STAINLESS STEEL
INFORMATION SERIES

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THE MECHANICAL PROPERTIES OF STAINLESS STEEL

Stainless steel is primarily utilised on account of its corrosion resistance. However, the scope of excellent mechanical properties offered by the various classifications and grades within the family of stainless steel render it extremely versatile.

Throughout this article nominal or typical values will be used to illustrate the different properties being discussed and will be referred to as nominal values.

The nominal values are those that are the norm for the various properties, but it is stressed that these must not be regarded as minimum, nor for some properties maximum, values for specification purposes.

The nominal values inevitably vary, depending on the reference or source of the publication. E.g. grade 304 hot rolled and annealed plate at room temperature.

	Tensile Strength	Yield
Source A	565 MPa	241 MPa
Source B	600 MPa	310 MPa
Specification ASTM A240	500 MPa (min)	205 MPa (min)

As may be seen from this example, it is usually the case that the specified values are of a lower (or more conservative) value than the nominal values.

Therefore, if guaranteed values are required, reference must be made to the actual specification.

Different specifications stipulate different values and this can lead to either less or more cost-effective utilization of stainless steel material, a factor that is of importance when considering the higher price of stainless steel relative to other materials of construction.

MECHANICAL PROPERTIES

The mechanical properties are a measure of the metal's response to an applied force.

Several properties are used to define material properties and are detailed on test certificates supplied:

- Yield and tensile strength
- Ductility
- Hardness

Additional properties are:

- Toughness
- Creep resistance
- Fatigue resistance

YIELD AND TENSILE STRENGTH

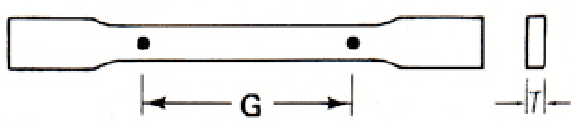
The most common mechanical property used for comparison, reference and design purposes is that of strength - both the yield strength and the tensile strength.

To determine both these strengths, standard test specimens, which are schematically shown in Figure 1, are machined from the material and then subjected to an increasing measured load in tension until rupture occurs.

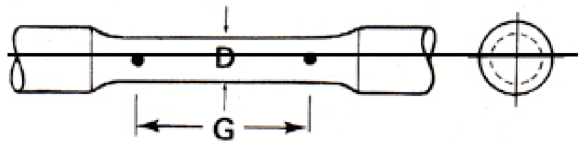
As the increasing tensile load is applied, a diagram (graph) is plotted to show the progressive relationship between the stress and strain. The stress-strain curve is typified by various regions. Refer to Figure 2 on the following page.

- From O to E the strain produced is elastic. On removal of the stress the specimen (or the material in actual use) will revert to its original dimensions. The stress value corresponding to E is termed the elastic limit.
- As the stress is raised above the elastic limit (E), the material will start to deform in a plastic manner and the material undergoes permanent deformation and increased dimensions.

Figure 1: Schematic illustration of rectangular and round tensile test specimens



(A) Rectangular tensile test specimen for flat product i.e. plate and sheet. "T" is the thickness of the material. "G" is the gauge (gage) length.



(B) Round tensile test specimen for rod, bar, forgings, etc., machined to a standard size. "D" is the diameter in the reduced section of the specimen. "G" is the gauge (gage) length.

STRESS is: $\dfrac{\text{Applied load}}{\text{Original Cross Section Area of the Specimen}}$

Units Mega Pascals (MPa)

<u>Useful conversion factors</u>

15.44 MPa = 1 ton f/ square inch (1tsi)
6.9 MPa = 1000 lb f/ square inch = 1000 psi = 1ksi
9.8 MPa = 1kg f/ square mm

STRAIN is: $\dfrac{\text{Increase in Length}}{\text{Original Length}}$

Units: Strain has no units, but it usually expressed as a percentage (%)

Figure 2: Schematic stress-strain curve for stainless steel

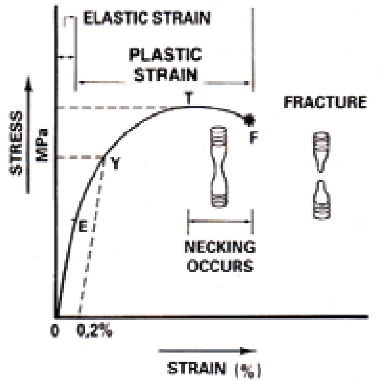
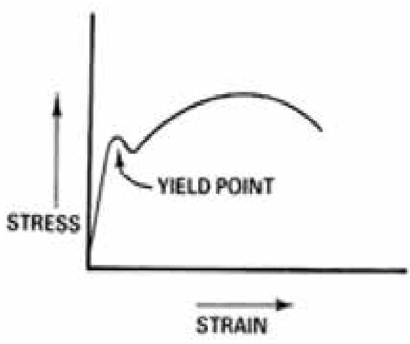


Figure 3: Schematic stress-strain curve indicating a yield point



Mild steel shows a pronounced yield point, as indicated in Figure 3 At the yield point the material shows a sudden increase of strain for no increase in stress. For such steel this is reported as the yield strength or the yield stress.

