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Development of Fire Resistance Steel for Structural Applications

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Abstract

Three grades of steel were chosen to evaluate for their fire resistance performance. The steel # 1 (0.18%C-1.37%Mn-0.35%Si-0.12%Cr-0.113%V) is a vanadium micro alloyed steel, while Steel #2 (0.24%C-0.81%Mn-0.19%Si-0.97%Cr-0.2%Mo-0.01%Ti-0.055%Nb) is a titanium and niobium micro-alloyed steel, whereas steel #3 (0.19%C-0.50%Mn-0.19%Si-1.23%Cr-0.40%Mo-0.018%Nb) is a Nb micro alloyed steel. The room temperature and high temperature (@600ºC) were evaluated for the fitness for fire resistance steel. It was found that the steel #1 is having the yield ratio (ratio of yield strength at 600ºC to room temperature yield strength) of 0.74 while the steel #2 and #3 are having yield ratio of 0.96 and 0.97 respectively. The higher yield ratio of the steel #2 and #3 are due to the presence of Cr, Mo as the solid solution strengthening in addition to the Nb or Nb & Ti micro-alloying. All the three steels with ferrite pearlite microstructure were qualified for the fire resistance norms (2/3=0.67, of the yield strength at 600ºC) and however considering the higher carbon equivalent of the steel#2 and #3 only steel#1 can be used for fire resistance structural applications for the replacement of E350 grade.

Keywords: fire resistance steel, structural applications, yield ratio, microstructure and mechanical properties

1. Introduction

Structural steels are widely used for the various structures such as stadium, bridge, sky scraper buildings etc. Various structural steels include E250, E275, E300, E350, E410 E450 and high strength structural steels such as E550, E650 etc.[123] Steel maintains its strength and structural integrity even at high temperatures, without ignition, softening or emission of toxic gases when exposed to fire due to their high melting temperatures unlike materials such as wood, concrete etc. (Amir Reza, 2023).

In accidental fire there is a great challenge to the existence of the structures as the yield strength of the steel drops with the increase in temperature. Collapse of the structures can not only lead to loss of property it can cause loss of human being and its reconstruction can further accounts for the additional cost. Hence, there is a need to use steels which can withstand fire for a reasonable period in which fire fighter workers can reach to the site to save the collapse of the structures by extinguishing the fires. Although, fire proof coatings are also growing in demand, thick coating on the steels increases the cost and weight to the structure. Therefore, steels need to be developed which can withstand fire for a reasonable time (1-3 hour). Fire resistance steels are the steels which can withstand the yield strength at high temperature with the yield ratio (ratio of yield strength at 600ºC to the room temperature yield strength) $\geq$ two third ($\geq$0.66) (Hiroshi Fujino, Kiyoshi Hitomi, Junji Hashimoto & Seiho Umezawa, 1993; Yasushi Mizutani, Kenichi Yoshii, Rikio Chijiiwa, Kiyoshi Ishibashi, Yoshiyuki Watanabe & Yuzuru Yoshida, 2004; Yu. D. Morozov, O. N. Chevskaya, G. A. Filippov, & A. N. Muratov, 2007)[4].

The steels need to have micro alloying such as Nb, V, Ti or combination of them for the precipitation strengthening at high temperature and solid solution elements such as Cr, Mn, Cu, Ni W, V and Mo to give solid solution strengthening to retain the strength at high temperature (Linxi Liu, et al., 2024; J.G. Speer, D.K. Matlock & S.G. Jansto, 2015; Chaoyong Xu, et al., 2024).

In the present study, three steels among which one is V microalloyed, second one is Nb & Ti micro alloyed and the third one is only Nb micro alloyed were evaluated for their fire resistance properties for the structural applications.

2. Experimental

Bar rod steel of diameter 16 mm manufactured at JSW Salem Works was used in the present study. The chemical composition of the steel evaluated through SPECTRO make OES shown in Table 1. Round specimens were prepared from the steels for room temperature (20ºC) and high temperature (600ºC) mechanical testing in a Zwick make 250 kN universal testing machine. Bulk hardness was carried out on a Rockwell-B Scale. Optical and SEM were used for the microstructural observations using Olympus make and Hitachi make microscopes respectively. The critical temperatures of the steels were obtained as shown in Table 2, through JMat Pro software by obtaining the advanced CCT diagram as shown in Figure 1.

Table 1. Chemical composition of the steels

Steel	**%C**	**Si**	**Mn**	**P**	**S**	**Cr**	**Mo**	**Ni**	**Cu**	**Ti**	**V**	**Al**	**Nb**	**Nppm**
#1	0.18	0.35	1.37	0.025	0.017	0.12	0.003	0.016	0.009	0.002	0.113	0.005	0.002	90
#2	0.24	0.19	0.81	0.024	0.017	0.97	0.20	0.010	0.01	0.010	0.007	0.021	0.055	77
#3	0.19	0.19	0.50	0.026	0.013	1.23	0.40	0.010	0.012	0.001	0.005	0.004	0.018	80

Carbon equivalent of the steels were evaluated through equation (1).

$$CE = C + Mn/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15 \qquad (1)$$

Carbon equivalent of steel #1, #2 and #3 evaluated from equation (1) are 0.46, 0.61 and 0.60 respectively. The carbon equivalent for the structural steels 0.36-0.40 is very good, 0.41-0.45 is good, and 0.46-0.50 is Fair and >0.50 is poor.[5]

