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Development of Mechanical Properties of Carbon Manganese Steels Subjected to Ultra Fast Heating

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Research Article

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ABSTRACT

The mechanical properties of cold rolled carbon manganese steel after ultra-fast heat treatments were investigated. Ultra fast heating is an innovative technique that produces an appealing range of mechanical properties due to the unique microstructure achieved. A medium carbon (0.35%) manganese steel grade in strip form was subjected to an ultra fast heating schedule using a thermo mechanical simulator and quenched in water. The heating rates involved were 10, 100, 300, 500, and 1000°C/s to 850°C. At 85°C, the holding time was varied between 1 second and 300 seconds before water quenching. The strength grew significantly with increasing heating rate, reaching a maximum at around 500°C and then decreasing around 1000°C/s. The optimal properties of 1878 MPa with 12% ductility may be attained. The observed attributes result from a bainitic martensitic microstructure corresponding with significant transformation.

Keywords: Ultra fast heating; Ultra high strength; Phase transformation; Bainite microstructure; Thermo mechanical simulator

INTRODUCTION

The mechanical properties of carbon manganese steels subjected to ultra fast heating investigations concerning alternative ways to produce advanced high-strength steels without the addition of expensive alloying elements seem very attractive. Ultra fast annealing might offer a solution to alter the properties of the material. It would be advantageous if c-mn steels could be adapted merely by heat treatment in such a way that the tensile strength and elongation of advanced high-strength steels can be reached without adding chrome, nickel, titanium, etc. alloy element. As metal scarcity will only become a more important issue in the future [1]. The ultra fast heating process involves rapid heating of steel at an abnormally high heating rate to austenitization temperature, which tends to suppress the recrystallization of the grains. A very fine grain size (<3 μm) is attained. Cold rolled low carbon (0.11% C) TRIP steel, 1 mm thick, with 1.26% Si and 2% Mn content, subjected to heating at 140°C/s, ~400°C/s and ~1500°C/s to a temperature between 500 and 1000°C and held for 1 to 2 s holding, followed by water quenching shows 1200 MPa strength with 20% elongation [2]. Cold rolled low carbon (0.11% C) TRIP steel, 1 mm thick, with 1.26% Si and 2% Mn content, subjected to heating at 140°C/s, ~400°C/s and ~1500°C/s to a temperature between 500 and 1000°C and held for 1 to 2 s holding, followed by water quenching shows 1200 MPa strength with 20% elongation [3]. Inadequate holding time leads to improper carbide dissolution, leading to low carbon and high carbon martensite due to improper homogeneity. In addition, the high heating rate suppresses the recovery and recrystallization. A simple ferrite pearlitic low carbon (0.1%) and 1.42% Mn subjected to 300°C/s heating rate produces 6 to 10 microns with a yield strength of 850 to 1080 MPa, tensile strength of 1040 to 1269 MPa and elongation of 15.7 to 19.7% [4]. A low carbon (0.19%), Al alloyed (1.06% Al) TRIP steel, with 1.61% Mn, subjected to ultrafast heating from 300°C to the peak temperature of 860°C at two different heating