Steel Casting Mechanical Properties

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Carbon and low alloy steel castings are used in parts for railroad cars, pumps and valves, heavy trucks, construction and mining equipment, and power generation equipment. Good applications utilize the performance of steel with the flexible geometry of a casting. Steel castings offer high mechanical properties over a wide range of operating temperatures. Cast steel offers the mechanical properties of wrought steel and can be welded.

Design Impact

Casting offers freedom of geometry, so casting part design plays a key role in mechanical performance. Sections of a cast part subject to higher stress can be beefed up while low stress regions can be reduced. This flexibility facilitates a part with optimum performance and reduces weight; both minimize cost. One way to ensure the best casting design is to work with a foundry on design. A foundry will have the technical expertise to partner on the casting the design and material selection.

There are several rules of thumb to the development of a good casting. First, reduce the number of isolated heavy sections and have smooth flowing transitions. It is feasible to cast any geometry but this may increase cost. Junctions within a casting should be designed not to add mass. Changing section thickness in a casting should be through smooth, easy transitions, adding taper and large radii help. Reducing undercuts and internal geometry help to minimize cost. The foundry and customer should agree upon tolerances. Specifying as-cast tolerances is also important in minimizing cost. Other post-processing such as machining and how the part will be held in a fixture also influence the final cost of the part. Datum points should be stated and machine stock should be added to required locations. Draft is the amount of taper or the angle, which must be allowed on all vertical faces of a casting tool to permit its removal from the mold without tearing the mold walls. Draft should be added to the design dimensions but metal thickness must be maintained. The amount of draft recommended under normal conditions is about 1.5 degrees. Design resources and tutorials are available at www.sfsa.org.

Material Impact

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. The response to heat treatment for a given section is hardenability. A steel with a high hardenability will have uniform hardness in thicker sections, than ones with low hardenability.

In general, adding alloying elements increases cost, improves some properties, but may reduce others. Most elements will increase the hardenability of steel. The effects of common alloying elements on steel properties are given in Table 1.

Table 1: Effect of Alloying Element

Element	Effect on Steel Properties
Carbon (C)	Increases strength but decreases toughness and weldability (most common and important)
Manganese (Mn)	Similar, although lesser, affect as carbon
Silicon (Si)	Similar to carbon but with a lesser affect than manganese (important for castability)
Nickel (Ni)	Improves toughness
Chromium (Cr)	Improves oxidation resistance
Molybdenum (Mo)	Improves hardenability and high temperature strength
Vanadium (V)	Improves high temperature strength
Tungsten (W)	Improves high temperature strength
Aluminum (Al)	Reduces the oxygen or nitrogen in the molten steel
Titanium (Ti)	Reduces the oxygen or nitrogen in the molten steel
Zirconium (Zi)	Reduces the oxygen or nitrogen in the molten steel
Oxygen (O)	Negative effect by forming gas porosity
Nitrogen (N)	Negative effect by forming gas porosity

Hydrogen (H)	In high quantities, results in poor ductility
Phosphorus (P)	Can increase strength but drastically reduces toughness and ductility
Sulfur (S)	Reduces toughness and ductility

When selecting a steel, it is important to first know the required properties. 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. The foundry can provide assistance with material selection to ensure the appropriate properties are purchased.

Design Considerations

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. It is often more desirable in steel casting design to use a lower strength grade and increase the section size or modify the shape. The design freedom makes castings an attractive way to obtain the best fabrication and material performance, and the needed component stiffness and strength. When designing a part, it is important to understand the design limit so that proper material selection can be made. Stress, strain, fatigue, impact, wear, creep, and corrosion are all common service conditions that can impose design limits.

Stress results from a mechanical load carried by a component. The strength of a steel 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 ensure that the part will not break or permanently deform. Thus, it is important to design a casting for stress levels below the yield strength or in the elastic region of the part. Typically1/2 the yield strength is used for safety, but 2/3 can be utilized with a thorough evaluation.

