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Mechanical properties and microstructure of high-manganese TWIP, TRIP and TRIPLEX type steels

L.A. Dobrzański*, W. Borek
Division of Materials Processing Technology, Management and Computer Techniques in Materials Science, Institute of Engineering Materials and Biomaterials, Silesian University of Technology, ul. Konarskiego 18a, 44-100 Gliwice, Poland
* Corresponding e-mail address: leszek.dobrzanski@polsl.pl

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Materials

ABSTRACT

Purpose: The aim of this paper is to determine the high-manganese austenite propensity to twinning induced by the cold working and its effect on structure and mechanical properties, and especially the strain energy per unit volume of new-developed high-manganese Fe-Mn-(Al, Si) investigated steels, including selected high-manganese austenitic TWIP steels containing 25-27.5% Mn, 1-4% Si, 2-3% Al, high-manganese TRIP steels containing 17-18% Mn, about 1% Si, about 3% Al and selected high-manganese TRIPLEX steels containing 24% Mn and about 11% Al and some of that steels with Nb and Ti microadditions, with various structures after their heat- and thermo-mechanical treatments.

Design/methodology/approach: The microstructure evolution in successive stages of deformation was determined in metallographic investigations using light, scanning and electron microscopies as well as X-ray diffractomiter.

Findings: New-developed steels achieve profitable connection of mechanical properties, i.e. (ultimate tensile strength) UTS~800-1000 MPa, (yield strength) YS0.2 = 250-450 MPa, and plastic (uniform elongation) UEl = 35-90%, and moreover, particularly strong formability and strain hardening occurring during forming. The new-developed high-manganese Fe-Mn-(Al, Si) steels provide an extensive potential for automotive industries through exhibiting the twinning induced plasticity (TWIP) and transformation induced plasticity (TRIP) mechanisms.

Practical implications: The obtained microstructure - hot-working conditions relationships and stress-strain curves can be useful in determination of power-force parameters of hot-rolling for sheets with fine-grained austenitic structures.

Originality/value: Results obtained for new-developed high-manganese austenitic steels with the properly formed structure and properties in the heat treatment- or thermo-mechanical processes indicate the possibility and purposefulness of their employment for constructional elements of vehicles, especially of the passenger cars to take advantage of the significant growth of their strain energy per unit volume which guarantee reserve of plasticity in the zones of controlled energy absorption during possible collision resulting from activation of twinning for TWIP steels, supported with martensitic transformation for TRIP steels, induced cold working, which may result in significant growth of the passive safety of these vehicles' passengers.

Keywords: High manganese TWIP, TRIP & TRIPLEX steels; TWIP & TRIP mechanisms; Fracture counteraction; Strengthening mechanisms; Mechanical properties

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1. Introduction

Automotive industry sets very high demands on both production technology and steel used for body of the car, construction elements and other parts of the car. These requirements are the result of continuous improvement of safety standards, which aim to develop a controlled crash area being subject to deformation (damage) according to the scenario, providing maximum absorption of large amounts of impact energy. With proper selection of chemical composition and manufacturing technologies, which guarantee obtaining the structure allowing for connections to provide a favorable strength and plastic properties of steel. In the last three decades have been developed a new group of high-manganese steels with very high strength for use in the automotive industry, which can be divided into TWIP, TRIP and TRIPLEX type steels [1-7].

New-developed steels achieve profitable connection of mechanical properties, i.e. (ultimate tensile strength) UTS~800-1000 MPa, (yield strength) $YS_{0.2}$ = 250-450 MPa, and plastic (uniform elongation) UEl = 35-90%, and moreover, particularly strong formability and strain hardening occurring during forming. The new-developed high-manganese Fe-Mn-(Al, Si) steels provide an extensive potential for automotive industries through exhibiting the twinning induced plasticity (TWIP) and transformation induced plasticity (TRIP) mechanisms. TWIP steels not only show excellent strength, but also have excellent formability due to twinning, thereby leading to excellent combination of strength, ductility, and formability over conventional dual phase steels or transformation induced plasticity TRIP steels. Conditions applied to high-manganese TWIP/TRIP/TRIPLEX steels sheets during deep drawing are different from those applied during tensile testing, the formability cannot be evaluated by mechanical properties obtained from the tensile test. In order to develop automotive steels with excellent properties for CO_2 reduction into the environment and increased efficiency, thus, researches on identifying and understanding these mechanisms are highly required [8-14].

High-manganese TWIP type steel (Twinning Induced Plasticity) is steel, where mechanical twinning is induced by cold plastic deformation. TRIPLEX steels contains 0.7-1.2% C, 18-28% Mn and 8.5 to 12% Al. These steels have a three phase structure consisting of grains of austenite γ-Fe(Mn,Al,C), the dispersion of separating κ-carbide $(Fe,Mn)_3AlC_{1-x}$ and α-Fe ferrite (Mn,Al.). During plastic deformation of the steel in the austenite takes place dislocation slip and mechanical twinning [8]. High manganese TRIP type steels (Transformation Induced Plasticity), contain 0.1 to 0.6% C and 15-22% Mn, 2-4% Si and 2 to 4% Al. In these steels, TRIP effect is repeated, the transformation of austenite into martensite as a result of cold plastic deformation. TRIP effect consisting in steel hardening in the consequence of $\gamma_{A1}\rightarrow\varepsilon_{A3}$ or $\gamma_{A1}\rightarrow\varepsilon_{A3}\rightarrow\alpha'_{A2}$ martensitic transformation occurring during cold forming. Martensite ε is formed during plastic strain only when stacking fault energy SFE of austenite is lower than 20 mJ/m^2. Addition of aluminium into steel increases SFE and austenite stability which leads to suppressed influence on martensitic transformation. While the addition of silicon decreases SFE and allows occurring of $\gamma\rightarrow\varepsilon$ transformation [1-3, 15-18].