rates, 10°C/s (conventional heating or CH) and 800°C/s (ultra-fast heating or UFH) followed by soaking at 860°C for 0.2 s. Such a short soaking time (0.2 s) eliminates the effect of annealing time on the microstructure and focuses entirely on the effect of heating rate on the microstructure of the ferritic matrix. The CH treatment results in the ferritic matrix consisting mainly of equiaxed recrystallized grains independently on the soaking time, while fine recrystallized grains and larger non-recrystallized (*i.e.,* recovered) ferritic grains are present in all UFH treated conditions. The fraction of recrystallized ferritic grains generally increases with increasing soaking time. The volume fraction of martensite tends to increase with increasing soaking time during UFH (ultra fast heating) treatment due to suppress cementite spheroidization, which, in turn, reduces the amount of energetically favorable sites for austenite nucleation and results in a longer soaking time to reach the equilibrium at the inter-critical peak temperature [5]. On cold rolled low carbon steel, ultrafast heating experiments at 150°C/s and 1500°C/s to different peak temperatures were carried out, allowing the formation of massive austenite during heating and the subsequent transformation of a mixture of pro eutectoid and widmanstatten ferrite, as well as marten site with heterogeneous carbon content. In all materials, the UTS increases with increasing heating rate up to 800°C/s, then it drops. As with the hardness measurements, the highest values of UTS were measured in 50% of M samples. In this case, the sensitivity of the UTS to the heating rate is higher for the range between 10°C/s and 400°C/s for 50% M samples, compared to the F+P samples. The 50% M samples show an increment of ~200 MPa from 10 to 800°C/s heating rate [6]. Flash processing of an AISI8620 steel sheet, which involves rapid heating and cooling with an overall process duration of <10 s, produced a steel microstructure with high tensile strength and good ductility similar to that of advanced high strength steels. Flash processed steel (Ultimate Tensile Strength (UTS): 1694 MPa, elongation: 7.1%), showed at least 7% higher UTS and 30% greater elongation than published results on martensitic advanced high-strength steel (UTS: 1585 MPa, elongation: 5.1%). As the overall processing time (<10 s) is very short, this process could be an alternative route for producing AHSS sheets [7]. The examine the microstructure evolution under ultra fast heat treatment a hot rolled, medium carbon, Chromium-Molybdenum (CrMo) steel ($42CrMo_4$) was used and in UFH and CH heat treated samples, submicron and nanostructured ferrite and martensitic laths were apparent as revealed *via* EBSD based on the difference of the IQ diffraction patterns. However, in UFH, the presence of bainite (or bainitic ferrite) was distinguished due to the carbide precipitation, observed at the interface of bainitic ferrite laths since the IQ values are similar to martensite. In the UFH sample, undissolved spherical carbides were also observed [8]. TRIP steel [9] and the quench partitioning process [10,11] as new developments. Studies on the microstructure of ultra-fast heating on 42CrMo$_4$ alloy steel showed finer prior austenite grain size long with bainitic ferrite with alloy carbides M7C3 and undissolved cementite where inadequate diffusion resulted in massive transformation [12].