The strength of steel depends on the composition and heat treatment. Steel is iron-based alloyed mainly with carbon. Other alloying elements add strength but are also important in determining how effectively the steel grade will respond to heat treatment. Heat treatment rearranges the crystal structure of the iron and the distribution of carbon. Slow cooling rates produce coarse microstructures, which have lower strength. 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. Steel must be reheated or tempered after quenching to improve ductility. Quenching and tempering gives the highest strength available from any grade. Varying the tempering temperature and time allows the production of a wide range of final strength levels with a quenched and tempered grade.

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

In general, increasing the strength of a steel grade reduces its ductility. While most designers think in terms of the material's strength, most of the production of steel is in the lower strength grades, which have good ductility. Carbon content and heat treatment influence strength and ductility; shown in Figure 1. Carbon contents are typically kept well below 0.30% to avoid problems with cracks in heat treating or welding.

The relationship between the ratio of stress to strain is the elastic modulus. 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 x 10^6 psi. Steels have the highest modulus of elasticity of commonly used materials. The larger the modulus the smaller the deflection of a part; steel provides good stiffness.

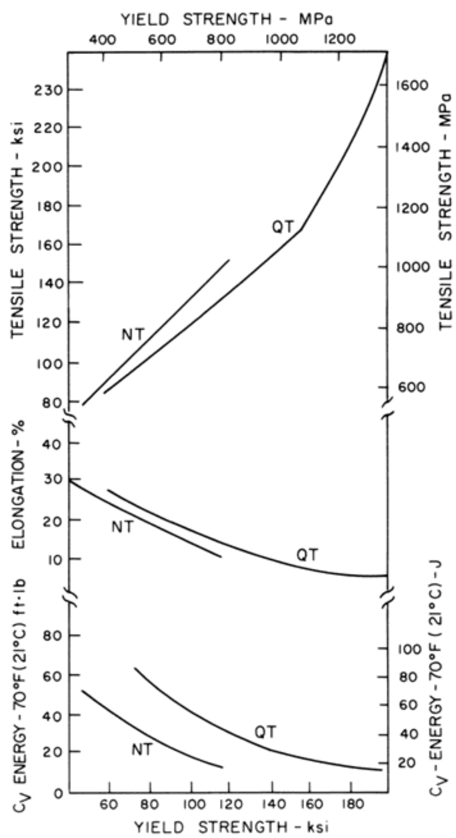

Figure 1: Cast low alloy steel properties at room temperature

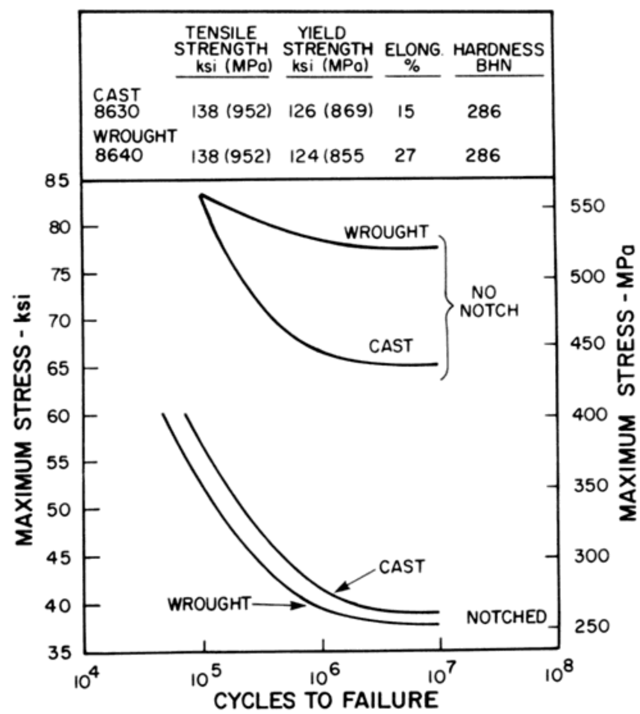

Figure 2: Cast and wrought 8600 series steel fatigue properties

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 to failure. A typical result of the stress versus cycles is shown in Figure 2. Low cycle fatigue is below 100,000 loadings where ductility is needed. High cycle fatigue is normally above 1,000,000 loadings and high strength is required.

