PROPERTIES OF LOW CARBON HIGH MANGANESE STEEL AFTER COLD ROLLING AND ANNEALING

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Abstract

Twinning Induced Plasticity steel, or TWIP steel, has had increased interest in recent years from various industry sectors. This is due to it being light weight, strong, and ductile; which are all properties that are useful in the automotive and aerospace industries. These steels potentially can offer lighter weight vehicles and parts with increased strength and other mechanical properties. This combination could offer greater fuel efficiency and performance while at the same time improving the safety features of the vehicle. This paper deals with the description of the behaviour of high manganese steel after cold rolling and subsequent annealing. Impacts on microstructure, phase composition, yield strength and tensile strength are described.

Keywords: TWIP steels, rolling, mechanical properties

1. INTRODUCTION

The main difference between TRIP-assisted and TWIP steel is that the austenite in the former is stable on cooling but not under mechanical load, i.e. phase transformation happens when the material is loaded. In contrast, there is no phase transformation in TWIP steel during cooling or deformation, but the orientation of part of austenite will change due to mechanical twinning. The different behaviour of the austenite is attributed to its stacking fault energy. SFE changes with the alloy composition and deformation temperature [1]. Steels with high concentrations of Mn, Si and Al exhibit high strength and plasticity when deformed due to the mechanical twinning (TWIP steels) or to deformation-induced martensitic transformation (TRIP steels) [2-6]. The martensitic transformation from austenite (γ) to ε martensite and/or α´ martensite occurs with γ SFE is typically below 20 mJ / m^2, whereas mechanical twinning is promoted if the stacking fault energy lies between 15 and 30 mJ / m^2.

For steels with a manganese content of less than 15 %, a deformation of austenite results in a TRIP effect, i.e. martensite conversion. With a manganese content of about 20 %, there is a combination of both phenomenon, TWIP and TRIP effects. For a manganese content above 25 %, the TWIP effect usually prevails. But the specific deformation/transformation behaviour depends on the specific chemical composition, i.e. the content of the other elements that affect the SFE. These are silicon, aluminium and carbon. At lower carbon contents, martensite transformation occurs even in high manganese content above 25 %. Carbon can suppress a martensitic transformation, but the amount of C that can be added is limited due to the formation of M_3C carbides [7]. The carbon content also limits the possibility of welding these steels together with standard ferritic grades. Therefore, the authors' previous studies were devoted to manganese steels with a medium content of manganese and a low carbon content. These steels achieve high strength (above 1400 MPa), mainly due to α´ and ε martensite content [6], [8-9]. For high manganese steels with predominant TWIP effect, it is usually achieved lower tensile strengths (below 1000 MPa) and low yield strengths (YS) of about 250 MPa [10]. This paper shows that proper heat treatment of the cold rolled sheet can achieve much better values of YS.

2. EXPERIMENT DESCRIPTION

2.1. Experimental material

Chemical compositions of steel employed in this experiment are given in **Table 1**. The heat was manufactured in a vacuum induction furnace and cast into a round ingot mould. After cooling, the ingot was reheated in a furnace to the forging temperature of 1100 °C. In a universal hydraulic press, the ingot was then forged into a slab of 280 × 130 mm cross-section. The slab was then hot-rolled to strip of a final thickness of 4 mm. The rolled strip was annealed at 950 °C for 2 hours. After grinding, the annealed strip was rolled passes to the final thickness of 1.5 mm. The rolled strip was annealed at 950 °C for 2 hours. After grinding, the annealed strip was rolled in six passes to the final thickness of 1.5 mm.

Table 1 Chemical composition of experimental steel

Heat nr.	Element [wt. %]				
	C	Mn	Si	Al	Fe
V16/89	0.12	28.53	1.57	0.78	Bal.