In the present study, 0.35 % carbon manganese steel with low mechanical properties has been subjected to ultra-fast heating in a Gleeble 3800 unit, leading to the development of ultra-high strengths with good ductility. The microstructure evolution and mechanical properties are brought out.

MATERIALS AND METHODS

Experimental

The experiment was performed in the Gleeble 3800 unit. The steel grade used for the study is 2.2 mm thick in the hot rolled condition-made steel in the JSW steel Vijayanagar unit. The steel was loaded in a thermo mechanical simulator Gleeble 3800. Cut steel samples of a known thickness were put in the Gleeble 3800 machine. Steel strips of prefabricated dimension as per micro tensile sample as per Figure 1, were subjected to ultra-fast heating. Samples were studied at fast heating rates 10°C/s, 100°C/s, 300°C/s, 500°C/s, and 1000°C/s. The sample is heated to a high temperature of 850°C followed by quenching in water. At each heating rate, the high temperature hold time varied between 1 s and 300 s. The heating rate imposed is shown in Figure 2 and Table 1.

Figure 1. Dimension of micro tensile sample used in the present study.

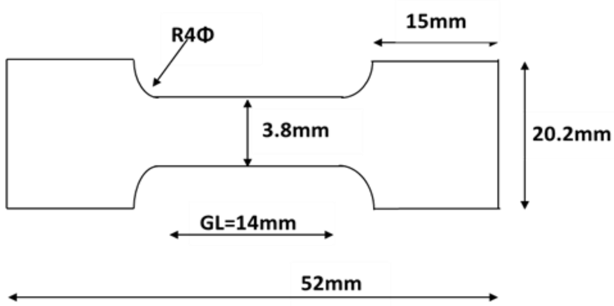


Figure 2. Schematic of ultra fast heating rate on the test sample.

