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Mechanical Properties of Stainless Steels

By:
Vipin Kumar Sharma

Maharaja Agrasen Institute of Technology




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Introduction

- ▶ Iron Chromium (Fe-Cr) alloys often with Nickel (Ni) additions known as stainless steels.
- ▶ These steels have at-least 10.5% of chromium with Varying additions of nickel, molybdenum, titanium, niobium and other elements may also be present.
- ▶ These steels “do not rust in sea water”, are resistant to concentrated acids”, “do not scale up to temperature of 1100 degree Celcius”



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Usage of Stainless Steels

- ▶ Usage of stainless steels in practical applications is less as compared to carbon steels but it exhibits a steady growth
- ▶ Figure 1: represents the worldwide steel production 1970- 2015.

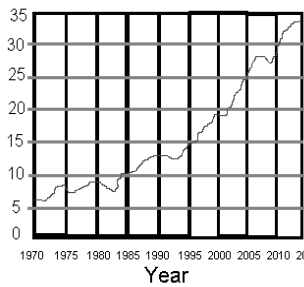


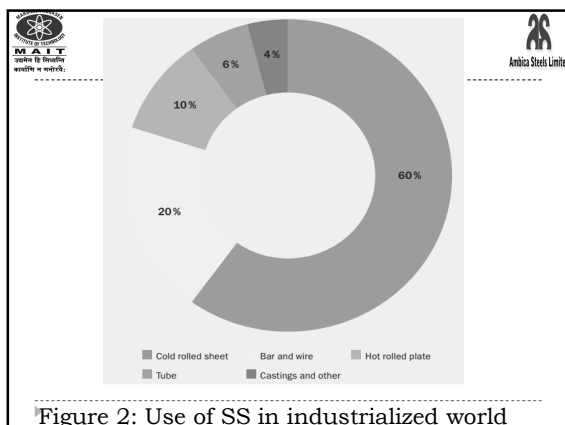


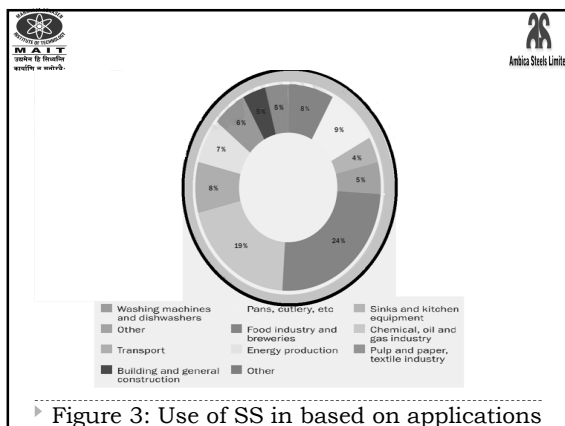
Figure 1: Worldwide steel production 1970-2015

▶ The most widely used stainless steel grades are the Austenitic Cr-Ni 18-8 type steels (EN 1.4301/1.4307) which is about 50 % of the global production of stainless steel.

▶ Ferritic Cr-Steel such as 1.4512 and 1.4016 and Molybdenum-alloyed Cr-Ni-Mo Austenitic steel 1.4401/1.4404 are the other most used stainless Steel.





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Mechanical Properties of Stainless Steel

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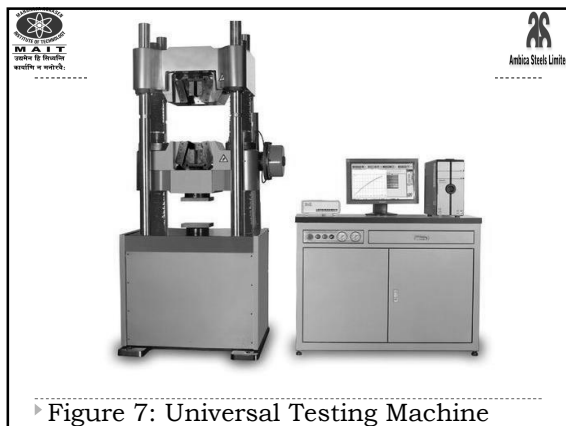
- ▶ Stainless steels are often selected for its corrosion resistance.
- ▶ Strength, High-Temperature Strength, Ductility, Hardness, Toughness are also important.
- ▶ Stress-Strain curves are generally used to visualize the difference between various mechanical properties.