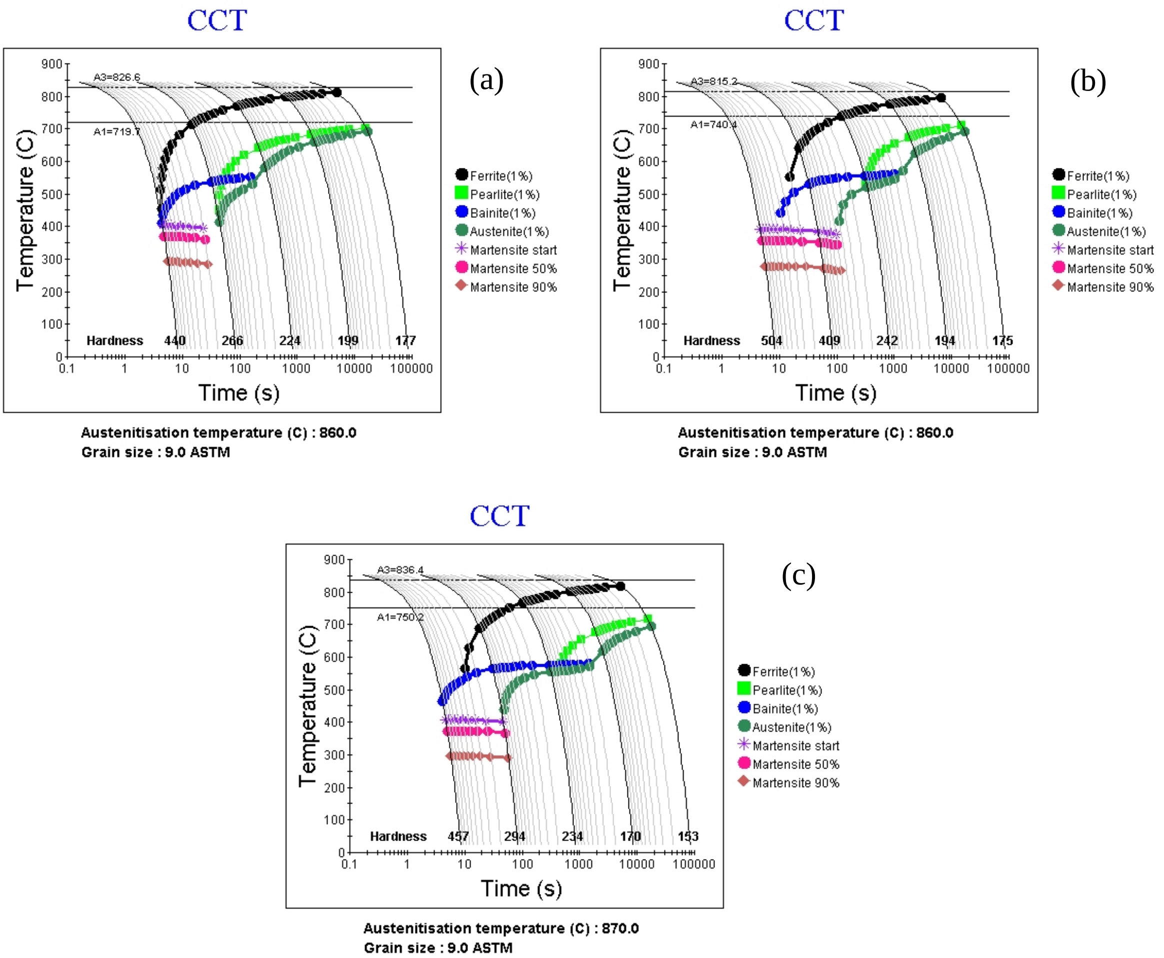

Figure 1. Advanced CCT diagram of the steels constructed through JMatPro software (a) Steel #1 (b) Steel #2 and (c) Steel #3

Table 2. Critical temperatures (A_1 and A_3)

Steel	A_1	A_3
#1	720	827
#2	740	815
#3	750	836

3. Results and Discussion

3.1 Microstructural Analysis

3.1.1 Optical Microstructure

Microstructure of the steel #1, #2 and #3 in as received condition and after tensile test at 600°C for 1 h is shown in (a) & (b) of Figure 1, 2 and 3 respectively with their high magnification images shown in (c) & (d) respectively. The microstructure of the steels is showing mostly ferrite-pearlite structure with the phase fractions and grain size of the steels summarized in Table 3.