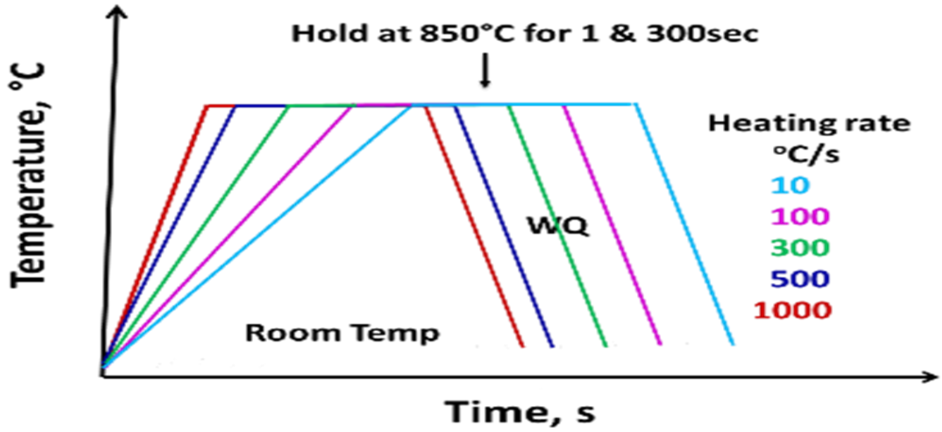


Table 1. Heating rate of samples in Gleeble 3800.

Heating rate (°C/sec)	Initial temp of sample, °C	Final temp of sample, °C	Temp difference, °C	Time (sec) to reach 850°C temp
10	22	850	828	82.8
100	22	850	828	8.28
300	22	850	828	2.76
500	22	850	828	1.656
1000	22	850	828	0.828

The samples were subjected to room temperature tensile testing using Zwick Roell make UTM machine of model Z250. The hardness was measured using FIE make Digital Hardness Tester of the RASNEB-3 Model. The optical microstructure was evaluated in the sample extracted from the grip using olympus opto digital microscope Model DSX 510. The SEM microstructure was evaluated using the QEMSCAN SEM model Quanta 650 FEG of FEI make.

RESULTS AND DISCUSSION

The chemical composition of the steel was studied in Table 2. The steel is a simple mild steel composition with 0.359% C and 1.35% Mn. The steel is Aluminium killed with residual Al of 0.035%. The other residual elements are 0.142% Si, 0.033% P, 0.021% Cr, 0.022% Cu, and 0.011% Ni. The received material was a hot rolled sheet of 2.2 mm thickness.

Table 2. The chemical composition of the steel studied in wt.%.

Sample ID	C	Mn	S	P	Si	Al	Cr	Ni	Nb	Mo	V	Ti	Cu	Ca
CM35	0.359	1.35	0.004	0.033	0.142	0.035	0.021	0.011	<0.000	0.002	0.002	0.003	0.022	0.001

The mechanical properties of the steel subjected to ultra fast heating with 1 second and 300 second holding times are shown in Table 3 and Figures 3. Figures 3 shows that the tensile strength as a function of heating rate shows an increase in tensile strength. The strength saturates at a value around 300 to 500°C/s where tensile strength as high as 1878 MPa with 12% ductility is achieved for 500°C/s with a holding time of 1 second. There is a strength decrease beyond 500°C/s with 10% ductility. Lean chemistry of steel creating such ultra-high strength and ductility shows potential for exploitation of the new type of processing. Rapid heating by induction heating or resistance heating is possible. The steel may be quenched in a high-temperature salt bath for a very low duration, followed by quenching new possibilities. It may also be possible to rapidly heat, hot stamp, and quench to achieve such high strengths.

