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HIGH TEMPERATURE TENSILE PROPERTIES OF NEW Fe-Cr-Mn DEVELOPED STEEL

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Abstract: *Nowadays, Ni-free austenitic stainless steels are being developed rapidly and high price of nickel is one of the most important motivations for this development. At present research a new FeCrMn steel was designed and produced based on Fe-Cr-Mn-C system. Comparative studies on microstructure and high temperature mechanical properties of new steel and AISI 316 steel were done. The results showed that new FeCrMn developed steel has single austenite phase microstructure, and its tensile strength and toughness were higher than those of 316 steel at 25, 200,350 and 500°C. In contrast with 316 steel, the new FeCrMn steel did not show strain induced transformation and dynamic strain aging phenomena during tensile tests that represented higher austenite stability of new developed steel. Lower density and higher strength of the new steel caused higher specific strength in comparison with the 316 one that can be considered as an important advantage in structural applications but in less corrosive environment.*

Keywords: *FeCrMn Austenitic Stainless Steel, High Temperature Tension Properties, Strength and Toughness, Strain Induced Transformation, Dynamic Strain Aging.*

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1. INTRODUCTION

There are 300 series austenitic stainless steels, widely employed in many industries because of their favorable properties such as good corrosion resistance, high ductility, adequate high temperature mechanical properties and welding ability[1, 2]. Despite many advantages, this group of stainless steels has some problems from economical and engineering points of view. Nickel that uses as a main austenite stabilizing element in stainless steels, is an element that increases significantly the price of steel[3]. Additionally, nickel can cause some allergy and cancers for both human and animals[4]. In engineering point of view, 300 series austenitic stainless steels have low yield strength[5], about 150 MPa in as solution annealed condition, and high specific density that can limit their usage in many structural applications[6].

The 200 series austenitic stainless steels usually consider as a substitution for 300 series steel, in which nickel element replaced partially by manganese and nitrogen[7]. Although 200 series austenitic stainless steels cover some problems, they also have to face some new problems for example: introducing N element into the steel needs a controlled atmosphere and special equipment that can increase the price of production [8].

Getting around these problems, some researchers have been directed to development of FeCrMn austenitic stainless steels that Ni replace totally by Mn and C[3, 9-11]. Since Mn is a weaker austenite stabilizer than Ni, so C addition is necessary to stabilize the austenite phase[12]. Simple production technology and absence of high price nickel element decrease sensibly the product prices. Additionally, since Mn (7.4 gr/cm3) is lighter than Ni (8.9 gr/cm3), decrease in density of these stainless steels can be attention to design of lightweight engineering structures. Addition of C and elimination of Ni may decrease corrosion resistance of stainless steel that must also be considered[9].

In the present work, a new FeCrMn austenitic stainless steel was designed and produced then its microstructural and some high temperature mechanical properties compared with those of 316 steel.

Table 1. chemical composition of steels used (wt.%)

material	C	Ni	Mn	Cr	Mo	Si	S	P
316	0.027	10.01	1.34	16.54	2.15	0.46	0.006	0.031
FeCrMn	0.13	-	23.51	12.21	-	0.1	0.009	0.005

2. EXPERIMENTAL PROCEDURE

FeCrMn steel, with chemical composition given in table 1, was fabricated in a vacuum induction furnace. The ingots were sectioned into 10×10×4cm^3 blocks. The blocks were homogenized at 1200°C for 2h, and were hot rolled at 1100°C up to 3 mm thickness sheets. The final temperature of hot rolling process was above 950°C. The 316 steel was supplied in form of 3mm sheet by nominal chemical composition given in table 1. Both specimens were then subjected to solution anneal treatment at 1050°C for 15 and 25minutes for FeCrMn and 316 steel respectively, under argon gas atmosphere and cooled in water to achieve same austenite grain size. The samples microstructure was characterized by optical microscopy, feritscope (Fischer MP30- with accuracy of ±0.1wt%) and XRD (Cu kα radiation at 40kv and 30mA) after grinding, polishing and etching with Behara etchant (20ml HCl +100ml water + 0.25gr K2S2O5) for 30s [13]. The mechanical properties were evaluated using hardness and tensile tests. Vickers hardness test were carried out at 10 Kg load. Uniaxial tensile tests were carried out at 25, 200, 350, 500°C in a rate of 0.3mm/min. Tensile specimens, with 25.4 mm gage length, were prepared based on ASTM-E8 [14]. Specific density of steels were also measured by a pycnometer.

