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Specific behavior of high-manganese steels in the context of temperature increase during dynamic deformation

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Abstract. In recent years, a development of AHSS steels for manufacturing parts for the automotive industry is the observed trend. The high-manganese steels with aluminium and silicon addition, exhibiting twinning induced plasticity (TWIP) effect, are one of the most interesting modern materials, due to their unique combination of both very good strength and great ductility. However, the material behaviour during plastic deformation depends not only on the chemical composition but also on deformation conditions, inter alia, strain rate and temperature. TWIP steels can be used for production of energy-absorbing parts, therefore it is very important to analyse their deformation behaviour at high strain rates. The paper presents the effect of deformation in quasi-static and dynamic conditions on the microstructure of an experimental TWIP steel. The experiments were performed on tensile testing machine and on the flywheel machine. The microstructure was analyzed by optical and scanning transmission electron microscopy. Thanks to the measurements during the quasi-static test and numerical simulations of both tensile tests, the temperature increase was determined in the sample region from which the sections for microstructural studies were taken. It was found that the temperature increase in dynamic conditions can affect the microstructure evolution in the investigated TWIP steel.

Introduction

The autobody components made of non-ferrous materials are nowadays more common than they used to be earlier, however, the most responsible parts in terms of passengers safety are still made of steel [1,2]. In recent years, considerable efforts have been focused on the development of high-manganese steels for the automotive industry. With the specific Mn, Al and Si content, these steels are characterized with the stacking fault energy (SFE) value in the range of ca. 20 to ca. 50 mJ/m^2 which favors twinning as a dominant deformation mechanism. This phenomenon was ultimately confirmed in many studies [2,3]. The concept of a steel with the so called twinning induced plasticity (TWIP) effect was proposed for the first time by Grassel and Fromayer [4]. During the analysis of steel with 15 and 25% of Mn content, the authors established that the unique combination of high mechanical properties and high ductility is determined by the mechanical twins formation in the austenitic grains [5]. The same authors proved that TWIP steel with an advantageous combination of mechanical and plastic properties should contain the amount of manganese within the range of 20% wt. to 30% wt., the aluminium content – from 3% wt. to 5%

wt. and the carbon content not exceeding 0.6% wt. The TWIP steels are characterized by good work hardening, which is mostly the result of twinning, but also dynamic strain ageing (DSA). Moreover, these steels are extremely sensitive to the strain rate [6]. The studied carried out in [7] proved an influence of the strain rate on the ability to transfer dynamic loads by the TWIP steel, confirming an increase in the impact resistance under the influence of increasing strain rate. The dynamic deformation conditions favors the mechanical twins growth in TWIP steel [8, 9]. However, the high strain rate causes the rapid temperature increase in a deformed region. It was proved that temperature rise above 200°C in numerous MnAl steels causes the increase of the SFE value which promotes the dislocation slip and slows down the mechanical twins growth [10]. There's a limited information in the literature about the effect of heat generated during dynamic deformation on the TWIP steel microstructure evolution [11].

The aim of the study was to determine a temperature increase due to conversion of the deformation work into the heat in experimental TWIP steel samples subjected to tensile tests at two different conditions and to analyse how the heat generated affects the deformation mechanism in the investigated steel.

Research Methodology

The research was carried out on an experimental high-manganese steel with the chemical composition given in Table 1. The steel was smelted in a vacuum induction furnace and cast using the gravity casting technique. 120 mm long ingots with a cross-section of 20 x 40 mm were homogenized in an air furnace at 1200°C and then hot-rolled to a thickness of ca. 2 mm. After hot rolling, the steel was subjected to solution heat treatment (1100°C / 2 h / water quenching).

Table 1. The chemical composition of the investigated steel.

Element content, wt. %										
C	Mn	Al	V	P	S	Ce	La	Nd	N	Fe
0.42	21.10	2.55	0.002	<0.01	0.006	0.011	<0.005	<0.005	43ppm	bal.