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Engineering Stress- Strain Curve

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▶ Figure 4: Typical stress strain curve



▶ Figure 7: Universal Testing Machine



The true stress strain curves are for example used to characterize the work hardening of steel, i.e. how much the stress increases with plastic strain. The amount of hardening depends on both the composition and the type of steel (austenitic, ferritic, duplex or martensitic). The commonly used work hardening exponent n is defined as

$$\sigma = K \cdot \epsilon^n$$

where σ and ϵ are true stress and true strain respectively. The exponent n gives a simple measure of the tendency to work harden and K is the strength hardening coefficient.

Room Temperature Properties

▶ In terms of mechanical properties, stainless steels can be roughly divided into four groups with similar properties within each group: martensitic and ferritic-martensitic, ferritic, ferritic-austenitic and austenitic. Table 2 gives typical mechanical properties at room temperature for a number of stainless steels.

▶ The work hardening is larger for austenitic steels than for ferritic steels. The addition of nitrogen in austenitic steels makes these grades particularly hard and strong: compare 316L and 316LN.

▶ The strong work hardening of the austenitic steels means that large forces are required for forming operations even though the yield strength is low.

▶ Work hardening can, however, also be deliberately used to increase the strength of a component.








Table 3 : Response of cold working on Austenetic stainless Steel to varying degrees.

Grade	% Cold work	Yield strength (0.2% offset) MPa	Tensile strength MPa
301	10% Cold work	585	1,035
	30% Cold work	1,035	1,275
	50% Cold work	1,310	1,445
304	10% Cold work	480	685
	30% Cold work	825	860
	50% Cold work	1,000	1,100
310	10% Cold work	470	744
	30% Cold work	854	965
	50% Cold work	1,010	1,145

Hardness

Hardness is a measure of how resistant a material is to a permanent shape change when a force is applied. For metals, indentation hardness is typically used and measures the resistance of deformation due to a constant compression load from a sharp object normal to the metal surface. The test measures the critical dimensions of an indentation left by a loaded indenter. Common hardness scales are Rockwell (HRB), Vickers (HV) and Brinell (HB) and they differ primarily in the shape of the indenter and how the hardness is determined from the indentation shape.

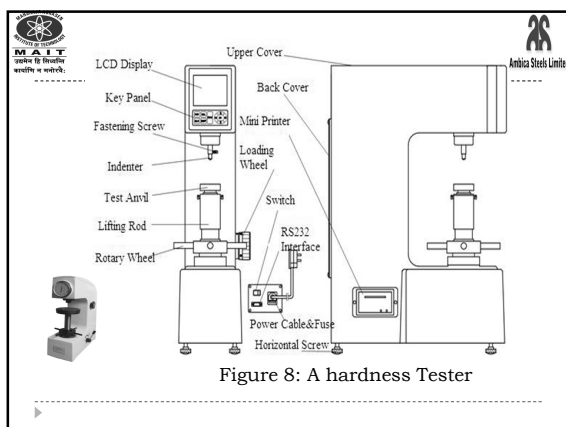




Figure 8: A hardness Tester



Brinell Hardness Test The Brinell test for determining the hardness of metallic materials consists of applying a known load to the surface of the material to be tested through a hardened steel ball of known diameter. The diameter of the resulting permanent impression in the metal is measured and the Brinell Hardness Number (BHN) is then calculated from the following formula in which D = diameter of ball in millimeters, d = measured diameter at the rim of the impression in millimeters, and P = applied load in kilograms.

$$BHN = \frac{\text{load on indenting tool in kilograms}}{\text{surface area of indentation in sq. mm.}} = \frac{P}{\frac{\pi D}{2} (D - \sqrt{D^2 - d^2})}$$

According to the American Society for Testing and Materials Standard E10-66, a steel ball may be used on material having a BHN not over 450, a Hultgren ball on material not over 500, or a carbide ball on material not over 630. The Brinell hardness test is not recommended for material having a BHN over 630.

Vickers Hardness Test The Vickers test is similar in principle to the Brinell test. The standard Vickers penetrator is a square-based diamond pyramid having an included point angle of 136 degrees. The numerical value of the hardness number equals the applied load in kilograms divided by the area of the pyramidal impression: A smooth, firmly supported, flat surface is required. The load, which usually is applied for 30 seconds, may be 5, 10, 20, 30, 50, or 120 kilograms. The 50 kilogram load is the most usual. The hardness number is based upon the diagonal length of the square impression. The Vickers test is considered to be very accurate, and may be applied to thin sheets as well as to larger sections with proper load regulation.

Rockwell Hardness Test The Rockwell hardness tester is essentially a machine that measures hardness by determining the depth of penetration of a penetrator into the specimen under certain fixed conditions of test. The penetrator may be either a steel ball or a diamond spheroidal penetrator.