Thermo-plastic treatment applied to form a fine-grained microstructure of austenitic steels used in the automotive industry have to be done in controlled conditions. Using too large deformation, or too long isothermal holding times after the last deformation results in excessive grain refinement of the structure up to about 2 mm, has an impact on increasing strength properties in particular increasing the offset yield point by about 150-200 MPa and tensile strength increase to 1000 MPa [26]. Whereas too large value for the average grain diameter of about 70 mm causes improvement of plastic properties, elongation can achieve even 80-90% at relatively low strength properties. Therefore the main objective of the application of thermo-plastic deformation is the selection of the processing parameters to achieve optimal value for the average grain diameter at which the product of tensile strength and elongation reaches a maximum value. This will allow to increased strain energy per unit volume of structural components of vehicles during traffic collision [19-30].

Application of thermo-mechanical treatment consisting in immediate cooling of products from a finishing temperature of hot-working in controlled conditions should increase mechanical properties [11]. Introduction of Nb and Ti microadditions to one of investigated steel could be the reason for additional strain hardening of high-manganese steels and allows forming a fine-grained microstructure in successive hot-working stages.

2. Materials and experimental procedure

Investigations were carried out on three high-manganese steels: TRIP - X11MnSiAlNbTi18-1-3 TWIP - X8MnSiAlNbTi25-1-3 and TRIPLEX X98MnAlNbTi24-11 containing 18-25% Mn, 0.2-1.20% Si, 3-11% Al, and with microadditions Nb and Ti. The chemical compositions of steel were shown in Table 1. Steels are characterized by high metallurgical purity, associated with low concentrations of S and P contaminants and gases. Melts were modified with rare earth elements.

Chemical composition of tested steels were chosen in order to obtain the structure of the austenitic matrix. For the investigated melts Nb and Ti microadditions were added in order to refine the structure and achieve precipitation hardening.

Table 1.
Chemical composition of new-developed high-manganese austenitic steels, mass fraction

Steel designation	Chemical composition, mass fraction										
	C	Mn	Si	Al	Nb	Ti	P_{max}	S_{max}	Ce	La	Nd
X11MnSiAlNbTi18-1-3	0.11	18.25	1.20	3.29	0.027	0.025	0.002	0.003	0.019	0.005	0.007
X8MnSiAlNbTi25-1-3	0.08	24.60	0.91	3.10	0.040	0.024	0.002	0.003	0.005	0.001	0.002
X98MnAlNbTi24-11	0.98	23.83	0.20	10.76	0.048	0.019	0.002	0.002	0.029	0.006	0.018

Investigated ingots with a mass of 25 kg were performed in a laboratorial vacuum arc furnace of the type VSG-50 from Balzers. Casting of ingots took place in argon atmosphere intended for cast-iron ingot moulds, round with a swage, downwards converging of inner dimensions: bottom - ∅122 mm, top - ∅145 mm, h=200 mm - without the swage (with the swage - 300 mm). After casting, 60 min were waited, which were required for ingot head to solidify, and subsequently the furnace chamber was opened and further cooling of ingot in the mould took place in the air.

Plastic pre-hot forming of ingots, on a flat bar of 20x220 mm cross-section, was performed by the open die forging method on a high-speed hydraulic press from Kawazoe capable of generating 300 ton pressure. Ingots were heated for forging in a gas forging furnace. The forging temperature ranged between 1200 and 900°C. Subjected to forging were only ingot bodies without ingot heads - cut off at the height to which contraction cavity and ingot feet were reaching - cut off at the height of 3 cm.

From the pre-forged ingot was prepared test sample. For the purposes of plastometric investigations cylindrical samples Ø10x12 mm were prepared. Continuous compression of samples were made with plastic strain rate equal 0.1, 1 and 10 s^{-1}, in temperature: 1050, 950 and 850°C. In order to simulate thermo-mechanical processing, DSI Gleeble 3800 simulator was used, which allowed for establishing of stress-strain curves of the tested steels and temperature and strain rate influence on processes controlling work hardening of investigated steels.

In the last stage of plastometric examination, a multi-stage compression process was devised for axially symmetric samples, which simulated final roll passes of rolling. The experiment was conducted using also Gleeble 3800 simulator. Reduction ratios, plastic deformation rates and intervals times between successive plastic deformation stages (Fig. 1) were selected taking into account conditions of planned hot rolling of flat bars with initial thickness of 4.5 mm, rolled down to 2 mm thickness samples. Apart from determining force and energy parameters of the hot plastic deformation, the samples were quenched in water, natural cooling in air, and in water after isothermal holding in the temperature of last deformation at 850°C.

