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Effect of thermomechanical treatment on the microstructure and mechanical properties of a low-carbon low-alloy steel

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Abstract. The effect of thermomechanical treatment on the microstructure, tensile strength and impact toughness of low-carbon low-alloy steel is considered. The developed microstructure is characterized by grain elongation along the rolling direction. Both the yield strength and the ultimate tensile strength increase with a decrease in test temperature. The ultimate strength at room temperature is 797 MPa, and at 77 K the ultimate strength increases to 1198 MPa. The steel samples subjected to tempforming exhibit impact toughness of KCV = 410 J/cm^2 at room temperature. A decrease in the test temperature to 233 K leads to a slight decrease in the KCV value to 340 J/cm^2. It should be noted that the impact specimens are not completely fractured even at a test temperature of 233 K, suggesting higher real values of impact toughness.

1. Introduction

High-strength low-alloy steels are one of the most widely used classes of materials. One of the significant disadvantages of such steels is their relatively high temperature of the ductile-brittle transition, below which the impact toughness of the steels drops sharply, i.e., the steel becomes brittle, which can lead to a sudden catastrophic failure of the construction.

Currently, special attention is paid to the development of structural steels and alloys adapted to the climatic conditions of the Far North, for use in facilities for the production, storage and transportation of gas and oil on the Arctic shelf, as well as for constructions for various engineering applications, operated under low temperature conditions. Comprehensive studies of fracture mechanisms and conditions of ductile-brittle transition had been being carried out from the middle of the last century [1–3]. This was caused by the need to create structures designed for operation at low temperatures such as arctic pipelines, tankers and ships, tanks and storage vessels, transportations of liquid gases, etc.

An interesting approach to increase the impact toughness and decrease the temperature of the ductile-brittle transition in carbon steels was proposed by Japanese scientists [4]. This approach consists in the formation of a lamella type structure with a transverse grain size of about 100 nm and a uniform distribution of dispersed nanoscale particles of secondary phases by means of warm rolling under conditions of tempering. Such thermo-mechanical processing was called tempforming, which allows us to get a promising combination of mechanical properties in low alloyed steels. Besides its high impact toughness, processed steel has high strength due to the reduction of grain size and precipitation hardening.

2. Experimental

A low-carbon low-alloy steel with a chemical composition of Fe - 0.03C - 0.23Si - 0.19Cr - 1.54Mn - 0.04Nb - 0.016Al - 0.12Mo - 0.21V (all in mass%), was subjected to initial heat treatment (annealing at 1423 K for 1 hour followed by oil quenching) and, then, rolling at 923 K to a total strain of 1.5 (tempforming). The structural observation were performed on the RD-ND sections (RD is the rolling direction and ND is the normal direction), using a Quanta Nova Nanosem 450 scanning electron microscope (SEM) equipped with an electron back scattering diffraction pattern (EBSP) analyzer incorporating an orientation imaging microscopy (OIM) system. The specimens for structural investigations were electro-polished using an electrolyte containing 10% perchloric acid and 90% acetic acid at a voltage of 20 V at room temperature. The OIM images were subjected to cleanup procedure setting minimal confidence index of 0.1. The mean grain size was evaluated on the OIM images as the average distance between high-angle boundaries with misorientations of $\theta \geq 15°$. The tensile tests were carried out by using an Instron 5882 testing machine on specimens with gauge dimensions of 12 mm in length, 3 mm in width, 1.5 mm in thickness cut out with the tensile direction parallel to the rolling direction. The specimens were tested at a crosshead rate of 2 mm/min. Standard Charpy V-notch specimens (length = 55 mm, width = 10 mm, thickness = 10 mm, notch depth = 2 mm) were tested using an Instron 450 J impact machine with an Instron Dynatup Impulse data acquisition system at temperatures ranging from 77 K to 293 K [5]. The specimens for impact tests were cut from the rolled plates so that the impact direction was parallel to the normal direction.

