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EFFECT OF THERMO-MECHANICAL PARAMETERS ON THE MECHANICAL PROPERTIES OF EUROFER97 STEEL FOR NUCLEAR APPLICATIONS

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Abstract

Eurofer97 steel has been recognised in Europe as the reference steel for nuclear application under high radiation density. Following to this a detailed knowledge of microstructure evolution after thermo-mechanical processing is required for such steel. In this paper the effect of thermo-mechanical parameters on the mechanical behavior of Eurofer97 is investigated by hot rolling and heat treatment on pilot scale. Results show a strong effect of reheating temperature before rolling on the material hardness, due to an increase of hardenability following the austenite grain growth. A poor effect of the hot reduction and of the following tempering temperature is detected in the total investigated deformation range. A loss of impact energy is found coupled with the hardness increase.

Keywords: Nuclear application steels, mechanical properties, quenching and tempering

1 Introduction

In Europe EUROFER97 has been recognised as reference steel [1] for the nuclear costructions under high radiation density for first wall of a fast breeder reactors as well as in other high stressed primary structures such as the divertors, blanklet and vessels, [2-7]. One of the main reason for this selection are the EUROFER97 steel high mechanical properties at service temperatures coupled with the low or reduced activation (RAFM) characteristic under radiation with the result of low mechanical properties loss. This material behavior has been reported in many literature studies and important initiatives are still ongoing [8-10]. The reduced activation ferritic/martensitic steels differ from conventional Cr-Mo steels because of W presence instead of Mo. With this respect EUROFER 97 steel is essentially a low carbon steel with 9 Cr (% wt) with controlled Ta and V content that can have an important influence on resulting final mechanical properties especially for creep properties [11-15]. EUROFER 97 reference chemical composition is reported in Table 1.

Table 1. EUROFER 97 chemical composition (mass, %)
(Ni, Mo, Cu, Nb, Al, B, Co: as low as possible (ALAP)

C	Mn	Cr	V	Ta	W	N	As+Sn+Sb+Zr
0.11	0.4	9.0	0.2	0.07	1.0-2.0	0.030	ALAP, 0,05

Moreover, other elements such us Mo, Nb, Ni, Cu and N, are maintained as low as possible. The irradiation tests carried on EUROFER 97 show that the resulting radioactivity levels over two orders of magnitude under those recorded for conventional Cr steels [16-18], with low affected mechanical and physical properties [9-10]. Low activation steels have a fully austenite structure when are austenitized in the temperature range from 850°C to 1200°C. Austenite phase transforms to martensite phase during air cooling or rapid cooling (quenching) to room temperature, and then steels are tempered to obtain a good combination of strength, ductility, and toughness. However, the use of these materials during long-time at high temperatures (thermal ageing) can produce microstructural changes (new precipitates, grain growth, segregation, etc.) which can significantly affect their mechanical properties (tensile, Charpy-V, fracture toughness, low cycle fatigue, etc.) [17][18]. For these reasons, an exhaustive knowledge of the metallurgical characteristics of these steels before and after thermal ageing is considered essential. In RAFM steels the desirable properties (low sensibility to radiation damage) are controlled by mean of the martensitic transformation thermal cycle design, and in particular are due the microstructure refinement (increase of the low and high angle boundaries) with clear advantages for applications in nuclear reactors [1]. The martensitic transformation occurs in steels by mean of a non-diffusional transformation when the material is cooled from above A_{c1} to a sufficiently lower temperature (M_s) with cooling rate higher than the “critical cooling-rate”: in these condition the transformation is lead from the energy decrease due to the metastable face-centered cubic (FCC) phase arrangement in the new stable body-centered cubic (BCC) phase [2]. The conventional EUROFER 97 thermal treatment consists in normalization at 980°C/30 minutes + temper at 760°C/90'/air-cooling, [12].

In this work the effect of thermo-mechanical treatment on the microstructure is analyzed, aimed to achieve higher tensile properties in order to evaluate its feasibility as possible structural material for fusion applications. In particular, the effect of thermo-mechanical and tempering treatment at T=750°C and 720°C is analyzed in comparison with standard tempering condition for improving fusion applications ranges.

