Steel Alloys

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Steel castings have a variety of end-use applications that require a heavy-duty component. These castings are used in parts for railroad cars, pumps and valves, heavy trucks, construction and mining equipment and power generation equipment. A good steel casting application can provide strength while utilizing a flexible geometry inherent with the metalcasting process. Steel castings offer high mechanical properties over a wide range of operating temperatures. Further, cast steel offers the mechanical properties of wrought steel and can be welded to produce multi-piece parts as well as large structures.

Design Influence

The metalcasting process offers freedom of geometry allowing casting design to play a key role in mechanical performance. Sections of a cast part subject to higher stress can be enhanced while low-stress regions can be reduced. This flexibility can help cast a part with optimum performance and reduced weight, both of which minimize cost. It is feasible to cast any geometry, but this may increase cost.

When in the preliminary design stages, it can be advantageous to work with a metalcasting facility. Metalcasters have the technical expertise to assist with the casting design and material selection.

To develop a good casting, first reduce the number of isolated heavy sections because junctions within a casting should be designed not to add mass. When working with metalcasters, datum points should be stated, and machine stock should be added to required locations. Section thickness in a casting should be changed through smooth, easy transitions, which can be achieved by adding taper and large radii. Draft should be added to the design dimensions, but metal thickness must be maintained. The amount of draft recommended under normal conditions is 1.5 degrees. Further, reducing undercuts and internal geometry help minimize cost. The metalcasting facility and customer also should agree upon tolerances because specifying as-cast tolerances is important in minimizing cost. Other post-processing details, such as machining and how the part will be held in a fixture, also influence the final cost of the part.

Material Influence

When selecting a steel, it is important first to know the required properties. The chemical composition and microstructure of a steel casting determine its mechanical properties. Heat treatment can change microstructure and provide a wide range of mechanical properties. A steel with high hardenability will have more uniform hardness in thicker sections than a steel with low hardenability.

In general, adding alloying elements improves some properties but increases cost and may reduce other properties. However, most elements will increase the hardenability of steel.

Carbon should be kept as low as possible to maximize weldability. Minimizing alloying elements to safely meet the performance requirements of the item will reduce cost. Here, metalcasting firms can provide assistance with material selection to ensure that the appropriate properties are purchased.

The effects of common alloying elements on steel properties are given in Table 1.

Performance Conditions

Design requirements are typically determined in terms of strength or maximum stress. The design is commonly constrained by modulus, fatigue, toughness or ductility. Increasing the strength of steel normally reduces the ductility, toughness and weldability. Therefore, it often is more desirable in steel casting design to use a low-strength grade and increase the section size or modify the shape. The design freedom makes castings an attractive way to obtain the best material performance as well as the needed component stiffness and strength. When designing a part, it is important to understand the limits of the design so the proper material selection can be made. Stress, strain, fatigue, impact, wear, creep and corrosion all are common conditions that can impose design limits on steel castings.
Stress
Stress results from a mechanical load carried by a component. The strength of a steel casting is the measure of its load-carrying ability. Loads can be applied and removed without deformation if they are small enough (elasticity). When a large enough load is applied, the material will stretch and deform permanently (plasticity). Plastic deformation starts to occur when the yield strength is exceeded. The maximum load that can be applied before the material fractures is the ultimate tensile strength. Designers need to make certain that the part will not break or permanently deform, so designing a casting for stress levels below the yield strength or in the elastic region of the part is important. Typically one-half the yield strength is used for safety, but two-thirds can be utilized as long as the design is thoroughly evaluated.

The strength of steel depends on the composition and heat treatment. Steel is iron-based and alloyed mainly with carbon. Other alloying elements add strength and are important in determining how effectively the steel grade will respond to heat treatment, which rearranges the crystal structure of the iron and the distribution of carbon. During the cooling process, slow cooling rates produce coarse microstructures, which have lower strength. There are several cooling processes or means to cool part processes. Cooling slowly in the furnace is called annealing and is not commonly used, except as an intermediate treatment to allow some grades to be machined. Cooling in still air is called normalizing and is the most common treatment, providing good strength and ductility. Rapidly cooling in water or oil is known as quenching. Although steel must be reheated or tempered after quenching to improve ductility, quenching and tempering gives the highest strength available from any grade. A wide range of final strength levels with quenched and tempered grades can be achieved by varying tempering time and temperature.

![Graph showing cast low-alloy steel properties at room temperature including yield strength, elongation percentage and ultimate tensile strength. NT denotes Normalize and Temper. QT denotes Quench and Temper.](image1)

![Graph showing 1080 steel alloy tire mold segment produced using a ceramic casting process and achieved an as-cast surface finish of 63 RMS or better, improving surface integrity.](image2)
Strain

Strain is the amount of stretching in a loaded component. Steel can be bent, twisted or stretched without breaking, and this ability to absorb strain without fracturing is critical to safety and reliability. Strain is measured by determining the amount of permanent stretch (plastic deformation) in the tensile bar test. The increase in length is elongation, and the change in area at the point of fracture of the bar is reduction of area. The ability to stretch without cracking is called ductility.