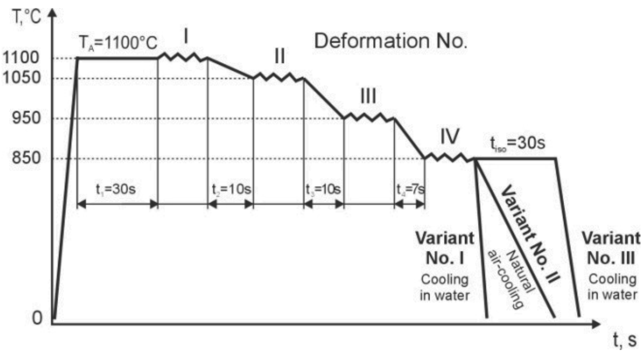

Fig. 1. Schematic and parameters of the multi-stage compression test carried out on Gleeble 3800 thermo-mechanical simulator. T_A - austenitizing temperature, t_{iso} - time of the isothermal holding of specimens at a temperature of last deformation - 850°C

Metallographic examination was carried out on samples in probed steel mounted in thermosetting resins. After the sample was mounted, it was grinded on the STRUERS's grinding machine using abrasive papers of 220-4000 μm/mm^2 grain size. Then the samples were subjected to mechanical polishing using diamond suspension of 6 and 1 μm grain coarseness. In order to reveal grain boundaries in the structure of high-manganese austenitic steels a digestion reagent was used, which was a mixture of nitrous acid, hydrochloric acid and water in 4:4:2 proportions respectively. Also used was a reagent being a mixture of hydrochloric acid, ethyl alcohol and water intended to reveal grain boundaries, as well as deformation bands and ε manganese plates. Digestion time for each sample was ranging between 5-10 s. Structural observations of probed materials were carried out on the LEICA MEF4A light microscope at magnification from 200 to 1000x. X-ray diffraction analysis of specimens in the initial state and after various stages of deformation was carried out using X'Pert PRO diffractometer with the X'Celerator strip detector from Philips, at 0.5° step record and 5 s registration time, using Kα radiation, of λ=1.54056 mm wavelength radiated from copper anode lamp, powered by 40 kV voltage at 30 mA filament current. Measurements were taken within the radial range from 20 to 140°. Identification of phases was completed based on data available in the database of Centre for Diffraction Data (ICDD).

3. Results and discussion

Starting points for microstructure analysis of specimens that were plastically hot-deformed in variable conditions are microstructures in the initial state of the investigated steels X11MnSiAlNbTi18-1-3, X8MnSiAlNbTi25-1-3, X98MnAlNbTi24-11 (Figs. 2b-4b). Differences between chemical composition of elaborated steels result in meaningful difference of a grain size in the initial state. Steel X11MnSiAlNbTi18-1-3 is characterized by homogeneous microstructure of austenite with a grain size in range from 50-60 μm (Fig. 2b). In steel X8MnSiAlNbTi25-1-3 mean grain size is about 70-80 μm (Fig. 3b). For TRIPLEX steel mean grain size of austenite is about 50-60 μm, and at the border of the large austenite grains there is a fine ferrite with the mean grain size about 5 μm. Application of Nb and Ti microadditions has influence on significant structure refinement and hampering influence of growth of grains size of austenite. For the investigated steels numerous annealing twins can be observed. Single-phase microstructure for TRIP and TWIP investigated steels was confirmed by X-ray diffraction pattern (Figs. 2a, 3a). Steel X98MnAlNbTi24-11 possess austenitic-ferritic initial structure what was confirmed by X-ray diffraction pattern presented in Fig. 4a.

Representative stress-strain curves of the TRIP type X11MnSiAlNbTi18-1-3 steel determined in continuous hot-compression test in various conditions of temperature and strain rate are shown in Figs. 5 indicate, that strain rate has an essential influence on value of flow stress. Steel X11MnSiAlNbTi18-1-3 is characterized by values of flow stress equal from 130 to 380 MPa for applied deformation conditions. Respectively the flow stress for TWIP type steel X8MnSiAlNbTi25-1-3 is equal from 135 to 360 MPa and for TRIPLEX type steel X98MnAlNbTi24-11 from 120 t0 485MPa. Increasing temperature of deformation or decreasing strain rate cause decreasing relatively high values of flow stress.

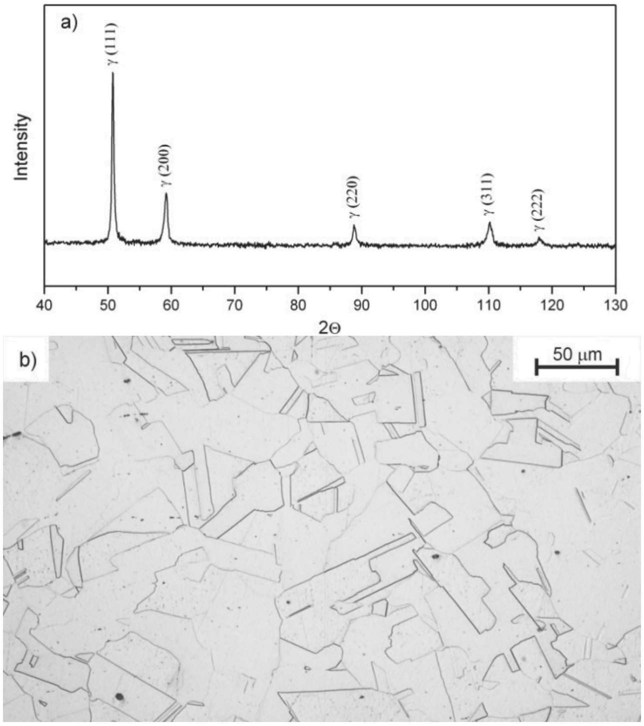

Fig. 2. X-ray diffraction pattern (a) and austenitic structure (b) of the X11MnSiAlNbTi18-1-3 steel in the initial state, containing annealing twins and some non-metallic inclusions

