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Study of historical developments in the use of fire resistant steels

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ABSTRACT

This paper presents a review of the most relevant articles on fire-resistant (FR) steels, as part of a research project at the University of the Basque Country (UPV/EHU) on the FR properties of steelstructures. An important characteristic of FR steels is that they maintain their mechanical properties at high temperatures better than the more widely used structural steels, mainly due to their special chemical composition and the thermal treatment used in their manufacture. The available information on FR steel tests has been analysed. All the data allow us to study the evolution of mechanical properties at different temperatures. We have, in particular, conducted a comparative evolution of the yield stress (YE) and the yield stress ratio (Ra) at different temperatures. A summary is also presented of the most important elements in their composition and the different manufacturing treatments of these steels and their influence on the initial YE and RA at different temperatures. For example, molybdenum and niobium improve the YE considerably at elevated temperatures. The alloy Cr–Mo–V–Nb is considered effective in FR steels and the use of boron is recommended, if an FR steelstructure is required to withstand temperatures higher than 700ºC and to decrease the percentage of carbon. In view of the temperatures associated with manufacturing treatments, it should be recalled that although accelerated cooling, such as quenching, increases YE at room temperature and at high temperatures, it reduces the Ra of these steels. The most effective thermal treatment is air cooling, although special attention should be paid to the influence of slab reheating and the finish rolling temperature.

KEYWORDS: fire-resistant steels, metal structure

1. INTRODUCTION

Today, there are two methods of designing the metal structure of a building in view of potential fire hazards. The first is to use materials that protect the structure, while as far as possible preventing fire and high temperature gases from reaching the steelstructure. The second is to use FR steels, which are known for maintaining their mechanical properties at elevated temperatures better than conventional steels. Generally, this second system, is the least used for various reasons, among which the first and foremost is its high cost, followed by the very limited availability of information on these steels from only very few manufacturers.

This article presents the partial results of a research project at the University of the Basque Country (UPV/EHU), which is currently examining the fire-resistant properties of steelstructures, using a combination of the two methods described above.

FR steels have the above-mentioned properties, mainly due to their special chemical composition (Mo, Nb…) and the thermal treatment employed in their manufacture.

A search for all articles on the topic of FR steels was conducted and this paper reviews most if not all of such articles published to date.

The information from previous tests on FR steels has been analysed to assist with the study of the evolution of mechanical properties at different temperatures; in particular, a comparative study of the evolution of yield stress (YE) and yield stress ratios (Ra). Ra is the ratio between the room temperature yield stress value related to the yield stress value at different ones. Moreover, a summary has been completed of the most important elements in the chemical composition of these steels and their various manufacturing treatments to examine their influence on the initial yield stress and the yield stress Ratios at different temperatures.

2. FR STEELS AND MANUFACTURING METHODS

Articles on the topic of FR steels first appeared in the early 1950s, but it was not until the middle of the 80s that information may be found on high strength low alloy steels, better known as HSLA. FR steels which fall into this large group of steels, which contain relatively small additions of alloys such as Mo, Nb and/or V maintain their mechanical properties at higher temperatures than conventional steels.

The first article relating to these steels was published in 1990, in the article Fire resistant high strength low alloy steels [1], presented by Assefpour-Dezfuly et al., although it made no reference to the term “FR steels”.

Their manufacturing process was as follows: the steels were induction melted as 25–30 kg heated in a vacuum furnace and then poured into rectangular cast for Fe molds, the ingots from which had the final dimensions of approximately 90 x 100 x 310 mm. The cropped ingots were soaked at 1200°C for 2 hours in a muffle furnace in an exothermic gas atmosphere and hot rolled in nine passes to 20 mm thick plate. The last three passes were carried out between 1000 and 900°C, finishing at about 900°C, and the plates were allowed to air cool to room temperature.

The article Development and practical application of fire-resistant steel for buildings [2], by Chijiiwa et al., was published in 1993. It reports a study that attempted to link the influence of the chemical composition of these steels and their manufacturing process to mechanical properties at ambient and high temperatures. The manufacture of fire-resistant steel with tensile strengths of 490 MN/m 2 was already a reality and the aforementioned article examined the performance and mechanical properties of these steels. It contained no information on its chemical composition.

The manufacturing process of this steel was as follows: chromium-bearing niobium-molybdenum steel was melted in a 300-ton basic oxygen furnace and continuously cast into 240-mm thick slabs. After reheating to 1100 to 1150 ºC, the slabs were rolled to 25.32 and 50-mm thick plates at finish rolling temperatures of 900 to 930ºC.

