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The European Stainless Steel Development Association

Stainless steel properties for structural automotive applications

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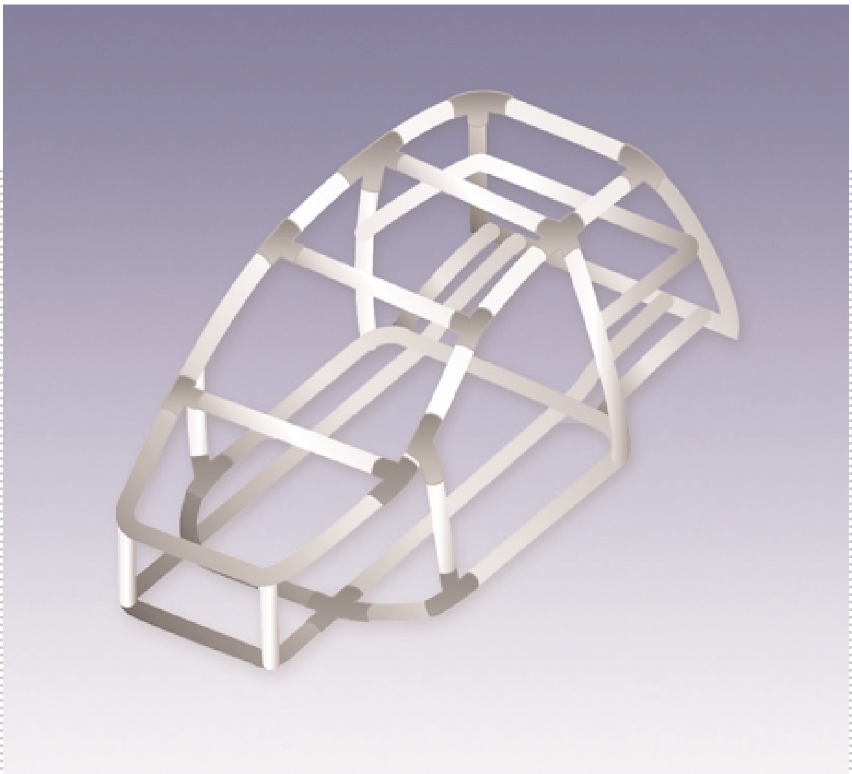


1. Introduction

Among the materials that withstand corrosion, stainless steel shows an excellent resistance in a large number of atmospheres, due to a phenomenon known as passivity. Stainless Steel is protected from its environment by the formation of a very thin passive film or passive layer. It is strongly bonded to the surface, which prevents further direct contact between the metal and its more or less aggressive environment. In Stainless Steel, the passive film also has the advantage, compared, for example, to a paint layer, being self-healing. Chemical or mechanical damage to the passive film will heal or repassivate in oxidising environments.

Physical and mechanical properties (toughness, strength and ductility), ease of fabrication (particularly ease of forming) excellent fatigue resistance and energy absorption capability are some of the properties of Stainless Steel which enable the specific requirements of structural components to be met.

The main advantages of Stainless Steels as a structural material are the exceptional combination of relationships that are developed in paragraphs 2 and 3.

2. Fracture Toughness (K) versus Strength (σ)

While strength is the controlling property if a component must withstand a specific load, toughness is the limiting property if a component must be capable of absorbing a specific quantity of mechanical energy without fracturing. In engineering structures, strength often must be combined with toughness, which indicates the amount of energy absorbed during the deformation and fracture. Austenitic and duplex Stainless Steels (Fe-Cr-Ni (Mo) alloys) and ceramics are compared in table 1. With the exception of austenitic and duplex Stainless Steels, most of the engineering materials, with high strength range go through a transition from ductile behaviour at room temperature to brittle at low temperatures. Thus to prevent brittle, i.e. catastrophic, failure, the service temperature of the structural component must be higher than the material’s ductile to brittle transition temperature. With austenitic and duplex Stainless Steels, the fracture toughness is independent of the temperature in the range of -200° C to 50° C.