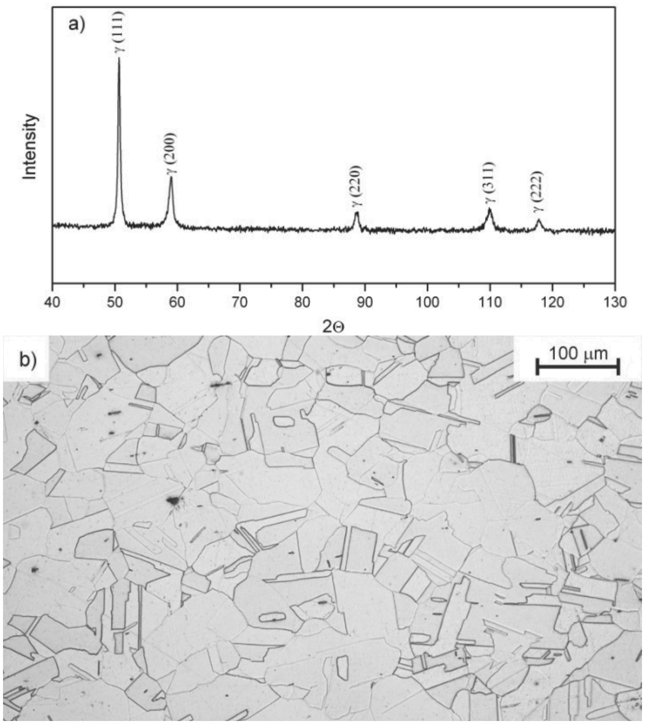

Fig. 3. X-ray diffraction pattern (a) and austenitic structure (b) of the X8MnSiAlNbTi25-1-3 steel in the initial state, containing annealing twins and some non-metallic inclusions

Stress-strain curves of steels plastically deformed according to the parameters shown in Fig. 1 are presented in Fig. 7. Multi-stage work-hardening curves of new-developed high-manganese TRIP, TWIP and TRIPLEX steels can be useful to estimate force-energetic parameters of industrial hot rolling. Application of true strain equal 0.23 during four-stage compression creates possibility of the course of dynamic recrystallization, which is indicated by peaks that can be distinguished on σ-ε curves, especially for deformations realized at temperature of 1100, 1050 and 950°C. The values of flow stress in the range of strain temperature from 1100 to 1050°C (Fig. 7) are comparable with values obtained in continuous compression test with the strain rate 10 s^{-1} (Fig. 5). Significant decrease of flow stress by about 40-50 MPa is noted for the third step of deformation realized at the temperature of 950°C for TRIP and TWIP steels. In the final deformation at the temperature 850°C values of flow stress are equal approximately 320 MPa which is about 40 and 50 MPa lower than the values obtained for the continuous compression tests at the temperature of 850°C with the strain rate $10s^{-1}$ respectively for investigated steels X11MnSiAlNbTi18-1-3 and X8MnSiAlNbTi25-1-3. It's a result of partial removal of strain hardening through metadynamic recrystallization that occurs during the intervals between second, third and fourth deformation. Additionally, cyclic deformations as well as the course of partial recrystallization result in much faster achievement of maximum on σ-ε curve for the fourth deformation when comparing to σ-ε curve of continuous compression at the temperature of 850°C.

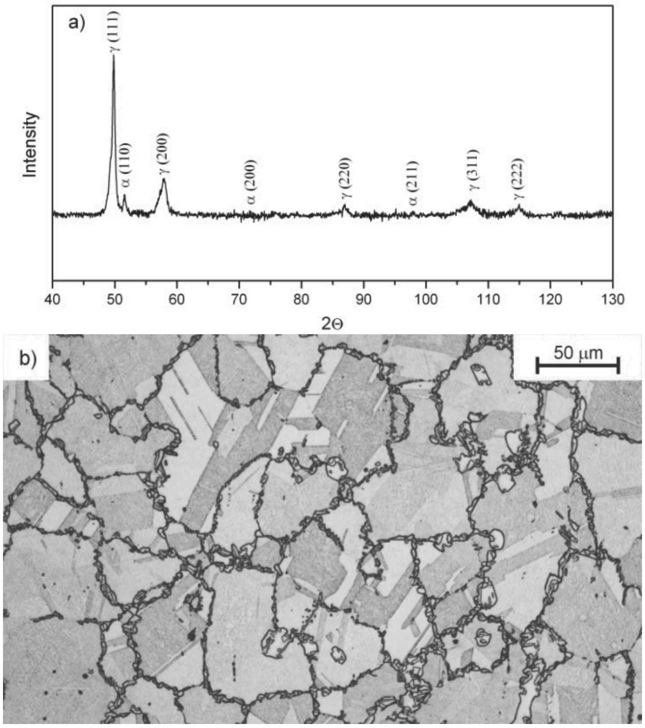

Fig. 4. X-ray diffraction pattern (a) and austenitic structure (b) of the X98MnAlNbTi24-11 steel in the initial state, containing annealing twins

