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Chemical and microstructural diversity of steel grades 355(•)

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Abstract The aim of the paper is to show, using theoretical and practical analyses, chemical and microstructural differences among individual types of steel grades 355 found in the market. The mechanical properties required for these steels are achieved by alloying or thermo-mechanical treatment. It was found that the individual types of this steel are poorly weldable, particularly those of large thickness.

Keywords Steel. Chemical composition. Microstructure. Mechanical properties. Weldability.

Diferencias en la constitución química y la microestructura de aceros calidad 355

Resumen El objetivo del artículo es presentar, en base a un análisis teórico y práctico, las diferencias químicas y microestructurales entre los diferentes tipos de aceros calidad 355 que pueden encontrarse en el mercado. Las características mecánicas requeridas en estos aceros se consiguen con aleaciones, o bien a través de tratamientos termo-mecánicos.Se ha llegado a la conclusión de que determinados tipos de acero son más dificiles de soldar, en especial cuando se trata de espesores grandes.

Palabras clave Acero. Composición química. Microestructura. Características mecánicas. Soldadura.

1. INTRODUCTION

Steel grades 355 are ferritic-pearlitic and seldom ferritic-bainitic structural steels in the hot-rolled, normalised or thermomechanically treated condition. They are found in steel groups such as common structural steels and fine-grained structural steels. In accordance with EN standards[1] the two groups are designated S355 and P355 respectively with additional letters and numbers. Characteristics of these steels are a guaranteed minimum yield strength R_e of 355 N/mm^2 for thickness t of up to 16 mm and a tensile strength R_m ranging between 490 and 630 N/mm^2. The steels differ in their guaranteed impact toughness at different temperatures depending on their chemical composition and condition.

Weldability of steel being dependent on its chemical composition, particularly carbon content, it is endeavoured to obtain the mechanical properties required by reducing the grain size and the carbon content in steel. Steel hardening by reducing the grain size by rolling at a temperature lower than the recrystallisation temperature of austenite is the only mechanism not increasing steel brittleness[2] and at the same time lowering the transition temperature to brittle fracture[3].

These steels are used for various structures, pipelines, and pressure vessels; therefore, their weldability is an important feature. The purpose of the paper is to show the differences existing among different grades and casts of steel grade 355 and their influence on steel weldability.

2. STANDARDIZED CHEMICAL COMPOSITION

The chemical compositions of steel grades 355 found in various standards and manufacturer catalogues[1,4,6 and 7] differ very much. The standards specify the maximum contents of the individual elements whereas national standards specify also different types of alloying and the admissible contents of the individual alloying elements.

In the group consisting of common structural steels grades 355, the common alloying elements are C, Si, Mn with or without Al. In fine-grained structural steel grades 355, in addition to or instead of Al, also special micro-alloying elements such as

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Nb, Ti, and V, more rarely Zr and B, separately or in a combination, are found. The micro-alloying elements bond with C, N, and O to form tiny precipitates of carbides, nitrides, carbonitrides, and oxides. This improves steel resistance to ageing, reduces C and N contents in the solid solution, increases the yield strength and tensile strength because of precipitation hardening, and reduces a tendency to grain growth at elevated temperatures. Because of stable precipitates dissolving at temperatures between 1100 °C and 1350 °C, depending on the type of precipitate, austenitic grain growth is prevented whereas in the reverse transformation of austenite into ferrite the precipitates act as crystal nuclei. This produces a fine-grained steel microstructure and reduces the susceptibility to grain coarsening in a wider region of the heat-affected zone of a weld. Unfortunately precipitation hardening is a rather brittle mechanism which gives favourable results only in the case of sufficiently small grains and precipitates[2].

Other alloying elements which may be present are Cr, Cu, Ni, and Mo (contents up to 1.0 wt. %) separately or in a combination. Cu is found in the form of elemental copper precipitates[8]. Cu precipitation increases the tensile strength of steel on the account of a minimum decrease in toughness; therefore, Cu hardening has an important role in low-carbon NiCuNb steels.

The limiting values for the alloying elements specified in various standards are the following (in wt. %): $C \leq 0.27$; $Si \leq 0.75$; $Mn \leq 1.70$; $Cr \leq 1.25$; $Ni \leq 0.85$; $Mo \leq 0.30$; $Cu \leq 0.70$; $Al \geq 0.015$; $Nb \leq 0.05$; $Ti \leq 0.20$; $V \leq 0.15$; $Zr \leq 0.15$; and $B \leq 0.005$. In this respect sums of some of the elements, i.e., $Cr+Mo+Cu \leq 0.60$; $V+Nb+Ti \leq 0.15$; $Zr+Ti \leq 0.20$, are very important. Steel grades 355 with these limiting values of the alloying elements stated will not be found since they belong to the group of heat-treatable steels.