Table 1: Yield strength and toughness comparison between austenitic Stainless Steels and ceramics

Material	Yield strength σ (MPa)	Toughness: Fracture Energy K (MPa x $m^{1/2}$)
Ceramics	140 - 450	5
Austenitic and duplex Stainless Steels	240 - 1500	100

3. Material Properties for Lightweight Structural Design

The specific types of Stainless Steel under consideration in this application belong to two families according to their alloying element composition, which determines their metallurgical structure as well as mechanical properties. These two families are:

a) Duplex austenitic-ferritic stainless steel

The most commonly used duplex grade is 0.02% C – 22% Cr – 5.5% Ni – 3% Mo – 0.15% N alloy, whose standard European designation is X2CrNiMoN22-5–3 / 1.4462.

b) Austenitic stainless steel

These steels have chromium (18 to 30 per cent) and nickel (6 to 20 per cent) as the major alloying elements. The austenitic phase is stabilised by the presence of a sufficient amount of nickel. The principal characteristics are the ductile austenitic condition, rapid hardenability by cold working and excellent corrosion resistance.

One of the most commonly used grade for structural applications is the 0.02% C – 17.5% Cr – 7% Ni – 0.15% N alloy, whose standard European designation is X2CrNiN 18-7/1.4318.

3.1 Young's Modulus (E) versus Density (ρ)

The stress-strain relationship (in its linear part) is usually described by Young's modulus: $E = \sigma/\varepsilon$, where σ is the "true stress" and ε is the "true strain". Specific stiffness E/ρ is a reliable indicator of material performance in bending. A simple comparison of specific stiffness gives a good indication of stiffness resistance of different materials. As it can be seen in table 2, the specific stiffness of Stainless Steel is very similar to that of aluminium alloy and the HSLA steel, which means that the three materials can all be considered as "light materials".

Table 2: Specific stiffness of Stainless Steels, 6061 aluminium alloy and high strength steel

Property	Duplex Stainless Steel	Austenitic Stainless Steel	6061 Aluminium Alloy	High Strength HSLA
Density: ρ (g/cm^3)	7.8	7.9	2.7	7.83
Density relative to steel	1	1	0.35	1
Young's modulus: E (kN/mm^2)	200	200	69	200
Specific stiffness E/ρ ($kN/ mm^2/g/cm^3$)	25	25	25.5	25

3.2 Strength (s) versus Density (ρ)

Specific strength i.e. the ratio between yield stress (σ_0) and density (ρ) is another relationship characterising the engineering properties of different materials. As it can be seen in table 3, the specific strength (σ_0/ρ), the specific strength of the austenitic Stainless Steel in the cold worked condition, is much higher than the one for the other materials.

Table 3: Specific Strength of Stainless Steels, 6061 Aluminium and High Strength Steel

Property	Duplex Stainless Steel (1)	Austenitic Stainless Steel			6061 Aluminium Alloy		High Strength Steel HSLA
		Annealed	C850 (2)	C1000 (3)	T4 (4)	T6 (5)	
Density: ρ (g/cm^3)	7.8	7.9	7.9	7.9	2.7	2.7	7.83
Yield Stress: σ (N/mm^2)	640	370	600	880	130	275	410
Specific strength σ_0/ρ ($N/mm^2/g/cm^3$)	82	46.8	76	111.4	48.1	100	52.4

(1) in the solution annealed condition
(2) in the cold worked condition: C 850 (850<UTS (N/mm^2)< 1000)
(3) in the cold worked condition: C 1000 (1000<UTS (N/mm^2)< 1150)
(4) in the solution heat treated condition
(5) in the precipitation heat treated condition

3.3 Other Relationsships

Without going into details, the following other exceptional relationship characterise the engineering properties of Stainless Steel:

- Fracture toughness (K) versus density (ρ)
- Fracture toughness (K) versus Young’s modulus (E)
- Young’s modulus (E) versus strength (σ)

The elongation level is also a good indication of the potential formability of the material in bending, deep drawing, hydroforming and other operations. The higher elongation levels of Stainless Steels are an indication of their excellent formability.