The mechanical properties of steel subjected to ultra fast heating at various rates for 300 seconds indicate a progressive increase in tensile strength reaching a peak value of 1402 MPa with 11% ductility. Following that, the strength declines while the ductility increases to 17%. As a result, the holding period at high temperature has an effect on the characteristics. Figures 4 and 5 depicts the hardness values of the sample measured at various heating rates. The hardness of the sample rises as the heating rate increases. The hardness reaches its maximum around a heating rate of 500°C/sec (Figures 4 and 5).

Table 3. Mechanical properties of CM35 subjected to ultra fast heating rate.

Heating rate, °C/sec	Holding time 1 second				
	YS	UTS	%El	YS/UTS	UTS X %El
As received	466 ± 9	648 ± 15	37 ± 2.8	0.72	23976
10	605 ± 13	817 ± 38	16.8 ± 2.5	0.74	13726
100	810 ± 22	1050 ± 41	14.3 ± 1.5	0.62	18690
300	889 ± 62	1307 ± 77	13.8 ± 2.3	0.85	13440
500	1385 ± 85	1878 ± 112	11 ± 1.9	0.74	20658
1000	569 ± 25	824 ± 42	14.7 ± 2.1	0.69	12113
Heating rate, °C/sec	Holding time 300 second				
	YS	UTS	%El	YS/UTS	UTS X %El
10	672 ± 13	834 ± 38	13.5 ± 1.9	0.80576	9591
100	835 ± 17	992 ± 28	12.8 ± 2.5	0.84173	9721.6
300	841 ± 12	1068 ± 13	11.7 ± 3.7	0.78745	8330.4
500	1067 ± 31	1402 ± 47	10.9 ± 1.2	0.76106	12758.2
1000	476 ± 36	781 ± 68	17.2 ± 1.5	0.60948	13433.2

Figure 3. The effect of heating rate on the mechanical properties of steel grade CM 35 with holding time at high temperature (a) 1 s; (b) 300 s.

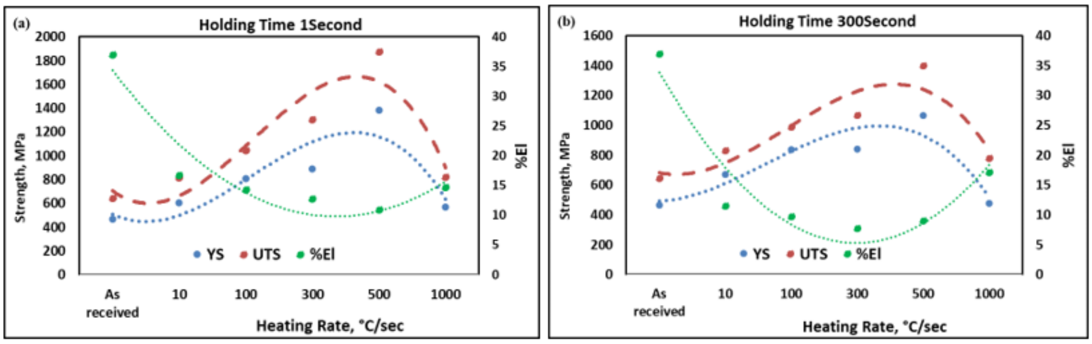


Figure 4. The hardness of the steel at various heating rates and holding times.