The hardness number is related to the depth of indentation and, as the number is higher, the harder the material.

A minor load of 10 kg is first applied, causing an initial penetration; the dial is set at zero on the black-figure scale, and the major load is applied. This major load is customarily 60 or 100 kg when a steel ball is used as a penetrator, but other loads may be used when necessary.

After the major load is applied and removed, according to standard procedure, the reading is taken while the minor load is still applied.









Table 4: Comparison of Hardness Scale for testing Applications


Scale	Indenter	Minor Load (kgf)	Major Load (kgf)	Testing Application
HRA	Brale Diamond	10	60	Cemented carbides, thin steel and shallow case hardened steel
HRB	1/16" ball	10	100	Copper alloys, soft steels, aluminum alloys, malleable iron
HRC	Brale Diamond	10	150	Steel, hard cast irons, pearlitic malleable iron, titanium, deep case hardened steel and other materials harder than B100
HRD	Brale Diamond	10	100	Thin steel and medium case hardened steel and pearlitic malleable iron
HRE	1/16" ball	10	100	Cast iron, aluminum and magnesium alloys, bearing metals
HRF	1/16" ball	10	60	Annealed copper alloys, thin soft sheet metals
HRG	1/16" ball	10	150	Phosphor bronze, beryllium copper, malleable irons. Upper limit G92 to avoid possible flattening of ball
HRH	1/8" ball	10	60	Aluminum, zinc, lead
HRK	1/8" ball	10	150	
HRL	1/4" ball	10	60	
HRM	1/4" ball	10	100	
HRP	1/4" ball	10	150	
HRR	1/2" ball	10	60	Bearing metals and other very soft or thin materials, including plastics. Use the smallest ball and heaviest load that do not give anvil effect.
HRS	1/2" ball	10	100	
HRV	1/2" ball	10	150	

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- ▶ In many cases there are no fatigue limit but the stress amplitude shows a slow decrease with increasing number of cycles.
- ▶ In these cases the fatigue strength, i.e. the maximum stress amplitude for a certain time to failure (number of cycles) is called the fatigue strength and it is always given in relation to a certain number of cycles.

 **Toughness**
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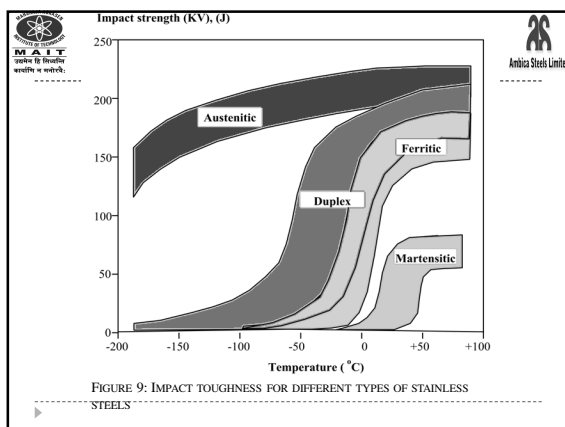
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- ▶ The toughness of the different types of stainless steels shows considerable variation, ranging from excellent toughness at all temperatures for the austenitic steels to the relatively brittle behaviour of the martensitic steels.
- ▶ Toughness is dependent on temperature and generally increases with increasing temperature. One measure of toughness is the impact toughness, i.e. the toughness measured on rapid loading.

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- ▶ Figure 9 shows the impact toughness for different categories of stainless steel at temperatures from -200 to +100 °C.
- ▶ It is apparent from the diagram that there is a fundamental difference at low temperatures between austenitic steels and martensitic, ferritic and ferritic-austenitic steels.



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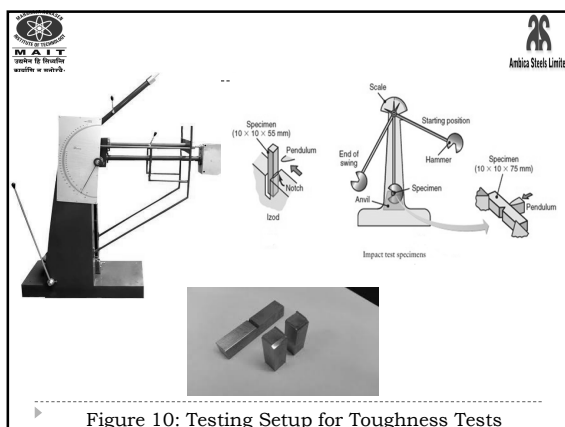
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- ▶ The martensitic, ferritic and ferritic-austenitic steels are characterised by a transition in toughness, from tough to brittle behaviour.
- ▶ For the ferritic steel the transition temperature increases with increasing carbon and nitrogen content, i.e. the steel becomes brittle at successively higher temperatures.
- ▶ For the ferritic-austenitic steels, an increased ferrite content gives a higher transition temperature, i.e. more brittle behaviour.
- ▶ .