4. Crashworthiness

Automotive crashworthiness, defined as the capability of a car structure to provide adequate protection to its passengers from injury in the event of a crash, plays an important role in the design of passenger cars. In addition to this, the trend today in the automotive industry is for crashworthiness to include the ability of the car to withstand minor accidents with little damage.

These different requirements are usually all very influential in the design of the car structure, specifically the following considerations are made :

- Low speed (0–8 km.p.h.) crash with minor or no damage. Usually the bumper or its supporting system will absorb all energy.
- Medium speed (13–20 Km.p.h.) crash with low cost repairs. All the energy must be absorbed in a contained area of structure that is easily repaired or replaced.
- High speed (50–60 Km.p.h.) crash with minimum injury levels. All the energy must be absorbed in an efficient and controlled manner.

Crashworthiness energy absorption is a key property of the material used for structural components or complete structures so-called “space frames”.

Austenitic Stainless Steels i.e. Fe – Cr – Ni containing alloys have the advantage over aluminium alloys and carbon steels of being highly strain rate sensitive. This means that the faster the loading is applied the more the material will resist deformation. In addition to that, Stainless Steel has the capability to collapse progressively in a controlled and predetermined manner.

The effects of high strain rates on mechanical properties have been investigated and reported in a small number of relevant papers. In this paper, we show that high strength Stainless Steels offer the highest energy absorption ability with the strain rate as reflected by the Cowper-Symonds model.

5. Energy absorption

In terms of energy absorption, the aim is to manage the energy of a collision in a predictable and reliable manner in order to provide maximum safety to the passengers of the car in the event of an accident. The main properties, which are involved in this process, are the stress-strain characteristics. Dependence of these properties on the loading mode encountered in a crash are of prime importance. This dynamic property of a metallic alloy is called strain rate sensitivity.

5.1 Strain Rate Properties

The strain rate domain can be divided into three main different categories:

- Low strain rates form 10^{-5} to 10^{-1} s^{-1}
- Medium strain rates 10^{-1} to 10^{2} s^{-1}
- High strain rates from 10^{2} to 10^{4} s^{-1}

Rates of strain from 10^{-1} to 10^{2} s^{-1} are characteristic of vehicle collisions. Strain rate sensitivity becomes pronounced at 10^{-1} s^{-1}. At a strain rate of 10^{2} s^{-1}, the behaviour of the material resistance to impact changes, Cowper and Symonds (ref. 1) suggested a mathematical model which described the strain rate sensitivity of metallic alloys to strain rate.

The relation between the dynamic stress σ and the strain rate ε' = dε/ dt of a particular material is given by :

$$\sigma = \sigma_0 [1 + (\varepsilon' / D)^{1/q}]$$

where ε' = strain rate (s^{-1})
D = constant (s^{-1})
q = constant
σ = dynamic stress (N/mm^2) at Uniaxial rate ε' (s^{-1})

The Cowper-Symonds relation is an empirical equation which, nevertheless has proved to be valuable within a range of strain rates and is used extensively in practice. Values for parameters D and q called Cowper and Symonds constants for two different Stainless Steel grades (duplex and austenitic), obtained from least mass squares method are given in table 4. Curves giving true stress σ are plotted against log ε' in figure 1.