2.2. Microstructure analysis

The specimens were prepared using standard metallographic techniques of grinding and subsequent polishing. Their microstructures were revealed by two-stage etching: first with 10 % Nital, and then with the Klemm's II colour reagent. [11]. Microstructures were documented using a Zeiss Axio Observer optical microscope. Phase analysis by X-ray diffraction was carried out at room temperature using a Bruker D8 Discover diffractometer. The diffracted radiation was detected by means of a one-dimensional detector. A cobalt X-ray source has been used. The instrument was equipped with a polycapillary lens focusing the primary X-ray beam into a circular spot with a diameter of 0.5 mm.

2.3. Mechanical properties

Tests were executed using servohydraulic testing system Zwick. Prior to testing, dimensions of samples were measured and recorded. Some samples from sheet had to be tested by means of a miniature tensile test because of lack of sufficient test material for the standard test. The dimensions of the miniature tensile test sample are 5 mm in gauge length and 0.5 x 1.5 mm in cross section. On test specimens of this small size, Digital Image Correlation (DIC) is used for strain measurement instead of conventional extensometers. This method of mechanical properties measurement on a small amount of experimental material has proved successful in earlier studies [12 - 15]. Additionally, the samples from this steel were subjected to strength testing at high strain rates (from 500 s^{-1} up to 2500 s^{-1}). These dynamic tests were done on the drop weight tower IMATEK IM10-T-30HV with high-speed camera Phantom v710.

3. RESULTS AND DISCUSSION

3.1. Microstructure analysis

The microstructure of the sheet after cold rolling without any heat treatment is shown in the **Figure 1** (a and b). Since etching with Klemm's reagent leaves ε martensite colourless, it appears white in micrographs. The colour of another phase - γ (austenite) is usually yellow to brown and could be also light blue to dark blue according to the degree of etching. Steels with manganese content above 28 % usually show the prevalence presence of γ (austenite). But as this was mentioned above, this fact is connected with higher carbon content (usually above 0.8 %). Lower carbon content affects the value of SFE and this brings the increasing amount of ε martensite in the microstructure especially in the deformed conditions of the material after cold rolling. The

Figure 1a shows the microstructure of deformed austenite with the presence of ε martensite (white phase). **Figures 1b - e** shows other states of this steel after different annealing temperatures at 950 °C, 800 °C, 700 °C and 500 °C for two hours with subsequent slow cooling in the vacuum furnace with a protective argon atmosphere. It is possible to observe recrystallized microstructure in the case of samples annealed from 950 °C to 700 °C.