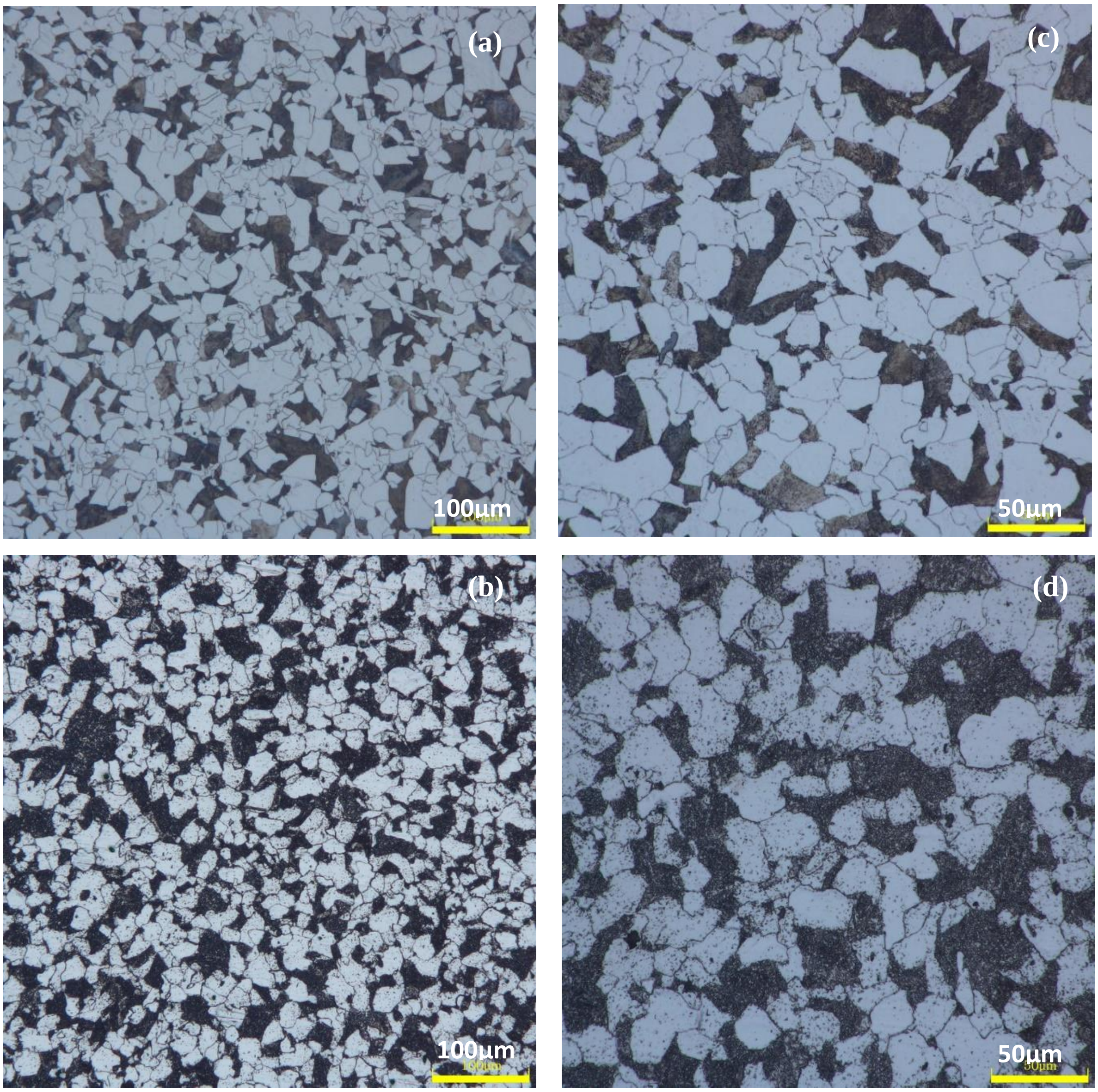

Figure 2. Microstructure of the steel #1 (a) as-received (b) tensile tested at 600ºC/1h, (c) & (d) are their corresponding microstructure at high magnification

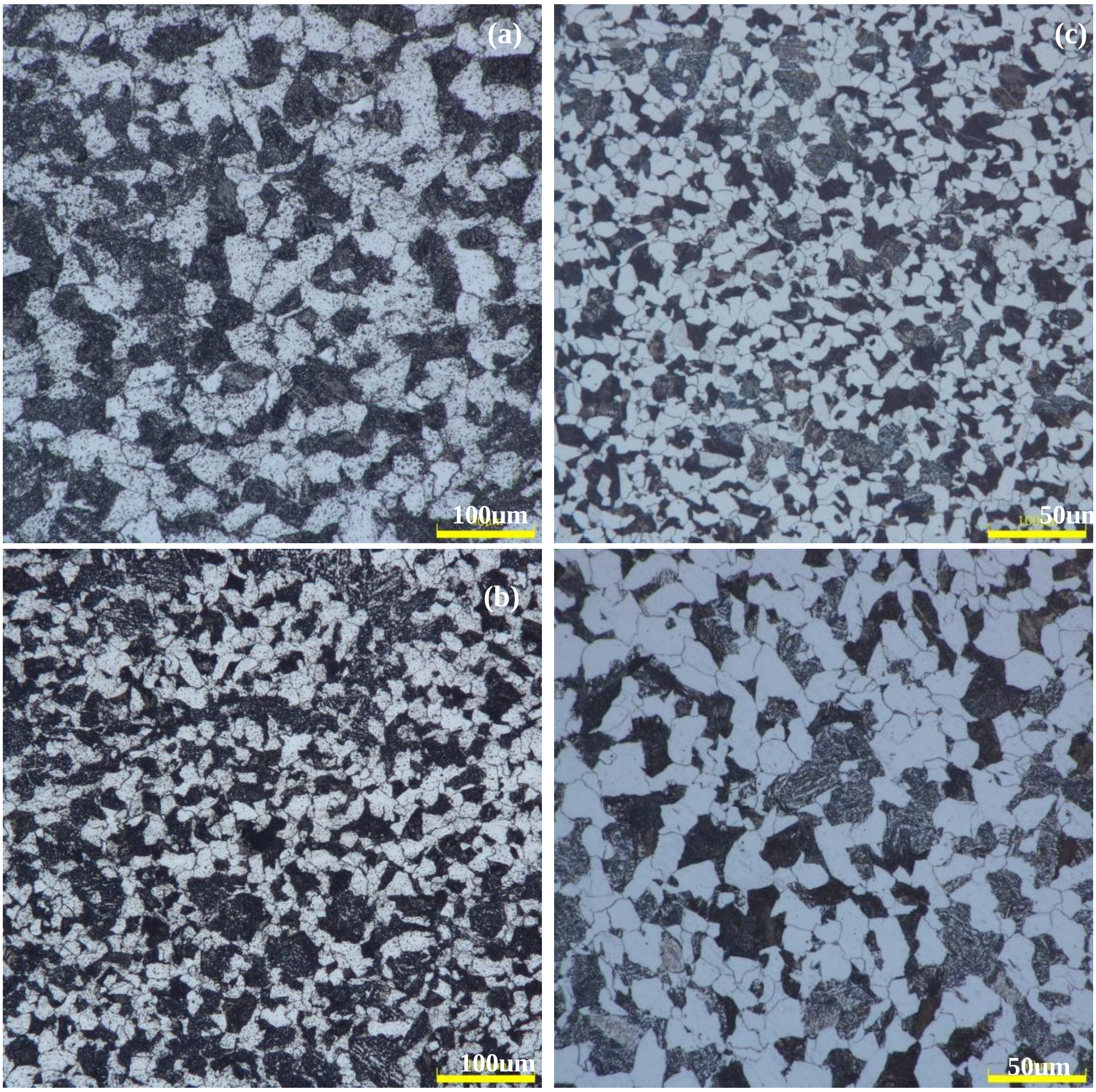

Figure 3. Microstructure of the steel #2 (a) as-received (b) tensile tested at 600ºC/1h, (c) & (d) are their corresponding microstructure at high magnification

Table 3. Grain size and phase fraction of the steels

	ASTME112-13		Phase Fraction	
	ASTM No.	Grain size	Pearlite	Ferrite
#1	9.07	13.80	45-48	52-55
#2	9.23	13.00	48-49	51-52
#3	8.94	14.40	40-44	56-60