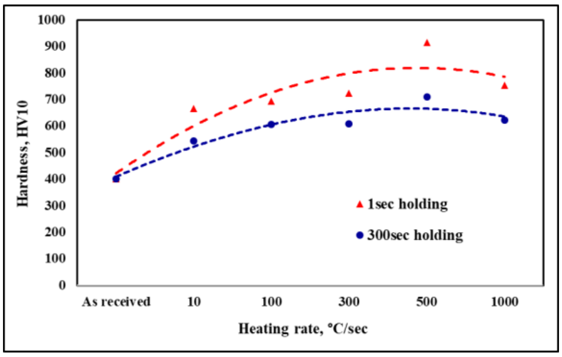
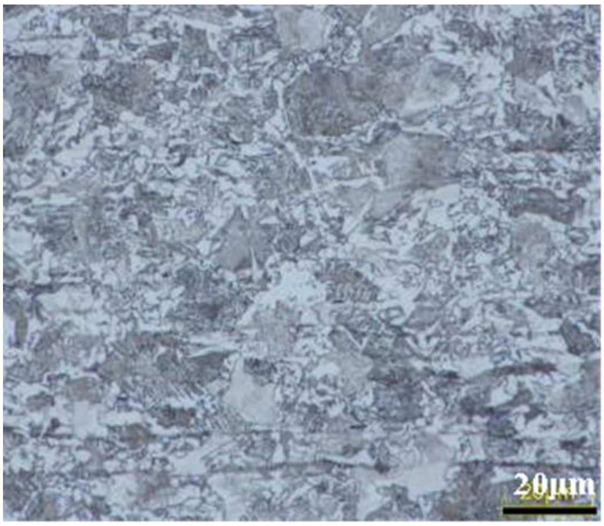


Figure 5. The microstructure of the steel CM35 studied in the as received condition.



The microstructure of the as received steel shown in Figure 5 is a simple ferrite in pearlite. The optical and SEM microstructures of the steel after ultra-fast heating rate and holding at 850°C for 1 s and 300 s are shown in Figures 6 and 7. At 1s holding with increasing heating rate, the extremely fine grained microstructure is observed in the optical metallography. With an increase in rapid heating rate, there is an increase in fineness in the grain structure. The fineness of the structure shows up as a granular carbide type appearance in the optical microstructure. But the structure is a fine ferrite and carbide distributed as a bainitic ferrite and carbide. The SEM microstructure shows up with carbide dissolution and there is a massive bainitic ferrite formation. In between the massive transformation, portions of martensite pocket enhance the strength and ductility. This increases till 300°C/s, and it decreases beyond this heating rate. At higher heating rates, the martensite pockets decrease, and the coarse bainitic ferrite predominates.

The 300's holding, on the other hand, shows martensite lath visible at all the austenitizing conditions. The lath sizes are enlarged as the holding temperature increases. Initially, rapid heating forms fine grains due to rapid nucleation. The grains have adequate time to recrystallize and form austenite. This implies that at long holding times, there is recrystallization, and there is a complete conversion of ferrite to austenite. On quenching, the austenite transforms into lath martensite. It is seen that the martensite formed has a higher density of the martensite laths to 300°C/s. The heating rate beyond that leads to coarse ferrite and higher carbide precipitation. The phase transformation during austenitization is usually a diffusion controlled reaction. During RTA, the mechanism changes to diffusion less massive austenite transformation beyond a critical heating rate. The velocity of γ/α interface is either a planar growth front or may also have an acicular growth front. The austenite can spontaneously nucleate within pearlite. The heating rate influences carbon relaxation in austenite and interface velocity. The austenite that forms during rapid heating is transformed back to ferrite. As the heating rate increases, the ferrite's recrystallised fraction at a given temperature decreases. The pinning effect of carbon atoms on dislocations is reported to slow the recrystallization. Nucleation occurs at α/pearlite and pearlite/pearlite boundaries. Nucleates on the pearlite plate imply enhanced local energy. During RTA, it is reported that a rapid dislocation rearrangement leads to rapid recovery that accelerates softening. The recrystallization is shifted to a higher temperature as the heating rate increases. The interstitial atoms act as a barrier to dislocation mobility and the atoms interact with deformed ferrite, which hinders with nucleation of grains. An aging step is responsible for recrystallization. The nano precipitate leads to significant strengthening. Austenite formation during ultra fast heating may lead to a diffusion controlled or massive transformation. A rapid massive transformation moves to grain interior similar to bainitic sheave formation. The austenite transformation takes place both in the ferrite and pearlite phases, and the growth is rapid in pearlite. Interestingly, lean medium carbon steel shows extremely high strengths with reasonably good ductility by manipulating microstructure consisting of higher bainite and martensite contents in the steel. The bainite produced in such processes is termed flash bainite. Although the study is based on the Gleeble thermomechanical process, commercial production may become feasible if the steel is processed through a high-temperature salt bath or induction heating.