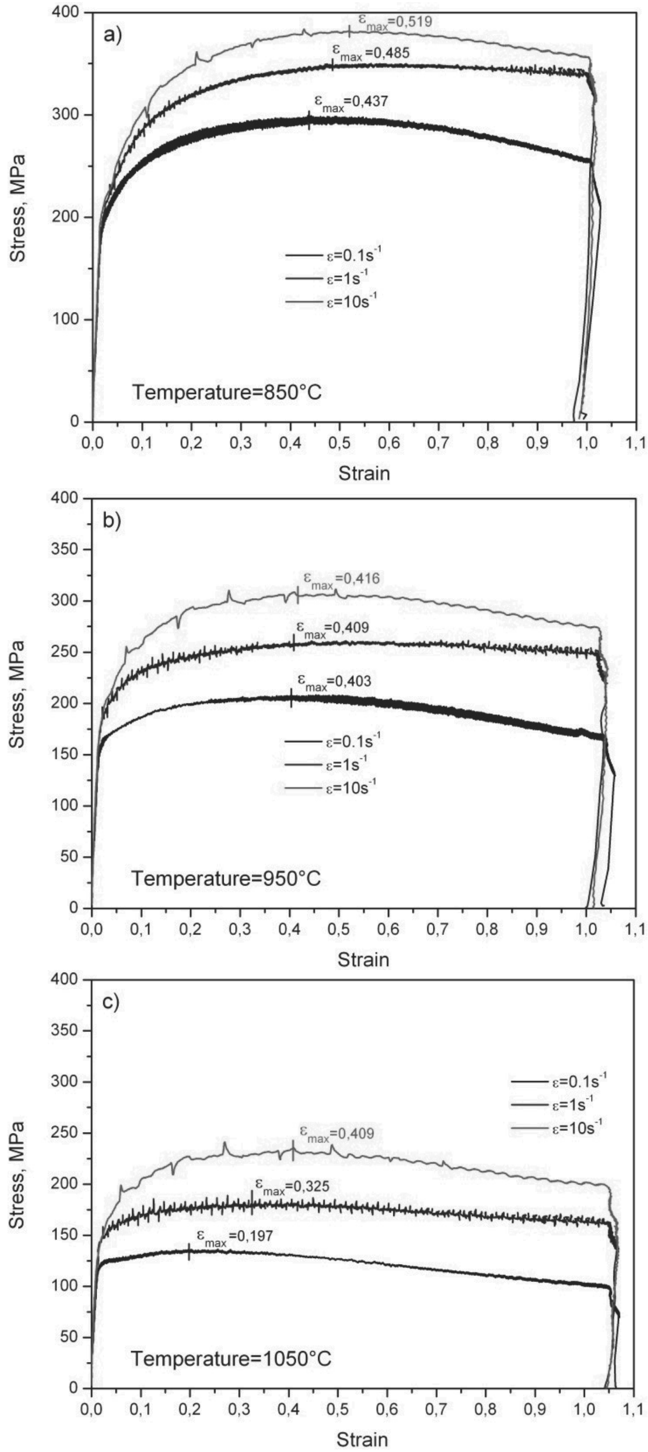

Fig. 5. Stress-strain curves of the X11MnSiAlNbTi18-1-3 steel obtained for different strain rate: 0.1, 1, 10 s^{-1}, and in a temperature: a) 850°C, b) 950°C and c) 1050°C

Along with strain temperature decreasing, the value of ε_{max} - corresponding to the maximum value of yield stress - is translating to a range of higher deformations. For steel X11MnSiAlNbTi18-1-3 the values of ε_{max} for samples deformed at rate of 0.1 s^{-1} at the temperature 1050°C is equal about 0.2 and increase up to 0.52 with decreasing the temperature to 850°C and increasing strain rate up to 10 s^{-1}. Whereas for TRIPLES type X11MnSiAlNbTi18-1-3 steel value of ε_{max} for applied deformation conditions increases from 0.19 to 0.25. It creates convenient conditions for using dynamic recrystallization for refinement of microstructure of investigated steels.

The fraction of the recrystallized phase in intervals between successive passes for steel X11MnSiAlNbTi18-1-3 and for X98MnAlNbTi24-11 steel can be evaluated from Fig. 6, showing results of softening kinetics of austenite in intervals between first and second stage of plastic deformations.

Progress of recrystallization as a function of time for the specimens compressed at the temperature 900°C with strain rate equal 10s^{-1} indicate that time necessary to form 50% fraction of recrystallized austenite is equal approximately 8 s for steel X11MnSiAlNbTi18-1-3 and 6 s at 900°C and 12 s at 1000°C for steel X98MnAlNbTi24-11. Time needed to reach total recrystallization for both investigated steel compressed at the temperature 900°C with strain rate equal 10 s^{-1} is approximately 400-500 s and even more for TRIPLEX steel at temperature 1000°C.

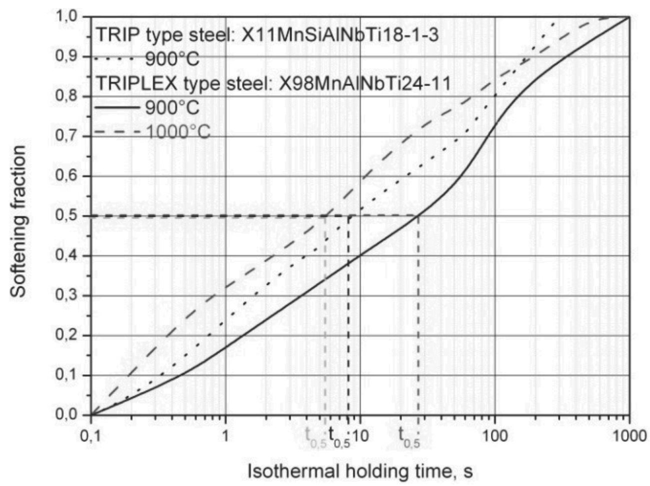

Fig. 6. Progress of recrystallization of the X11MnSiAlNbTi18-1-3 and X98MnAlNbTi24-11 steels isothermally held after plastic deformation compressed at the temperature 900°C and/or 1000°C with strain rate equal 10 s^{-1}

Some of the typical optical micrographs of high-manganese austenitic X11MnSiAlNbTi18-1-3 TRIP type steels after hot working in the thermo-mechanical simulator Gleeble 3800 are shown respectively in Fig. 8.