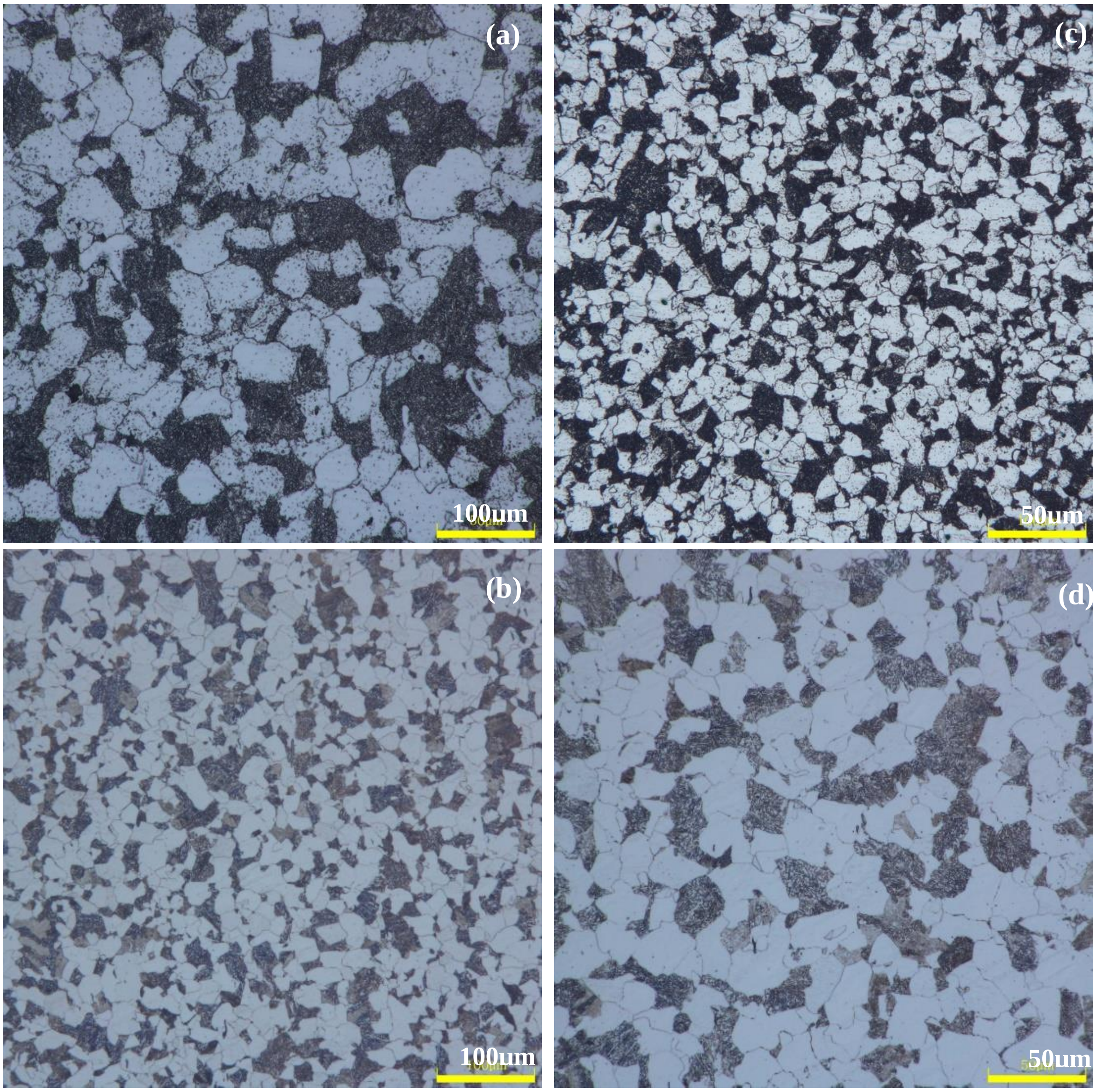

Figure 4. Microstructure of the steel #4 (a) as-received (b) tensile tested at 600ºC/1h, (c) & (d) are their corresponding microstructure at high magnification

3.1.2 Scanning Electron Microscopy (SEM)

SEM Micrograph of the steel #1, #2 and #3 in as received condition and after tensile test at 600ºC for 1 h is shown in (a) & (b) of Figure 5, 6 and 7 respectively with their high magnification micrographs shown in (c) & (d) respectively. It can be observed that no precipitates are present in the as-received condition whereas fine precipitates are present in the high temperature exposed condition. Such fine precipitates impede the dislocations at high temperature to give high temperature strength to the steels. The precipitates mostly MX type carbides, nitrides or carbonatites form. In addition, solid solution strength by Mn, Cr, V also helps in providing high temperature strength to the steels.