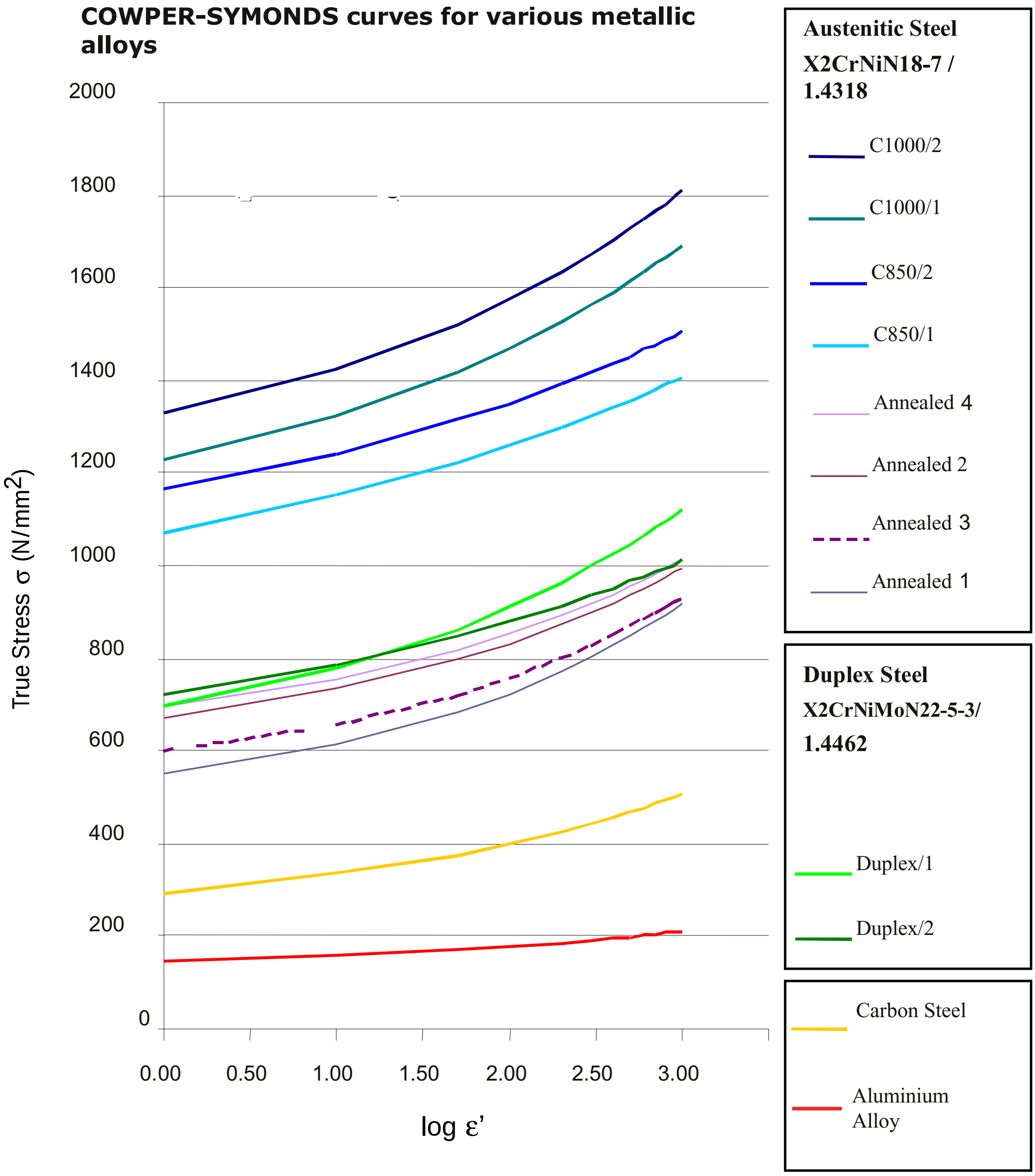
Table 4 : Values for constants D and q for various metallic alloys at room temperature according to the COWPER-SYMONDS Model

