Effect of Thermo-Mechanical Parameters on Microstructure and Mechanical Properties of Microalloyed Steels

G.R. Ebrahimi and M. Javdani
Metallurgy and Materials Engineering Department, Sabzevar Tarbiat Moallem University, Sabzevar, Iran

H. Arabshahi
*Physics Department, Ferdowsi University of Mashhad, Mashhad, Iran**
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In this work the effects of controlled rolling parameters and adding of Niobium have been studied. In this order two steel grades with and without Niobium are planed and after steelmaking and continuous casting, rolling process are done. Then, laboratory investigations such as microstructure, mechanical properties and grain size analysis were performed Tensile and Charpy impact tests specimens were machined out of the central part of the rolled billets. The microstructure of the specimens was examined for each experimental condition using optical microscopy. The results indicate that increasing the reheating temperature above the dissolution temperature of Nb (C, N) improved the impact energy values. By increasing the cooling rate from 0.5 to 1.5 °C/s both tensile strength and impact toughness were improved. High elongation percent was also observed on samples reheated at higher temperature and/or cooled with the higher cooling rates. The obtained mechanical properties were related to the characteristics of microstructural components including acicular ferrite, retained austenite, pearlite and ferrite.

Keywords: Microalloyed steel, hot rolling, Niobium, microstructure, mechanical properties.

1. INTRODUCTION

Nowadays, most of ferritic-perlitic precipitation hardening steel grades are microalloyed steel. These steels after rolling or forging process would be cooled as completely controlled. The properties of these steel grades would be affected by solidification microstructures, thermomechanical process and cooling process after rolling [1]. Niobium has a threefold influence on the mechanical properties of steel which are as grain size refinement during thermomechanical hot forming, precipitation hardening and lowering the γ to α transition temperature. Grain refinement is the only mechanism that simultaneously increases strength, toughness and ductility. Niobium-microalloyed steel has become a standard material in plate and strip for line pipe, automotive and construction use. Until now, the high potential of microalloyed high strength steel has not been used to the same extent in long products.

Nb (C, N) precipitates that have formed and grown at high temperature and in austenite phase, prevent from grain coarsening in the subsequent stage of hot deformation. Other diffusion controlled process that occur with solution of niobium in austenite are retarding of γ to α transformation that cause to increase nucleation of ferrite and reduce grain growth rate, forming of quasi-equivalence structures like bainit and finally appearance very fine Nb(C, N) precipitates during transformation that being coherent interface cause to increase strength with precipitation hardening mechanism [2,3].

*Electronic address: arabshahi@um.ac.ir

2. EXPERIMENTAL EQUIPMENT, MATERIAL AND PROCEDURE

The material used in this investigation was produced in an electric arc furnace equipped with semi-automatic charging system. Secondary steelmaking operations were performed in a ladle furnace with vacuum degassing units to eliminate oxygen and nitrogen as well as inclusion modification capabilities. For improving mechanical properties of structural steels, quantitative amount of Niobium would be added to general composition of these steel. For this purpose after preparation melting of base composition in an electric arc furnace, in steel making process two grades of these steels with and without Niobium are provided. Then in heavy section mill the blooms were hot rolled to a cross section of 125×125 mm^2 billets. Finally in light section mill the billets hot rolled to 65 mm diameter bars. Steel bars were inspected by magnetic particles inspection method to identify and remove any possible surface cracks.

To reveal prior austenite grain boundaries and to determine the effect of reheating temperature on austenite grain size, specimens with 15 mm diameter and 25 mm height with their axis parallel to the axis of the bar were prepared from the material. They were then heated in an electrical furnace with SiC heating elements between 1000 to 1250 °C for 25 min followed by water quenching. The specimens were then tempered at 450 °C for 4 h to improve grain boundary etching. After usual grinding and polishing operations they were etched in a supersaturated solution of warm picric acid and water with the addition of cupric chloride. Digital pictures were prepared by using optical microscopy and average austenite grain sizes were measured using the linear intercept method.