Stainless steel does not typically show this clear yield point and the change from elastic behaviour to permanent plastic deformation is not usually easy to detect.

This has led to the design strength of stainless steel being reported using a different factor, which may cause confusion. In the initial stages of plastic deformation, only a small amount of permanent strain occurs for relatively large increases in stress.

Therefore the yield strength of stainless steel is usually taken as the stress that will produce a 0.2% permanent strain (offset).

Referring to Figure 2, this is obtained by a line drawn parallel to OE from 0.2% strain to intersect the curve at Y. The stress value corresponding to Y is taken as the yield strength.

The yield strength for stainless steel is therefore reported as the 0.2% proof stress ($R_{P0.2}$).

- With further tensile loading permanent strain continues, as indicated by the curve between Y and T in Figure 2 and reaches a maximum at T.

The stress corresponding to T, reported as the tensile strength. This value is also sometimes termed the ultimate strength or the ultimate tensile strength (UTS).

- After this the plastic deformation becomes localised and rapid decrease of the cross-sectional area occurs, known as necking.
- The final fracture (breakage) of the specimen occurs at F.

ELONGATION AND REDUCTION OF AREA (RA)

During the determination of the yield and tensile strengths, the mechanical properties of elongation and/or reduction of area (RA) are also determined.

<u>ELONGATION</u> is determined as follows:

Before the tensile test specimens are subjected to the load, a standard length is marked on the reduced section of the test specimen. This is known as the Gauge (Gage) Length and is indicated by "G" in Figures 1(A) and 1(B).

Different specifications lay down different gauge lengths,
e.g. 50mm (2"), 200mm (8")
or sometimes as a formula:
Gauge length - 5.65 √So (i.e. 5.65 x square root of the original cross-sectional area).
This is known as proportional elongation and is designed to remove the effect that thickness has on elongation.

After fracture the two pieces are carefully put together and the increased distance between the marks is taken.

The Elongation is calculated by:

$$\frac{\text{Distance between marks after fracture - Original Gauge Length}}{\text{Original Gauge Length}} \times 100$$

and is thus reported as a percentage, with the gauge length specified.
E.g. Elongation in 50 mm = 28%.

<u>REDUCTION OF AREA</u> (RA) is determined as follows:

After fracture the two pieces of the specimen are carefully fitted together and the average diameter, or the width and thickness, of the smallest cross section to which the specimen has been reduced by necking is measured.

The RA is calculated by:

$$\frac{\text{Original cross sectional area - smallest cross sectional area after fracture}}{\text{Original cross sectional area}} \times 100$$

and is thus reported as a percentage.
Eg. RA = 55%.

Both Elongation and RA are a measure of the DUCTILITY of the material, i.e. the ability of the material to deform in a plastic manner without fracturing.

Elongation is the property most often used in this respect. RA suffers from the drawback that even at relatively low levels of ductility the RA has values of ±50%. As the ductility increases RA rapidly increases to high values ±70-75%, which renders it insensitive to a meaningful assessment of ductility.

HARDNESS

Hardness is an often a reported mechanical property and is useful as a means of giving an indication of the tensile strength and as a non-destructive test for checking heat treatment and the sorting of material.

Hardness is determined by measuring the resistance of the material to penetration (indentation).

- Brinell Test: A hardened steel ball indentor (10mm diameter) is forced into the material by a standard load. The diameter of the impression gives, from tables, the Brinell Hardness Number (BHN).
- Rockwell Test: Either a hardened steel ball (Rockwell B - HRB) or a diamond brale (Rockwell C - HRC) is forced into the material by standard applied loads.

The depth of penetration is used to give a Rockwell number directly from the scale on the equipment. HRB is used for soft materials and HRC for hard materials.

- Other hardness tests are also sometimes used, these include:

Vickers Test: Vickers Pyramid Number (VPN), usually only used in the laboratory.

