THE INFLUENCE OF ELEVATED AND REDUCED TEMPERATURE ON THE MECHANICAL PROPERTIES OF Fe-Al-Mn-C STEELS

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Abstract

The paper presents the results of mechanical properties tests at reduced and elevated temperature after a four-stage hot-rolling and cooling in water, microstructure tests and fractographic studies of breakthroughs of high-strength high-manganese steel X98MnAlSiNbTi24-11 and X105MnAlSi24-11 TRIPLEX type. In order to determine the mechanical properties of the tested steels, a static tensile test was performed, on the basis of which the yield strength, tensile strength and elongation were determined. Structural investigations using light microscopy and scanning electron microscopy enabled the identification of austenitic-ferritic structure in steels numerous deformation twins in austenite grains. Diffraction in SEM was also used to analyse the structure. The obtained test results allow assess the influence of reduced and elevated temperature on the strength properties of the tested steels. The test steels Fe-Mn-Al-C achieve very good strength properties at relatively high elongation at low temperature -70 °C.

Keywords: Fe-Mn-Al-C steels, mechanical properties, fractography, microstructure

1. INTRODUCTION

Exploitation of the structure occurs in a variety of complex load condition's circumstances and often at different temperatures. Taking into account the conditions of use, it is necessary to predict strength and durability of the structure, both at room temperature, as well as at elevated and reduced temperature. Most often, the structures work in the temperature range from -70 ° C to 200 ° C, which is related to environmental conditions and the influence of solar radiation, therefore these tests were carried out in the above-mentioned temperature range.

Fe-Mn-Al-C steels, depending on the chemical composition of the alloy and thermo-mechanical treatment, are characterized by a wide range of strength properties. The stress-strain graphs are a key tool for determining mechanical properties. Bausch, Frommeyer et al. were the first to describe the steels of TRIPLEX type with high strength (925 ÷ 1175 MPa) and plasticity (up to 36 %) with austenitic-ferritic structure with nanometric κ carbides. The proportion of ferrite in these steels was ~ 7 %. In their work Bausch, Frommeyer and others also presented mechanical properties in the temperature range -60 ÷ 550 °C. The tested steels achieve very good mechanical properties at a low temperature of -60 °C where the tensile strength is 1050 MPa, which makes it possible to apply Fe-Mn-Al-C steels in cryogenic applications [1÷4]. Hamada in his work presents the results of static tensile test for steels with different Al content at temperature between -80 °C and 100 °C. On the basis of the results it concludes that both the Al content and the temperature have a significant effect on the strength and elongation. The higher Al content raises the yield strength, but the tensile strength and elongation depend essentially on the deformation mechanism, i.e. the stacking fault energy, which is associated with the contents of Mn and Al, and the test temperature [5].

The aim of the work was to determine how and to what extent mechanical and plastic properties in high manganese steels X98MnAlSiNbTi24-11 and X105MnAlSi24-11 TRIPLEX type change with the decrease or increase temperature (in the range -70 °C do 200°C).

2. EXPERIMENTAL (MATERIALS AND METHODS)

The subject of the analysis was the experimental high-melange steels X98MnAlSiNbTi24-11 (steel A) and X105MnAlSi24-11 (steel B) TRIPLEX type. Detailed chemical compositions of the tested steels are presented in **Table 1**.

Table 1 The chemical compositions of the examined steels

Elements	C	Mn	Al	Si	Nb	Ti	Ce	La	Nd	P_{max}	S_{max}
Steel X98MnAlNbTi24-11 (steel A)											
[wt. %]	0.98	23.83	10.76	0.20	0.048	0.019	0.029	0.006	0.018	0.002	0.002
Steel X105MnAlSi24-11 (steel B)											
[wt. %]	1.05	23.83	10.76	0.10	-	-	0.037	0.011	0.015	0.005	0.005

Steels were melted in a laboratory vacuum induction furnace under argon and cast into the cast iron mould. After cooling in air, plastic working was performed on the ingot by hot forging at high speed hydraulic press with pressure of 300 tonnes. Then the material was subjected to a four-step rolling process at a temperature range of 1100 °C to 850 °C with at a deformation of 0.23 for each pass. A detailed diagram of the rolling process is shown in **Figure 1**. After the last rolling stage, the samples were cooled in water.