3. Results and discussion

3.1. Microstructures

The initial microstructure of the low-carbon low-alloy steel is shown in figure 1a. The mean grain sizes and the fraction of high-angle grain boundaries are about 11 μm and 0.44, respectively. The tempforming leads to the evolution of a fine grained microstructure consisting of grains elongated along the RD (figure 1b). The mean transverse grain size is 2.9 μm. The fraction of high-angle grain boundaries is 0.29. The tempformed steel is characterized by strong ⟨001⟩ ||ND and ⟨111⟩ ||ND fiber textures (corresponding to red and blue colors, respectively, in figure 1b).

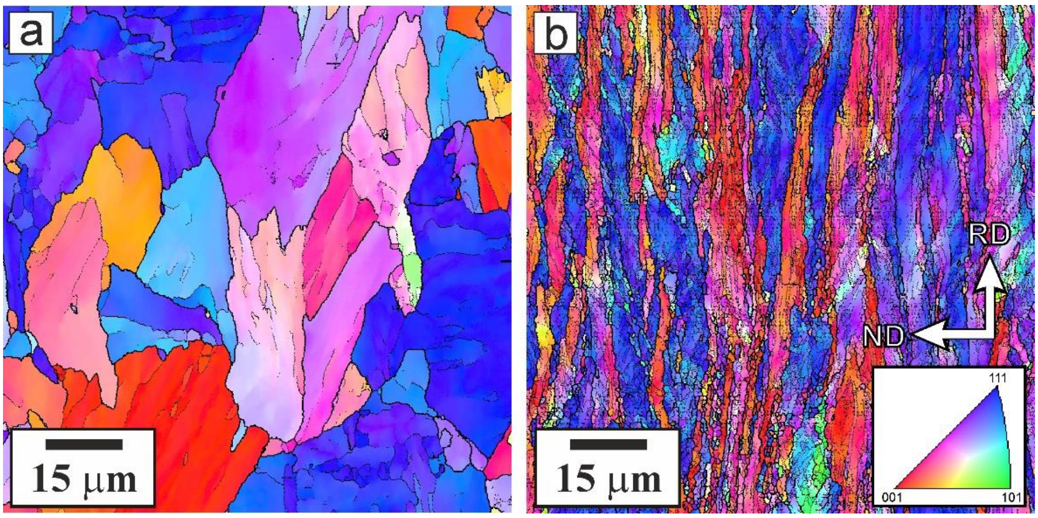

Figure 1. Microstructures developed in a low-carbon low-alloy steel subjected to initial heat treatment (a) and tempforming at 923 K (b). The colors correspond to the crystallographic direction along the normal direction (ND). High-angle and low-angle boundaries are indicated by thick black and thin black lines, respectively.

3.2. Tensile properties

The engineering stress–elongation curves obtained for the low-carbon low-alloy steel samples by tension at different temperature are presented in figure 2. Following the onset of plastic flow, the tempformed specimens exhibit a negligible short stage of strain hardening and a well-defined peak stress followed by a plateau that is discontinuous yielding. The same type of curves was observed in previous studies on tempforming [6, 7].

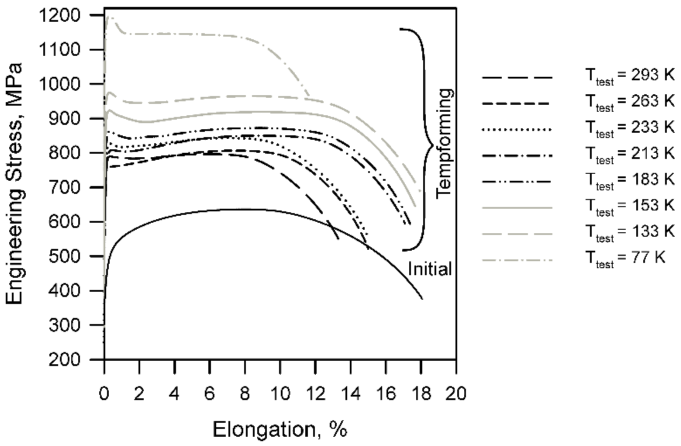

Figure 2. Tensile curves of a low-carbon low-alloy steel subjected to initial heat treatment and tempforming at 923 K.