Shore Test: Measures the rebound of a hardened ball up a standard tube. Used when no indentation can be tolerated.

Some indicative comparisons

(Relative basis of hardness)

Very Hard	62HRC	688 BHN
Hard	48 HRC	455 BHN
Medium Hardness	30 HRC	286 BHN
Soft	90HRB	185 BHN
Very Soft	72 HRB	130 BHN

TOUGHNESS

Toughness is the capacity of a material to yield plastically under conditions of highly localised stress. It is an important engineering property.

The test most often used is the Charpy V Notch Impact Test . Similar tests such as the Charpy Keyhole and Izod Test are also used

Impact values are reported as the energy absorbed, with the type of test and the temperature noted. The units are joules (J).

E.g. impact strength: Charpy V (20°C) = 60J.

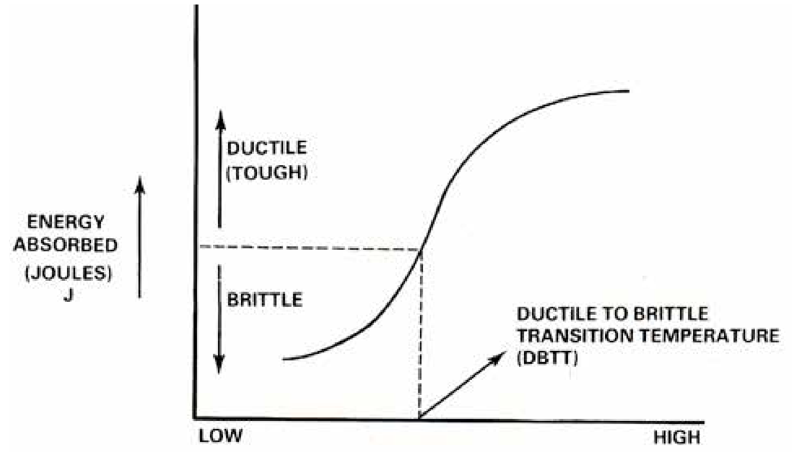
The values determined are qualitative comparisons and although often reported, or specified as acceptance criteria, they cannot be converted to energy values that can be utilized in engineering calculations.

Impact testing can also be used to assess the effect of lower temperatures on a material. Impact specimens are uniformly heated or cooled to various temperatures and quickly tested before they lose or gain heat from the surroundings.

A plot of the energy absorbed is made against the testing temperature of the specimens. The ductile to brittle transition temperature (DBTT) is taken at the temperature at which the slope of the curve changes. This is shown schematically in Figure 5.

Most steel suffers from a loss of toughness as the temperature drops to freezing point (0°C) and below. The actual impact strength at the DBTT varies for different types of steel. As a general rule, if this value is less than

Figure 5: Schematic representation of loss of toughness (ductility) as temperature is lowered, with indication of ductile to brittle transition temperature (DBTT)



about 35J, the material is described as brittle. This does not necessarily preclude the use of the material. However, it does indicate that the material must be used with caution. Applications that involve any impact loads or dynamic stress are very susceptible to the presence of defects or imperfections and are best avoided. Applications involving static or constant loads are generally acceptable.

Some steels exhibit impact strengths in excess of 35J at the DBTT and even at lower temperatures and therefore are considered tough at all temperatures.

MECHANICAL PROPERTIES OF DIFFERENT STAINLESS STEEL TYPES

The various different types of stainless steel exhibit distinctly different ranges of mechanical properties:

AUSTENITIC STAINLESS STEEL

YIELD STRENGTH AND TENSILE STRENGTH

Nominal room temperature yield strengths (0.2% offset) and tensile strengths for some annealed austenitic stainless steel are given in Table 1.

Table 1: Nominal room temperature yield and tensile strengths for annealed austenitic stainless steel

AISI Type	301	304	304L	305	309S	310S	316	316L
Yield strength (0,2% offset) MPa	275	290	270	262	310	310	290	290
Tensile Strength MPa	755	580	560	585	620	655	580	560

- Austenitic stainless steels show a marked response to cold working, which significantly increases both the yield and tensile strengths.

The degree to which work-hardening affects the strength levels depends on the chemical composition of the different steels, particularly with regard to the content of the elements that stabilise the austenitic crystal structure, especially nickel.

ELEVATED TEMPERATURE PROPERTIES

Austenitic stainless steel shows excellent properties at elevated temperatures. Elevated temperature properties are reported in two different ways: long and short time properties.