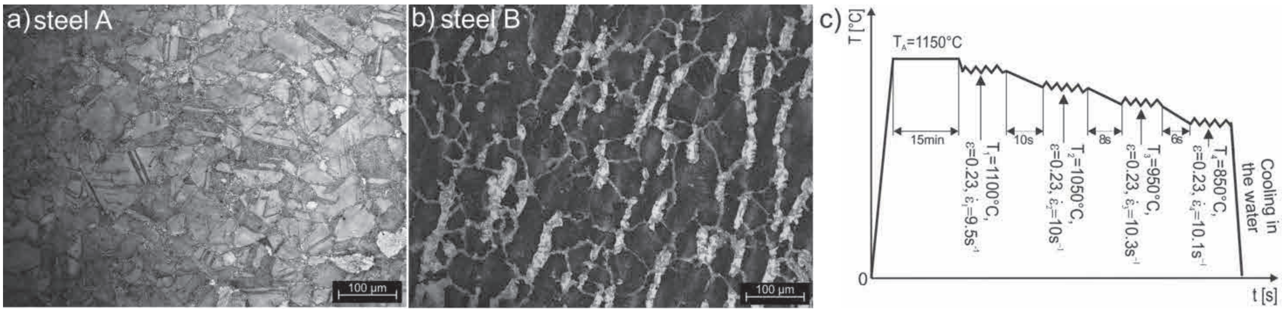

Figure 1 a),b) Microstructures of the examined steels before hot rolling [6,7] c) scheme of hot rolling process and cooling of tested steels

Tests of the mechanical properties at elevated and reduced temperatures from -70 °C to 200 °C were made on testing machine Insight by MTS with a maximum force of 10kN. To assess the mechanical properties of the steel at a reduced and elevated temperature a testing machine, equipped with a chamber allowing cooling or heating of the stretched sample in the range from -100 °C to 350 °C, was used. Strength tests were carried out in the temperature range from -70 °C to 200 °C, due to the need of using the extensometer for mechanical tests at elevated and reduced temperatures and the associated maximum temperature of use limited to 200 °C. For mechanical properties tests at elevated and reduced temperatures, flat samples with a measuring length of 25 mm, a width of 3 mm and a thickness of 2 mm were used.

Steel structure investigations were carried out using light microscope Zeiss AxioObserver after etching in a 5 % HNO_3 solution in ethyl alcohol. Pictures of structures were made at 200x magnification. The examinations of the fractures after the static tensile test were performed on a scanning electron microscope Zeiss Supra 35 at an accelerating voltage of 20 kV using secondary electrons detection (SE). Pictures of the fractures were performed with 1000x magnification.

3. RESULTS AND DISCUSSION

Structural analysis of the investigated steels after four-stage hot rolling and cooling in the water was carried out on samples cut in accordance with the direction of the rolling (**Figure 2**). On the basis of metallographic studies, it was found that the structures of both steels are austenite grains with numerous deformation twins and a ferrite bands. A characteristic feature of austenitic-ferritic structures are elongated ferrite grains, this is due to the low tendency to recrystallize ferrite. The relatively high aluminium content (~ 11 %) in steels affects the formation of ferrite strips parallel to the direction of rolling. [1,11]. In steel B, the proportion of ferrite is about 20 % greater than in steel A. In the structure of the steel A was observed that the bands have a partial recrystallization of ferrite, stronger than steel B. Ferrite strips in the steel A are larger in width but occur in a greater distance from each other than in steel B. It is believed that the mechanical properties are strongly related to the morphology and the percentage of ferrite strips in the investigated steels.