Figure 6. The optical microstructure (at 3000 x) of the steel heated at heating rates 10 °C/s, 100 °C/s, 300 °C/s, 500 °C/s and 1000 °C/s. and hold at 1 second and 300 seconds.

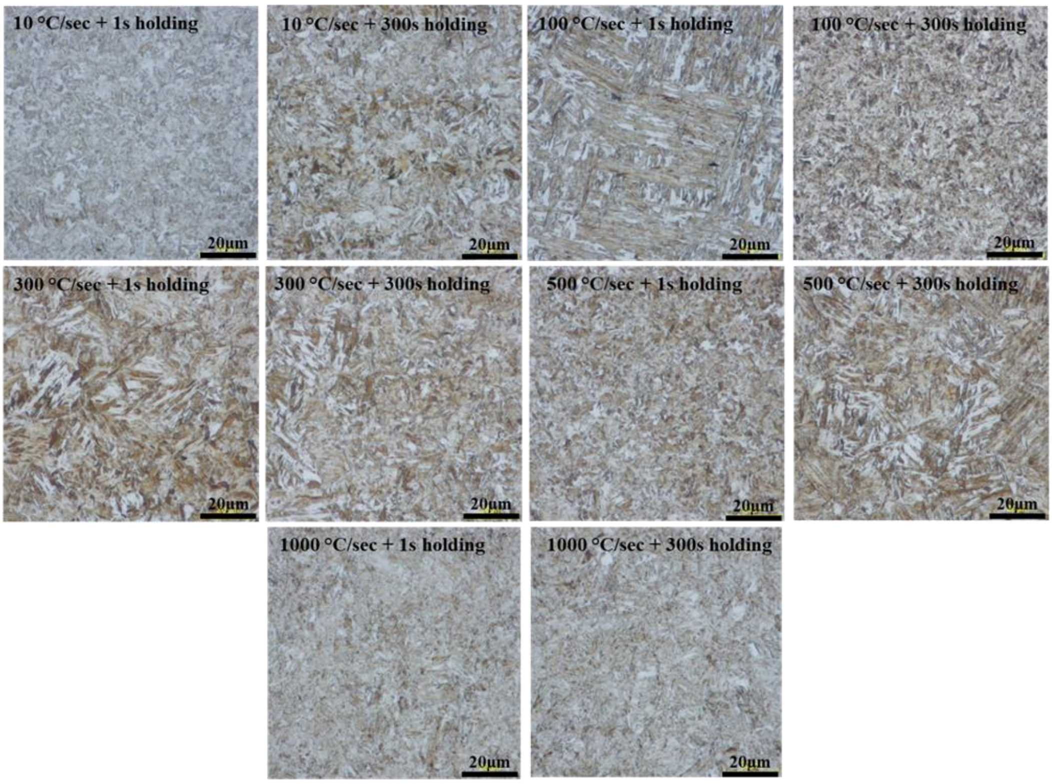
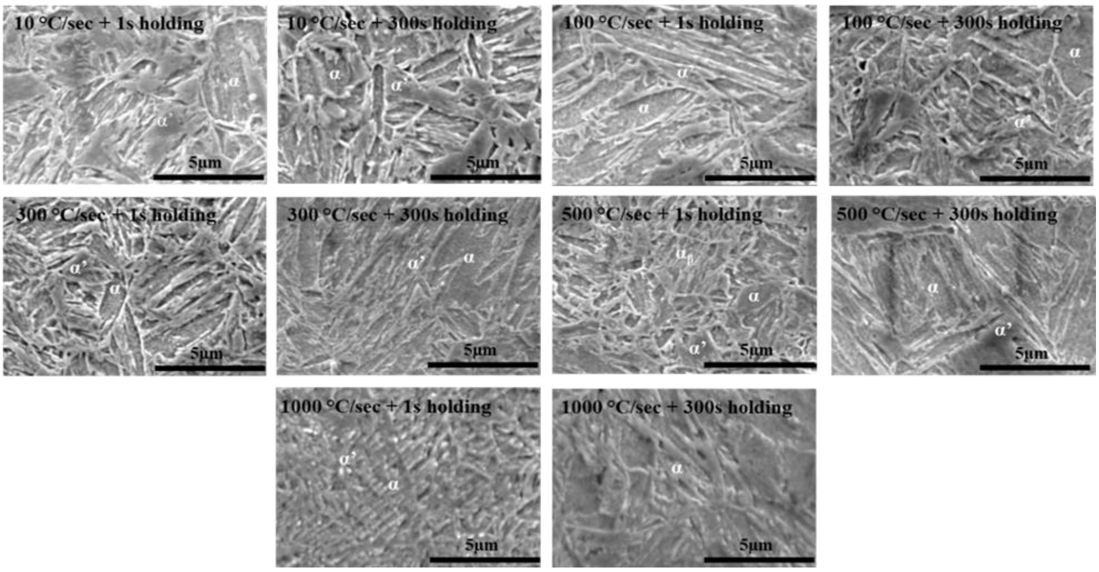