The dog-bone samples with the dimensions given in Fig. 1a were cut-out of the obtained strips to perform the quasi-static tensile test (at the strain rate of 0.5 s^{-1} – Fig. 1b) on the Instron tensile testing machine and the dynamic one (at the strain rate of 1000 s^{-1} – Fig. 1c) on the flywheel machine. The latter method is described in [12]. The initial temperature of samples was ca. 20ºC. The temperature changes in the sample tested at the lower strain rate were recorded by FLIR T840 thermal imaging camera. Temperature measurement methodology during quasi-static tensile tests was presented in [13].

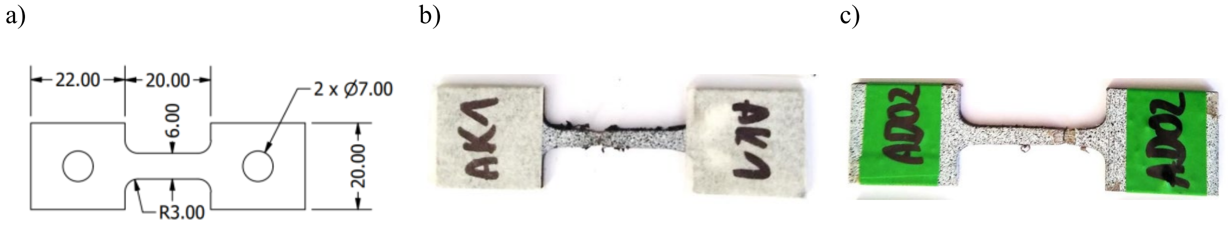

Fig. 1. The sample dimensions used in tensile tests (a) and samples after quasi-static (b) and dynamic (c) tensile tests.

The numerical modelling of quasi-static and dynamic tensile tests were performed in Forge NxT 3.2 – a commercial finite element method software dedicated for metal forming and heat treatment simulations. To reduce the computation time, a geometric model of ⅛th of a sample was used (Fig. 2). The fine tetrahedral mesh was generated in the sample volume.

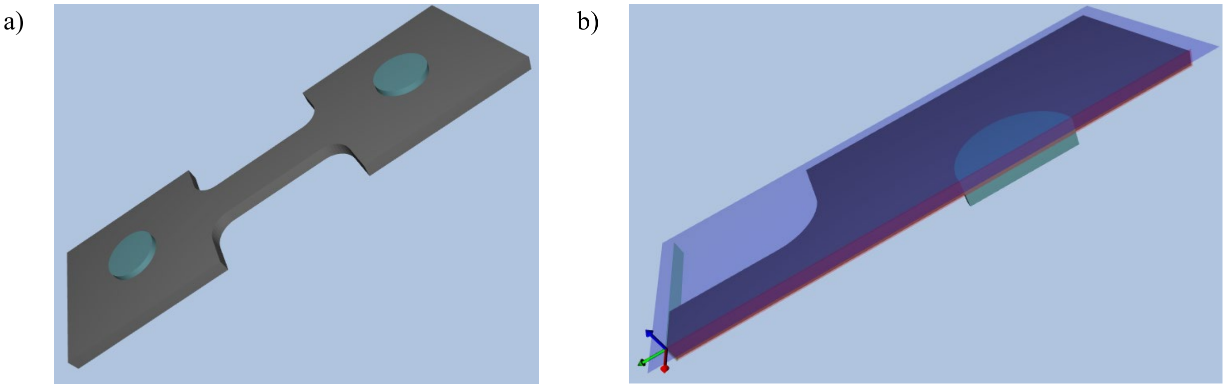

Fig. 2. The geometric model of a sample used in tensile tests with the gauge length of 10 mm, the width of 6 mm and the thickness of 1.4 mm (a) and symmetry planes utilized in simulations (b).

The flow stress of the investigated TWIP steel was defined with the equation:

$$\sigma_p = A \cdot \exp(m_1 T) \cdot (\varepsilon + \varepsilon_{b0})^{m_2} \tag{1}$$

where: T – temperature of the sample, ε – equivalent strain, A, m_1, m_2, ε_{b0} – coefficients of the Eq. 1.