A further article, Fire-safe design of modern steel buildings in Japan [3], by Sakkumoto and Saito, which was published in 1995, discussed an FR steel (NSFR490A) and studied its fire-resistant properties in two buildings in Japan, using a combination of FR steel and passive protection. This was the first article to use the term FR steels.

A comparison of the mechanical properties of fire-resistant and S275 structural steels [4], by Kelly and Sha, was published in 1999. It compared two FR steels with conventional steel S275 and discussed the alternative of those FR steels to conventional steels in buildings designed to resist fire.

Later, in 2004, the article Parametric studies on fire resistance of fire-resistant steel members [5], written by Ding et al., was published, in which the mathematical equations of the mechanical properties of FR steels (SM490-FR) were determined.

Shortly afterwards in 2006, the article Microstructures and properties of low-alloy fire resistant steel [6], by Panigrahi, was published, an article that attempted to link the influence of the chemical composition of these steels and their manufacturing process to their mechanical properties at ambient and high temperatures.

Six experimental laboratory heats (steels A–F) and one industrial heat (steel G) were melted in a 0·1 T air induction (IF) and in a 6 T electric arc furnace (EAF), respectively, for processing to plate and beam. The ingots from the IF heats were soaked at 1250ºC for 2 h and thermo-mechanically processed (TMP) in an experimental rolling mill to 12–14 mm thick plates in nine passes. The ingot from EAF heat was soaked at 1320ºC for 4 h and rolled to blooms sized 230x160 mm. These blooms were soaked at 1250ºC and subsequently thermo-mechanically processed to 200x100 mm beam section. The finishing rolling temperatures (FRT) for plates and beam were measured with an infrared pyrometer up to an accuracy of +5ºC and were between 800 and 925ºC. The finishing pass reduction was 20–30% for the plates and about 10% for the beam. The plates and beam were left to cool in natural air after rolling.
The article Fire-resistant structural steels [7], by Morozov et al., published in 2007, attempted to link the influence of the chemical composition of these steels and their manufacturing process to mechanical properties at ambient and high temperatures.

The manufacturing process of the FR steels analysed, with the rolling temperature and cooling rates are reflected in Table 1.

Table 1: Rolling temperature and cooling rates of FR steels (2007)

No. of heat in the series	Temperature (ºC)					Cooling rate (ºC/seg)
	Heating prior to rolling	Rough rolling	Beginning of finish rolling	End of finish rolling	End of accelerated cooling	
1–1(2007)	1160	1090	860	815	540	20,1
1–2(2007)	1160	1080	850	800	445	30,0
1–3(2007)	1160	1110	855	795	540	19,2
2–1(2007)	1180	1160	905	855		3,5
2–2(2007)	1180	1165	910	860		3,5
2–3(2007)	1180	1155	905	865		3,5
2–4(2007)	1180	1160	910	855		3,5
3–1(2007)	1160	1100	840	790	555[a]	12,9
3–2(2007)	1160	1000	900	860	540	3,5
3–3(2007)	1170	1050	820	780	550	3,5
3–4(2007)	1170	940	820	770	560[a]	7,8
3–5(2007)	1170	1050	890	840	555	3,5
4–1(2007)	1170	1050	820	750		2
4–2(2007)	1170	1000	820	740	550	3,5
4–3(2007)	1180	970	820	760		2
4–4(2007)	1180	975	820	765		2
[a] Slow cooling to room temperature						

Finally, 2010 saw the publication of the Application of fire-resistant steel to beam-to-column moment connections at elevated temperatures [8], by Chung et al., which discussed an embedded metal union combining an FR steel (SN490CFR) with a non-FR steel at high temperatures and compared it with the use of a non-FR steel in the same case, concluding that the use of the two steels have better results. The chemical composition of all cited steels appears in Table 2 (% wt).

C_{eq} and P_{CM} data for steel NSFR490A (1995), has been taken out using the following equations:

$$C_{eq} = C + Mn/6 + Si/24 + Ni/40 + Cr/5 + Mo/4 + V/14(\%) \quad (1)$$

$$P_{CM} = C + Si/30 + Mn/20 + Cu/20 + Ni/60 + Cr/20 + Mo/15 + V/10 + 5B\ (\%) \quad (2)$$

where, C_{eq}, carbon equivalent to measure the steel weldability and P_{CM}, is the C_{eq} used in Japan, that consider in deep the effect of the alloying elements in FR steels attending its weldability.