3. RESULTS AND DISCUSSION

3. 1. Phases and Microstructure

Figure 1 shows the microstructure of FeCrMn and 316 steels in solution annealed condition. Both steels showed single austenite phase as the stable phase at room temperature. The austenite

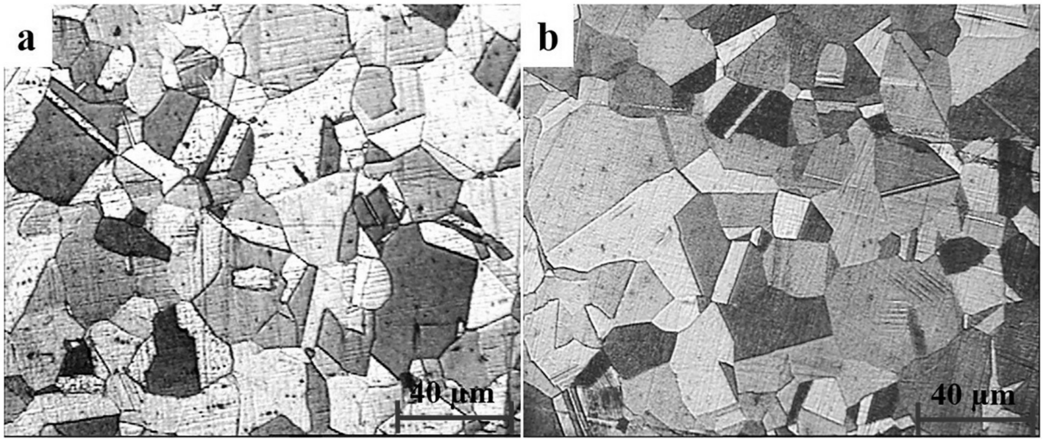

Fig. 1. optical micrograph of solution annealed steels a) 316 steel b) FeCrMn steel.

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grain size were also measured about 30±3μm for both steels by using linear intercept method according to ASTM-E112[15]. Actually, to achieve the same austenite grain size, in order to minimize the grain size effect on the mechanical properties, the solution anneal treatment time, at same temperature (1050°C), individually determined to each steel.

Strategy of designing chemical composition of Fe-Cr-Mn stainless steel, based on some aspects, includes: Mn is considered as the best replacement for Ni, but Mn has lower austenite stabilizing capacity than that of Ni, and since excess amount of Mn produces undesirable intermetallic compounds, such as sigma phase, it is not impossible to replace entirely Ni with only Mn [9, 12]. C is considered as strong austenite stabilizer, so this element can compensate the weakness of manganese. C also increases yield strength and prevents sigma phase formation, but it is noticeable that the excess amount of C decreases corrosion resistance [9, 12, 16], thus 23wt% and 0.1wt% was considered to upper level of Mn and C content, respectively. Stainless feature of austenitic stainless steels arises from Cr element, in which protective chromium oxide layer forms and improves corrosion resistance. A Cr content more than 11wt% can form protective oxide layer but Cr is a strong ferrite stabilizer that decreases austenite stability and also promotes undesirable intermetallic compounds [4, 17]. Accordingly, 12wt% was considered to upper level of Cr. Based on the above discussion the adjustment of alloying elements and chemical composition resulted in Fe-23Mn-12Cr-0.1C steel.

