equipment, procedures, etc. If this approach is taken, then the initial allowable defect length (\( L_i \)) is specified based on the available inspection method and the propagation life \( N_p \) is based on \( a_i = \frac{1}{2} L_i \) and everything else is the same as described above. This approach is often used for moderate to low performance castings whose life is not critical.
F. FINAL ALLOWABLE DEFECT CRITERIA

For critical casting applications, where fatigue life and the rate of crack propagation is unknown, criteria for rejection is based on the defect length and depth that will result in failure. To be conservative, the failure length will be 2 x failure (critical) depth.

G. INSPECTION REQUIREMENTS

Either the No-Bake sand or Investment process is selected based on which process, because of tolerances, can result in “as-cast” features. Supplement 3 of the Steel Founders Society Handbook has the tolerance values for No-Bake sand and the Investment Casting Handbook by the Investment Casting Institute has the tolerance values for investment castings. Typically there are one or more areas that are more highly stressed than all other areas. These regions are identified as critical areas and the remaining areas are identified as non-critical. If the component loading during FEA is established, the critical and non-critical areas can be identified on the casting drawing or CAD solid model for inspection purposes and different initial allowable defect criteria can be established for surface inspection, subsurface defect criteria for radiographic inspection, weld repair conditions and dimensional inspection. The following inspection requirements are typically employed: Magnetic Particle, Liquid Penetrant, Radiographic, Visual and Dimensional, and each is discussed below with the applicable acceptance criteria based on experience and test equipment limitations.

1. Magnetic Particle Inspection (MPI) required via rectified ac, wet, fluorescent, continuous method per ASTM E1444. Acceptance criteria:
   a) Critical Areas – max. length of indications is 0.12”
   b) Non-Critical Areas – max. length of indications is 0.25”

2. Liquid Penetrant Inspection (LPI) – required via type I (fluorescent dye), method A (water washable) per ASTM E1417.

3. Radiographic inspection required per ASTM E1742 and reference radiographs, quality level 2T. Sample frequency per Table 2 of SAE AMS 2175. Acceptance criteria:
   a) Critical Areas – Level I per ASTM E446
   b) Non-Critical Areas – Level II per ASTM E446

4. Dimensional Inspection – critical dimensions including their geometric tolerance identified with the symbol “c” are to be measured on each casting. All other dimensions are to be measured on one (1) out of every ten (10) castings. If a dimension/tolerance is not met on one casting, all remaining castings shall be inspected for the specific dimensions/tolerances that failed.
5. Visual Surface Inspection -

   b) Investment Casting Processes – Visual surface inspection per Level II per ASTM A997

H. CASTING REPAIRS

Many castings have surface anomalies or defects identified through the inspection techniques listed above. Material removal (probing) blended into the surrounding area is permitted in non-critical areas and the maximum depth of the remaining cavity is .06”, which is the maximum depth of MPI detection. Experience has also shown that most castings perform exceptionally well after weld repair, thermal treatment (i.e., austenitize-quench-temper, or localized stress relief) and re-inspection. Thermal treatment ensures that the properties of the weld repair match those of the cast component. The typical procedures for weld repair are based on defect size and location and weld repair and welder qualification procedures per ASTM A488 with filler metal ER120S-1 (or equivalent, to approximate the expected properties of the typical alloys used) per AWS/ASME SFA 5.28, and are reviewed for approval by the responsible engineering authority as follows:

   a) Minor welds – Welds are permitted in non-critical areas and with a depth of 20% or less that the section thickness and a length of 1” or less or a depth of 0.12” max (no length limitation). Welds made after heat treatment of the casting require only a stress relief at 50 +/- 250°F below the final tempering temperature. These welds shall be visually and magnetic particle inspected per the casting drawing requirements but do not require radiographic inspection.

   b) Major welds and critical areas – All major welds and welds made in critical areas shall be made prior to final heat treatment of the casting. These welds require visual, magnetic particle and radiographic inspection per the casting drawing requirements.