Table 2: The chemical compositions of FR steels (%wt)

Chemical compositioins (wt-%)														
Steel	**C**	**Mn**	**Mo**	**V**	**Nb**	**B**	**Si**	**Al_{sol}**	**Ti**	**P**	**S**	**N**	**C_{eq}**	**P_{CM}**	**Cr**
A(1990)	0,09	1,85	0,37	0,044	<0,005	0,0004	0,17	0,01	0,003	0,009	0,004	0,0107			
B(1990)	0,04	1,64	0,2	0,058	0,051	0,0003	0,27	0,013	0,002	0,005	0,001	0,0028			
C(1990)	0,11	1,71	0,,34	0,057	<0,005	<0,0003	0,26	0,024	<0,002	0,005	0,001	0,0047			
NSFR490A(1995)	0,1	1,11					0,2			0,019	0,003		0,42	0,2	
FR1(1999)	0,11	1,14	0,52		0,03		0,24				0,002				
FR2(1999)	0,1	0,64	0,51				0,1				0,005				
A(2006)	0,11	1,02	0,2				0,35	0,0033		0,019	0,022	0,0042			0,31
B(2006)	0,12	1,02	0,2				0,35	0,099		0,025	0,032	0,0063			0,29
C(2006)	0,12	1,08	0,14				0,29	0,097		0,027	0,029	0,0067			0,4
D(2006)	0,13	0,99	0,26		0,02		0,31	0,0034		0,021	0,025	0,0047			0,38
E(2006)	0,13	1	0,26	0,07			0,31	0,0039		0,022	0,026	0,0047			0,39
F(2006)	0,12	0,96	0,26	0,12	0,02		0,3	0,0039		0,021	0,025	0,007			0,38
G(2006)	0,17	0,74	0,22				0,31	0,052		0,027	0,034	0,0124			0,54

1_1 (2007)	0,069	0,68	0,41	0,12	0,045		0,37	0,017	0,009	0,017	0,003	0,55			0,55
1_2 (2007)	0,08	1,1	0,37		0,04		0,3	0,01	0,004	0,01	0,003	0,4			0,4
1_3 (2007)	0,044	0,65	0,6	0,065	0,1		0,4	0,05	0,021	0,01	0,002	2,2			2,2
2_1 (2007)	0,097	0,73	0,5	0,12	0,046		0,29	0,019	0,02	0,019	0,003	0,7			0,7
2_2 (2007)	0,089	0,73	0,49	0,12	0,045		0,85	0,026	0,018	0,018	0,003	0,71			0,71
2_3 (2007)	0,1	0,73	0,45	0,12	0,05		0,45	0,019	0,015	0,017	0,003	2,1			2,1
2_4 (2007)	0,068	0,73	0,48	0,11	0,05	0,0027	0,28	0,04	0,02	0,006	0,002	0,6			0,6
3_1 (2007)	0,061	0,73	0,43	0,1	0,04		0,3	0,025	0,018	0,016	0,003	0,5			0,5
3_2 (2007)	0,075	0,72	0,5	0,12	0,06		0,85	0,02	0,01	0,017	0,003	0,67			0,67
3_3 (2007)	0,072	0,62	0,38	0,05	0,039		0,25	0,018	0,037	0,011	0,004	0,05			0,05
3_4 (2007)	0,06	0,51	0,42	0,086	0,044		0,25	0,016	0,003	0,018	0,004	0,39			0,39
3_5 (2007)	0,073	0,67	0,37	0,09	0,038		0,28	0,04	0,003	0,005	0,003	0,41			0,41
4_1 (2007)	0,037	0,61	0,33	0,087	0,05	0,004	0,3	0,018	0,002	0,015	0,003				
4_2 (2007)	0,073	0,6	0,41	0,11	0,04		0,25	0,019	0,003	0,02	0,004	0,33			0,33
4_3 (2007)	0,05	0,91	0,4		0,031	0,003	0,32	0,02	0,015	0,016	0,004				
4_4 (2007)	0,055	0,78	0,51	0,087	0,036	0,0025	0,35	0,018	0,015	0,011	0,003	0,59			0,59
SN490C-FR(2010)	0,08	0,9	0,33	0,036	0,024		0,23		0,015						

C_{eq}=C + Mn/6 + Si/24 + Ni/40 + Cr/5 + Mo/4 + V/14 (%).
P_{CM}=C + Si/30 + Mn/20 + Cu/20 + Ni/60 + Cr/20 + Mo/15 + V/10 + 5B (%).