Figure 7. The SEM microstructure (at 10000 x) of the steel heated at heating rates 10 °C/s, 100 °C/s, 300 °C/s, 500 °C/s and 1000 °C/s. and hold at 1 second and 300 seconds. Where α- Ferrite; α'-martensite; αB–Bainite.



After the tensile test, an SEM fractography image was taken as a received sample, as shown in Figures 8 and 9. Fractography in the necked region of tensile samples revealed that the strain was micro structurally localized in samples subjected to Conventional Heating (CH), but more homogeneously distributed in samples treated at heating rates above 500°C/s. Furthermore, a complex microstructure is formed owing to the occurrence of carbon gradients during UFH and the subsequent transformation of several austenite transformation products during cooling.

Figure 8. Fractography image at necked region after the tensile test as received sample.

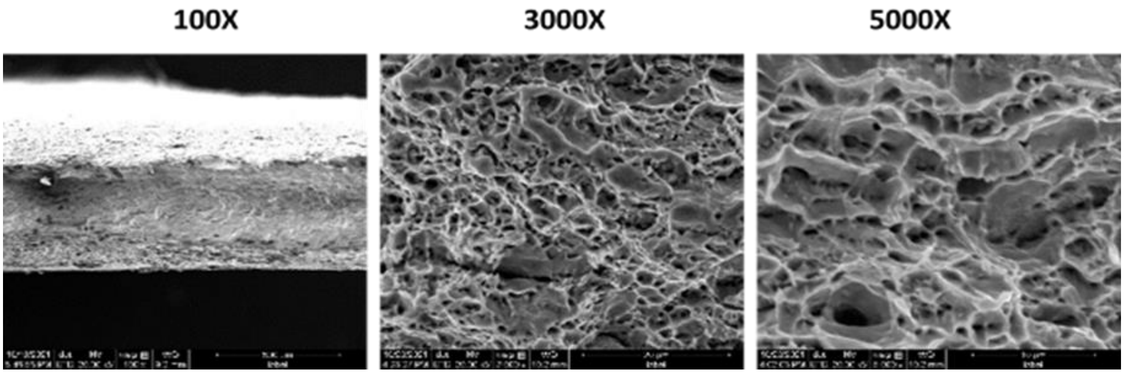
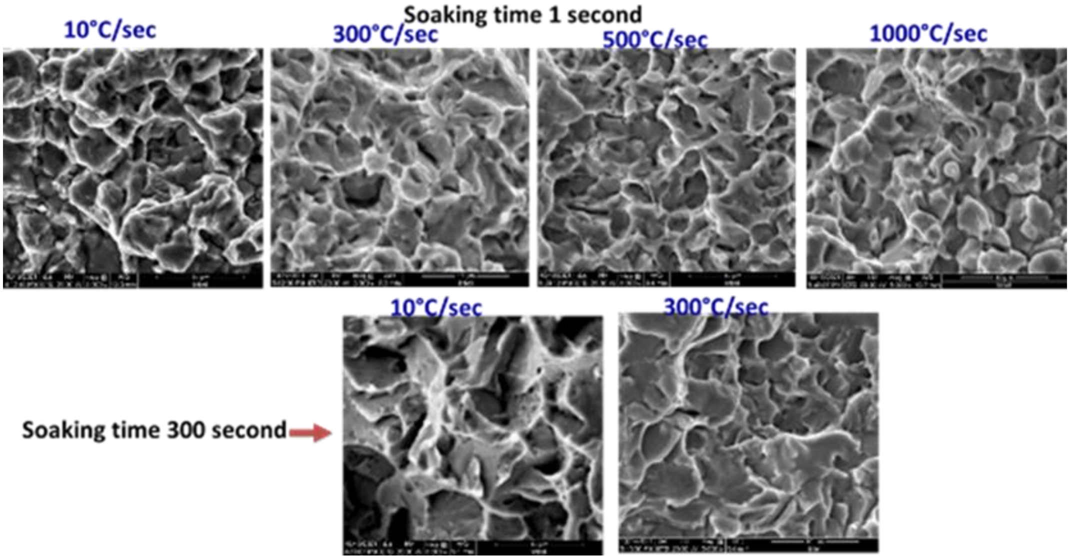


Figure 9. Fractograph image at necked region after tensile test the steel heated at heating rates 10°C/s, 300°C/s, 500°C/s and 1000°C/s. and hold at 1 second and 10°C/s, 300°C/s of 300 seconds.



CONCLUSIONS

- An austenite holding time is 1 s, and an increasing heating rate between 100 and 1000°C/s, leads to an increase in the fineness of the grain size. There is the formation of bainitic type ferrite with acicular morphology. With increasing heating rate, the grain size as well becomes finer. The microstructure shows acicular bainite with fine martensite distributed within the bainitic ferrite till 500°C/s. At 1000°C/s the martensite islands disappear, leading to a lowering of strength.
- At a short holding time of 1 second at austenitization time, the strength increases with the heating rate steeply till initially 500°C/s with a tensile strength of 1894 MPa and a ductility of 12% and a further increase in heating rate till 1000°C/s leads to lowering of strength. This may be associated with coarsening of the bainite to have more ferrite content. With the increasing heating rate, the ductility decreases till 100°C/s beyond which it remains the same.
- At 300 second austenite holding time, there is an increase in tensile and yield strength with heating rate till 500°C/s. With further increase in the heating rate, the strength values decrease at 1000°C/s heating rate. The ductility decreases with the heating rate and remains in a narrow range beyond 10°C/s.
- With a 300 second austenite holding time, the microstructure shows complete lath martensite, implying that the grains have recrystallized and there is a complete conversion of austenite to martensite. The lath density is high for heating rates up to 300°C/s. At 500 and 1000°C/s, the martensite coarsens, and the precipitation of carbides deteriorates the mechanical properties.
- The RTA process is one effective simple steel that gives ultra-high strength with good ductility and fractography in the necked region of tensile samples as received shows a ductile dimple fracture, and UFH heated sample shows a brittle fracture.

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