2 Experimental

Starting from a EUROFER 97 rolled plate with the steel chemical composition reported in Table 1, the effect of reheating temperatures (before hot rolling) and rolling temperatures is analyzed. The plate was hot rolled on a pilot scale adopting two different reheating temperatures (1075°C and 1175°C), together with two finish rolling temperatures (750°C and 650 °C) and two different total reductions (30% and 40%). The effect of tempering treatment after hot rolling is also analyzed (in the temperature range 720°C-760 °C). Hardness and Charpy-V impact tests at -20 °C are carried out on transverse specimens. Microstructure is analyzed by light microscopy after Vilella etching.

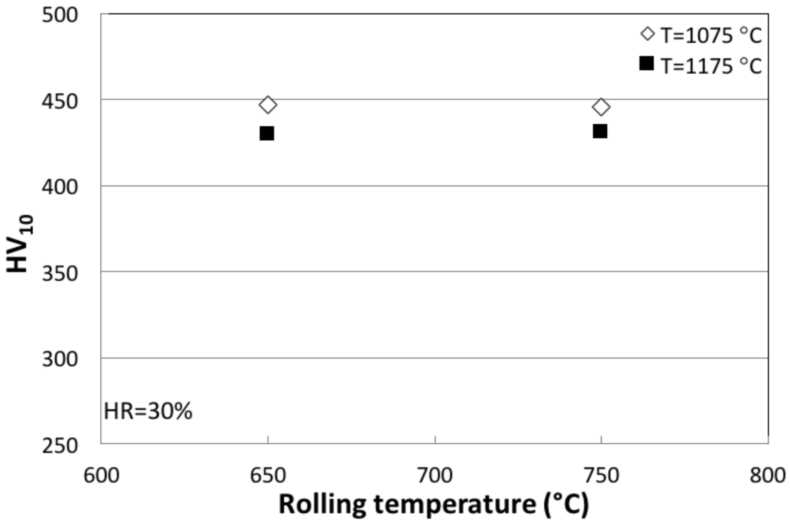
3 Results and discussion

A limited effect is found following to the variation of rolling temperature, reheating temperature and reduction in the considered range (Figure 1).

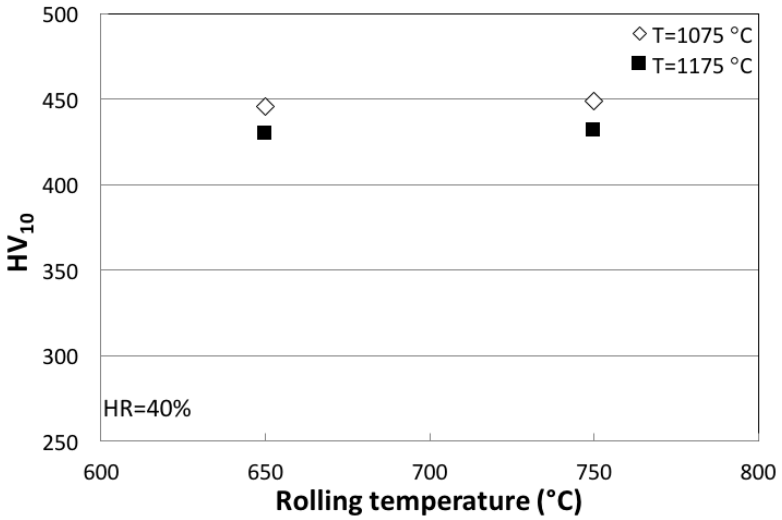
The effect of tempering following the hot rolling as a function of thermo-mechanical parameters is reported in Table 2. Results show that higher hardness values are found after re-heating at higher temperature (1175°C).