Tables 3 and 4 present the content levels of the main alloying elements in FR steels from 1990 to 2010. Note the variations of Mn, and micro alloy elements, carbides formers, as Ti, V and Nb since their presence balance the mechanical properties after thermal treatments.

Table 3: Chemical composition (wt%) of FR steels

Year	C	Mn	Mo	V	Nb	B	Si
1990	0,04-0,11	1,64-1,85	0,2-0,37	0,044-0,058	<0,005-0,051	<0,0003-0,0004	0,17-0,26
1995	0,1	1,11					0,2
1999	0,01	0,64-1,14	0,51-0,52				0,1-0,24
2006	0,11-0,17	0,74-1,08	0,14-0,26				0,29-0,35
2007	0,037-0,1	0,51-1,1	0,33-0,6	0,036-0,12	0,024-0,1		0,23-0,85
2010	0,08	0,9	0,33	0,036	0,024		0,23

Table 4: Chemical composition (wt%) in some elements of FR steels

Year	Alsol	Ti	P	S	N	Cr
1990	0,01-0,024	<0,002-0,003	0,005-0,009	0,001-0,004	0,0047-0,0107	
1995			0,019			
1999				0,002-0,005		
2006	0,0033-0,099		0,019-0,027	0,022-0,034		0,29-0,54
2007	0,01-0,05	0,002-0,021	0,005-0,02	0,002-0,004		0,05-2,1
2010		0,015				

The following cited articles were also identified in the bibliographic research, from which valuable information has also been extracted:

Recrystallization following hot-working of a highstrength low-alloy (HSLA)steel and a 304 stainless steel at the temperature of deformation [9], by Capeletty et al., was published in 1972. It is one of first articles to analyses microalloyed steels (HSLA) operating at high temperatures.

In 1999, Microstructure and properties of nippon fireresistant steels [10], by Sha et al., was published. This article investigated the microstructure of FR steels and analysed the reason for their fire-resistant properties at high temperature. Its findings suggest that these advantageous properties are related to high lattice friction stresses.

This was followed, in 2000, by A new model describing the hot stress-strain curves of HSLA steel at high deformation [11], by Schindlerand Hadasik, an article that proposed a new method for analysing the stress-train curves of FR steels based on torsion tests.

In 2002, Carbide precipitation and high-temperature strength of hot-rolled high-strength, low-alloy steels containing Nb and Mo [12], by Won et al., was published. This article analysed the effects of additions of Mo on both the precipitation kinetics and the high-temperature strength of an Nb carbide in hot-rolled high-trength, low-alloy (HSLA) steels containing both Nb and Mo. The steels containing both Nb and Mo exhibited a higher strength at high temperatures (600 ºC) in comparison to the steel containing only Nb. The addition of Mo increased the hardenability and led to the refinement of the bainitic microstructure.

In 2005, the article A practical approach for fire safety design of fire-resistant steel members[13], by Guo et al., was published, which established formulas to define the mechanical properties of these steels and to assist with the practical design of structural elements subjected to compression and flexion.

In 2007, Technology for the commercial production of fire-resistant steel for building structures [14], by Muratov et al., presented the main chemical compositions and manufacturing processes of FR steels.

In 2012, the article Development and study of high-strength low-Mo fire-resistant steel [15], by Wan et al., described how an FR steel may be obtained with very good properties at elevated temperatures using a small percentage of Mo (0.15%, instead of 0.30%), adding microalloys of Nb, Ti and V, and applying controlled cooling.

Finally, in 2012, Effects of Mo on high-temperature strength of fire-resistant steel [16], again by Wan et al., was published. This article analysed a number of steels with different Mo ratios, to describe the influence of this element on mechanical properties at different temperatures.

3. RESULTS AND ANALYSIS

Following this extensive and thorough literature review, we conducted a study of YE and Ra values for a set range of temperatures.

Figure 1 shows the YE for the temperature range from 0°C and 800°C for all FR steel analysed in this article and Figure 2 shows the Ra in the same temperature range.