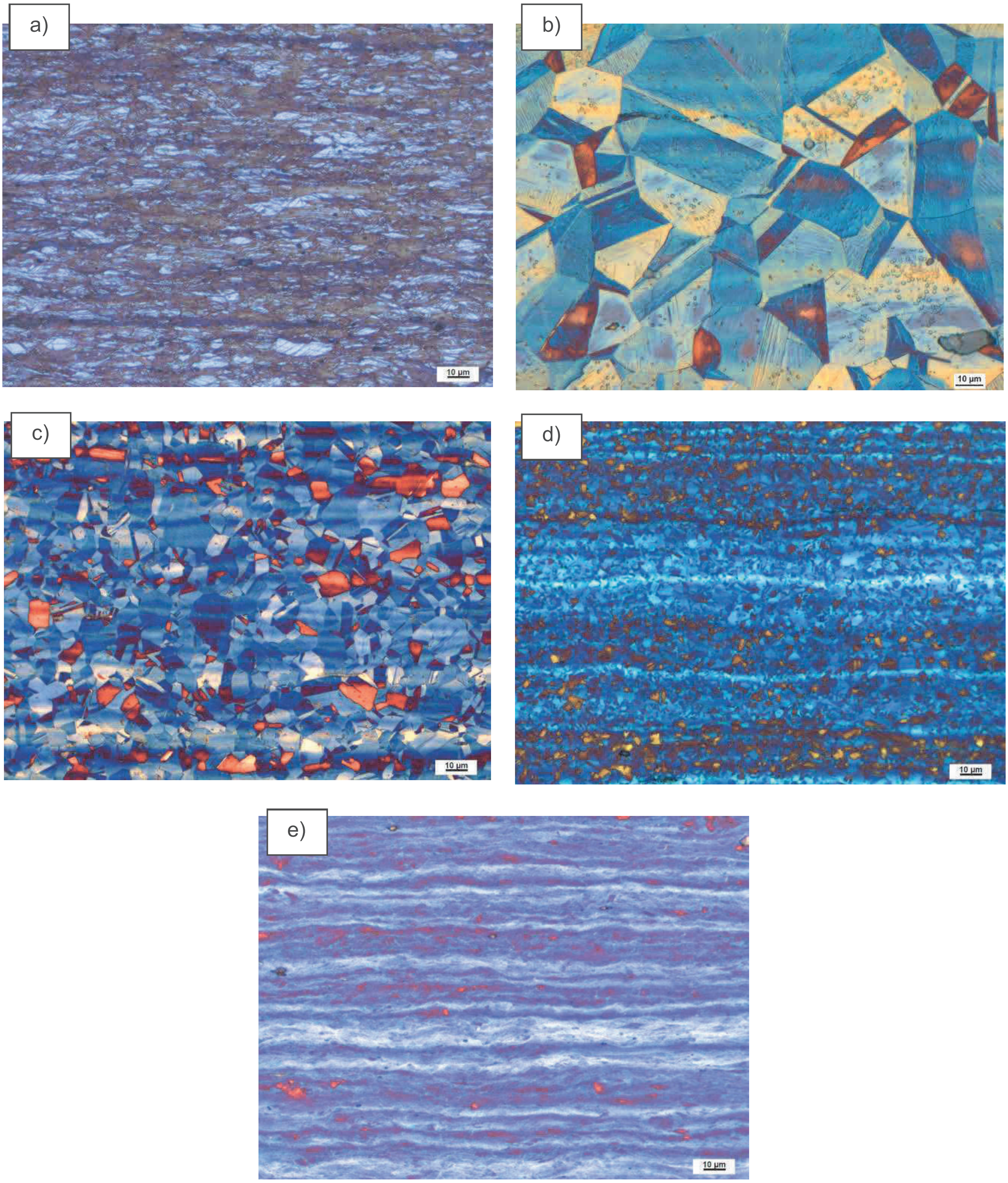


Figure 1 Microstructures of the sheet with thickness 1.5 mm after: a) cold rolling, b) annealing at 950 °C / 2h, c) annealing at 800 °C / 2h, d) annealing at 700 °C / 2h, e) annealing at 500 °C / 2h

The microstructure of the sample annealed at 950 °C is rather coarse-grained in comparison to cold rolled state and it shows the grain size G = 6.5 (according to ASTM E112). Decreasing the temperature of annealing leads to the substantial decrease of the grain size (see **Figures 1c - d**). The influence of the annealing temperature on the grain size is summarised in the following **Table 2**. It was not possible to measure the grain size of sample annealed at 500 °C because it is still deformed and the grain boundaries are not visible.

Table 2 Grain size after different heat treatment

Annealing temperature [°C]	950	800	700
Average dimeter [μm]	31.9	11.1	3.2
Grain size G [ASTM E112]	6.5	10.0	13.5

The phase analysis by x-ray diffraction (see **Table 3** and **Figure 2**) shows that none was detected in the sample annealed at 500 °C. The highest volume fraction of ε martensite was measured on the sheet subjected to the cold rolling without any heat treatment. Further increasing of temperature of annealing (above 500 °C) leads to the increase of ε martensite volume fraction (in comparison to the lower annealing temperature). A possible explanation of this behaviour could consist in the coarsening of the microstructure. Larger grains could promote the austenite decomposition. Similar behaviour - in the case of medium manganese TWIP steel - was observed in previous studies [8 - 9].