An extensive number of relationships have been proposed for the dissolution temperature of Nb carbonitrides in microalloyed steels. In the present study, the above temperature was estimated using the following relationships proposed by Tamura *et al.* [4] whose steel compositions are the same as

TABLE 1: Chemical composition of steel investigated (wt %).

Designation	C	Si	Mn	S	Nb	N
1	0.36	0.42	1.08	0.01	-	130
2	0.30	0.39	0.98	0.006	0.036	220
3	0.30	0.39	0.97	0.015	0.041	145

used in this work,

$$\text{Log [Nb] [C]} = -(6661/T) + 2.54$$
$$\text{Log [Nb] [C]} = -(10960/T) + 5.43$$
$$\text{Log [Nb] [C]} = -(7900/T) + 3.42$$

The above relationships lead to dissolution temperatures between 1195 °C to 1220 °C for both of compositions [5-6]. The billets were reheated to 1180 °C or 1240 °C in a continuous walking beam furnace for 60 min. The selection of the reheating temperature was made with the objective to study the effect of smaller austenite grain size and larger carbonitrides (reheating at 1180°C) versus large austenite grain sizes and very fine carbonitrides (upon cooling from 1240 °C) on final mechanical properties. Special pyrometer was used to measure the temperature of the billets at the exit of the walking beam furnace. The specimens were then immediately started to deform as shown schematically in figure 1a. After 17 passed rolling and 93% reduction of area, the bars with 65mm diameter were produced. The as rolled bars were then cooled at room temperature with different cooling rates. These were approximately air cooled (0.5 °C/s), and water-spray with forced air cooled (1.5 °C/s). Tensile and impact test specimens were prepared from the center of the deformed bars according to ASTM E8 and E23 standards, respectively. Metallography samples, perpendicular to the rolling direction, were extracted from the extremities of the impact test specimens. They were then cold mounted in bakelite, polished, and etched with 5% nital. An optical microscope instrumented by image analysis software was used for microstructure examination.

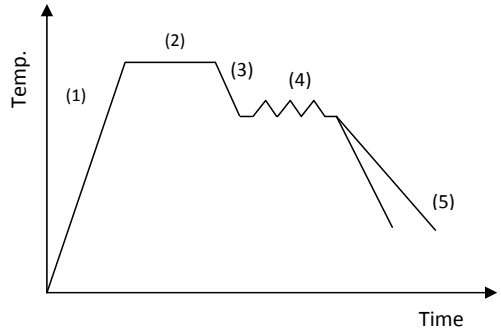

FIG. 1: Schematic diagram of thermo-mechanical processing: (1) Reheated to (1180,1250 °C) at a rate of 10 K/s; (2) Held for 20 min in reheating temperature; (3) gap time to receiving billets from furnace to mill; (4) Deformed at temperatures generally between (1150- 980 °C) (5) cooling after rolling process (0.5, 1.5 °C/s).

3. RESULTS AND DISCUSSION

Figures 2 and 3 show the variation of charpy impact energy and elongation percent with chemical composition, cooling rate and reheating temperatures. The results indicate that, impact energy increases with increasing cooling rate, reheating temperature and with modification of chemical composition. As indicated in figure 2 impact energy increases from 73 to 85 J when cooling rate increases from 0.5 to 1.5 °C/s for billets with 0.041 Nb reheated at 1240 °C. It is interesting to note that, for the latter cooling condition (i.e. 1.5 °C/s) the elongation percent during tensile testing approaches 24.5%, which represents very good ductility. However the specimen without Nb and high content of Carbon shows different behavior.

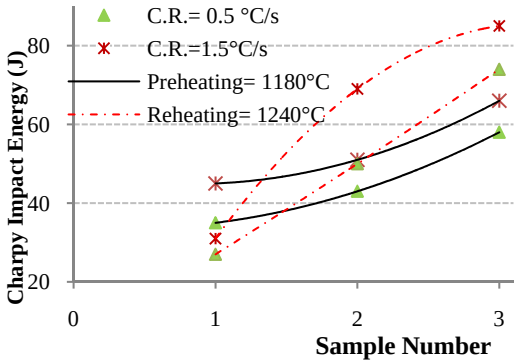

FIG. 2: Variation of charpy impact energy with rolling parameters.