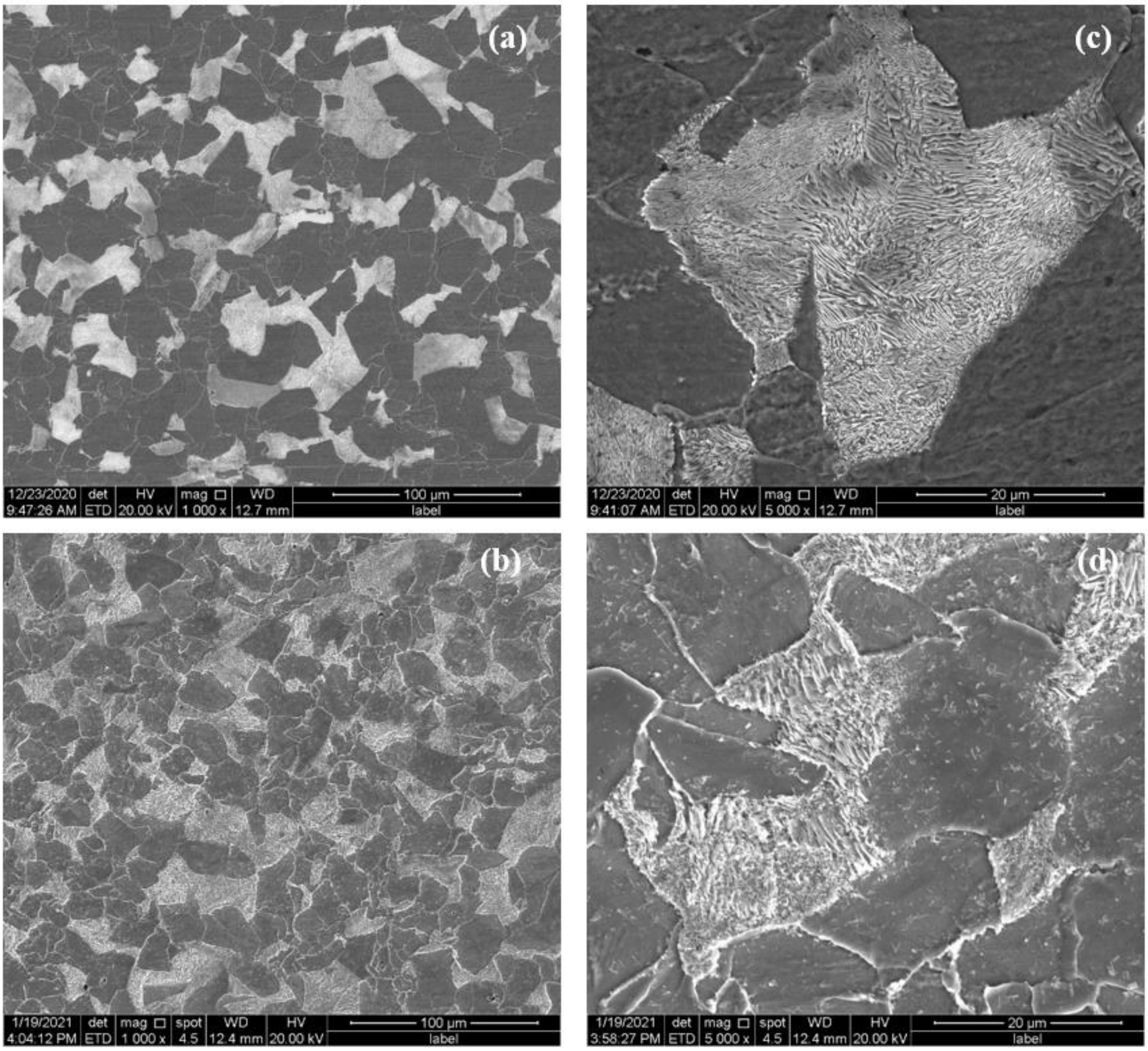

Figure 5. SEM Micrograph of the steel #1 (a) as-received (b) tensile tested at 600ºC/1h, (c) & (d) are their corresponding micrograph at high magnification

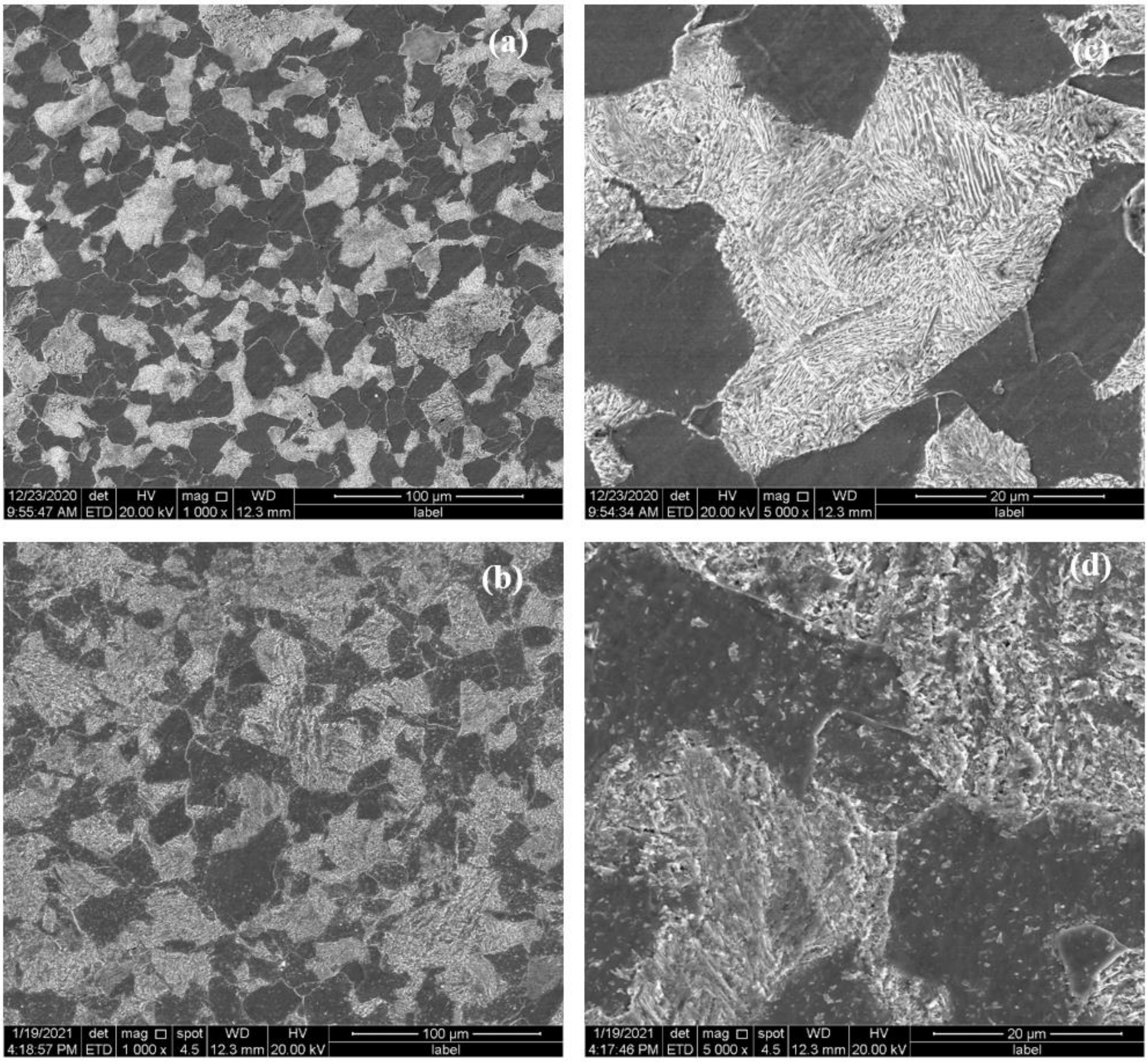

Figure 6. SEM Micrograph of the steel #1 (a) as-received (b) tensile tested at 600^{o}C/1h, (c) & (d) are their corresponding micrograph at high magnification

