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Hot deformation and recrystallization of advanced high-manganese austenitic TWIP steels

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ABSTRACT

Purpose: The aim of the paper is to determine the influence of hot-rolling conditions on structure of new-developed high-manganese austenitic steels.
Design/methodology/approach: Flow stresses during continuous and multi-stage compression tests were measured using the Gleeble 3800 thermo-mechanical simulator. To describe the hot-working behaviour, the steels were compressed to the various amount of deformation (4x0.29, 4x0.23 and 4x0.19). The microstructure evolution in different stages of hot-rolling was determined in metallographic investigations using light microscopy as well as X-ray diffraction.
Findings: The steels are characterized by different microstructure in the initial state. Steel with higher Al concentration has stable microstructure of austenite with annealing twins, while steel with higher Si concentration consists of certain portion of ε martensite in form of plates. The flow stresses are in the range of 200-430 MPa for the applied conditions of hot-working and are up to 40 MPa lower compared to continuous compressions. Results of the multi-stage compression proved that applying the true strain 4x0.29 gives the possibility to refine the austenite microstructure as a result of dynamic recrystallization. In case of applying the lower deformations 4x0.23 and 4x0.19, the process controlling work hardening is dynamic recovery. On the basis of analysis of thermo-mechanical treatment carried out in continuous axisymetrical compression test and multi-stage compression test using the Gleeble 3800 simulator allowed to work out a schedule of three different variants of hot-rolling for each of investigated steels 26Mn-3Si-3Al-Nb-Ti and 27Mn-4Si-2Al-Nb-Ti.
Research limitations/implications: To fully describe the hot-rolling behaviour of the new-developed steels, further investigations in wider temperature and strain rate ranges are required.
Practical implications: Various conditions of hot-rolling for advanced high-manganese austenitic steels can be useful to determine influence of microstructure on mechanical properties obtained in static and dynamic tensile test.
Originality/value: Microstructure evolution in various conditions of hot-rolling for advanced high-manganese austenitic steels were investigated.
Keywords: High-manganese austenitic steel; Hot-rolling; Grain refinement; Dynamic recrystallization; Static recrystallization

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1. Introduction

Dynamic worldwide development of the automotive industry brought a new groups of steels, which allowed to decrease the weight of different elements of vehicles, what is directly connected with lowering fuel consumption and environment pollution [1-5]. At the present time, apart from limiting fuel consumption, special pressure is placed on increasing safety of car's passengers. Constructional solutions and steels used in the frontal part of a vehicle are the most significant due to the possibility of accident occurrence. The goal of structural elements such as frontal frame side members, bumpers and the others is to take over the energy of an impact. Therefore, steels that are used for these parts should be characterized by high product of UTS and UEl, proving the ability of energy absorption. Among the wide variety of recently developed steels, high-manganese austenitic TRIP/TWIP steels with low stacking faulty energy (SFE) are particularly promising, especially when mechanical twinning occurs [3-6, 25-30]. Beneficial combination of high strength and ductile properties of these steels depends on structural processes taking place during cold plastic deformation, which are a derivative of stacking fault energy (SFE) of austenite, dependent, in turn on the chemical composition of steel and deformation temperature [1-4, 7-11, 19-24]. In case, when SFE is equal from 12 to 20mJm^{-2}, partial transformation of austenite into martensite occurs, making use of TRIP effect (TRansformation Induced Plasticity) [1-4, 9]. Values of SFE from 20 to 60mJm^{-2} determine intense mechanical twinning connected to TWIP effect (TWinning Induced Plasticity) [6-12]. The steels cover a very wide carbon concentration in a range from about 0.03 to 1 wt.%, 15-30% Mn, 0-4% Si, 0-8% Al.

The best conditions for obtaining the total elongation up to 80%, due to a gradual increase of mechanical twins, acting as obstacles for dislocation glide, occur when the carbon concentration is in the range of 0.4-0.8% and manganese from 17 to 22% [10, 11]. Because of these reasons, Frommeyer et al. [1-4] proposed a group of high-manganese steels with carbon content, less than 0.1%. Lower hardening due to decreased carbon concentration was compensated by Si and Al additions, which together with Mn decide about SFE of the alloy and the main deformation mechanism.

Results of our earlier investigations [13-18] indicate that ε martensite plates can appear in the initial structure of the (0.04-0.05) C-25Mn-4Si-2Al alloys as a result of Nb and Ti microadditions. The amount of C combined in precipitated carbonitrides reduces its content in the solid solution, thus decreasing the SFE of austenite and resulting in a presence of ε martensite despite high manganese concentration in the investigated steels. It was found [16] that the fraction of ε martensite plates is also dependent on a grain size of the γ phase and hot-working conditions. It was also observed that the fraction of mechanical twins within the austenite grains corresponds to the initial grain size, and at the same time affects the mechanical properties [6].

The hot-working behaviour of high-manganese steels is of primary importance for elaborating manufacturing methods consisted of hot-rolling and successive cooling to room temperature. Hot-rolling of sheets consists of many passes characterized by the changing amount of deformation and strain rate from pass to pass. This means that the flow stresses should be determined during multi-stage straining testing and for various deformation values. In earlier investigations [13-18] we characterized the force-energetic parameters of hot-working of new-developed low-carbon high-Mn-Si-Al steels in continuous and four-stage compression tests. The aim of the paper is to describe in details the microstructure evolution and phase composition of 26Mn-3Si-3Al-Nb-Ti and 27Mn-4Si-2Al-Nb-Ti steels subjected to four-stage compression and hot-rolling with various amount of deformation.