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

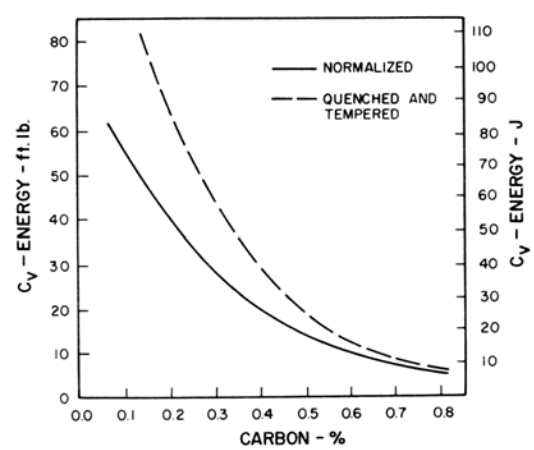

Figure 3: Cast carbon steel Charpy V-notch properties at room temperature

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 better. Since hardness increases with strength, higher carbon, higher strength steels are commonly used. It is important to retain adequate toughness at the high hardness levels to avoid cracking and premature failures.

Creep occurs at elevated temperatures when the material permanently stretches at loads below the yield strength. Resisting creep requires complex alloys with relatively high carbon content. Generally as the temperature or load increases, higher alloy contents are required for adequate performance. Creep rate is the rate of stretching at a particular load and temperature. Stress rupture is the time to failure under a given load at a particular temperature. Selection of a material for creep service must also take into account the oxidation or other high temperature corrosion, which might limit the service life of the component.

Corrosion is a chemical attack, which 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 considered when selecting a material for service.

Alloy Selection

The structure of rolled sections of 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, Figure 4. The lack of a rolling direction in steel castings gives them uniform properties in all directions. The cold rolling of steel can also strengthen the steel but reduces ductility and toughness. Cast steel grades achieve the same trade off by alloying and heat treatment. Therefore, casting grades with similar mechanical properties to wrought are called out with a different name (e.g. ASTM A216 grade WCB is the cast counterpart to wrought 1020). ASTM A915 and A958 both use grade names similar to their wrought counterparts.

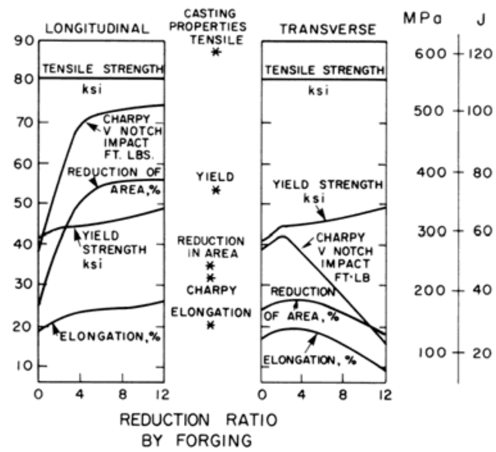

Figure 4: Directionality impact on properties of formed steel

Selecting a steel alloy begins with understanding the design limit. Knowing the major mode of failure is key. Material selection can be utilized to address the design limit. Alloying elements can be added to improve performance; thus, starting with a carbon steel and building from there is the best practice. A material selection guide for five major design applications is shown in Figure 5. This chart is meant to provide some initial guidance. It is important to consult with a foundry to select the right material for each application. This is especially true of higher alloyed materials (outer rings in figure). Other alloys may be better, and the alloy and heat treatment can be tailored for specific conditions.