The mode of alloying is left to the discretion of manufacturers, who are to guarantee the mechanical properties of steel. Generally the C content is lower with higher contents of the other alloying elements and vice versa. With thermo-mechanically rolled fine-grained steels, the C content can be $C \leq 0.1$ wt. %. These are so-called pearlite-free steels or steels with a low pearlite content. These steels are usually alloyed with Ni or B.

The mechanical properties of steel grades 355 are achieved, as a rule, by alloying (C, Si, Mn with or without Al) or in combination with thermo-mechanical treatment (usually one or more microalloying elements are added).

3. WELDABILITY

Steel grades 355 show supposedly good weldability. It is known, however, that in welding of these steels, particularly of large thicknesses, a microstructure having a hardness of 350 to 400 HV, which is susceptible to cold cracking, may occur in the heat-affected zone. According to the International Institute of Welding (IIW), the steels having a carbon equivalent $CE_3 \geq 0.45$ are already susceptible to cold cracking[3].

In a standard specifying the welding procedure approval, the hardness values mentioned are the highest permissible hardness values for a weld on structural steel of group 1 [5]. Group 1 steels in accordance with EN 288-3 show a nominal yield strength $R_e \leq 360$ N/mm^2 and a chemical composition (in wt. %): $C \leq 0.24$; $Si \leq 0.60$; $Mn \leq 1.70$; $Mo \leq 0.7$; other individual alloying elements ≤ 0.30, but their sum ≤ 0.8. Steel grades 355 are thus found at the top of the group 1 steels since they are characterised by the limiting values of the mechanical properties and the chemical composition.

4. STEEL ANALYSIS

Ten different steel grades 355 were analysed. Account was taken of the upper limiting contents of the alloying elements specified in different standards whereas the chemical compositions of three steels were taken from the accompanying approval test certificates. These three steels were delivered as S 355 J2 G3 steels in thicknesses *t* of 15 mm, 16 mm, and 60 mm. They were analysed and compared by the calculation of carbon equivalent and the preheat temperature and subjected to metallographic and mechanical testing [tensile testing in accordance with EN 10002, Charpy impact test (V-notch) in accordance with EN 10045, Vickers hardness test HV 30 in accordance with EN ISO 6507]. The test specimens were taken in the direction transverse to rolling. The chemical compositions of the steels are given in table I.

4.1. Carbon equivalent CE

The carbon equivalent *CE* is used as a criterion to assess susceptibility of steel to hardening in the

Table I. Chemical analysis of the analysed steel grades 355

Tabla I. Composición química de los aceros 355 analizados

Steel	References	Chemical composition (wt. %)											
		C	Si	Mn	Cr	Ni	Cu	Mo	Ti	B	V	Nb	Al
1	certificate	0.056	0.277	1.122	0.01	0.031	0.025	–	0.063	0.0231	–	0.10	0.035
2	certificate	0.128	0.166	0.944	0.024	0.049	0.019	0.005	0.003	0.0096	–	0.017	0.049
3	certificate	0.19	0.44	1.15	–	–	–	–	–	–	–	–	0.028
4	[5], Group1	0.24	0.60	1.70	0.30**	0.30**	0.30**	0.70	-**	-**	-**	-**	-**
5	[4] p. 219, steel no. 594	0.24	0.50	1.50	0.25	0.50	0.35	0.08	–	–	–	–	–
6	[4] p. 219, steel no. 606	0.27	0.35	1.40	–	–	0.30*	–	–	–	0.10*	–	–
7	[4], p. 111, steel no. 255	0.20	0.50	1.70	0.30	0.50	0.30	0.08	0.03	–	0.10	0.05	0.03*
8	[4] p. 111, steel no. 272	0.14	0.50	1.60	–	0.50	–	–	0.05	–	0.10	0.05	0.03*
9	[6]	0.12	0.75	1.00	1.25	–	0.55	–	–	–	–	–	–
10	[6]	0.16	0.50	1.50	0.80	–	0.55	–	–	–	–	–	–

* the standard specifies a minimum value Cu ≥ 0.18, V ≥ 0.01; the above values are based on a comparison with similar steels with certain maximum values of Cu and V

** standard EN 288-3 mentions these elements as "other elements", with which the individual values should not exceed 0.30 %; we decided for Cr, Ni and Cu due to their common presence in the expressions for *CE*

heat-affected zone of the weld and to cold cracking. It is a sum of all the alloying elements (in wt. %) increasing the susceptibility of steel to cold cracking. In the literature numerous equations indicating the influence of the individual elements with reference to carbon can be found, but they are all applicable to unalloyed and low-alloyed steels[2]. Some of the equations are used for the calculation of preheat temperature or hardness in the heat-affected zone whereas others indicate the limiting values of the carbon equivalent, i.e., when steel is susceptible to cold cracking.