The structure of designed steel was evaluated according to Schaeffler diagram. The Schaeffler diagram is normally used to predict the available phases at room temperature for Ni-Cr stainless steels, and cannot be directly applied to Mn-Cr stainless steels, because Ni and Mn are not equivalent for stabilizing austenite phase against ferrite and martensite formation[12]. Klueh et al [12, 17] redrawn Schaeffler diagram boundaries to apply for Fe-Mn-Cr-C stainless steels. Fig. 2 shows the austenite phase as predicted stable phase at room temperature on modified Schaeffler diagram, developed by Klueh et al [12], for designed steel according to following Cr and Ni equivalent formulas:

$$Creq = (Cr) + 2(Si) + 1.5(Mo) + 5(V) + 5.5(Al) + 1.75(Nb) + 1.5(Ti) + 0.75(W)$$

$$Nieq = (Ni) + (Co) + 0.5(Mn) + 0.3(Cu) + 25\,(N) + 30(C)$$

where the concentrations of elements are in weight percent.

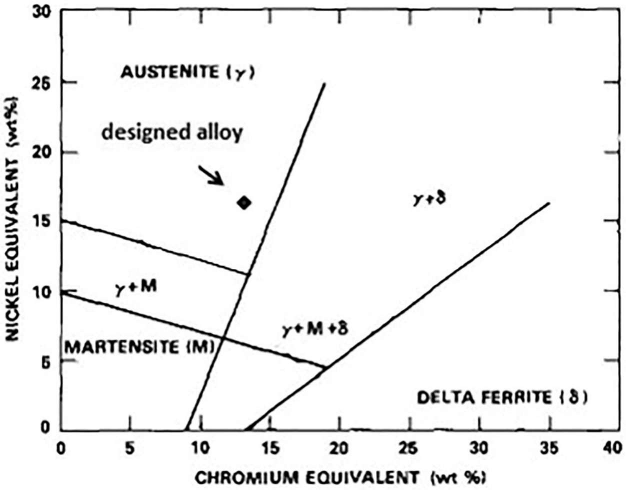

Fig. 2. Prediction of stable phases on modified Schaeffler diagram for Fe-23Mn-12Cr-0.1C steel [12]

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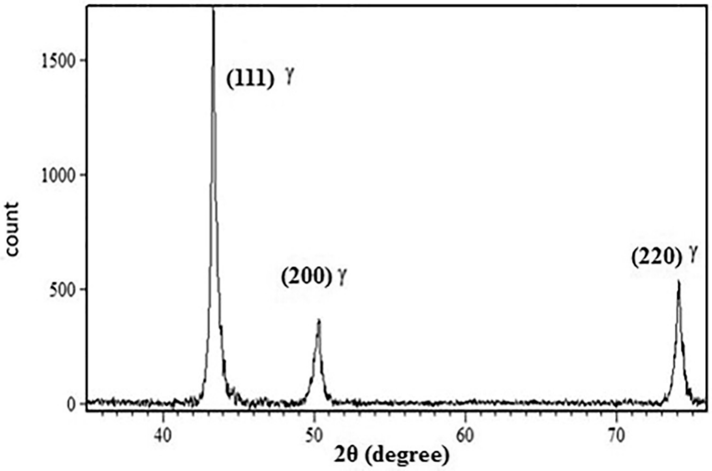

Fig. 3. XRD diffraction pattern of FeCrMn steel at solution annealed condition

Figure 3 shows the XRD pattern for FeCrMn steel at solution annealed condition. As can be seen XRD pattern shows just austenite picks and confirms the prediction of modified Schaeffler diagram and optical micrographs that austenite is the stable phase at room temperature in FeCrMn steel.

Magnetic test (feritscope measurements) was also conducted on solution annealed samples and did not detect any ferromagnetic phase such as martensite, delta ferrite and etc, and confirmed XRD results and optical micrographs.