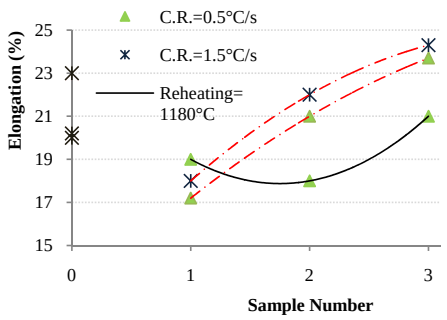

FIG. 3: Variation of elongation with rolling parameters.

The influence of thermomechanical processing parameters on yield and tensile strengths are illustrated in figures 4 and 5. The results indicate that, yield strength decreases with increasing cooling rate for both reheating temperatures while increasing cooling rate and reheating temperature result to higher tensile strength values.

Figure 6 shows the variation of mean austenite grain size with reheating temperature. As indicated, for reheating temperatures between 1000 and 1150 °C the average austenite

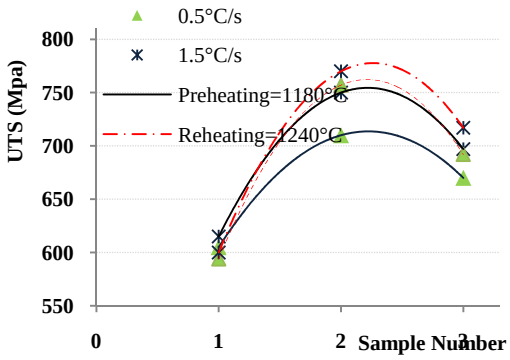

FIG. 4: Variation of yield strength with rolling parameters.

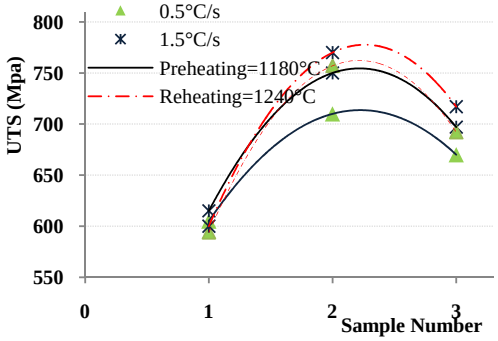

FIG. 5: Variation of tensile strength with rolling parameters.

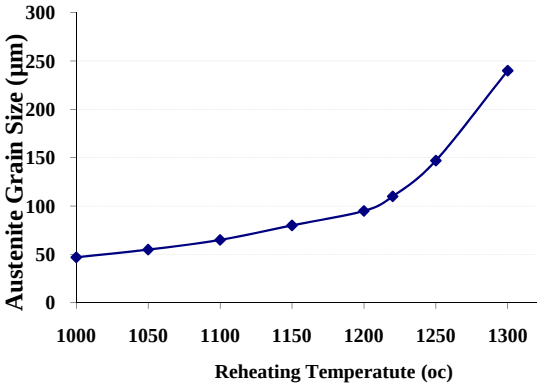

FIG. 6: Variations and optical micrography of austenite grain size versus reheating temperature.

grain size increases slightly, passing from 47μm at 1000 °C to 80μm at 1150 °C. However, a sudden increase is observed after 1200 °C, which becomes even more important at 1250 °C where the average grain size reaches 145μm. This clearly indicates that, the lower end dissolution temperature of Nb (C, N) precipitates is in the vicinity of 1200 °C. The obtained results confirm that the dissolution temperature of Nb (C, N) precipitates is in the interval 1200–1220 °C as predicted based on relations reported previously.