Solution heat treatment of X11MnSiAlNbTi18-1-3 steel in water directly after last deformation causes significant refinement of structure in consequences of dynamic recrystallization especially during first and second stage of deformations. After last deformation of the specimen at a temperature of 850°C and subsequent cooling in water, the steel is characterised by uniform, austenite microstructure with a mean grain size of about 25-30 μm (Fig. 8a).

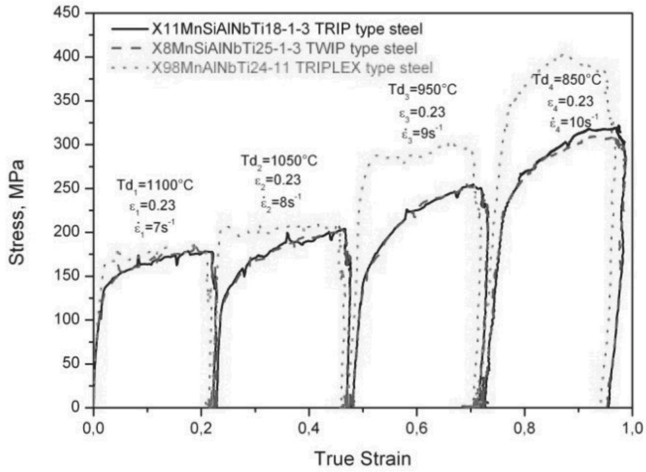

Fig. 7. Representative stress-strain curves of X11MnSiAlNbTi18-1-3, X8MnSiAlNbTi25-1-3 and X98MnAlNbTi24-11 steels after multi-stage compression axially symmetrical specimens deformed in a temperature range from 1050 to 850°C according to the scheme shown in Fig. 1

The initiation of metadynamic and static recrystallization after the last deformation and subsequent air-cooling leads to obtain mean grain size of about 20 μm (Fig. 8b). Appling isothermal holding of specimens at 850°C for 30 s leads to obtain mean grain size of about 8-12 μm (Fig. 8c) as a result of metadynamic and static recrystallization. Application of different variants of thermo-mechanical treatment has no influence on stability of austenite. Confirmation of that fact is the X-ray diffraction patterns shown in Fig. 12 for X11MnSiAlNbTi18-1-3 steel which presents the comparison of diffraction after different stages of thermo-mechanical treatment. Is connected with significant structure refinement and hampering influence of grain boundaries of austenite.

In the next step of instigation static and dynamic tensile tests were performed in order to investigate mechanical properties, especially strain energy per unit volume of new developed high-manganese steels, with various structures after their heat- and thermo-mechanical treatments, applied on constructional elements which can transfer loads during front or side impact collisions. Mechanisms of twinning and martensitic transformation by the cold working were observed. Mechanical twinning induced by the cold working of the high-manganese austenitic TWIP steels has a significant effect on forming their structure and mechanical properties and especially on the fracture counteraction.

On Figs 9 and 10 are presented austenitic structures of high manganese TWIP steels with mechanical and micro twins and slip bands obtained after hot-rolling with a true strain 0.23 and after static tensile tests. Martensitic transformation induced by the cold working of the high-manganese austenitic TRIP steels has also substantial effect on forming their structure and mechanical properties. Fig. 11 presented austenitic structures of high manganese TRIP steels with intersected ε martensite plates obtained after hot-rolling with a true strain 0.23 and after static tensile tests. Mechanism of twinning and martensitic transformation induced by the cold working of the high-manganese austenitic steels results in growth of the strain energy per unit volume after the successive cold deformation. On Fig. 13 is presented representative tensile curve of the TRIP type steel with designated strain energy per unit volume after the cold deformation equal 492.74 MJ/m^3. The high-manganese austenitic steels with the properly formed structure and properties, and especially with the big strain energy per unit volume yield the possibility to be used for the constructional elements of cards affecting advantageously the passive safety of the vehicles' passengers.

a)