3. 2. Mechanical Properties

3. 2. 1. Hardness

The results of hardness measurements are shown in Fig. 4 for both steels in solution annealed condition. The FeCrMn steel has higher hardness, about 50 Vickers, than 316 steel. Ohkubo et al [18] reported that interstitial elements have the main effect on austenite hardness in solution annealed condition. As FeCrMn steel has higher content of carbon, about

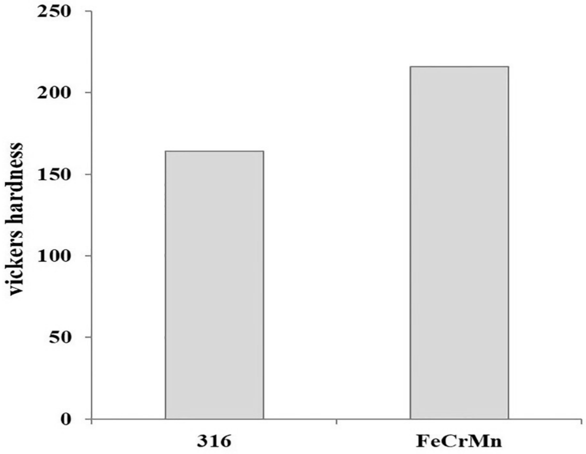

Fig. 4. Hardness results of FeCrMn and 316 steel in solution annealed condition

0.1%, than 316 one, so its higher hardness in comparison with that of 316 steel is understandable.

3. 2. 2. Tensile Properties

3. 2. 2. 1. Yield Strength

The engineering strain-stress curves at various temperatures for both steels are shown in Fig. 5. Fig. 6 shows the inverse temperature dependence of yield strength for both steels. It means that the yield strength decrease with increasing temperature in a same rate for both steels due to the easier movement of dislocations with increasing temperature [1]. The FeCrMn steel has higher yield strength than 316 steel at all temperature ranges. As both steels have single austenite phase structure and the same austenite grain size, the difference between chemical compositions of austenite is the main reason to the difference between yield strengths[18]. Alloying elements with solid solution strengthening mechanism enhance austenite strength. The addition of interstitial and larger solute substituted atoms increase the lattice dimensions and there is a direct correlation between lattice expansion and yield strength[19, 20]. Since the carbon content of FeCrMn steel is about 0.1% more than that of 316 one and additionally manganese has larger atomic radius than nickel [3], so the higher yield strength of FeCrMn steel to 316 steel is logical.

3. 2. 2. 2. Ultimate Tensile Strength

The variation of ultimate tensile strength with temperature are plotted in Fig. 7. The tensile

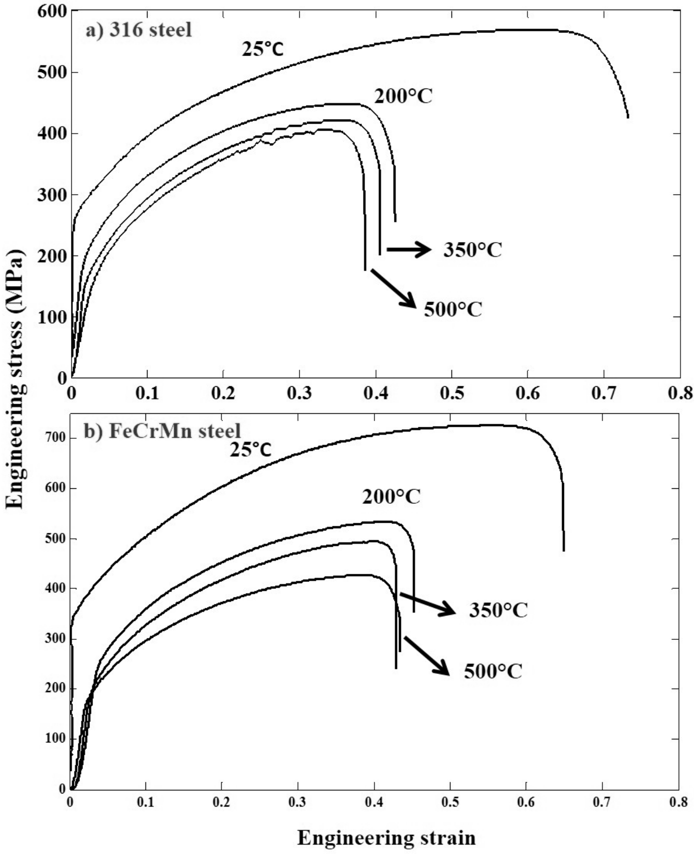

Fig. 5. The engineering stress-strain curves at various temperatures for a) 316 steel and b) FeCrMn steel