Short Time Properties

The tensile test specimen is heated to the required temperature of the test and actually tested at this temperature to obtain the stress-strain curve and the resultant yield and tensile strengths.

The effect of elevated and high temperatures on both the yield and tensile strengths in MPa, is taken on a short time basis, as indicated in Table 2.

In general terms it may be seen that the L grades suffer a greater loss of properties with a rise in temperature, particularly with regard to their tensile strengths.

Long Time Properties

At high temperatures (in excess of about 500ºC) the strain is dependent on the applied stress and time.

The metal undergoes a continuous slow deformation, which is termed creep. Creep can occur at stresses below the short time yield strength.

Long time strength properties are generally expressed in two ways: -

- The Creep Stress is that which will cause a specific rate of deformation in a given time (i.e. within the secondary creep range) at a specific temperature.
- The Rupture Stress is that which will cause rupture (i.e. encompasses all stages of creep) in a given time and at a specific temperature.

DUCTILITY

Annealed austenitic stainless steel has excellent elongation values of typically 50-60% and higher.

They therefore possess a superior ability to be cold formed, pressed, drawn and spun into deep shapes.

Cold working does bring about a decrease in the ductility. Elongation of ± 20% are typical for material which has undergone 30% cold work - still a very acceptable ductility by normal engineering standards. At sub-zero temperatures the Elongation decreases only slightly, giving a typical elongation value of 40-50%.

HARDNESS

In the annealed condition typical hardness is 150-160 HBN. Small amounts of cold work can rapidly increase the hardness up to levels of ± 250 HBN. Further cold work results in a slower increase in hardness. Spring temper wires and grade 301 cold rolled to full hard temper have hardnesses in the order of 340-380 HBN.

TOUGHNESS

Annealed austenitic stainless steel has excellent toughness, with Charpy V (room temperature) typically in excess of 165J. Charpy V values at sub-zero temperatures do decrease, but even at temperatures as low as 196°C below zero they are typically between 90J and 120J, i.e. not approaching values that are considered as brittle.

From the above it may be seen that austenitic stainless steel has exceedingly good low temperature mechanical properties. It is for this reason that they are used virtually exclusively for the manufacture of vessels to contain liquid gases at cryogenic temperatures.

Table 2: Indicative short time elevated and high temperature yield and tensile strengths for various austenitic stainless steel grades
(Note: YS = yield strength, TS = Tensile Strength both in MPa)

TempºC	304		304L		316		316L		321		347	
	YS	TS	YS	TS	YS	TS	YS	TS	YS	TS	YS	TS
150	191	465	180	431	205	510	176	450	156	475	224	480
260	166	445	152	409	173	500	149	435	131	468	198	437
370	150	445	140	400	157	500	134	435	121	468	182	426
480	137	428	130	382	152	475	123	415	116	468	176	426
595	125	365	116	327	144	407	109	360	112	400	173	402
705	112	266	=	245	134	298	=	272	102	276	161	324
815	79	145	=	142	112	172	=	168	95	141	113	168

FATIGUE

If metals are subject to repeated fluctuating (reversing) loads at stresses below the tensile strength, a fatigue crack can initiate in the material, which then with increasing cycles of loading propagates until final failure by fracture occurs.

The resistance to fatigue at various stress levels is therefore required for many engineering applications.

FERRITIC STAINLESS STEEL

YIELD STRENGTH AND TENSILE STRENGTH

Nominal room temperature yield strengths (0.2% offset) and tensile strengths for annealed ferritic stainless steel is given in Table 3.

• Ferritic stainless steel shows little response to cold working. An increase in both the yield and tensile strengths takes place, but to a minor degree only.

Table 3: Nominal room temperature yield and tensile strengths for annealed standard and proprietary alloy ferritic stainless steel

Steel Grade	Yield Strength 0.2% offset (MPa)	Tensile Strength (MPa)
409	320	500
430	345	510
444	340	515
3CR12 / Utility Ferritics	340	500

• Ferritic stainless steel has useful elevated temperature strengths, but these strengths tend to fall off rapidly at high temperatures so ferritics are seldom used at high temperatures, except for their oxidation resistance.

FATIGUE

Nominal Fatigue strengths for ferritic stainless steel is between 310-330 MPa.

DUCTILITY

Ferritic stainless steel has nominal elongation values as indicated below:

409	=	22%
430	=	25%
18-2 super ferritic	=	30%
3CR12	=	22%

They therefore have a ductility equivalent to carbon mild steel and are suitable for cold forming operations of a moderate degree.