Table 2. Effect of tempering after hot rolling

Specimen n.	Reheating T (°C)	Rolling T (°C)	Hot reduction, (%)	Tempering T (°C)	
				720	760
				HV_{10}	HV_{10}
1	1075	750	30	278	225
2			40	267	225
3		650	30	271	228
4			40	270	234
5	1175	750	30	284	251
6			40	290	246
7		650	30	298	254
8			40	306	259



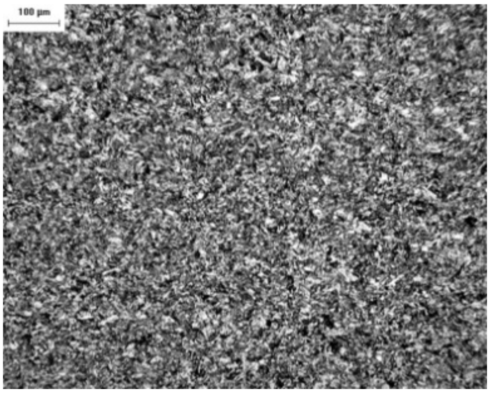
a



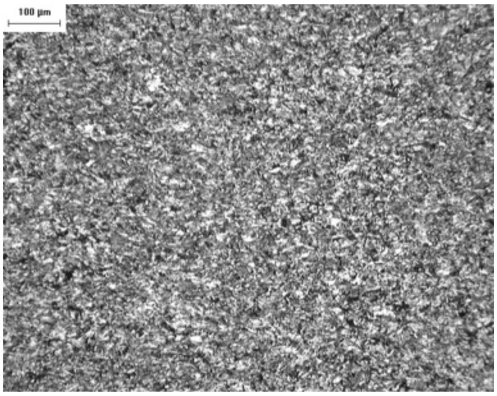
b

Figure 1. Effect of thermo-mechanical parameters on EUROFER 97 hardness (a: 30% hot reduction, b: 40% hot reduction)

This is due to an improvement of hardenability following an increase of austenite grain size. In Figure 2 the microstructure evolution is reported for specimens 1-8 after tempering at T=720 °C. Results show a clear effect of reheating temperature on austenite grain growth. The same effect is independent and effective also in the case of specimens after tempering at T=760 °C.

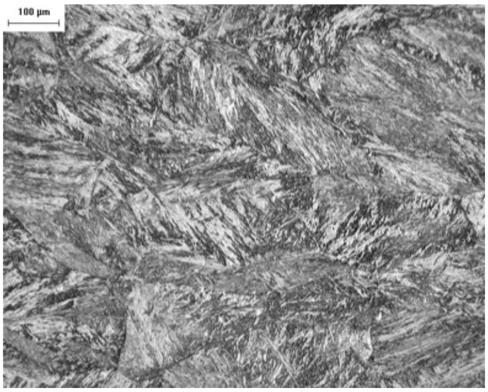


Specimen n.1



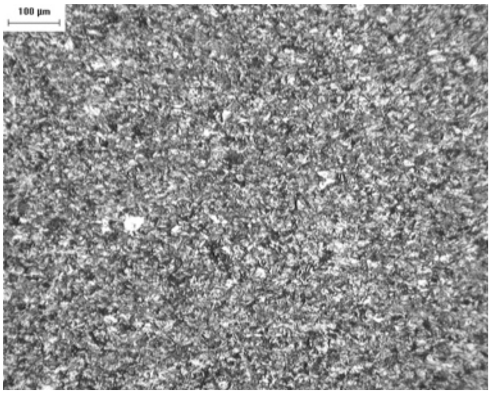
Specimen n.2

Specimen n.5



Specimen n.6

Figure 2a. Microstructure evolution of EUROFER 97 after thermo-mechanical processing according to Table 2 (Final rolling temperature=750°C)