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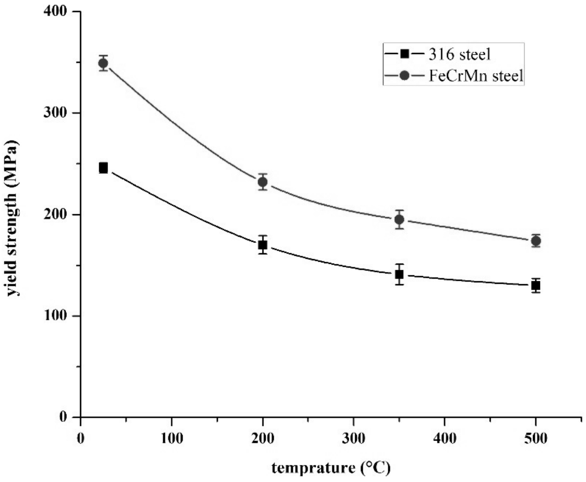

Fig. 6. variation of yield strength with temperature for both steels

strength of FeCrMn is higher than that of 316 one at room temperature. The magnetic test (feritscope measurements) detected 6.1% ά strain induced martensite at the fracture surface of 316 steel that was tensioned at room temperature, while there was no strain induced martensite at fracture surface of FeCrMn steel.

It should be noted that Md temperature and stacking fault energy (SFE) attitude are the most important metallurgical parameters that effect on microstructural and mechanical properties of austenitic steels[5]. Therefore, these parameters have to be considered. The Md (30/50)°C regarded as temperature at which 50% martensite is formed by 30% true strain[5]. Angel [21]have formulated the dependence of the Md temperature with composition for different steels in the form of below equation:

$$Md(30/50)°C=413-462(C+N)-9.2(Si)-8.1(Mn)-13.7(Cr)-9.5(Ni)-18.5(Mo) \quad (1)$$

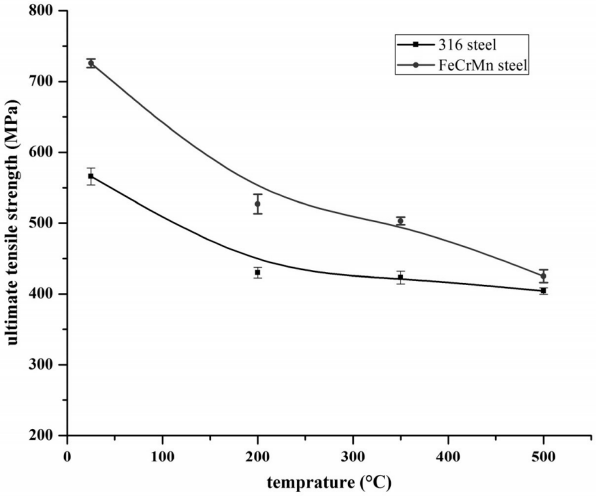

Fig. 7. Variation of tensile strength with temperature for both steels

where the concentrations of the respective elements given in parentheses are in weight percent. Equation (1) calculates the Md values -3.7 and 23.7°C for FeCrMn and 316 steels, respectively. There are several empirical equations showing the relationship between the chemical composition and SFE for Cr-Ni austenitic stainless steels. Two more important of these equations are[4]:

$$SFE(mJ/m^2)=-53+6.2Ni+0.7Cr+3.2Mn+9.3Mo \quad (2)$$

$$SFE(mJ/m^2)=25.7+2Ni+410C-0.9Cr-77N-13Si-1.2Mn \quad (3)$$

The SFE was calculated as 34.7 and 44.9mJ/m^2 for the 316 steel according to the equations (2) and (3), respectively. The equations (2) and (3), have been developed for Cr-Ni austenitic stainless steels and cannot be used for Cr-Mn austenitic stainless steels. Mujca et al [22] reported 37mJ/m^2 for SFE of Fe-20Mn-12Cr-0.24C-0.32N steel using transmission electron microscopy measurements. Their results also showed that increasing 5wt% Mn causes increment of SFE about 12mJ/m^2 in this steel, which confirmed earlier results given by Nakano [23], that suggested manganese with amounts higher than 15wt% increases SFE in Fe-Mn and Fe-Mn-C systems [22]. In other research [24] it was shown that increasing nitrogen about 0.2wt% in Cr-Mn steels, with amount of less than 0.5wt%, decreased SFE about 6 mJ/m^2, which is in agreement with Stolense's [25] results. Researchers [24, 26] also pointed out that decreasing carbon content about 0.23wt% decreases SFE of Cr-Mn steel about 8mJ/m^2. Using a good correction and with respect to above explains, an energy between 50-55mJ/m^2 can be estimated for SF of the new steel. Thereby, formation of strain induced martensite was attributed to lower stability of austenite phase in deformation during tensile test in 316 steel, which is due to lower SFE and higher Md. Actually, formation of deformation induced martensite, as a hard phase, in soft austenite matrix can increase strength of steel[27]. It implies that strain induced transformation in 316 steel could not compete the solid solution strengthening mechanism caused by alloying elements of carbon and manganese at austenite phase in FeCrMn steel. As can be seen in Fig. 7, tensile strength of both steels decreases with increment of temperature to 200°C, but by increasing temperature to 350 and 500°C the reduction of strength for 316 steel is slower than that of the FeCrMn one. There was no strain induced martensite in tensioned 316 steel samples at 200, 350 and 500°C. The SFE attitude of this steel increases by increasing temperature in which prevents formation of strain induced martensite[28]. A detailed attention to stress-strain curves for 316 steel, in Fig. 5, reveals a serrated plastic flow behavior at 350 and 500°C in the engineering stress-strain curve which implies the dynamic strain aging phenomenon occurred at mentioned temperatures. On the other hand, there is a continues plastic flow behavior for FeCrMn steel in all temperature ranges. As FeCrMn steel has high content of manganese and this element reduces the mobility of the carbon atoms, by formation of Mn-C pairs in steels, hence it prevents catching dislocations and DSA phenomenon or will shift it to higher temperatures[29]. Actually the occurrence of DSA phenomenon at 350 and 500°C increases strength and compensate loss strength caused by increasing temperature[30] in 316 steel. However the FeCrMn steel showed higher tensile strength at all temperatures.

3. 2. 2. 3. Elongation

Fig. 8 shows the temperature dependence of uniform elongation of steels. It is clearly seen that 316 steel has higher uniform elongation than FeCrMn steel at room temperature. As mentioned earlier, about 6.1% ά strain induced martensite forms during tension of 316 steel at room temperature. Formation of SIM during tensile test delays the necking and increases the uniform elongation thereby leads to higher ductility[31]. By increasing temperature to higher value the FeCrMn steel showed higher uniform elongation. The attitude of SFE increases by increasing temperature[32] and strain induced martensite does not form in 316 steel, so this steel showed higher decrease in uniform elongation than that

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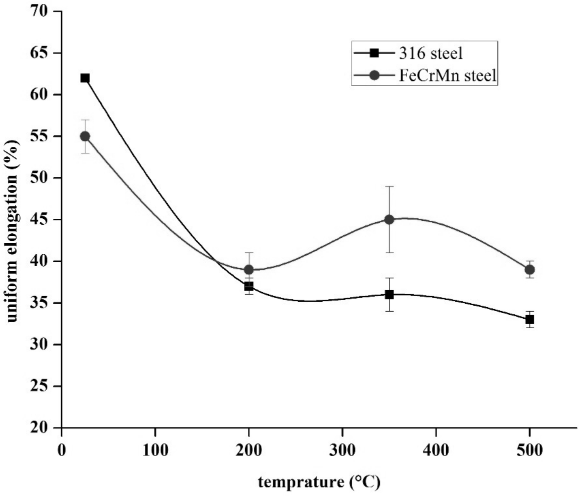

Fig. 8. uniform elongation of two steels versus temperature

of FeCrMn steel at 200°C. The occurrence of DSA phenomenon at 350 and 500°C in 316 steel restricts dislocations cross-slip and promotes strain localization which results in crack nucleation or higher crack initiation rate and leads to reduce uniform elongation[33, 34].