The graphs in Figure 1 show that the FR steels retain their initial YE until about 600°C and beyond these temperatures they fall abruptly. Figure 1 can also be seen as the initial YE of each of these steels, but on the whole the steelstudied in article Fire-resistant structural steels [7], published in 2007, stands out because it has a much higher initial YE than the other steels.

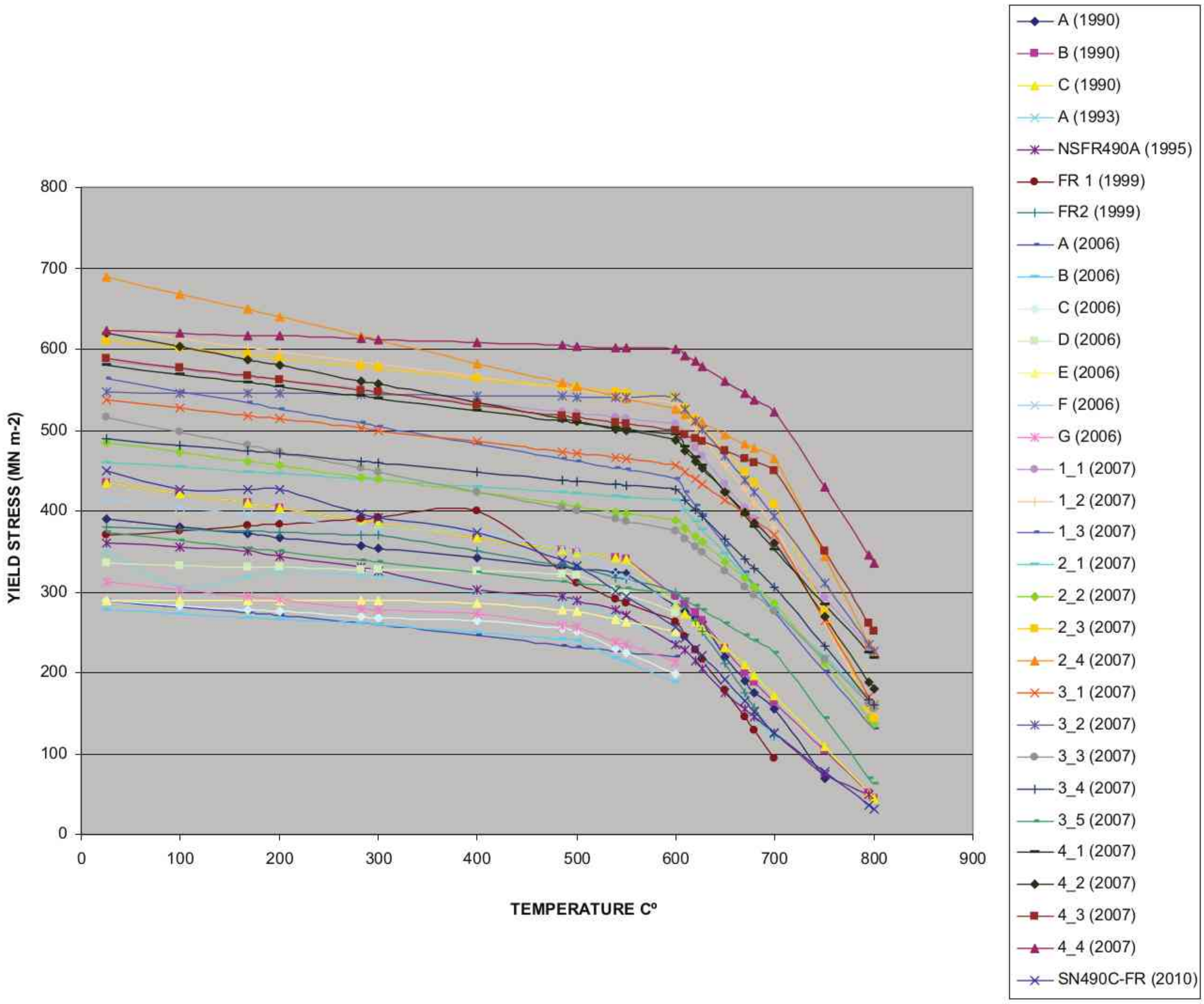

Figure 1: Yield stress based on the temperature of the FR steels.

Although the YE in FR steels stays fairly constant until around 600ºC, Figure 2 shows that each type of steel in the temperature range of 0–600ºC has a different downward slope, which represents the initial YE decline.