The coefficients in Eq. 1 were calculated separately for each strain rate on the basis of the experimentally determined mechanical properties (such as the offset yield strength $R_{p0.2}$,, the ultimate tensile strength R_m and the uniform elongation A_g), by means of Cold Rheology Generation Tool included in the Forge NxT 3.2 software, The Eq. 1 coefficient values as well as the mechanical properties obtained in experiments are collected in Table 2. The physical and thermal properties such as density (7400 kg/m^3), specific heat (500 J/kgK) and thermal conductivity (17 W/mK) were taken from [14]. Adiabatic conditions on the sample-die interface were assumed.

Table 2. Mechanical properties and coefficients of the flow stress function.

Strain rate [s^{-1}]	$R_{p0.2}$ [MPa]	R_m [MPa]	A_g [%]	A	m_1	m_2	ε_{b0}
0.5	245	523	54	1169.71	-0.0009	0.468808	0.0370259
1000	410	650	48	1397.58	-0,0009	0.467435	0.0753929

Microstructural observations were made on microsections parallel to the longitudinal sample axis, in the necked region, by means of the light microscope Olympus GX71 and scanning transmission electron microscope Hitachi HD-2300A. In order to reveal the microstructure, the material was etched in 6% Nital (94 ml of ethyl alcohol, 6 ml of HNO_3 acid).

Results and Discussion

To verify the correctness of the simulation results, calculated temperature distributions and the maximum temperature change in the sample deformed at 0.5 s^{-1} were compared to the corresponding experimental measurements (Fig. 3). It seems like quite good accuracy of simulation results was obtained. In both cases the maximum temperature started to rise intensively on the onset of necking which was predicted in the simulation almost in the same moment as it happened in the experiment. The most notable difference is the necking location. In the real test it has occurred in the weakest cross-section of the gauge length while in the simulation – at the sample center. It is obvious that the numerical model definition has forced prediction of the necked region at the center of a sample. The other solution would be possible if some inconsistency or a flaw in the sample geometry, the finite element mesh, the material model or boundary conditions appeared or was there something like that defined on purpose.

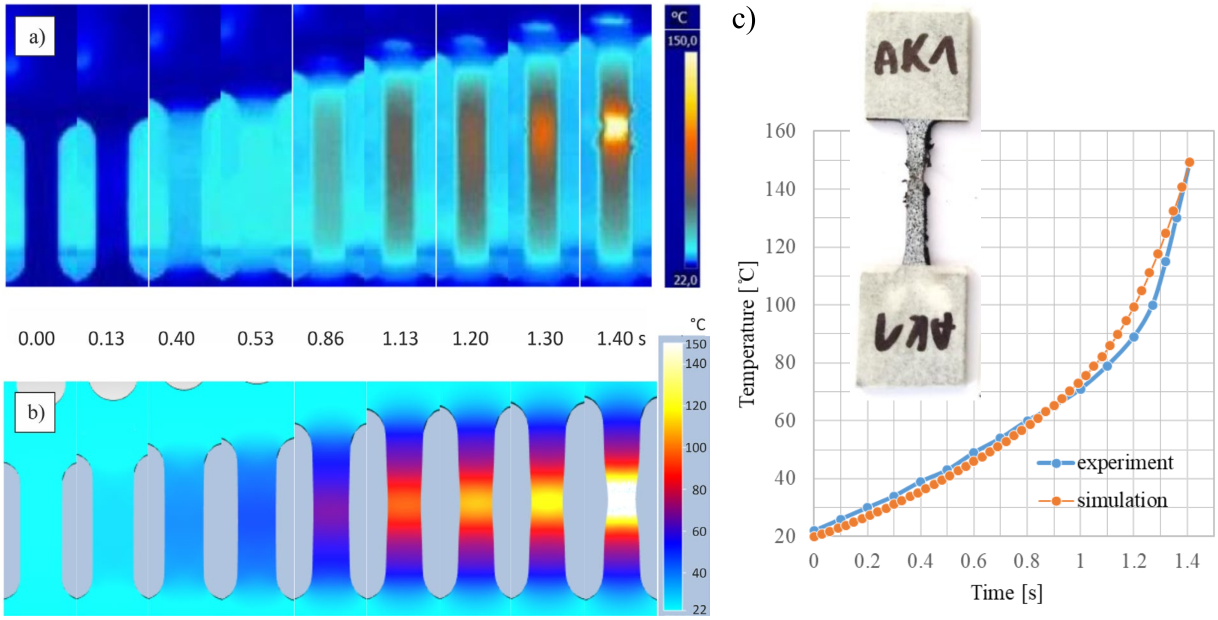

Fig. 3. Comparison of measured (a) and calculated (b) temperature distributions and the maximum temperature (c) in the sample tested at the strain rate of 0.5 s^{-1}.