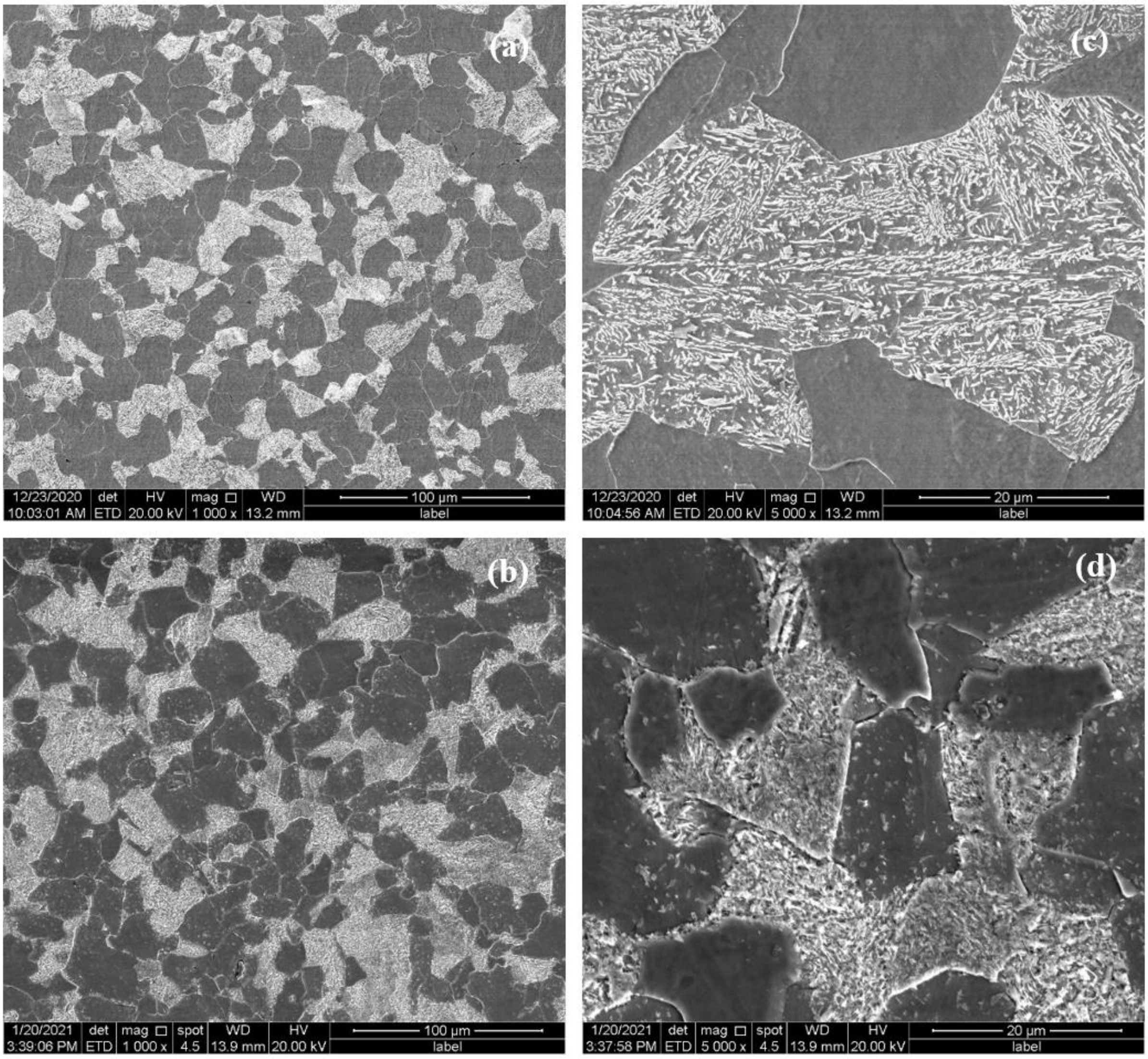

Figure 7. SEM Micrograph of the steel #1 (a) as-received (b) tensile tested at 600^{o}C/1h, (c) & (d) are their corresponding micrograph at high magnification

3.2 Mechanical Properties of the Steels

Stress strain diagram of the steel #1, #2 and #3 at room temperature and at high temperature (600^{o}C) is shown in Fig.8 (a), (b) and (c) respectively. Mechanical properties of the steels with the hardness and yield ratio are shown in Table 4. All the three steels are having yield strength ≥350MPa and hence can be used as the fire resistance steel E350 categories. The tensile strength for the E350 grade is generally ≥490MPa and total elongation ≥22% and all the three steels are qualifying for the same.[6] The steel #1 is having yield ratio of 0.74 whereas the steel#2 and #3 showing yield ratio 0.96 and 0.97 respectively.