$$\sigma = \sigma_0[1 + (\varepsilon'/D)^{1/q}]$$

Metallic Alloy	Condition	σ_0(5%) (N/mm^2)	σ_0(10%) (N/mm^2)	D(s^{-1})	q
Austenitic Steel X2CrNiN18-7/ 1.4318	Annealed (2B)	480		1402	3.8
	Thickness 1.05 mm		575	4405	4.70
		530		3048	4.08
	Thickness 2.05mm		608	6108	4.49
	C 850 (850 < UTS (*) < 1000)	868		29783	7.11
			992	70714	6.45
	C 1000 (1000 < UTS (*) <1150)	1041		13889	5.57
			1164	19899	5.07
Duplex Stainless Steel X2CrNiMoN22-5-3/ 1.4462		σ_0(0.1%) (N/mm^2)	σ_0(0.2%) (N/mm^2)		
	Annealed (2B)	545		770	5.1
			575	596	6.4
Carbon Steel ZstE180BH (**)	Thickness 0.8 mm		230	424	4.73
Aluminium Alloy (***)			6500		4

(*) UTS : Ultimate Tensile Strength (N/mm^2)
(**) After light weight automotive construction with steel, report EUR 18412, 1999
(***) After Jones N, Structural Impact, Cambridge University Press 1989

Figure 1: COWPER-SYMONDS curves for various metallic alloys at room temperature



5.2 Energy Absorption Performance

In order to compare the energy absorption performance of the materials stress-strain curves were used. For each alloy, an idealised stress strain curve was derived from the lowest to the highest stress strain curves by interpolating and by an integral calculation applied on the curve $\sigma = f(\varepsilon)$ for which it was possible to determine the absorbed energy. Values for absorbed energy for the different materials within the scope of this survey are given in table 5.

Table 5: Values for absorbed energy for various metallic alloys at room temperature

Material	Rp 0.2 (N/mm^2)	Rm (N/mm^2)	Rm / Rp	A_{80} (%)	n (1)	Absorbed Energy (J/cm^3)	Density (g / cm^3)	Absorbed Energy (J / g)
Stainless Steel X2CrNiN18-7 / 1.4318								
- Annealed	370	800	2.16	53	0.6	300	7.9	38.0
- C 850 (2)	600	900	1.50	35		265	7.9	33.5
- C 1000 (3)	880	1160	1.32	20		205	7.9	25.9
Aluminium 6061 – T4	145	240	1.65	22	0.22	55	2.7	20.4
Steel HSLA	410	480	1.17	22	0.15	98	7.83	12.5

(1) Strain – Hardening coefficient
(2) In the cold worked condition : C 850 ($850 < Rm (N/mm^2) < 1000$)
(3) In the cold worked condition : C 1000 ($1000 < Rm (N/mm^2) < 1150$)