The carbon equivalent *CE* was calculated using the following equations:

$$CE_1 = C + (Mn + Si)/4\ ;\ \text{Williams}^{[13]} \qquad (1)$$

$$CE_2 = C + Mn/6 + (Cr + Mo + V)/5 + (Si + Ni + Cu)/15\ ^{[13]} \qquad (2)$$

$$CE_3 = C + Mn/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15;\ \text{IIW}\ ^{[2,3,9,11 \text{ and } 14]} \qquad (3)$$

$$CE_4 = C + (Mn + Si)/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15\ ^{[9]} \qquad (4)$$

$$CE_5 = C + (40Mn + 40Cr + 20Ni + 28Mo)/360;\ \text{Seferian}^{[2 \text{ and } 3]} \qquad (5)$$

$$CE_6 = Pcm = C + Si/30 + (Mn + Cu + Cr)/20 + Ni/60 + Mo/15 + V/10 + 5B;\ \text{Ito-Bessyo}^{[2,3,9,11 \text{ and } 14]} \qquad (6)$$

The equations provide very different results (see Table II). The highest values of the carbon

Table II. Carbon equivalents *CE* of the analysed steel grades 355 calculated using different equations

Tabla II. Equivalentes del carbono (CE) de los aceros 355 analizados, calculados con diferentes ecuaciones (%)

Steel	1	2	3	4	5	6	7	8	9	10
CE 1	0.406	0.405	0.587	0.815	0.740	0.707	0.750	0.665	0.557	0.660
CE 2	0.267	0.307	0.411	0.803	0.646	0.567	0.666	0.493	0.623	0.640
CE 3	0.249	0.296	0.382	0.763	0.613	0.543	0.633	0.460	0.573	0.607
CE 4	0.295	0.323	0.455	0.863	0.696	0.602	0.716	0.543	0.698	0.690
CE 5	0.183	0.239	0.318	0.533	0.468	0.425	0.456	0.345	0.370	0.415
CE 6	0.239	0.232	0.262	0.427	0.375	0.377	0.355	0.255	0.285	0.319

equivalent are obtained using equation (1) and the lowest using equation (6), except with very low-carbon steel, where the lowest value is obtained using equation (5). The results obtained were different because some equations take into account more alloying elements than others and because the equations include different numeric factors for the individual alloying elements. Consequently, in the calculations, e.g. of a preheating temperature, care should be taken to select the right equation for the calculation of *CE*. For example, to calculate a preheating temperature according to Seferian, only the Seferian equation for the calculation of *CE* should be used.

Thus for steel nº 1 the lowest value of the carbon equivalent CE_5 is equal to 0.183 and the highest CE_1 to 0.406 whereas with steel nº 4 the lowest one CE_6 is equal to 0.427 and the highest one CE_1 to 0.815.

In accordance with the IIW equation, steels show good weldability at $CE_3 \leq 0.45$. All steel grades 355 with their highest admissible contents of the alloying elements show a poorer weldability since with all the carbon equivalent $CE_3 > 0.45$. The poorest weldability is shown by the steel which has the highest carbon equivalent in group 1 (EN 288-3), i.e., $CE_3 = 0.763$. This steel also represents the upper limit of the welding parameters required for all steel grades 355, i.e., mainly the preheat temperature and the cooling rate to control the microstructure of the weld metal and the heat-affected zone, with which cold cracking is prevented.

4.2. Preheat temperature

There are several methods for the calculation of the preheat temperature. Each method has its own equation for the calculation of the carbon equivalent; therefore, it is not irrelevant which equation is used. Other influencing factors such as heat input, workpiece thickness, joint shape and the content of diffused hydrogen in the weld, separately or in a combination, are to be taken into account as well.

Well-known are the methods of Seferian, Ito-Bessyo, Suzuki-Yurioka, BWRA[2 and 3], Frank[10], and Uver-Höhne[11 and 12]. The preheat temperatures were calculated using Seferian's method[2 and 3] which clearly shows the influence of the chemical composition and thickness of steel grades 355 on their weldability:

$$T = 350 \cdot \sqrt{C_s - 0.25} \qquad (7)$$

where T (°C) is the preheat temperature and C_s is the total carbon equivalent. We have:

$$C_s = CE_5 \cdot (1 + 0.005t) \qquad (8)$$

where CE_5 is the carbon equivalent calculated using Seferian's formula and t is the thickness of steel (in mm).