Both the yield strength and the ultimate tensile strength increase with a decrease in test temperature. The ultimate strength at room temperature is 800 MPa, and at 77 K the ultimate strength increases to 1200 MPa. The total elongation comprises 13.5% at a temperature of 293 K. A decrease in temperature to 183 K leads to an increase in elongation to 17.9%. Then the total elongation decreases to 11.6% as the test temperature decreases to 77 K (table 1).

Table 1. Mechanical properties of a low-carbon low-alloy steel at different temperatures.

Treatment	Offset yield strength, MPa	Ultimate tensile strength, MPa	Elongation, %
Initial	465	635	18
Tempforming (T_{test} = 293 K)	780	800	13.5
Tempforming (T_{test} = 263 K)	755	805	15
Tempforming (T_{test} = 233 K)	820	840	15
Tempforming (T_{test} = 213 K)	790	850	17
Tempforming (T_{test} = 183 K)	855	870	17.5
Tempforming (T_{test} = 153 K)	920	925	17.7
Tempforming (T_{test} = 133 K)	970	975	17.9
Tempforming (T_{test} = 77 K)	1190	1200	11.6

3.3. Impact Toughness

Figure 3 shows the effect of thermomechanical treatment on the impact toughness of low-carbon low-alloy steel. The steel samples subjected to tempforming exhibit an impact toughness of KCV = 410 J/cm^2 at room temperature. A decrease in the test temperature to 233 K leads to a slight decrease in the KCV value to 340 J/cm^2. A further decrease in the test temperature leads to an increase in KCV to 425

J/cm^2. It should be noted that the impact specimens are not completely destroyed even at a test temperature of 183 K, suggesting higher real values of impact toughness. Upon further cooling to 77 K, the impact toughness decreases to 19 J/cm^2. The high fracture toughness is attributed to delamination, when fracture is accompanied by splitting along the rolling plane with high absorption energy.

The specimens after impact tests are shown in figure 3b. It is seen that the Charpy specimens in the tempformed condition exhibit delaminations, i.e., the cracks branch along the impact test specimens without their complete rupture that suggest a rather high absorbed impact energy.

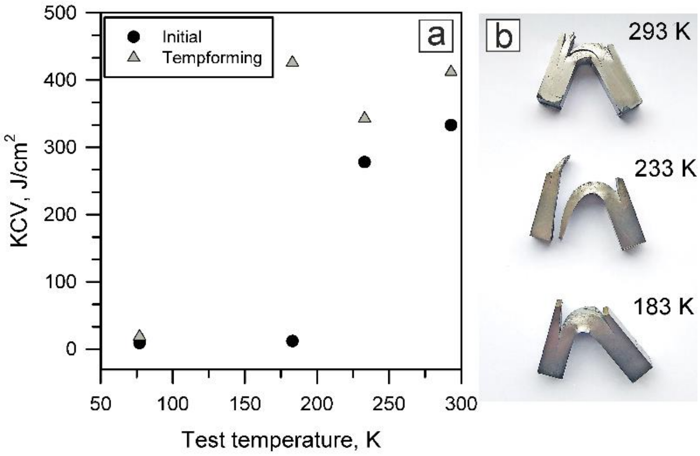

Figure 3. Effect of test temperature on impact toughness of low-carbon low-alloy steel subjected to initial heat treatment and tempforming at 923 K (a); and specimens of low-carbon low-alloy steel tempformed at 923 K after impact tests at the indicated temperatures (b).

4. Conclusion

The effect of thermomechanical treatment on the microstructure and mechanical properties of low-carbon low-alloy steel was studied. The main results can be summarized as follows:

1. Tempforming results in the formation of a fine grain microstructure with an average transverse grain size of 2.9 μm and strong ⟨111⟩ ||ND and ⟨001⟩ ||ND fiber textures.

2. Tempforming strengthens the steel remarkably. The ultimate tensile strength at room temperature is 797 MPa, and the total elongation comprises 13.5%

3. Tempforming leads to a significant increase in the values of impact toughness at room and negative temperatures. The impact toughness of the tempformed steel reaches its maximum value at a temperature of 183 K (KCV = 430 J/cm^2).

Acknowledgments

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