The mechanical properties, presented in Table 2, as well as the corresponding flow curves (Fig. 4c) indicate that significantly higher stresses are required to deform of the investigated steel under dynamic loading. It is well reflected in the von Mises stress distributions presented in Figs. 4a and 4b. However it is worth to notice that the steel still exhibits the excellent uniform elongation (A_g) at very high strain rates. It is only slightly smaller than the elongation observed in the quasi-static conditions.

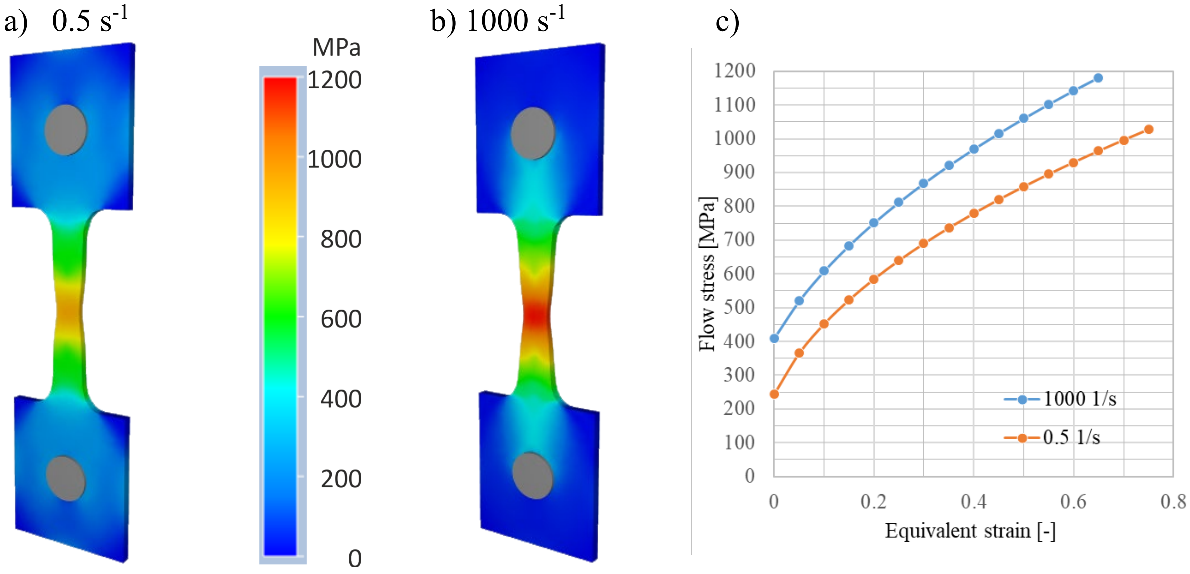

Fig. 4. Calculated von Mises stress distributions in the investigated TWIP steel samples subjected to (a) quasi-static and (b) dynamic tensile tests as well as a comparison of TWIP steel flow curves for the analysed strain rates (c).

A comparison of temperature changes in both selected deformation cases is presented in Fig. 5. As it was expected, the significantly higher flow stress of the investigated steel during deformation at the strain rate of 1000 s^{-1} caused more intensive temperature increase in the sample. According to the numerical simulation results, the temperature at the center after reaching equivalent strain of ca. 0.8 can exceed 200°C. Similar research results were presented in the work [11]. Such a deformation temperature in some MnAl steels increases stacking fault energy (SFE) and promotes dislocation slip.