The influence of rolling parameters on the propensity of the microstructure to produce semi-equilibrium phases is illustrated in figure 7. For instance, the microstructure of the second sample reheated at 1180 °C and 0.5 °C/s cooling rate is composed for polygonal ferrite, pearlite and quantitative acicular ferrite (Fig. 7c) but by increasing the reheating temperature to 1240 °C the volume percent of pearlite and granular ferrite decreases and acicular ferrite increased (Fig. 7d). Increasing the cooling rate to 1.5 °C/s eliminates almost all the pearlite and granular ferrite and replaces them by acicular ferrite as can be observed in Figs. 7f.

At higher reheating temperature, the increase in the amount of acicular ferrite (Fig. 7f) can be related to significantly higher austenite grain sizes of the specimen. Reheating at 1180 °C and 1240 °C produces mean austenite grain sizes of 85 and 145μm, respectively. With respect to transformation, austenite grain boundaries are preferred sites for the nucleation of proeutectoid ferrite, pearlite and bainite. Therefore, with larger austenite grains, fewer nucleation sites will be available for the above phases and the diffusion controlled transformation process becomes limited. As a result, upon transformation, intragranular nucleation will be promoted in expense of grain boundary transformation products. It is well known that, acicular ferrite nucleates on inclusions located at the interior of austenite grains, by a combination of displacive and reconstructive mechanisms with less need to diffusion than products, such as ferrite and pearlite, that are diffusion controlled. Finally, because in hypoeutectoid steels, pearlite nucleates also at the interior of austenite grains, by initially increasing austenite grain size, the nucleation of acicular ferrite is promoted and the amount of pearlite is reduced as can be observed by comparing figures 7c, 7d, 7e and 7f.

Increasing cooling rate, decreases the diffusion time and reduces the transformation temperature, thus limiting the effectiveness of reconstructive mechanisms. Also, transformation at lower temperatures enhances displacive mechanisms and therefore promotes shear transformation products such as acicular ferrite [7-8].

As reported in figure 2 charpy impact energy increases with increasing cooling rate and reheating temperature. This can be attributed to the volume percent of pearlite and acicular ferrite as well as to the size of Nb (C,N) particles. Acicular ferrite has a chaotic type structure and its multidirectional thin plates deflect crack propagation whereas pearlite is susceptible to cleavage fracture. Thus, increasing acicular ferrite and decreasing pearlite, improves significantly impact toughness values. Specifically, increased acicular ferrite content obtained at higher cooling rates and reheating temperature should improve charpy impact energy [7-9].

Acicular ferrite is usually accompanied with some retained austenite. So, the microstructures of the specimens in figures 7d and 7f consisted of acicular ferrite with significant volume percent of retained austenite. The latter transforms to martensite during deformation, increasing plastic deformation and resulting to higher percent elongation. The decrease