HARDNESS

Ferritic stainless steel in the annealed condition has a nominal hardness of 165 HBN. It is non-hardenable, either by heat treatment nor by cold work.

■ TOUGHNESS

The impact strengths of ferritics varies significantly according to the chemical composition, particularly with respect to the ductile to brittle transition temperature (DBTT).

Standard ferritic stainless steel is tough at room temperature and in general its DBTT is between 20°C and 0°C. Thus below 0°C, the steel would be considered to have a low toughness.

Super ferritic stainless steel and 3CR12, with specially controlled chemical compositions, particularly with respect to specified low levels of both carbon and nitrogen, have a DBTT below freezing point.

In general ferritic stainless steel is not suitable for use at low temperatures.

Note: It is stressed that welding has a marked effect on the toughness of standard ferritics within the weld zone, due to changes to the crystal structure brought about in the heat affected zone (HAZ).

MARTENSITIC STAINLESS STEEL

Martensitic stainless steel is usually supplied in the annealed condition for ease of machining. As such it has mechanical properties similar to ferritic stainless steel, because in this condition it possesses a ferritic structure. To develop attainable mechanical properties (and corrosion resistance) it requires heat treatment by quenching and tempering, (also sometimes referred to as hardening and stress relieving). This involves:-

- Heating the steel to within a specified high temperature range for sufficient time to ensure the uniform attainment of this temperature throughout the cross-section.
- Rapidly cooling (quenching) the steel from this high temperature, usually in oil.
- Immediately tempering the quenched steel by re-heating to a temperature necessary to produce the desired combination of strength, hardness, ductility and toughness.

Nominal values for the yield strength (0.2% offset), tensile strength, elongation, hardness and toughness for some quenched and tempered martensitics is given in Table 4.

Table 4: Mechanical properties of quench and tempered martensitic stainless steel

*Note: Historically the Izod Impact Test was used. These figures are still quoted in most references. It is not possible to convert results from one method of impact testing to another

Grade of Steel	Tempering temperature °C	Yield strength (0.2% offset) MPa	Tensile Strength MPa	Elongation in 50mm %	Hardness	Izod V Notch J
420	200	1000	1310	15	41HRC	
	315	965	1240	15	39HRC	47
	425	1035	1345	17	41HRC	47
	538	790	1000	20	31HRC	102
	648	585	758	23	97HRB	136
	760	415	620	30	89HRB	
420	200	1380	1755	10		
	315	1345	1725	10		
	425	1380	1755	10	48HRC	14
	538	1000	1170	15		
	648	585	790	20		
431	200	1070	1415	15	43HRC	
	315	1035	1345	15	41HRC	41
	425	1070	1415	15	43HRC	61
	538	895	1035	18	34HRC	68
	648	655	860	20	24HRC	
440A	315	1655	1795	5 3	51HRC	5
440B	315	1860	1930	2	55HRC	4
440C	315	1895	1965		57HRC	3

The fatigue properties of martensitic stainless steel may be correlated to the quenched and tempered tensile strength level. As a nominal value, the fatigue limit may be taken as approximately 45% of the tensile strength. At such high levels, fatigue performance is adversely lowered by the presence of any surface imperfections or defects.

Quenched and tempered martensitic stainless steel shows a marked drop in toughness as the temperature is lowered to 0°C and below.

DUPLEX STAINLESS STEEL

Duplex stainless steel has a combination of both austenitic and ferritic microstructures, so its properties share some of the characteristics of both types. However the presence of nitrogen in most of the grades generates very high proof and tensile strengths, while maintaining acceptable levels of ductility and toughness.

Typical mechanical properties are shown in Table 5.

Table 5: Nominal room temperature yield and tensile strengths for common duplex stainless steel

Steel Grade	Yield Strength (0,2% offset) (MPa)	Tensile Strength (MPa)	Elongation %
2001/2101	480	680	30
2304	400	650	25
2205	460	700	25
2507	530	750	20

Due to the formation of intermetallic phases at elevated temperatures, duplex grades are not usable above about 300°C.

Duplex stainless steel has adequate ductility and toughness even at sub-zero temperatures to make it a versatile engineering product.

CONCLUSION

The mechanical properties of the four main classifications of the family of stainless steel have been covered in a general manner.

How they are measured and the factors that govern and influence their values are similar for the other classifications of stainless steel and, in fact, for steel in general.

The range of attainable values for the different mechanical properties is vast and this is more so for austenitic stainless steel. This factor is one of many that renders stainless steel an extremely versatile material.