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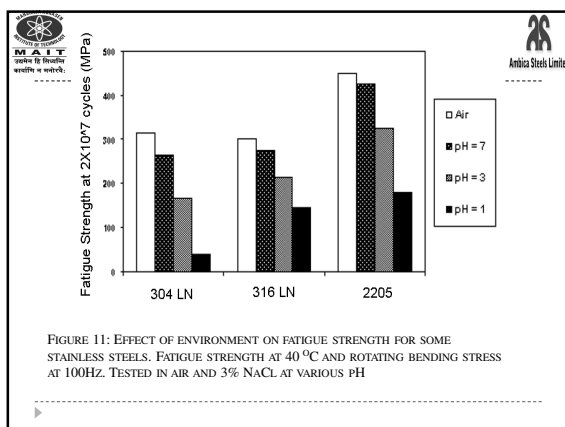
- ▶ Martensitic stainless steels have transition temperatures around or slightly below room temperature, while those for the ferritic and ferritic-austenitic steels are in the range 0 to - 60°C, with the ferritic steels in the upper part of this range.
- ▶ The austenitic steels do not exhibit a toughness transition as the other steel types but have excellent toughness at all temperatures. Austenitic steels are thus preferable for low temperature applications

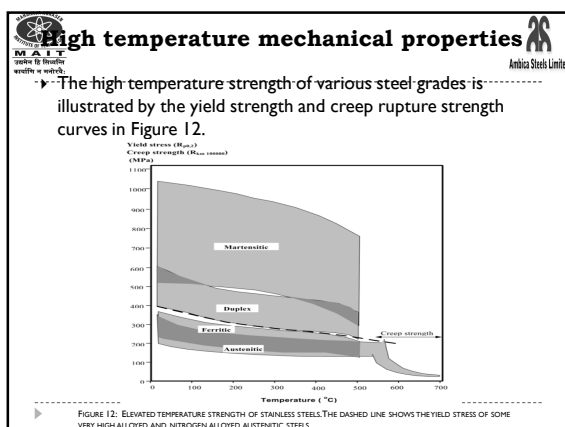


Effect of pH level on fatigue strength

- ▶ The fatigue strength is sensitive to the service environment and under both cyclic loading and corrosive conditions, corrosion fatigue, the fatigue strength will generally decrease. In many cases there is no pronounced fatigue limit, as observed in air, but a gradual lowering of the fatigue strength with increasing number of load cycles. The more aggressive the corrosive conditions and the lower the loading frequency the higher the effect of the environment. During very high frequency loads there is little time for the corrosion to act and the fatigue
- ▶ Properties of the material will mostly determine the service life. At lower frequencies the corrosive action is more pronounced and an aggressive environment may also cause corrosion attacks that will act as stress concentrations and thus contribute to a shorter life.

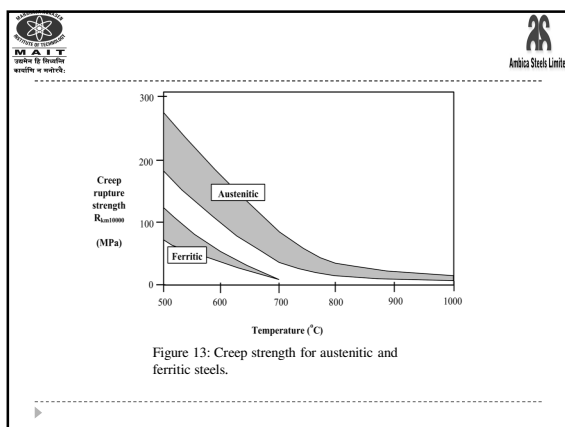
- ▶ A lower pH, i.e. a more aggressive condition, gives a lower fatigue strength. Comparison of the two austenitic steels shows that the higher alloyed grade, 316LN, that has the higher corrosion resistance also has a higher corrosion fatigue strength.





Ferritic steels have relatively high strength up to 500°C. The creep strength, which is usually the determining factor at temperatures above 500°C, is low. The normal upper service temperature limit is set by the risk of embrittlement at temperatures above 350°C. However, due to the good resistance of chromium steels to high temperature sulphidation and oxidation a few high chromium grades are used in the creep range. In these cases special care is taken to ensure that the load is kept to a minimum.