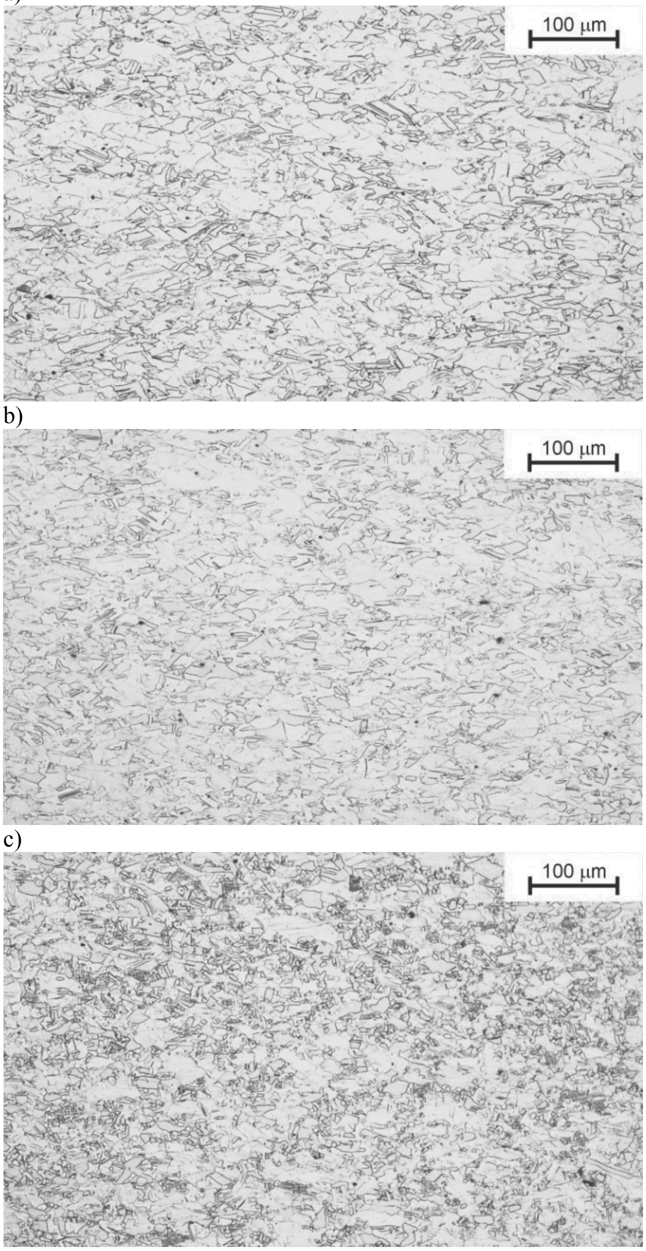

Fig. 8. Microstructures of high-manganese austenitic X11MnSiAlNbTi18-1-3 steel after thermo-mechanical processing according to schedule shown in Fig. 1, and cooling from temperature of last deformation at 850°C b) in water, c) air-cooling, d) in water after isothermal holding 30 s at 850°C

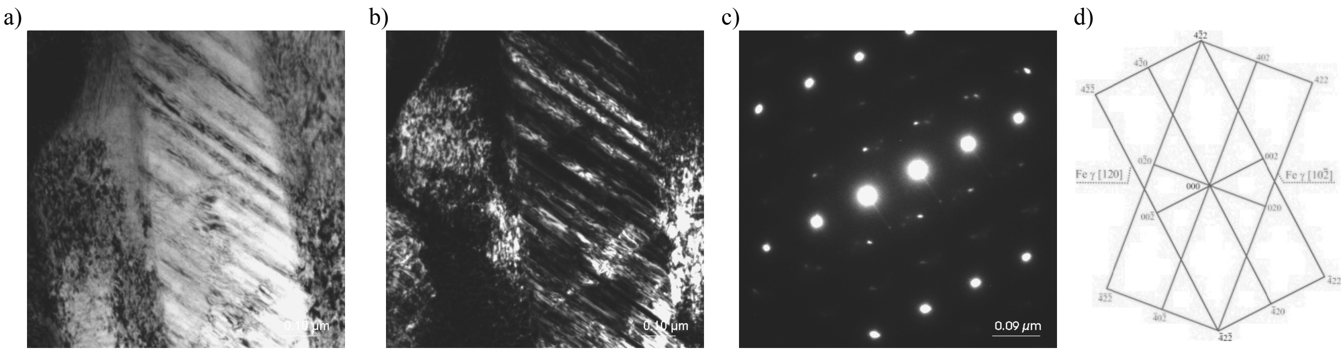

Fig. 9. Twinned austenite area in the X8MnSiAlNbTi25-1-3 TWIP type steel in the heated state with a rolling reduction of 20%, with air cooling according to the II type of thermo-mechanical treatment, and a following strain test until elongation of 30%: a) bright field, b) dark field from the $(1\bar{1}1)$plain Feγ, c) diffraction pattern, d) solution of the diffraction pattern in fig. c

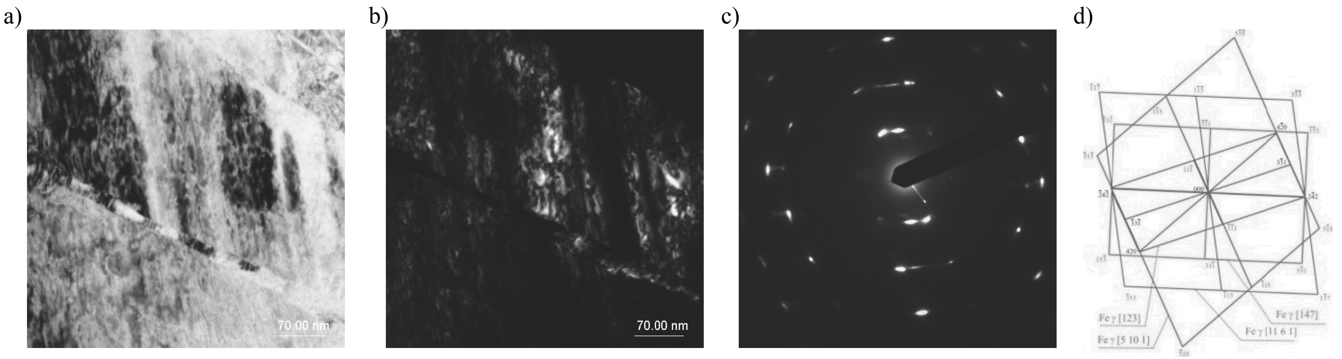

Fig. 10. Deformation twins in the X11MnSiAlNbTi18-1-3 TRIP steel in the heated state with a rolling reduction of 20%, with air cooling according to the II type of thermo-mechanical treatment, and a following strain test until elongation of 10%: a) bright field, b) dark field from the $(11\bar{1})$ plain Feγ, c) diffraction pattern, d) solution of the diffraction pattern in fig. c. Feγ [123] is the zone axis of the matrix as well the corresponding zone axis of the twins Feγ $[5\ 10\bar{1}]$