Table 3 Volume fraction of structural phases according to the X-ray diffraction

	Annealing temperature [°C]			
Phase [volume %]	Cold rolled	950	700	500
γ - austenite	34.8	88.5	95.6	100
ε - martensite	65.2	11.5	4.4	x

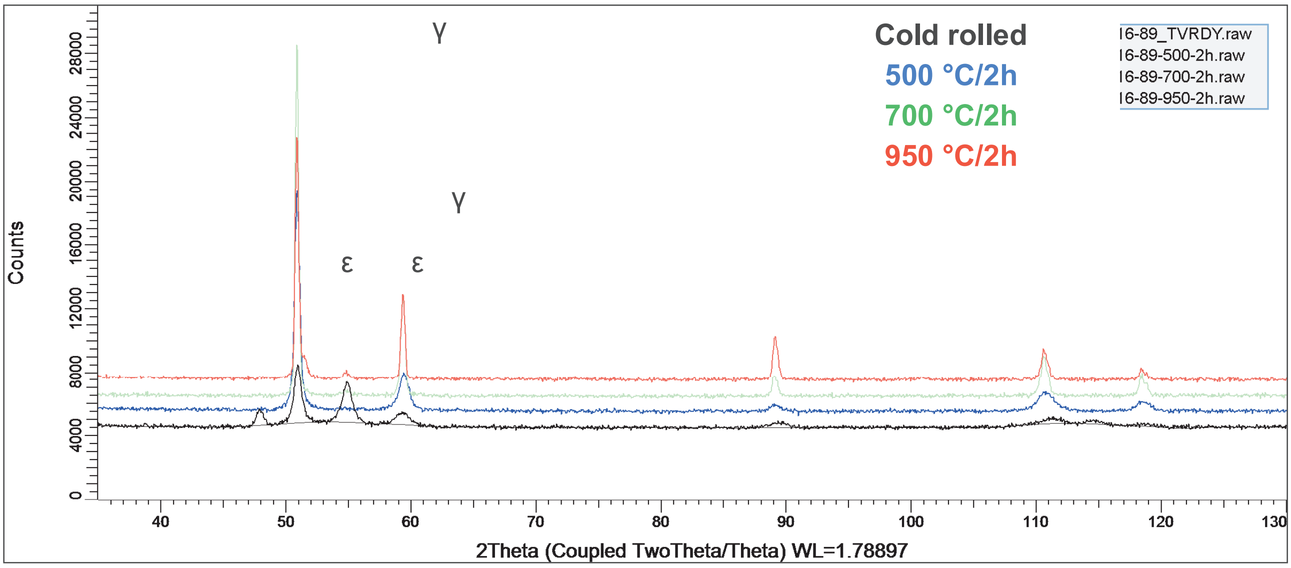
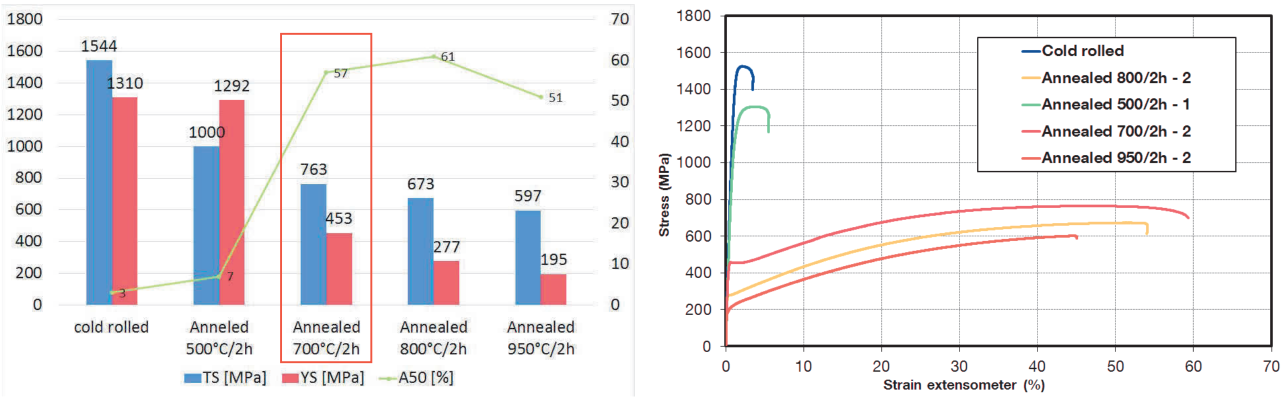