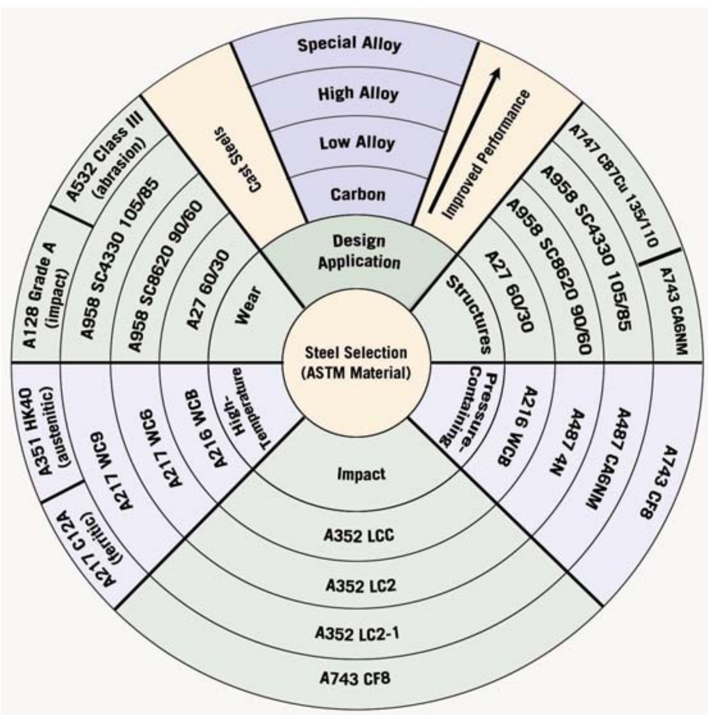

Figure 5: Cast steel material selection guide

Structures apply to general applications governed by strength, deflection, and fatigue. Strength and ductility are still 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, it 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. Higher strength alloys also require more extensive weld procedures and may crack in heat treatment especially at high carbon contents.

Table 2: Common Cast Steel Properties

ASTM A915 (Grade)	Minimum Low Strength Tensile (ksi) Yield (ksi) Elongation (%)	Minimum High Strength Tensile (ksi) Yield (ksi) Elongation (%)	Median Composition Ideal Critical Diameter (inches)
SC1020	65-35-24	70-36-22	0.4
SC1030	65-35-24	80-50-22	0.7
SC1040	70-36-22	90-60-20	0.9
SC8620	80-50-22	115-95-14	2.0
SC8630	80-50-22	150-135-7	3.5
SC4130	80-50-22	150-135-7	3.0
SC4140	90-60-20	165-150-5	5.5
SC4330	90-60-20	210-180-4	6.0
SC4340	90-60-20	210-180-4	8.0

Fatigue resistance 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 and component testing is not unusual to verify the design and part durability. Analytical tools like computer modeling of service loads, along with the development of useful materials properties, reduces the number of design iterations. 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 more aggressive use of material. 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.

<u>Pressure containing</u> 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.

<u>Impact</u> resistance, or toughness, is required when a part performs a safety critical function, is subject to low temperatures, 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 by using a quench and temper heat treatment. When toughness is needed, it should be a required test. These steels can be ordered in ASTM A352 and A743 for stainless.

<u>High temperature</u> 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 normalize and temper. These steels are found in ASTM A216 and A217. When the service temperatures exceed 1200 F, the alloyed steels are no longer adequate and the cast heat resistant grades containing high levels of chromium and nickel are used. These alloys are in ASTM A297 and A351.

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 while maintaining high toughness. Severe environments, such as salt water and chemical processing, require high alloy stainless steels or nickel based alloys. Generally, higher 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.

Conclusions

Cast steel alloys provide a wide range of options. One can increase different performance characteristics such as corrosion resistance and wear resistance through alloying and heat treatment. Mechanical properties such as strength and elongation can be adjusted. A summary of steel casting material specifications can be found in Supplement 2 at www.sfsa.org/sfsa/pubs/index.html.

When purchasing parts, it is important to supply a part design with material and requirements. Material should be called out with a specification and grade (e.g. 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. Two, start with carbon steel for most applications; modify the heat treatment and then add alloying elements to improve properties. Three, know the design limit for an application and work with a foundry to design the part and select a material.

References

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