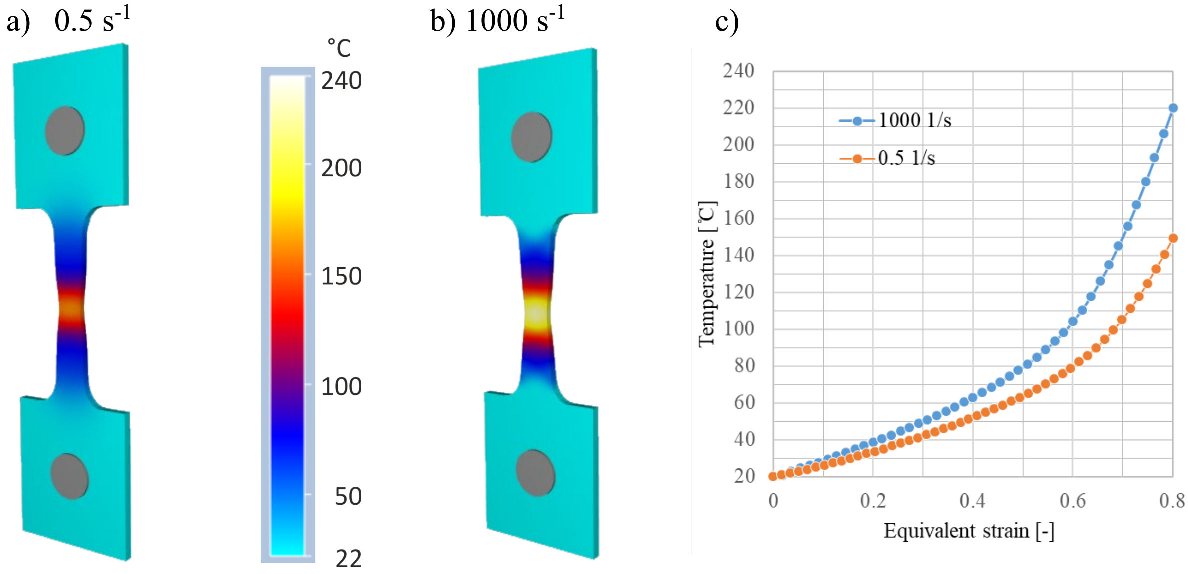

Fig. 5. Calculated temperature distributions in the investigated TWIP steel samples subjected to (a) quasi-static and (b) dynamic tensile tests as well as a comparison of the maximum temperature (c).

Microstructure Analysis

The microstructure of the studied steel at the initial state is fully austenitic (Fig. 6a). It is characterized by the presence of austenite grains with characteristic coherent annealing twins (Fig. 6b) and tangled dislocations observed near the grain boundaries (Fig. 6c).

After the tensile tests, effects of deformation are clearly visible in the microstructure. The austenite grains are elongated towards the tensile direction (Figs. 6 d,g). In the austenite matrix containing dislocations cells, the generation of mechanical twins occurs in the primary and secondary twinning system (Figs. 6 e,f). At the strain rate of 1000 s^{-1}, the generation of multi-twins as well as nano-twins is observed (Figs. 6 h,i). This leads to the activation of several slip and twinning systems. Moreover, the twin bundles can be observed. The interactions between twins take place and individual micro shear bands appear (Fig. 6h).

The development of micro shear bands results from the evolution of dislocation structure. This phenomenon can be associated with the intensive temperature increase calculated in the sample deformed at the strain rate of 1000°C. It could cause the increase of stacking fault energy and thus, possibly, the *rearrangement of the dislocation structure*.