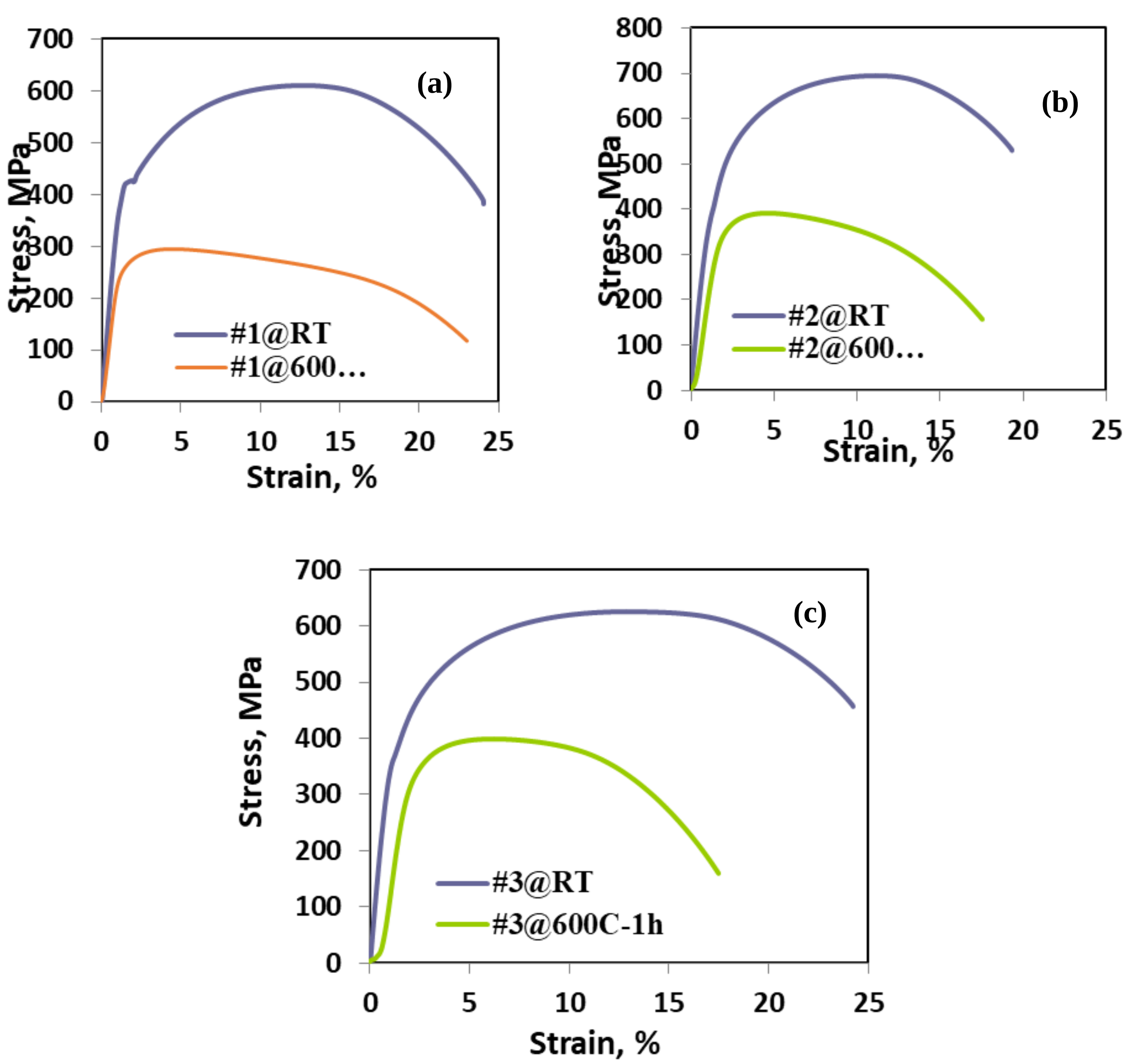

Figure 8. Stress-strain diagram of the steel #1, #2 and #3 tensile tested at room temperature and at 600ºC

Table 4. Mechanical Properties of the Steels

Steel	Room temperature				High Temperature@600ºC				Yield Ratio
	PS, MPa	UTS, MPa	EL, %	Hardness, HRB	YS, MPa	UTS, MPa	EL, %	Hardness, HRB	
#1	372	611	24.1	91	305/247	312/295	23	96	0.74
#2	360	695	19.3	93	342/350	392/381	17.5/20.4	97	0.96
#3	355	625	24.3	95	340/351	399/414	17.5/14.7	99	0.97

3.3 Fractography Analysis

3.3.1 Fractography Analysis-Room Temperature Tensile Test

Fractography of the as-received steels after tensile test is shown in Figure 9. From left to right the steels with increase in magnification is shown. It can be found that large dimples and voids are present for the steel #1 as compared to the steel #2 and #3. Indicating that the steel #1 is more ductile compared to the steel#2 and #3.