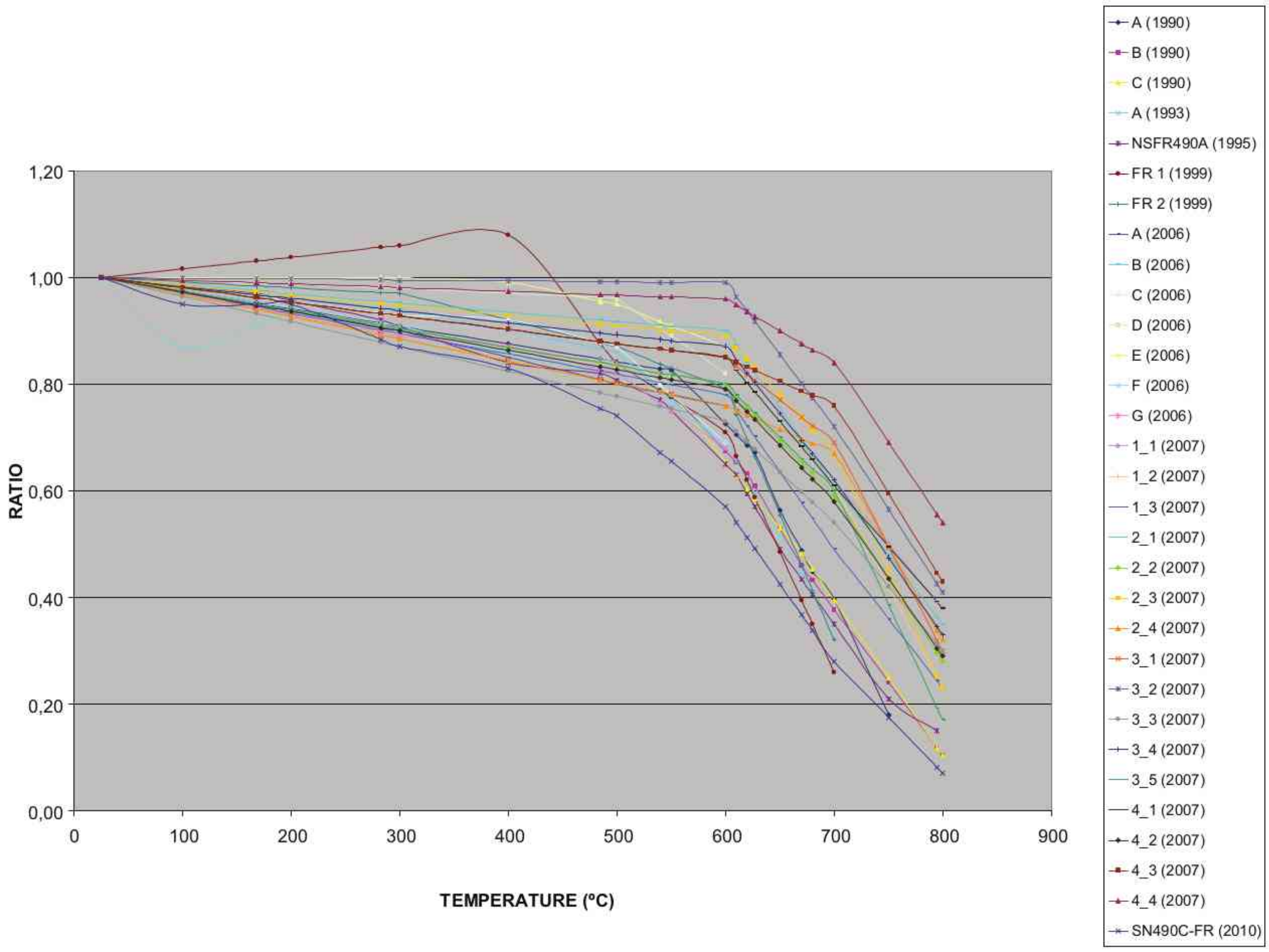

Figure 2: Ratio of yield stress as a function of temperature.

As shown in Figure 3, the percentage of Mo does not affect the YE of the FR steels at room temperature; instead, it may be said that an increase in the percentage of niobium increases the YE at the room temperature of these steels.