5.3 Energy Absorbers

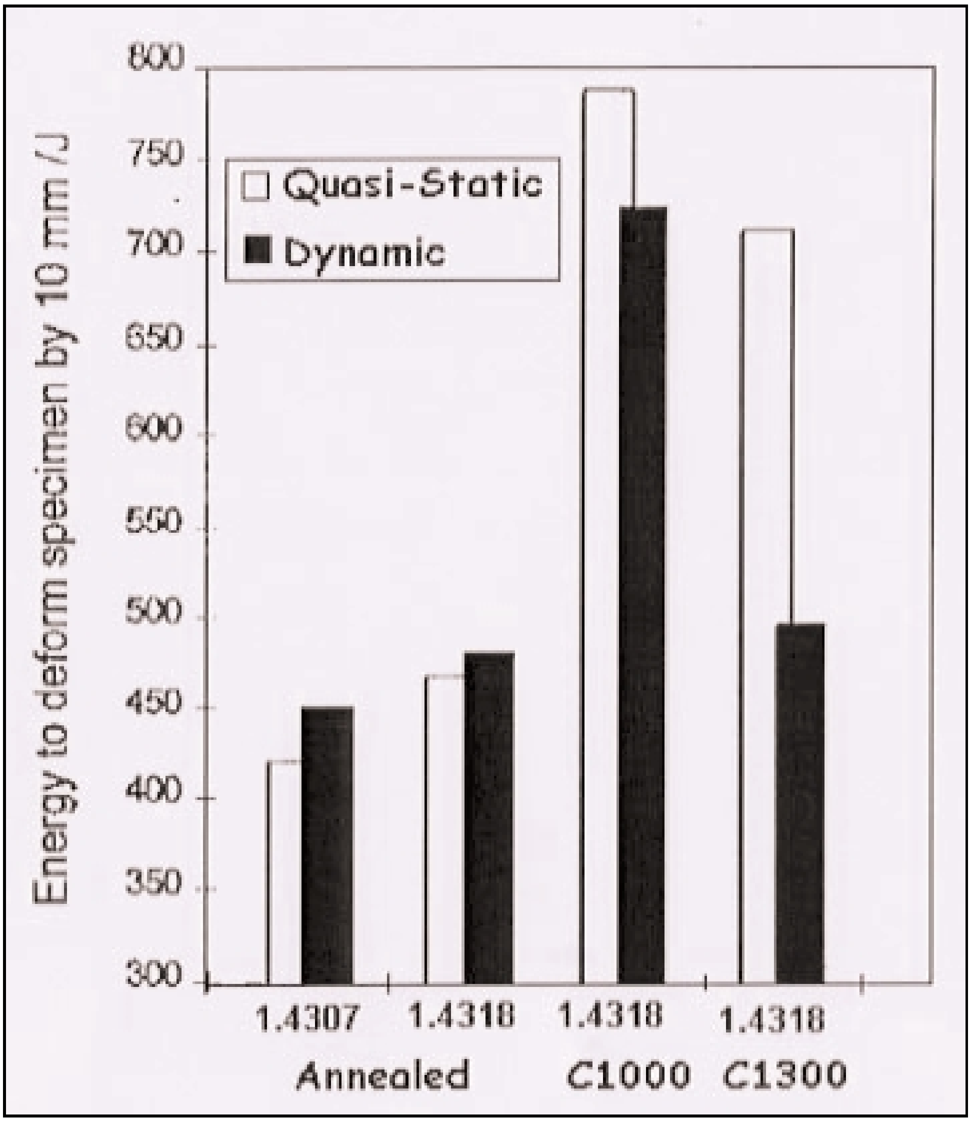
There are different designs for energy absorbers which are mainly produced as columns and which are compressively loaded. Structural sections were fabricated to investigate the behaviour of spot welds subject to realistic conditions (ref. 5).

Under dynamic loading, the buckling behaviour was found to be similar to that observed under quasi-static loading with the exception of X2CrNiN 18-7/1.4318– C 1300. Peak buckling loads were observed to be significantly higher that these observed under quasi-static loading. However, the mean loads and hence energy absorption, were found to be remarkably similar (within 10%).

In order to compare the energy absorption performance of the specimens, the energy required to deform the specimen by 10 mm, E_{10}, was measured.

This is shown in Figure 2 for spot welded structures. Up to a certain limit, increasing parent material strength leads to improve energy absorption performance.

Figure 2: Energy required to deform spot – welded structures



1.4307 = X2CrNi18–9
1.4318 = X2CrNiN18–7

6. Conclusions

Stainless Steels, which are well known for their excellent corrosion resistance, also exhibit a combination of outstanding characteristic which make them particularly attractive in the automotive field.

In the intense competition between different materials, Stainless Steel products have significant advantages with respect to corrosion resistance, fatigue resistance and crashworthiness over aluminium alloys and high-strength low-alloy steels.

As it is shown and illustrated by examples, Stainless Steels (duplex and austenitic) exhibit properties that meet the very stringent requirements of crash energy management. These requirements based on large elongation percentages linked to high strain rate sensitivities and high strength properties are typical of high strength Stainless Steels (duplex and austenitic). It is these characteristics along with the other usual benefit which make Stainless Steels ideal candidates for application in the field of crashworthy in passenger car structures.

References

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