I. MECHANICAL PROPERTY TESTING

The specified heat treatment for the high performance Ni-Cr-Mo alloy steels of interest is to normalize, austenitize, liquid quench, and temper to obtain the mechanical property values. Two (2) standard round tensile specimens shall be manufactured and tested per ASTM E8/E8M and two (2) charpy V-notch specimens shall be manufactured and tested per ASTM E23. The specimens shall be removed from Keel blocks produced from each heat and heat treated with the castings. The keel blocks are per Fig 1 or 2 of ASTM A1067 and individual mechanical property requirements are as follows (typical for high strength Ni-Cr-Mo alloy steels):

   Yield strength (0.1% offset) – 140/160 ksi
   Reduction in Area – 30% min.
   Charpy V-Notch resistance @ - 40 +/- 2°F – 20 ft-lb
Two (2) hardness tests shall be made on the castings at locations indicated on the solid model or drawing component and on the keel blocks produced from each heat. The hardness of the casting shall be within 25 HB (Brinell) of the keel blocks average hardness.

J. CORROSION PROTECTION

Except where stainless or corrosion resistant alloys are used, many of the high strength alloys will require surface treatments or coatings to protect against environmental corrosion and oxidation. Standard coatings for low allow steels are as follows:

Phosphate per MIL-DTL-16232, type M (Mn Phosphate Base) or Z (Zn Phosphate Base),

  - class 1 (solid film lubricant per MIL-PRF-46010 to be applied over the phosphate).
  - OR class 2 if supplementary treatment is to be lubricating oil (per MIL-PRF-3150).

K. GEOMETRIC DIMENSIONING/TOLERANCING

A final consideration is that dimensional requirements can sometimes get lost in interpretation if a standard CAD format is not used for the 3D solid model or 2D drawing, so it is essential that Geometric Dimensioning and Tolerancing (GD&T) is used. What is GD&T? It is the symbols and rules for controlling dimensions and tolerances on component drawings provided by the documents named ASME Y14.5 and Y14.8.

Why use GD&T? – It is a simple and efficient language for controlling form, orientation, and location of features depicted on a drawing. It eliminates ambiguities because it specifies which features, named datum features, are to be contacted by the inspection equipment that creates the datum planes and/or axes, used for making measurements. To apply GD&T properly the designer of the component has to consider function, manufacturing processes, and inspection methods. Also it simplifies inspection because hard gages and inspection fixtures are used.

Datums – there are three (3) types of datums (features, planes and/or axes, targets).

a) Datum Feature – existing features (surfaces) on a component. Features of size (a cylinder or opposed parallel surfaces associated with a size dimension) - location is controlled by a position tolerance and is located from datum planes/axes with basic dimensions. Features without size - location controlled by a profile tolerance and is located from datum planes/axes with basic dimensions.

b) Datum Plane and/or Axis – established by inspection equipment/devices such as surface plates, flat bottom or spherical pins, 3-jaw chuck, 60° centers, etc.

c) Datum Targets – they are the inspection devices that simulate or establish the datum planes and/or axes. They are necessary for contacting features that are not round or
flat or straight such as exist on castings. Also for contacting large features because if targets are not specified the entire feature has to be contacted by a simulator which may not exist. The assembly of the datum targets creates an inspection fixture. If the initial machining fixture duplicates the inspection fixture, layout for assuring machining stock is not required.

CONCLUSIONS

The decision to use castings in critical, high performance applications is based on the ability to produce an economic design for performance, as well as to specify the requirements for inspection and repair to reduce the risk of manufacturing variability or casting defects affecting the final part prior to use. The actual geometry or shape of the casting is only a small part of the many considerations that are used to ensure that the finished component will perform well in its intended service. It is necessary to prepare for real defects that will influence the fatigue and crack growth life through modeling and simulation, inspection of components, and by mechanical testing of actual materials for validation and verification prior to use.