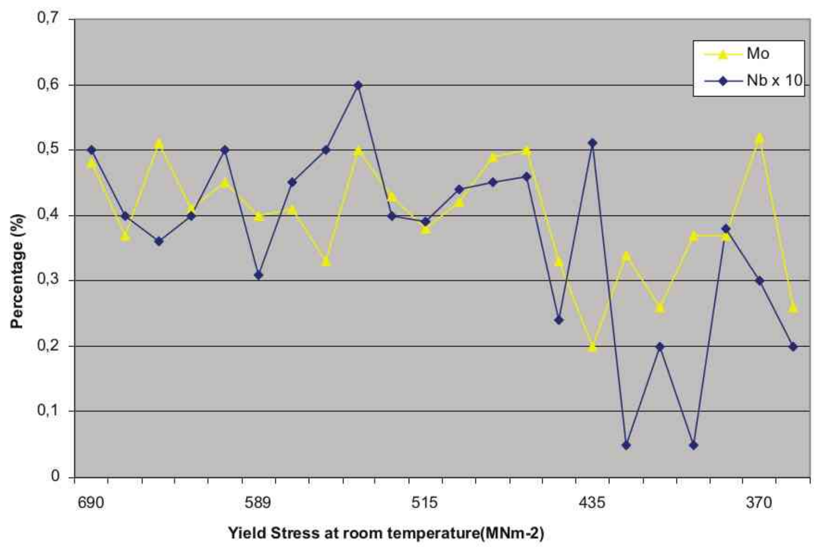

Figure 3: Relationship between YE and the percentages of Mo and Nb.

Figure 4 shows the importance of the Mo and Nb for the maintenance of YE at high temperatures; it may be seen how a higher percentage of these two elements in general contribute to maintaining the initial YE, in other words, a higher Ra.

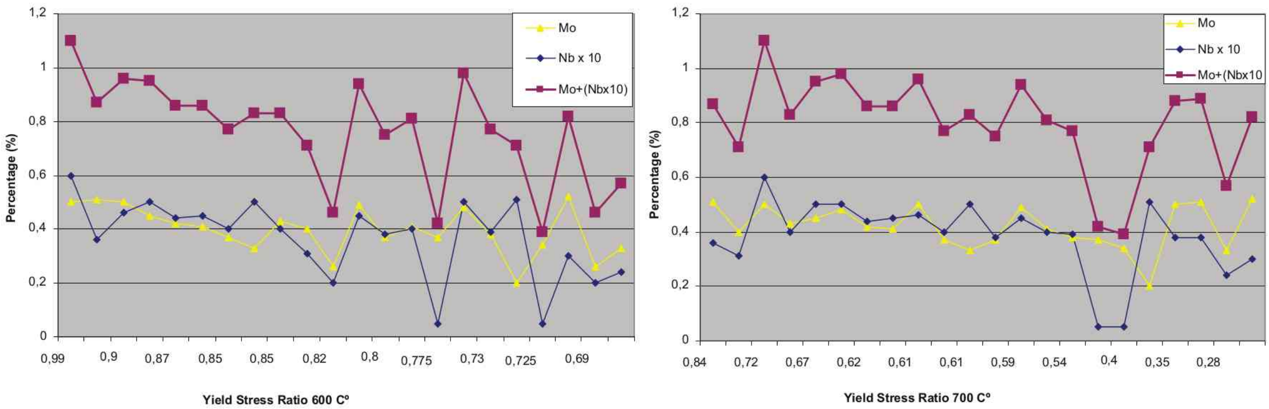

Figure 4: Relationship between Ra at 600 and 700°C and the percentages of Mo and Nb.

Figure 5 shows this trend also: the lower percentage of Mo and Nb tends to present the smaller value of Ra (red columns) so , the value percentage of YE is at room temperature tends to decrease.