Figure 2 X-Ray diffraction pattern of the samples

3.2. Mechanical properties

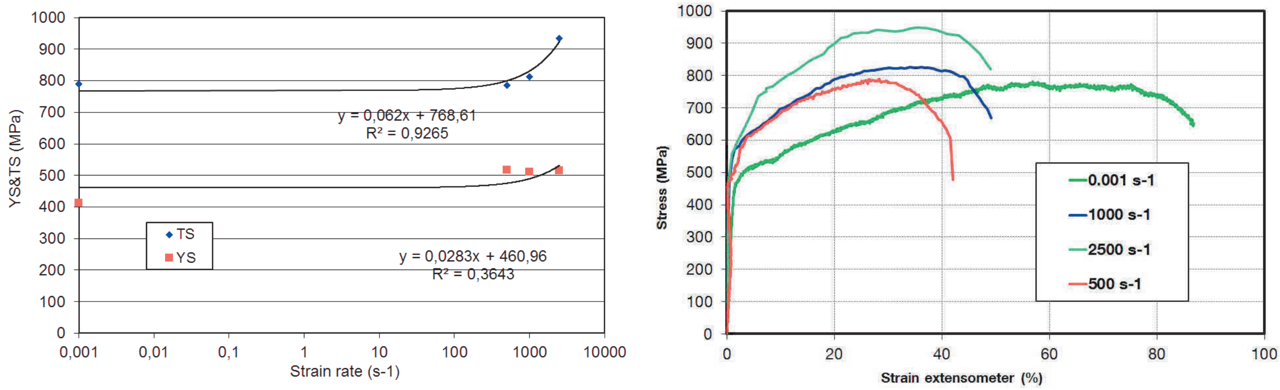
Tensile tests were carried out according to EN ISO 6892-1: Metallic materials - Tensile testing - Part 1: Test method at room temperature. The chosen strain rate for standard test was 0.001 s^{-1}. Evaluated mechanical properties YS, TS and A50 are summarised in **Figure 4a, Figure 4b)** shows the engineering stress-strain curves. These results show that the best combination of tensile properties - TS, YS, and elongation - was reached by means of annealing the cold-rolled sheet from the new TWIP steel at 700 °C for 2 hours. Especially the value of yield strength - 453 MPa combined with the elongation of 57 % is very good for this type of TWIP steel.



a) b)

Figure 3 Mechanical properties of experimental TWIP steel: a) Comparison of mechanical properties of cold rolled and heat treated samples, b) Engineering stress-strain curves

The samples annealed at 700 °C were further subjected to the tests with higher strain rate 500, 1000 and 2500 s^{-1}. Results of this test are shown in **Figure 4**.



a) b)

Figure 4 Results of the dynamic tensile tests: a) comparison of YS and TS at different strain rates, b) Stress-strain curves at different strain rates

4. CONCLUSION

Microstructural and mechanical properties of the experimental heat of low carbon high manganese TWIP steel were studied. This steel shows austenitic microstructure in the annealed condition with the low volume fraction of ε martensite. Annealing of this steel at 700 °C for 2 hours (from cold rolled state) leads to very good combination of mechanical properties with 760 MPa of TS, 453 MPa of YS and 57 % of uniform elongation. This state shows very fine grained microstructure with grain diameter below 3.3 µm (Grain size = 13.5 according to ASTM E112). The high strain rates tests show typical increasing of yield and especially the tensile strength up to 940 MPa at highest strain rate 2500 s^{-1} where the total elongation still reaches a good value of 40 %.

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