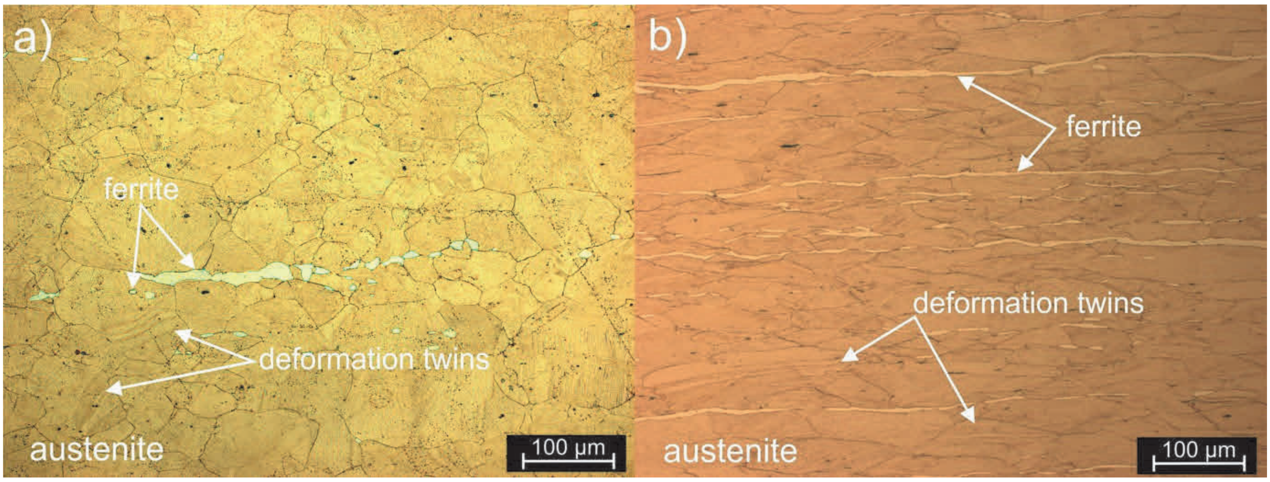

Figure 2 Microstructure of the steel after hot rolling and cooled in water a) steel A, b) steel B

The results of mechanical properties tests at reduced and elevated temperature (-70 °C ÷ 200 °C) of TRIPLEX type steels A and B after a four-step hot rolling with 20% draft and cooling in water are shown in **Figure 3**. At 23 °C, the test steels have similar strength and plastic properties that are for steel A: $R_{p0.2}$ = 1086MPa, R_m = 1142 MPa, A = 24 %, while for steel B: $R_{p0.2}$ = 1057 MPa, R_m = 141MPa, A = 27%. In steel A with decreasing temperature from room temperature of 23 °C to -70 °C during plastic deformation increases the mechanical properties R_m increases by approximately 110 MPa, but $R_{p0.2}$ about 56 MPa. Plastic properties decrease by about 10 - 12 %, i.e. they decrease from 24 % to about 12 - 14 %. Steel A for a temperature increase from 23 °C to 50 °C reduces the plastic properties of 16%, while increasing the tensile strength of 121 MPa, a yield strength of 120 MPa. Further increase of temperature to 80 °C does not cause significant changes in strength properties, while plastic properties decrease by nearly 50 %. With the further increase of the test temperature to 150 °C, the strength and plastic properties increased ($R_{p0.2}$ = 1218 MPa, R_m = 1267 MPa, A = 30 %). Steel A at a temperature of 23 °C and 200 °C has similar values of tensile strength and elongation. In the case of steel B at temperatures of -70 °C and 80 °C, there is a marked increase in strength properties while maintaining good plastic properties. Lowering the temperature from room temperature 23 °C to -70 °C in the case of steel B causes an increase in strength properties by about 20 %. However, as in the case of steel A, the plastic properties of steel B decrease by about 4 % of the total elongation. For steel B, the temperature rises to 50 °C causes a slight decrease in strength and plastic properties. Raising the temperature to 80°C causes the strength properties to increase by 292 MPa, but the elongation is reduced by about 4 %. With a further increase in temperature, it is followed by a drop of the mechanical properties with a total elongation of 11 - 16 %. At temperatures of 150°C and 200°C in both steels a teething course of the stress - strain curves was noticed (**Figure 4**), as a result of the Portevin-Le Chatellier effect, which is explained by the Cotrell's atmosphere mechanism. This effect occurs when it exceeds a certain critical strain, followed by the avalanche detachment of the dislocations arising from them during the movement of the atmosphere of foreign atoms [12-14]. Based on the analysis of the results, it has been found that the maximum strength and plastic properties of steel A have been achieved at a test temperature of 150 °C, in which $R_{p0.2}$ = 1218 MPa, R_m=1267MPa and A=30%. In the case of steel B, high strength and plastic properties are achieved at a temperature of 80 °C ($R_{p0.2}$ = 1337 MPa, R_m = 1433 MPa, A = 23 %).