3. 2. 2. 4. Toughness

Absorbed energy before failure (E_f), that can be regarded as a measurement of toughness, can be calculated using true stress-true strain curves [35]. This parameter includes both factors of strength and ductility together. Fig. 9 presents the E_f calculations as a function of test temperature for both steels. As can be seen, the E_f value for FeCrMn steel is higher than that of 316 steel in all temperatures. This implies that FeCrMn steel has better combination of strength and ductility to 316 steel in all tested temperatures.

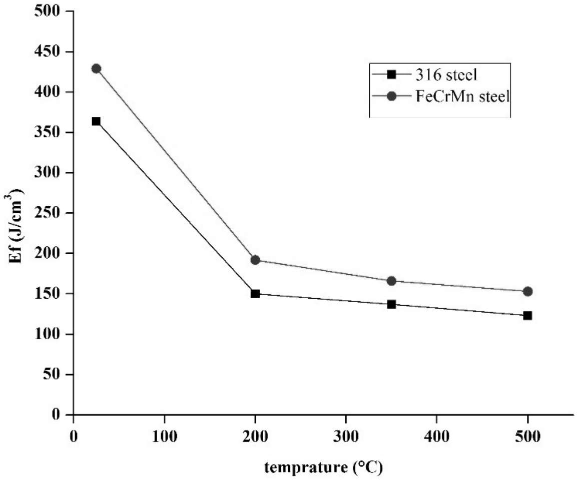

Fig. 9. Absorbed energy before the failure at various temperatures for both steels

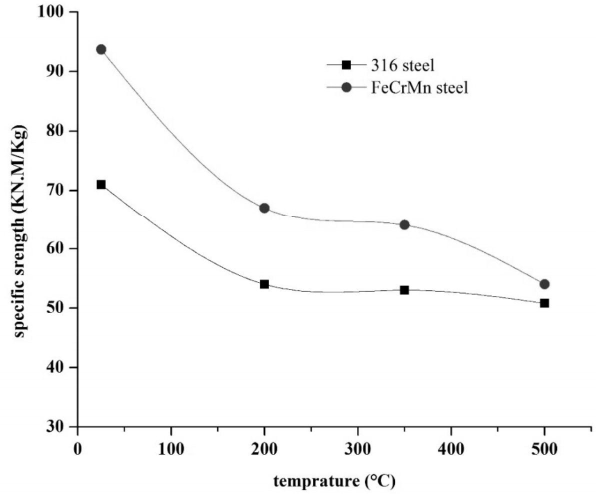

Fig. 10. Specific strength as a function of temperature for both steels

3. 2. 2. 5. Specific Strength

Fig. 10 presents the specific tensile strength, tensile strength over density, for both steels. The measurement of density showed that FeCrMn steel has lower density (7.80 gr/cm^3) than 316 steel (7.94 gr/cm^3), therefore FeCrMn steel has higher specific strength than 316 steel.

4. CONCLUSIONS

A new FeCrMnC steel was designed and produced based on Fe-Cr-Mn-C system. Then a comparative study on microstructure and mechanical properties of new steel and 316 steel was done. It was found that:

1. Microscopic assessments, X-ray diffraction result and magnetic measurements showed single austenite phase as the stable phase at room temperature for new designed steel as predicted by modified Schaeffler diagram.
2. Strain induced martensite transformation observed during tensile test in 316 steel at room temperature because of higher Md temperature and lower SFE than those of FeCrMn steel.
3. Dynamic strain aging phenomenon appeared in 316 steel at 350 and 500°C whereas a continuous plastic flow observed in FeCrMn steel in all temperature ranges.
4. New FeCrMn steel showed higher yield, ultimate strength and toughness than 316 steel at all temperature ranges.
5. Lower density and higher strength of new steel caused higher specific strength in comparison with to the 316 one that can be considered an important advantage in structural applications.

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