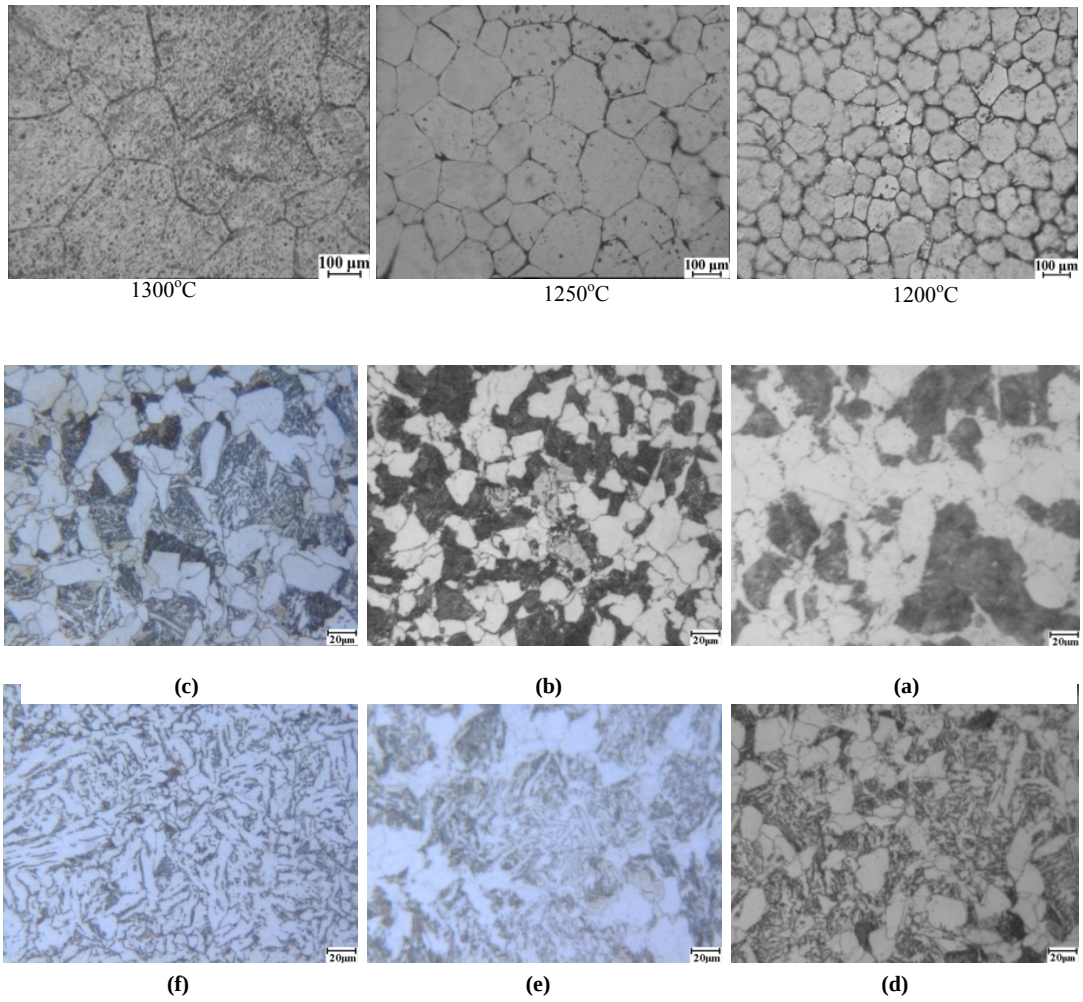

FIG. 7: Showing optical micrography of various samples: a and b at 1180°C, c and d at 1240°C, e and f at 1180°C. Cooling Rate in all Micrographs was 0.5°C/s (expect f that was 1.5°C/s).

in yield strength with increasing cooling rate, as observed in figure 4, can be related to the lower content of pearlite, the presence of low strength ferrite, and some austenite in agreement with results reported by other investigators. Also, the higher yield strength of specimens with 1240 °C reheating temperature compared to those reheated at 1180 °C can be related to the precipitation of NbC dissolved during reheating at 1240 °C, which does not exist at the lower reheating temperature. By contrast, the higher yield strength obtained for specimens without Nb, reheated at 1180 °C and cooled with 0.5 °C/s can be attributed to the presence of a higher volume percent of pearlite. Therefore, at samples without Nb where the microstructure consists mainly of pearlite, this constituent determines the yield strength; whereas, in sampels consisting Nb, precipitates have the major role in determining the yield strength. The increase in tensile strength with cooling rate observed for both reheating temperatures may be related to the transformation of retained austenite to martensite during uniform straining. The higher resistance of martensite to deformation increases strain hardening and ultimately the tensile strength [7- 9].

4. CONCLUSION

- Thermomechanical processing parameters to obtain high strength-high impact toughness Nb–V microalloyed steels were optimized.

- Increasing reheating temperature from 1180 to 1240°C decreased considerably pearlite content in samples consisting Nb, while the volume percent of acicular ferrite increased. The high volume fraction of acicular ferrite as well as the presence of very fine Nb(C,N) precipitates increases the impact toughness and tensile strength simultaneously.

- Increasing cooling rate decreases pearlite content and increases acicular ferrite volume percent. Increasing cooling rate up to 1.5°C/s produces acicular ferrite in

expense of pearlite and granular ferrite. These microstructural variations increase impact energy, tensile strength, and elongation percent of specimens with 1240°C reheating temperature.

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