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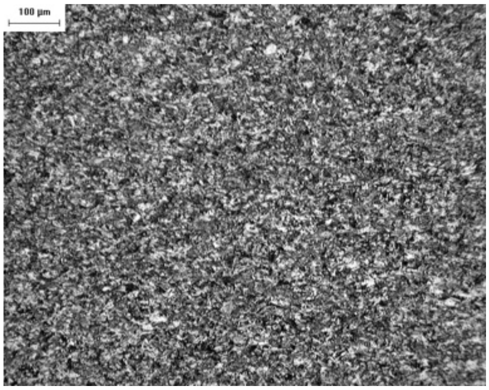
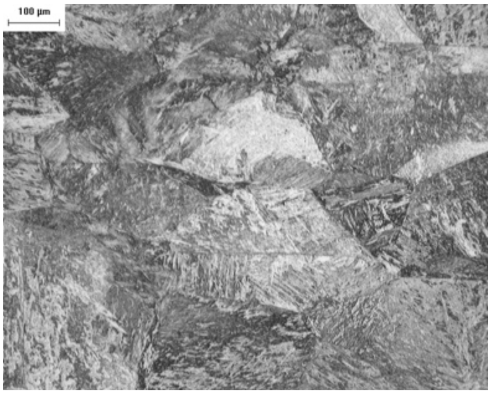
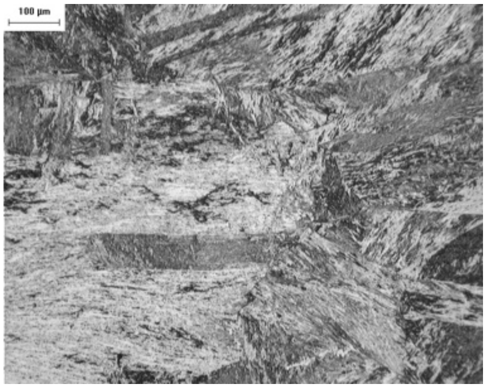


Specimen n.4



Specimen n.7

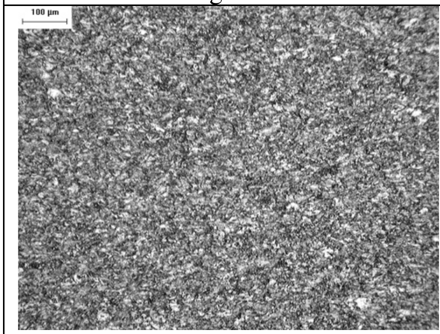
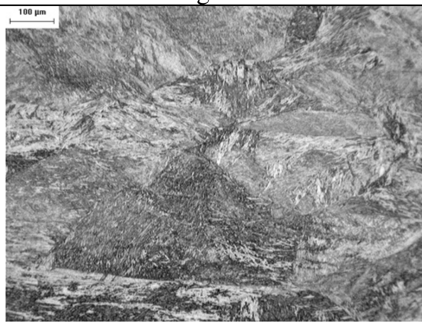


Specimen n.8

Figure 2b. Microstructure evolution of EUROFER 97 after thermo-mechanical processing according to Table 2 (Final rolling temperature=650°C)

At the same time larger austenitic grain size (due to higher austenitization temperature) leads to a dramatic decrease of impact toughness behavior. The effect of austenite grain size growth following an increase of reheating temperature on CVN is reported in Table 3.

Table 3. Effect of reheating temperature on Charpy-V notch toughness

Reheating T=1075 °C		Reheating T=1175 °C	
			
HV_{10}=267		HV_{10}=306	
CVN-Test T= -20°C ASTM A673 full size - specimen		CVN-Test T= -20°C ASTM A673- full size specimen	
mean Value (J) (three tests)	Dispersion (J)	Mean Value (J) (three tests)	Dispersion (J)
63	+/- 15	9	+/- 2
Fracture appearance=100% ductile		Fracture appearance=100% brittle	

4 Conclusions

The effect of thermo-mechanical parameters on the mechanical behavior of EUROFER 97 has been investigated by hot rolling and tempering heat treatment on pilot scale. Results show that EUROFER 97 is a high sensitive material to the thermo-mechanical process and thermal post process cycle. In fact, a strong effect of reheating temperature before rolling on the material hardness, due to an increase of hardenability following the austenite grain growth. A poor effect of the hot reduction and of the following tempering temperature is detected in the total thickness reduction range: 30-40%. A dramatic loss of CV-N impact energy is found coupled with the hardness increase when the reheating temperature is increased from 1075°C up to 1150°C.

Acknowledgement

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