Although many designers think in terms of the material’s strength, most steel production is in the lower strength grades, which have good ductility. Carbon content and heat treatment also influence strength and ductility, as shown in Fig. 1. Carbon contents typically are kept well below 0.3% to avoid problems with cracks in heat treating or welding.

The ratio of stress to strain is the elastic modulus, and the data is derived from a tensile test. The modulus of elasticity is based solely on the material; heat treatment does not affect modulus. Steels have a modulus of approximately $30 \times 10^6$ psi, which is the highest modulus of elasticity of commonly used cast or wrought materials. The larger the modulus, the smaller the deflection of a part. Therefore, steel provides good stiffness.

Fatigue

Fatigue is the failure of a component when it is repeatedly loaded, even at levels well below the yield strength of the steel. It is measured by repeated loadings of several bars at different stress levels and determining...
the number of cycles until failure. A typical result of the stress versus cycles is shown in Fig. 2. Low-cycle fatigue is below 100,000 loadings where ductility is needed. High-cycle fatigue is normally above 1 million loadings, and high strength is required.

Impact
Impact affects the steel’s ability to resist fracture or cracking during use. The steel’s ability to resist cracking at low temperatures or during impact loading is known as toughness, which is measured by the amount of energy required to break the material at a certain temperature. A common test that measures this is the Charpy impact test. Unlike ductility, toughness tends to decline as the strength of the material increases. The reduction in toughness at higher carbon contents for two heat treatments is shown in Fig. 3.

Wear
Wear occurs when materials rub against each other under load and material is lost from the contacted surface. There is no standard test for wear-resistant materials. Gouging, abrasion, impact and corrosion must be considered in different types of applications. Typically, harder materials resist wear more effectively. Because hardness increases with strength (due to higher carbon content) higher strength steels are commonly used. Retaining adequate toughness at the high hardness levels to avoid cracking and premature failures is important.

Creep
Creep occurs at elevated temperatures when the material permanently stretches at loads below the yield strength. Creep resistance requires complex alloys with relatively high carbon contents. Often, as the temperature or load increases, higher alloy contents are required for the casting to perform efficiently. Creep rate is the rate of stretching at a particular load and temperature, and stress rupture is the time to failure under a given load at a particular temperature. When selecting a creep-resistant material, oxidation or other high-temperature corrosion must be considered because they might limit the service life of the component.

Corrosion
Corrosion is a chemical attack that removes material from the exposed surface. It can be a general loss of material or a localized condition like pitting, cracking or selective attack. There are standard tests for corrosion, but these rarely replicate service conditions or the nature of the environment. Corrosive conditions, such as temperature, pH, oxygen, chlorine and other variables, must be taken into account when selecting the proper cast materials.

Alloy Selection
There is a structural-direction difference between cast and wrought material. The structure of sections of rolled steel is elongated in the direction of rolling. The strength and ductility is improved in that direction, but they are reduced across the rolling direction. The cold rolling of steel also can strengthen the steel but reduces ductility and toughness. Contrarily, the lack of a rolling direction in steel castings gives them uniform properties in all directions. Cast steel grades achieve the same tradeoff by alloying and heat treating. Therefore, castings grades with similar mechanical properties to wrought are designated with a different name (ASTM A216 grade WCB is the cast counterpart to wrought 1020). ASTM A915 and A958 use grade names similar to their wrought counterparts.

When selecting a steel alloy, the design limit first should be understood. It is essential to know how and where failures may occur, and selecting a material can help address the design limit. Alloying elements can be added to improve performance, thus, the best practice is starting with a carbon steel and building from there. A material selection guide for five major design applications is shown in Fig. 4. This chart is meant to provide some initial guidance, but it also is important to consult with a metalcasting facility to select the right material for each application. This is especially true of higher-alloyed materials (outer rings in the figure). Other alloys may be better, and the alloy and heat treatment can be tailored for specific conditions.

There are a number of applications for steel castings, but following are descriptions of the common uses.

Structural Applications
Structures apply to general applications controlled by strength, deflection and fatigue. Strength and ductility still are the main properties used to designate available steel grades. Increasing the strength of steel is easily achieved through more severe heat treatments or increases in the alloy content. The addition of alloying elements not only increases the strength that an alloy can achieve but also increases the section size of the part, which can be effectively heat treated.