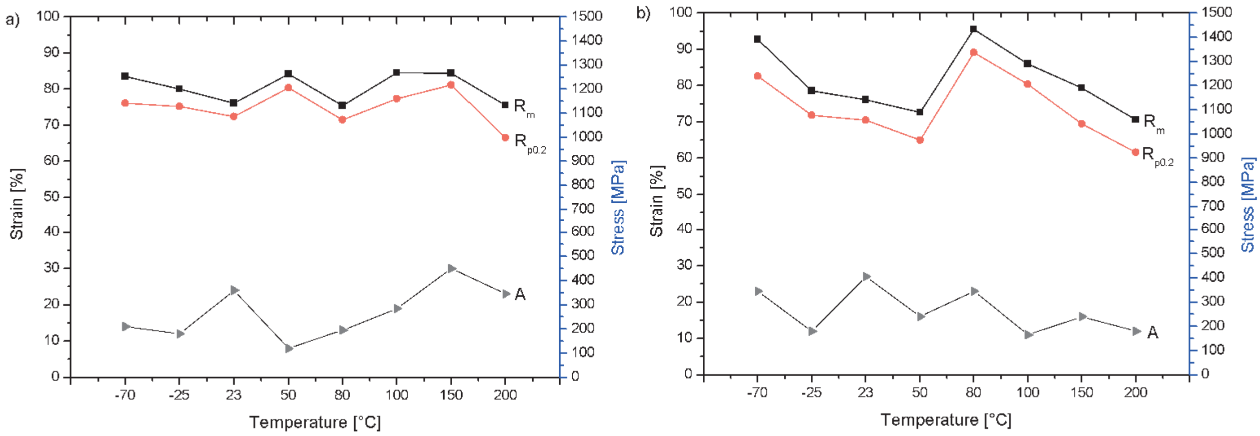

Figure 3 The effect of plastic deformation temperature on mechanical properties $R_{p0.2}$, R_m and A: a) steel A, b) steel B, after a four-step hot rolling with 20 % draft and cooling in water