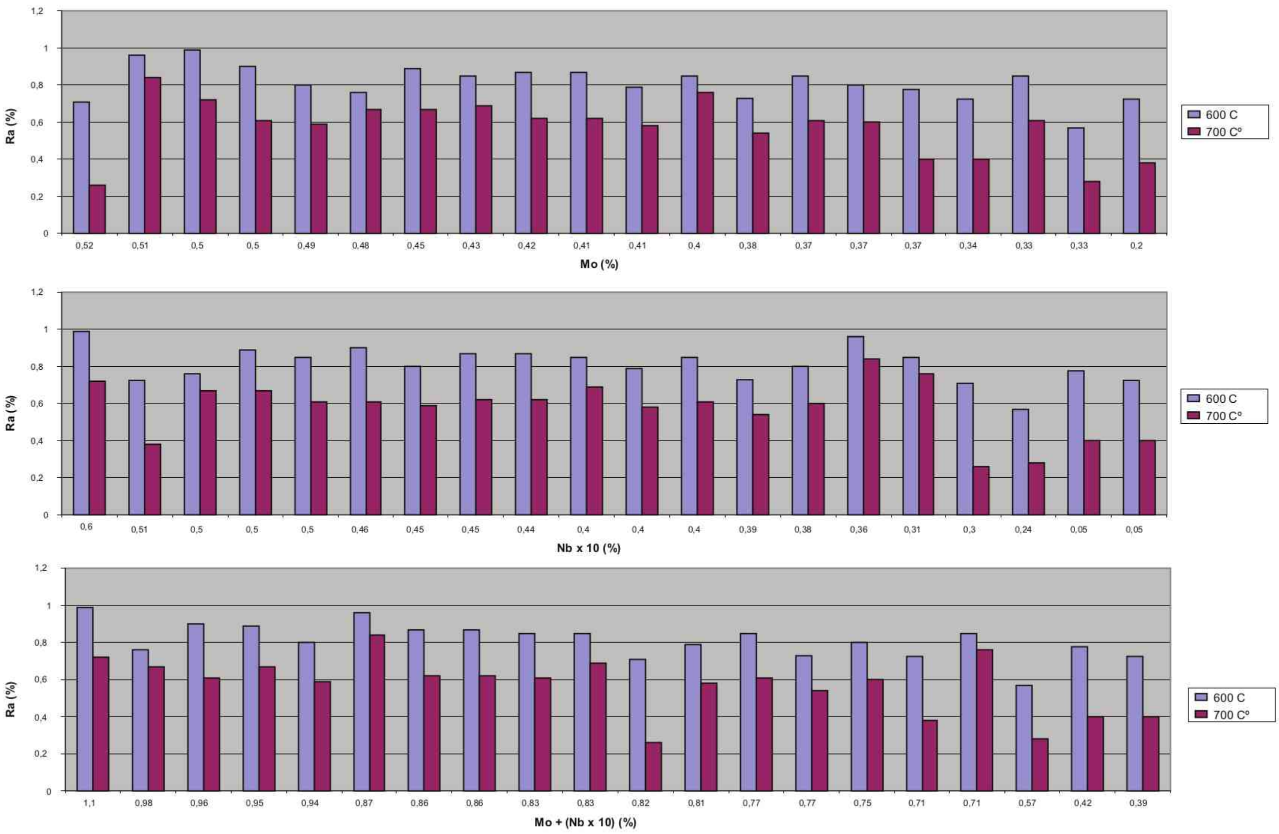

Figure 5: Relationship between Ra at 600 and 700°C and the percentages of Mo and Nb.

Despite the general conclusions drawn from Figures 3 and 4, it can be seen that in some cases they are not met, which is because the YE at room temperature and the Ra at different temperatures is also very important in the manufacturing treatment of the FR steels.

With regard to the slab reheating temperature, the higher the temperature of the reheating, the higher the YE at room temperature and the YE at high temperatures, although the Ra will not change a great deal for steel that has not had this treatment.

It may said, with regard to the finish rolling temperature, that whenever it exceeds approximately 950ºC, then the higher the final temperature of rolling, the better the properties of the FR steel . However, if the choice were between 800°C and 950ºC, it would be advisable to keep the rolling temperature at around 800ºC, because within that range, the properties of the FR steels worsen.

4. CONCLUSIONS

Following this study, it has been observed that the most recent papers published to date have concluded that the manufacture of FR steels must be used on a Cr–Mo–V–Nb system, with a chemical composition that should be approximately within the following ranges (%weight): C (0.06–0.09), Mn (0.6–0.9), Si (0.2–0.4), Cr (0.3–0.5), Mo (0.25–0.4), V (0.07–0.11), Nb (0.02–0.05), Ti (≤0.01) and N (0.007–0.01). The use of Boron (B) is recommended for FR steels that will be used at temperatures of over 700ºC, with a reduced percentage of carbon (between 0.025 and 0.045).

With regard to the manufacturing process that considered in the articles reported in this review, we concluded that accelerated cooling, such as quenching, although increasing YE at room temperature and YE at high temperatures, worsened the Ra of these steels. The most effective thermal treatment is air cooling, although special attention should be paid to the influence of slab reheating and the finish rolling temperature. The recommended treatment is a finish rolling temperature of over 950 °C followed by air cooling.

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