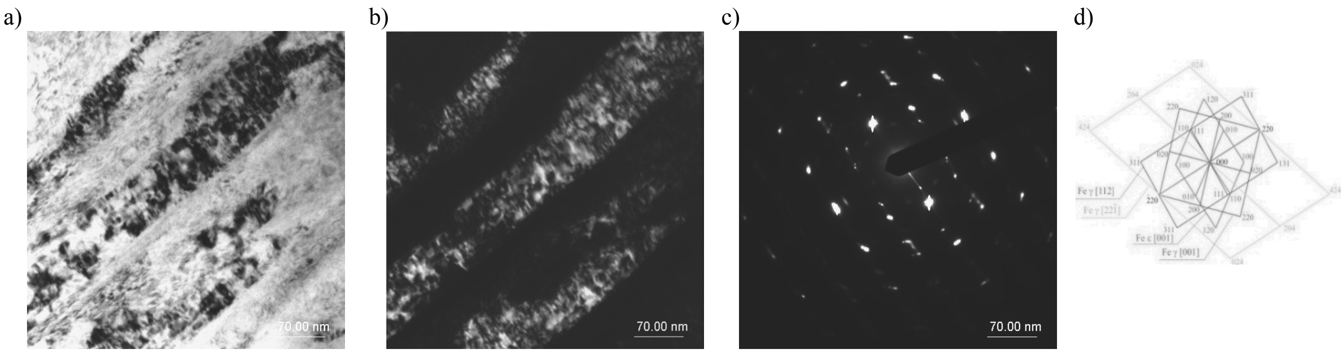

Fig. 11. Deformation twins in the X11MnSiAlNbTi18-1-3 TRIP steel in the heated state with a rolling reduction of 20%, with air cooling according to the III type of thermo-mechanical treatment, and a following strain test until elongation of 20%: a) bright field, b) dark field from the $(11\bar{1})$ plain Feγ, c) diffraction pattern, d) solution of the diffraction pattern in fig. c. Feγ [001] is the zone axis of the matrix as well the corresponding zone axis of the twins Feγ $[22\bar{1}]$

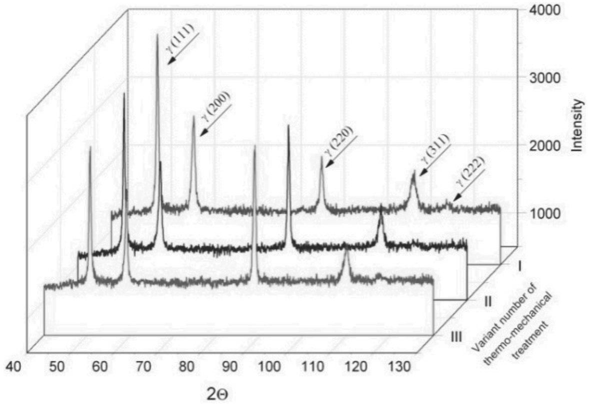

Fig. 12. X-ray diffraction patterns for X11MnSiAlNbTi18-1-3 steel after various variants of the thermo-mechanical treatment according to the scheme shown in Fig. 1

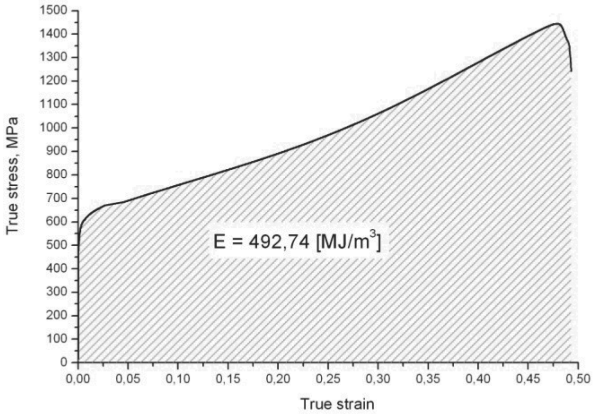

Fig. 13. Representative tensile curve for a steel X11MnSiAlNbTi18-1-3 with designated strain energy per unit volume after the cold deformation

4. Conclusions

- High-manganese Fe - Mn - (Al, Si) steels provide an extensive potential for automotive industries through exhibiting the twinning induced plasticity (TWIP) and transformation induced plasticity (TRIP) mechanisms for the fracture counteraction.
- In high-manganese TRIP, TWIP & TRIPLEX steels, the cracking or fracture does not take place during deep drawing, because of twinning induced plasticity (TWIP) and transformation induced plasticity (TRIP) mechanisms.
- Results obtained for high-manganese austenitic steels with the properly formed structure and properties in the thermo-mechanical processes indicate the possibility and purposefulness of their employment for constructional elements of vehicles, especially of the passenger cars to take advantage of the significant growth of their strain energy per unit volume which guarantee reserve of plasticity in the zones of controlled energy absorption during possible collision resulting from activation of twinning for TWIP steels, supported with martensitic transformation for TRIP steels, induced cold working as the fracture counteraction factor, which may result in significant growth of the passive safety of these vehicles' passengers.

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