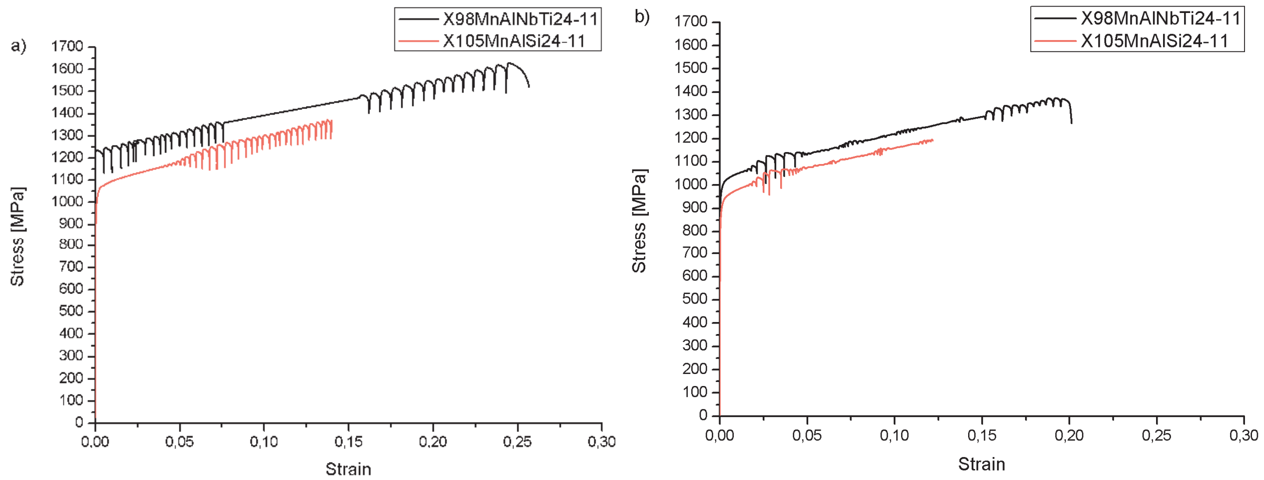

Figure 4 Static tension curves: stress-strain at temperature: a) 150 °C, b) 200 °C

The fractures after a static tensile test at 150 °C are shown in **Figure 5**. Steel A is characterized by a ductile fracture with small areas of transcrystalline and intercrystalline brittle fracture (**Figure 5a**). Dimple morphology was observed, with a characteristic arrangement of depressions and protuberances of various shapes and sizes. Numerous secretions were noticed in the dimples. The dimples are formed from micropores, microcracks or micro emptiness formed during load [8-11]. Quasi-cleavage and steps were noted in the transcrystalline areas. Steps arise when the cracking face encounters screw dislocations which intersect the plane of cleavage [8-10]. In addition to numerous secondary cracks in steel B quasi-cleavage areas, as well as steps and dimple morphology, were observed (**Figure 5b**). Steps in the form of tongue morphology are formed by deflecting cleavage fractures at the moment of twins encounter [9,10]. **Figure 6** shows fractures after a static tensile test at -70 °C. Both tested steels are characterized by a ductile fracture, however, in steel A, areas of intercrystalline brittle fracture were noted.

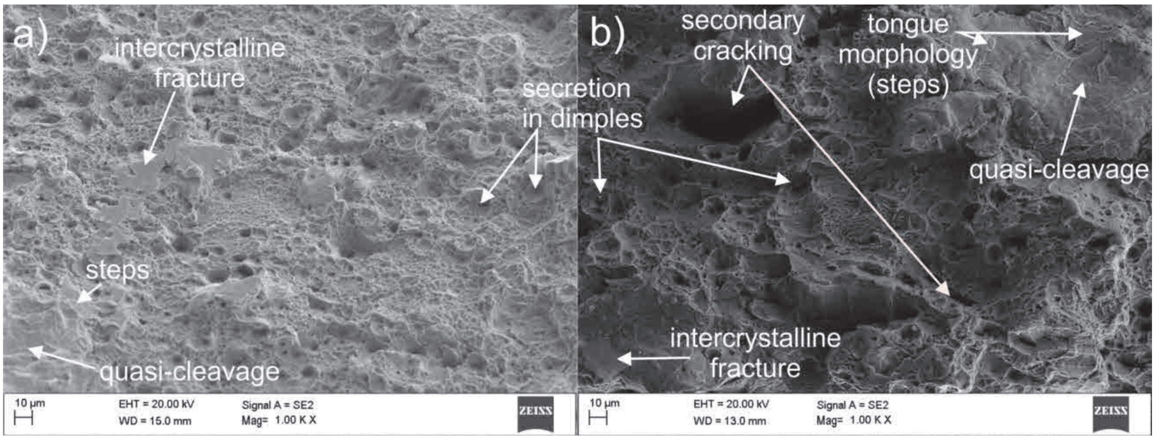

Figure 5 Fractures after static tensile test at 150 °C after hot rolling and cooling in water a) steel A, b) steel B