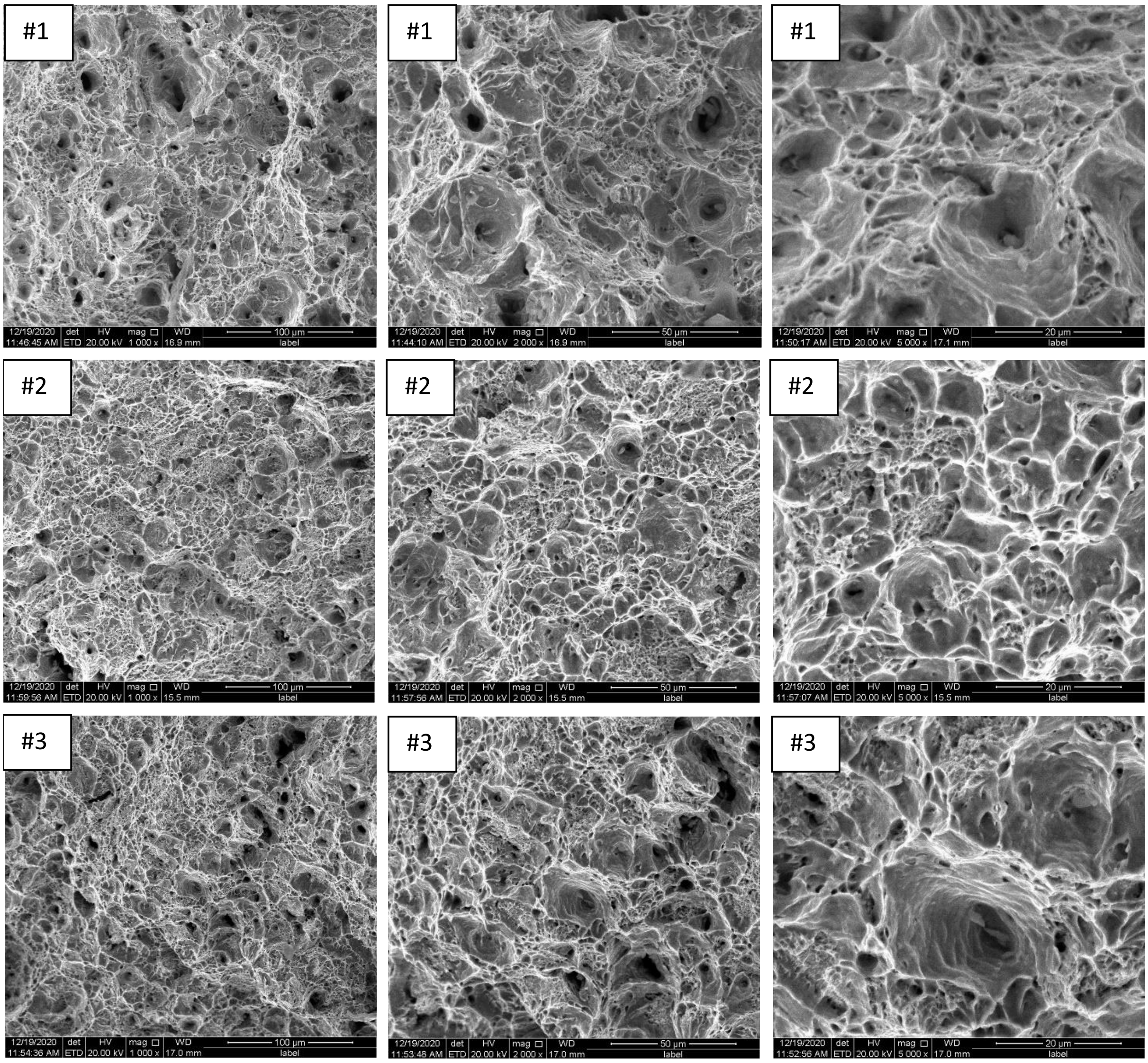

Figure 9. Fractography of the steel #1, #2 and #3 at three different magnification (left to right increase in magnification)

3.3.2 Fractography Analysis-High Temperature Tensile Test (600°C)

Fractography of the steels after tensile test at 600°C for 1 hour is shown in Figure 10. Large size dimples and voids are found in the steel #1 compared to the steel #2 and #3. However, all the three steels are showing ductile failure.

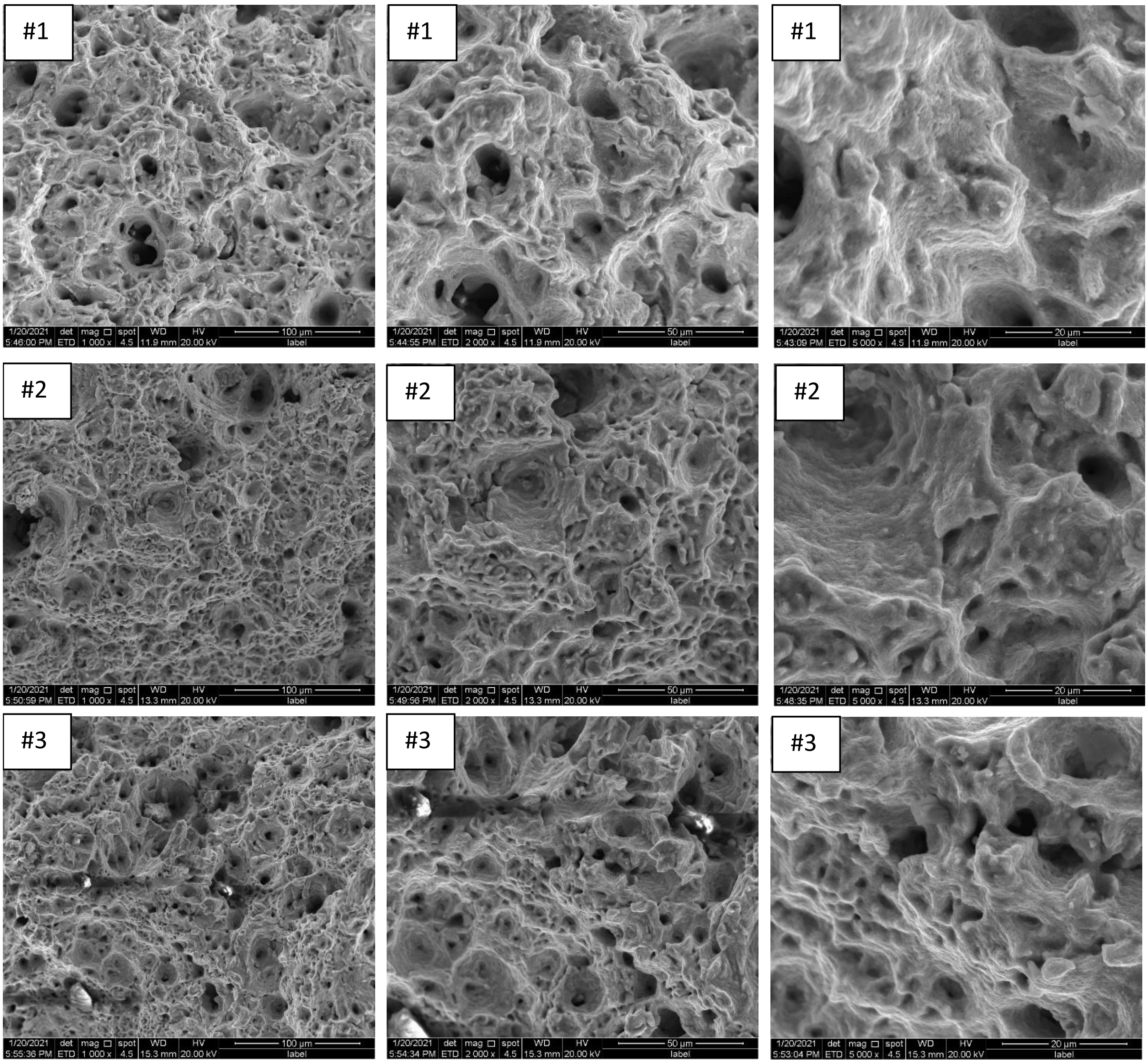

Figure 10. Fractography of the steel #1, #2 and #3 after tensile test at 600ºC/1h at three different magnification (left to right increase in magnification)

4. Conclusion

The three steels used in the present study qualifies for the fire resistance norms of existing two-third or more of their room temperature yield strength at 600ºC. The steels are qualifying for E350 fire resistance structural steel with yield strength ≥350 MPa, ultimate tensile strength ≥ 490 MPa and total elongation ≥22%. Hence, the steels can be used as fire resistance steel for structural applications with the replacement of E350 grade with fire resistance properties. Although in the present case wire rod steels were studied flat products of similar composition can be rolled to develop the fire resistance steels. In terms of carbon equivalent, the steel #2 and #3 are having more carbon equivalent and hence need to be discarded for structural applications and steel#1 is close to the requirement of structural steels and hence steel#1 need to be considered for the fire resistance structural steel development of E350grade.

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