The preheat temperatures calculated using Seferian's equation are given in figure 1. It can be noticed that the weldability of steel grades 355 can be very different due to their very wide range of allowable chemical composition. The higher the carbon equivalent and the steel thickness, the higher the preheat temperatures.

Steel nº 1 with $CE_5 = 0.183$ should be heated up to a temperature T of 55 °C with a thickness t of 100 mm, while steel nº 2 with $CE_5 = 0.239$ at a thickness of 30 mm must be preheated at the same temperature. With a thickness of 100 mm, this steel should be preheated to a temperature T of 115 °C.

Steel nº 3 with $CE_5 = 0.318$ should be preheated to a temperature T of 100 °C, with a thickness t of 10 mm and to a temperature T of 170 °C at a thickness t of 100 mm.

Steel nº 4 with the highest theoretically possible carbon equivalent , i.e., $CE_5 = 0.533$, here for steel grades 355 should be preheated to a temperature T of 195 °C with a thickness t of

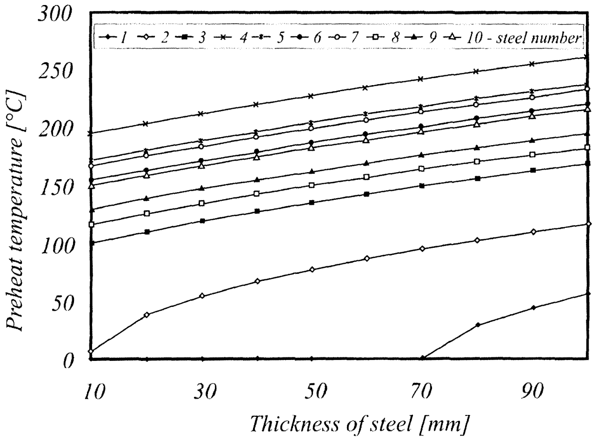

Figure 1. Preheat temperature of analysed steel grades 355 (according to Seferian).

Figura 1. Temperatura de precalentamiento de los aceros 355 analizados (en base al método de Seferian).

10 mm and to 260 °C with a thickness of 100 mm. Steel nº 4, i.e., thus represents the upper limit of preheating for all steel grades 355.

4.3. Mechanical properties

It is known that the alloying elements increase the tensile strength of iron. Based on the data on the influence of the individual alloying elements on the increase of tensile strength of iron[15], the tensile strength of steel in the hot-rolled or normalised state is equal to

$$R_m = 215 + 900C + 100(Si+Mn) + 90Cr + 40Ni \ (N/mm^2) \quad (9)$$

where R_m is the tensile strength of steel, 215 (N/mm^2) is the average tensile strength of pure iron, and C, Si, Mn, Cr, and Ni are the contents of these elements in steel (wt. %).

The calculation using equation (9) shows that the standardised contents of the alloying elements for steel grades 355 are such that the tensile strength R_m ranging between 490 and 630 N/mm^2 can be obtained by alloying. This is logical since these contents are a result of development of steel grades 355 around sixty years ago. In recent times the C content is particularly lowered whereas the mechanical properties required are achieved by other mechanisms described in sections 1 and 2.

The tensile strength values for steels nº 1, 2 and 3 calculated using equation (9) are the following: R^1_m = 407 N/mm^2, R^2_m = 445 N/mm^2, R^3_m = 545 N/mm^2. A comparison of the calculated and measured values (Table III) shows that the tensile strength of steel nº 3 was achieved only by alloying whereas with steel nº 1 other mechanisms, e.g. fine grain, precipitates, were strongly present as well. This was confirmed by the ferritic-pearlitic microstructure of steel (Fig. 2). Steel nº 1 is a typically fine-grained steel, microalloyed with Ti, B, Nb and Al. The other two steels are representatives of common Al killed steel grades 355. The influence of C on the pearlite content is clearly seen. The lowest content is found with steel nº 1 and the highest with steel nº 3.

The measured mechanical properties are in agreement with the microstructure. The fine-grained steel nº 1 shows the highest yield strength, tensile strength, toughness and hardness. Steel nº 3 shows a higher tensile strength and hardness but poorer toughness as steel nº 2. This is due to a higher content of C and, consequently, of pearlite in steel. Steel nº 2, however, shows a higher yield strength, which is probably due to finer ferrite grains.

It is interesting to note that all three steels were delivered as S355J2G3 steels. This indicates that the same steel designation can represent great differences in the chemical compositions and microstructures.