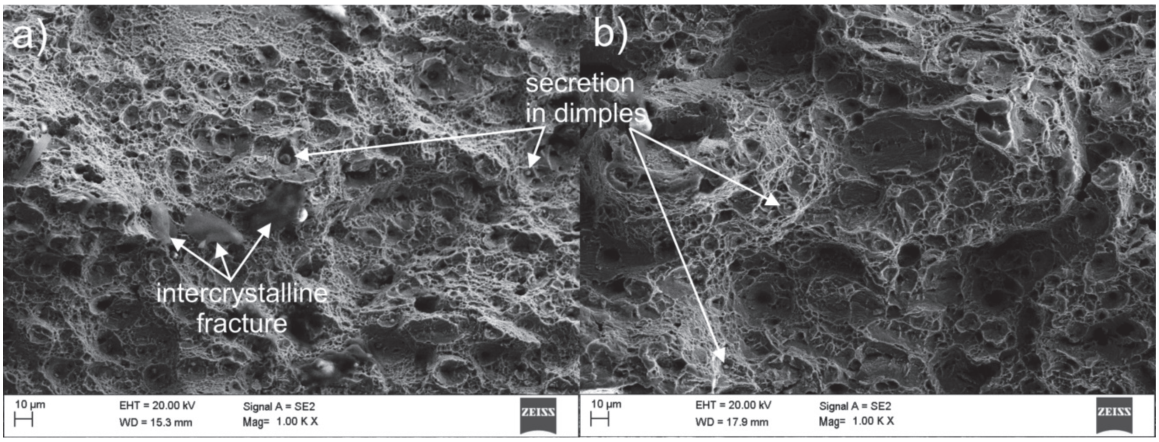

Figure 6 Fractures after static tensile test at -70 °C after hot rolling and cooling in water a) steel A, b) steel B

4. CONCLUSION

On the basis of the obtained research results and their analysis, the following conclusions were formulated:

Fe-Mn-Al-C solid steels achieve very good mechanical properties at low temperatures of -70 ° C, tensile strength was 1252 MPa for steel A and 1391 MPa for steel B. However, steel B exhibits a higher about 10 % of the elongation compared to the elongation of steel A at the same temperature. At 80 ° C, steel B achieves the highest strength properties over the entire temperature range of R_m = 1433 MPa, $R_{p0.2}$ = 1337MPa and A = 23 %. Steel A achieves maximum strength and plastic properties at temperature at 150 °C, where R_m = 267MPa, $R_{p0.2}$ = 1218 MPa and A = 30 %. At the temperature of 150 °C and 200 °C in both steels teething course of the stress - strain curves according to the Cottrell's atmospheres theory were noticed [12-14]. No clear correlation between the temperature of the test and changes in the mechanical and plastic properties requires further research in this field also for other thermo-plastic treatment variants of these materials.

The structures of both steels after hot rolling and cooling in water consist of austenite grains with numerous twin deformations and ferrite strips. The relatively high aluminium content in steels affects the formation of ferrite strips parallel to the direction of the rolling. The elongated grains in austenitic-ferritic structures are a result of a low tendency to recrystallization of the ferrite or a faulty thermo-plastic process [1,3].

On the basis of the fractographic analysis, it was found that the tested steels are characterized by mixed fractures. The mechanism of brittle fracture-ductile is formed by nucleation of brittle fracture in local areas and their propagation in the final surface decohesion by the activation of plastic deformation mechanisms [8-11]. Both steels are dominated by ductile fractures with dimple morphology with secretions at the bottom of the dimples. It is also noted that areas of the brittle intergranular cracking that occurred after the grain boundaries, due to the reduced cohesion of the material, may be caused by the reduction of material cohesion, probably caused by the accumulation of impurities, brittle phases or segregation of alloy components. Transcrystalline cracking in the tested steels is accompanied by steps, which arise when the cracking face comes across screw dislocations or deflection of the cleavage at the twin encounter [9,10].

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