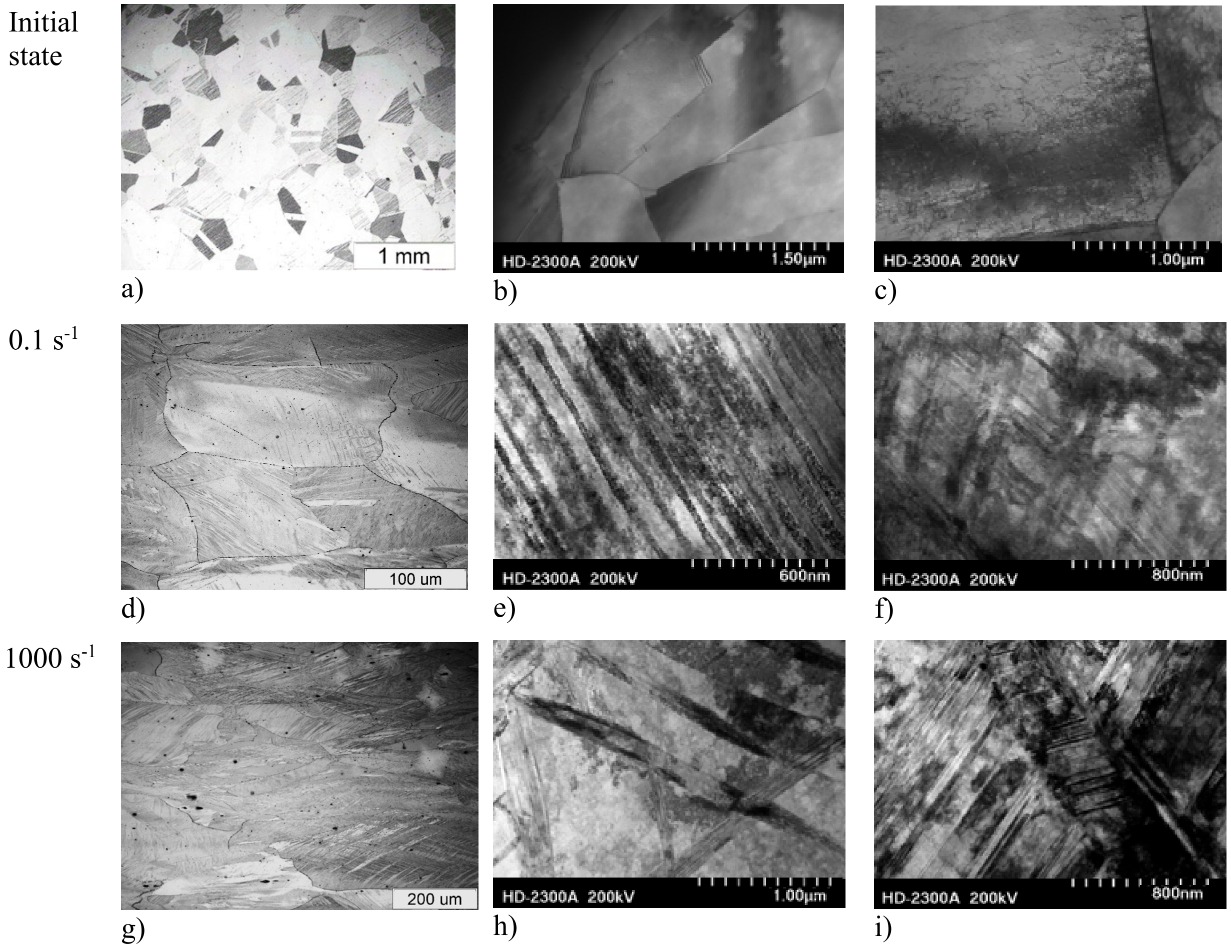

Fig. 6. The microstructure of the investigated steel in the initial state and after deformation at various strain rates; taken from the necked regions where the equivalent strain was ca. 0.8.

Summary

The experimental, high-manganese austenitic steel tested in this work can be classified as a material exhibiting TWIP effect. It was proved that it has good strength, comparable to the currently used steels for elements that increase the safety of vehicles, and very high elongation, even during deformation at very high strain rates. This unique features indicate that TWIP steels are excellent materials for the production of energy-absorbing parts that are designed to withstand severe deformation without fracture during a collision.

The convergence of experimental and simulation results was obtained for the test performed in the quasi-static conditions. This suggests that the prepared simulation model can provide correct results also for dynamic deformation conditions. The conducted numerical simulations made it possible to determine the temperature increase in the sample tested at high strain rate, which was not possible during the experiment.

During deformation at the strain rate of 0.1 s^{-1}, the temperature of the investigated steel reached over 150°C in the necked region of the tensile sample. In these conditions the mechanical twinning is a dominant deformation mechanism. However, at the strain rate of 1000 s^{-1}, the temperature noticeably exceeding 200°C was calculated in the region from which micro-sections for microstructural investigations were taken. The effects of microstructure evolution observed in the sample indicate that such a high temperature probably affected the stacking fault energy of the investigated steel as well as promoted the development of micro-bands and the rearrangement of dislocation structure.

Acknowledgments

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