The grades in Table 2 are common alloys of steel available for casting ASTM A915 or A958. The first column is the alloy designation, the second is the minimum requirements for the lowest strength grade commonly available from that alloy, the third column is the minimum requirements for the highest strength grade, and the last column is the calculated largest section, which can be effectively heat treated through the section. It is apparent that higher-strength alloys have lower ductility but can be heat treated more effectively in larger sections.

<table>
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<tr>
<th>Table 2. Common Steel Alloys for Casting ASTM A915 or A958</th>
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<tr>
<td><strong>ASTM A915</strong> <em>(Grade)</em></td>
</tr>
<tr>
<td>SC1020</td>
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<tr>
<td>SC1030</td>
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<tr>
<td>SC1040</td>
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<td>SC8620</td>
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However, higher strength alloys also require more extensive weld procedures and may crack in heat treatment, especially at high carbon contents.

Resistance to fatigue depends on the strength, ductility, service conditions, corrosion, residual stresses in the component, design (particularly in high-stress areas), surface finish and required service life of the component. Fatigue analysis is difficult, but component testing is not unusual to verify the design and part durability. Properties, such as strain-controlled cyclical properties, crack growth rates, integration of inspection standards and life prediction, improve designs by reducing the traditional requirements for factor of safety and allow for a more aggressive use of material. Analytical tools like computer modeling of service loads, along with the development of useful materials properties, reduce the number of necessary design iterations. Castings allow the geometry to be tailored to the service requirements. Steels for structural applications can be found in ASTM A27, A148, A747, A915 and A958.

Pressure-Containing Applications

These applications have similar characteristics to structural applications. Specifications for pressure-containing applications have been developed to meet ASME Boiler and Pressure Vessel Code. These steels can be ordered in ASTM A217, A487, A352, A389 and A757.

Impact-Resistant Applications

Impact resistance, or toughness, is required when a part is subject to low temperatures, performs a safety-critical function or is impact loaded in service. It can be improved through careful control of composition and heat treatment. Adding nickel is the common way to improve toughness. The toughness of all grades can be improved by lowering carbon, sulfur and phosphorus and using a quench and temper heat treatment. Further, toughness tests should be required when necessary. These steels can be ordered in ASTM A352 and A743 for stainless.

Temperature-Resistant Applications

High temperature resistance, or creep strength, is required to carry loads at elevated temperatures. As the temperature increases, the alloy content required also increases. Commonly, chromium and molybdenum are added to the steel to improve elevated temperature properties. Higher carbon content also helps. The preferred heat treatment of carbon and low alloy steels is normalizing and tempering. These steels are found in ASTM A216 and A217. When the service temperatures exceed 1,200°F (649°C), the alloyed steels are no longer adequate, and the cast heat-resistant grades containing high levels of chromium and nickel are used. Such alloys are ASTM A297 and A351.

Wear-Resistant Applications

Wear applies to mechanical wear and chemical corrosion. Severe wear or corrosion environments require high alloy steels. Wear resistance is usually improved through using high hardness materials. Strength and hardness are related, so the high-strength materials are commonly used when wear is a problem. Increasing carbon content also increases wear resistance. Special materials like austenitic manganese alloys or high-chromium irons are used to give better wear resistance. Toughness must be adequate to avoid premature catastrophic failure. High-chromium irons offer good wear resistance in abrasion or even in corrosive environments. When impact loading is a part of the wear environment, austenitic manganese alloys work-harden, allowing them to resist wear.

The REX 77 requires some assembly to make it dive-ready, but the stainless steel casting combines a shell and locking mechanism that were cast separately on its bronze predecessor.
while maintaining high toughness. Severe environments, such as salt water and chemical processing, require high-alloy stainless steels or nickel-based alloys. Generally, higher contents of chromium and molybdenum are needed as the environment becomes more severe. Corrosion-resistant materials heavily depend upon the end-use environment for selecting the correct alloy; thus, a metallurgist should be consulted. Wear materials are found in ASTM A128, A351, A532, A743, A744, A890 and A494. Carbon or alloy steels may be used in less severe environments.

**Keys to Steel Use**

Cast steel alloys provide a wide range of options. With cast steel, engineers can design components to increase different performance characteristics, such as corrosion resistance and wear resistance through alloying and heat treatment. Mechanical properties, such as strength and elongation, also can be adjusted. When purchasing parts, supplying a part design with material and requirements is important, and material should be designated with a specification and grade (i.e. ASTM A 27/A 27M - 95 Grade 60-30 Class 1). Requirements should call out both the test method and acceptance criteria specifications. Mechanical properties are typically obtained from separately cast test bars.

There are three keys to selecting the right steel casting alloy for optimized performance and cost. One, utilize the geometry of the steel casting to uniformly carry the loading. Secondly, start with carbon steel for most applications, modify the heat treatment and then add alloying elements to improve properties. Finally, engineers should know the design limit for an application and work with a metalcasting facility to design the part and select a material.