5. CONCLUSIONS

The theoretical and practical analyses of the steel grades 355 showed how very different the relevant chemical compositions can be. The C content can range from 0.05 wt. % up to 0.27 wt. %, which is inadmissible as far as weldability is concerned. Theoretically the weldability of these steels is close to critical since the highest carbon equivalent evaluated in accordance with the IIW equation is equal to 0.763. The preheat temperature of steel with such a carbon equivalent is also the upper limiting value of the preheat temperature of all steel grades 355, and is equal, according to Seferian, to 195 °C with a thickness of 10 mm and to 260 °C with that of 100 mm.

Table III. Mechanical properties of experimentally tested steel grades 355

Tabla III. Características mecánicas de los aceros 355 analizados en forma experimental

Steel (Table 1)	Thickness (mm)	Yield strength R_e (N/mm^2)		Tensile strength R_m (N/mm^2)		Toughness (J) T = - 20 °C		Hardness HV 10* (HV)
		requir.	measur. *	requir.	measur. *	requir.	measur. *	
1	16	≥ 355	489	490 to 630	582	≥ 27	117	203
2	15	≥ 355	383		502		60	144
3	60	≥ 335	345		532		48	169

* The average of three measurements.

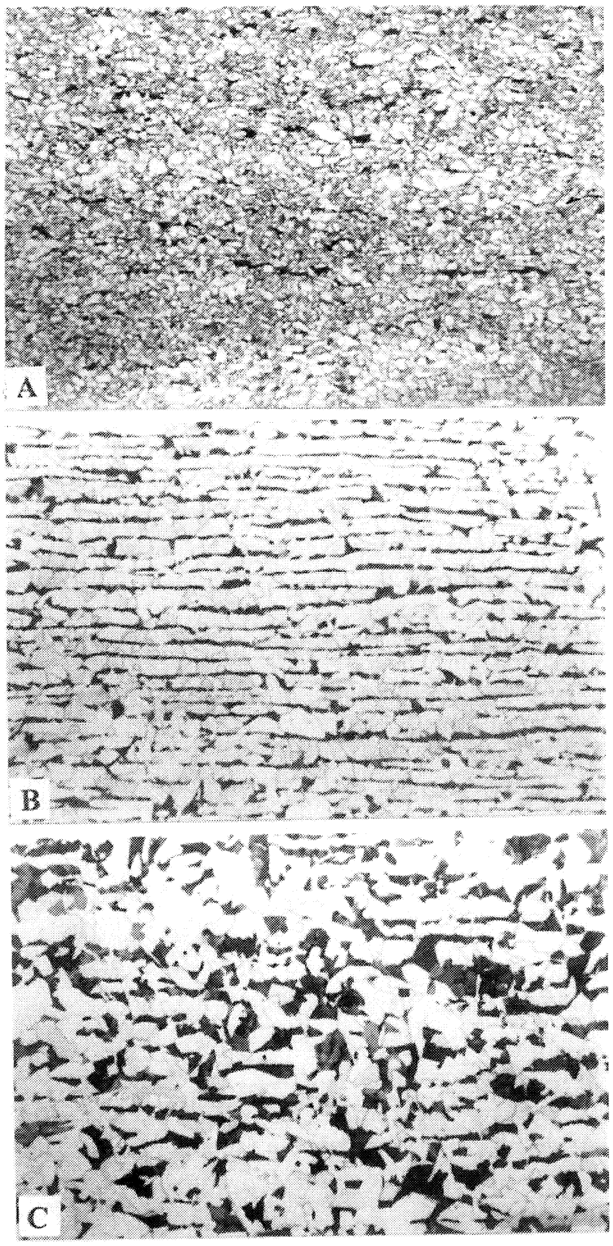

Figure 2. Microstructure of experimentally tested steel grades 355. (A) Steel nº 1; (B) Steel nº 2; (C) Steel nº 3. ×100.

Figura 2. Microestructura de los aceros 355 estudiados en forma experimental. (A) Acero nº 1; (B) Acero nº 2; (C) Acero nº 3. ×100.

Nowadays steel grades 355 never have the chemical compositions specified in standards since the C content rarely exceeds 0.20 wt. %. The mechanical properties required for 355 steel are achieved usually by alloying (common steel grades 355) or thermo-mechanical treatment (fine-grained microalloyed steel grades 355).

The steels classified under the same designation can differ very much; therefore, welding technologists in firms should pay particular attention to the chemical composition of the steel grades 355 delivered and, if required, apply preheating, particularly with thicker plates and stiff structures.

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