The ferritic-austenitic (duplex) steels behave in the same way as the ferritic steels but have higher strength. The creep strength is low. The upper service temperature limit is normally 350°C due to the risk of embrittlement at higher temperatures. Most austenitic steels have lower strength than the other types of stainless steels in the temperature range up to about 500°C. The highest elevated temperature strength among the austenitic steels is exhibited by the nitrogen alloyed steels and those containing titanium or niobium. In Figure the elevated temperature strengths of most of the ordinary austenitic steels fall within the marked area. The dashed line represents the elevated temperature strength of a few high alloyed and nitrogen alloyed austenitic steels. In terms of creep strength the austenitic stainless steels are superior to all other types stainless steel.



The effects of the alloying elements



The alloying elements each have a specific effect on the properties of the steel. It is the combined effect of all the alloying elements and, to some extent, the impurities that determine the property profile of a certain steel grade.

► **Chromium (Cr)**
 This is the most important alloying element in stainless steels. It is this element that gives the stainless steels their basic corrosion resistance. The corrosion resistance increases with increasing chromium content. It also increases the resistance to oxidation at high temperatures. Chromium promotes a ferritic structure.

► **Nickel (Ni)**
 The main reason for the nickel addition is to promote an austenitic structure. Nickel generally increases ductility and toughness. It also reduces the corrosion rate and is thus advantageous in acid environments. In precipitation hardening steels nickel is also used to form the intermetallic compounds that are used to increase the strength.

► **Molybdenum (Mo)**
 Molybdenum substantially increases the resistance to both general and localised corrosion. It increases the mechanical strength somewhat and strongly promotes a ferritic structure. Molybdenum also promotes the formation secondary phases in ferritic, ferritic-austenitic and austenitic steels. In martensitic steels it will increase the hardness at higher tempering temperatures due to its effect on the carbide precipitation.



► **Copper (Cu)**
 Copper enhances the corrosion resistance in certain acids and promotes an austenitic structure. In precipitation hardening steels copper is used to form the intermetallic compounds that are used to increase the strength.

Manganese (Mn)

Manganese is generally used in stainless steels in order to improve hot ductility. Its effect on the ferrite/austenite balance varies with temperature: at low temperature manganese is an austenite stabiliser but at high temperatures it will stabilise ferrite. Manganese increases the solubility of nitrogen and is used to obtain high nitrogen contents in austenitic steels.

- ▶ **Silicon (Si)**
Silicon increases the resistance to oxidation, both at high temperatures and in strongly oxidising solutions at lower temperatures. It promotes a ferritic structure.
- ▶ **Carbon (C)**
Carbon is a strong austenite former and strongly promotes an austenitic structure. It also substantially increases the mechanical strength. Carbon reduces the resistance to inter-granular corrosion. In ferritic stainless steels carbon will strongly reduce both toughness and corrosion resistance. In the martensitic and martensitic-austenitic steels carbon increases hardness and strength. In the martensitic steels an increase in hardness and strength is generally accompanied by a decrease in toughness and in this way carbon reduces the toughness of these steels.






▶ **Nitrogen (N)**

Nitrogen is a very strong austenite former and strongly promotes an austenitic structure. It also substantially increases the mechanical strength. Nitrogen increases the resistance to localised corrosion, especially in combination with molybdenum. In ferritic stainless steels nitrogen will strongly reduce toughness and corrosion resistance. In the martensitic and martensitic-austenitic steels nitrogen increases both hardness and strength but reduces the toughness.

▶ **Titanium (Ti)**

Titanium is a strong ferrite former and a strong carbide former, thus lowering the effective carbon content and promoting a ferritic structure in two ways. In austenitic steels it is added to increase the resistance to inter-granular corrosion but it also increases the mechanical properties at high temperatures. In ferritic stainless steels titanium is added to improve toughness and corrosion resistance by lowering the amount of interstitials in solid solution.

▶ **Niobium (Nb)**

Niobium is both a strong ferrite and carbide former. As titanium it promotes a ferritic structure. In austenitic steels it is added to improve the resistance to inter-granular corrosion but it also enhances mechanical properties at high temperatures. In martensitic steels niobium lowers the hardness and increases the tempering resistance.

▶ **Aluminium (Al)**

Aluminium improves oxidation resistance, if added in substantial amounts. It is used in certain heat resistant alloys for this purpose. In precipitation hardening steels aluminium is used to form the intermetallic compounds that increase the strength in the aged condition.

▶ **Cobalt (Co)**

Cobalt only used as an alloying element in martensitic steels where it increases the hardness and tempering resistance, especially at higher temperatures.