2. Materials and experimental procedure

The researches were carried out on two new-developed low-carbon high-manganese austenitic Mn-Si-Al steels with microadditions of Nb and Ti. The chemical composition of melted steels is given in the Table 1. Melts were prepared in the Balzers VSG-50 vacuum induction furnace. The steels are characterised by high metallurgical purity, related to low concentration of S and P impurities and gases. After homogenization at 1200°C for 4 h to remove the segregation of Mn, ingots with a mass of 25 kg were submitted for open die forging on flats with a width of 220 mm and a thickness of 20 mm. Then, cylindrical machined samples ∅10x12 mm were prepared. Determination of processes controlling work hardening was carried out in continuous axisymetrical compression test using the DSI Gleeble 3800 thermomechanical simulator. The stress – strain were defined in a temperature range from 850 to 1050°C with a strain rate of 10 s^{-1}.

In order to determine σ-ε curves, the four-stage compression tests were carried out. The temperatures of the successive deformations were 1100, 1050, 950 and 850°C. To simulate various conditions of hot-rolling, the amount of true stain were 0.29, 0.23 and 0.19 (Fig. 1). The processes controlling the course of work-hardening were evaluated on a basis of the shape of σ-ε curves. Hot-rolling was performed on two-high reversing mill powered by 470 kW engine, rolls diameter 430 mm, with rolls working at 0.65 ms^{-1} tangential velocity. The workpiece temperature was measured between roll passes using pyrometer from Raytek.

Table 1.
Chemical composition of the investigated steels, mass fraction

Designation	C	Mn	Si	Al	P	S	Nb	Ti	N
27Mn-4Si-2Al-Nb-Ti	0.040	27.5	4.18	1.96	0.002	0.017	0.033	0.009	0.0028
26Mn-3Si-3Al-Nb-Ti	0.065	26.0	3.08	2.87	0.004	0.013	0.034	0.009	0.0028

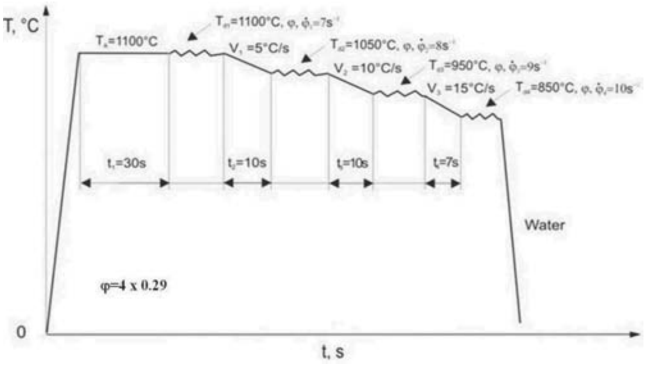


Fig. 1. Parameters of the multi-stage compression test realized in the Gleeble simulator

Metallographic investigations were performed on LEICA MEF4A optical microscope. In order to reveal the austenitic structure, samples were etched in nitric and hydrochloric acids mixture in 2:1 proportion as well using a mixture of nitric acid, hydrochloric acid and water in 2:2:1 proportion. X-ray diffraction analysis of specimens in the initial state and after various stages of deformation was carried out using the Co Kα radiation in the X'Pert PRO diffractometer with the X'Celerator strip detector.

3. Results and discussion

Minor differences between chemical composition of elaborated steels result in slightly different microstructure in the initial state. Steel 26Mn-3Si-3Al-Nb-Ti is characterized by homogeneous microstructure of austenite with a grain size in range from 100 to 150 μm, in which numerous annealing twins can be identified (Fig. 2b). Single-phase microstructure of the steel is confirmed by X-ray diffraction pattern in Fig. 2a. Increased concentration of silicon up to 4% and decreased concentration of aluminium to 2% in steel 27Mn-4Si-2Al-Nb-Ti have influence on the decreasing of the stacking fault energy of austenite result in the presence of some fraction of ε martensite in the austenite matrix containing many annealing twins. This phase is present in a form of parallel plates, not exceeding boundaries of specified grain (Fig. 3b). The presence of ε martensite is confirmed by X-ray diffraction pattern shown in Fig. 3a.

It was shown in the earlier experiments [13-18] that the investigated steels under conditions of continuous hot-compression is characterised by relatively high values of flow stress. For the deformation temperature in a range from 850 to 1050°C, flow stresses of the specimens compressed with a strain rate of 10 s^{-1} are equal from 240 to 450MPa. The relatively low values of ε_{max} create convenient conditions to refine the austenite microstructure during hot-rolling by dynamic recrystallization process, especially at a temperature higher than 950°C. Dynamic recrystallization behaviour, which is typical for alloys with low SFE energy is additionally enhanced comparing to pure Fe-Mn and Fe-Mn-Al alloys by 4% Si, decreasing the stacking fault energy of austenite.

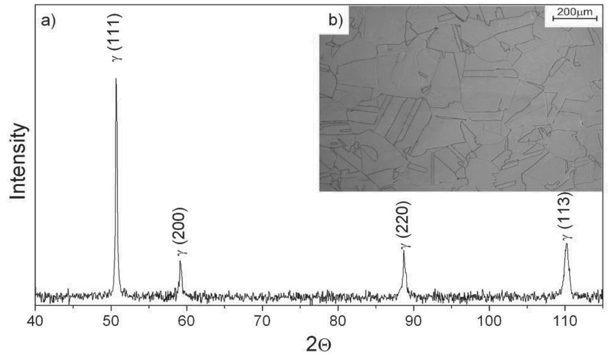


Fig. 2. X-ray diffraction pattern (a) and austenitic microstructure with numerous annealing twins of the 26Mn-3Si-3Al-Nb-Ti steel in the initial state (b)

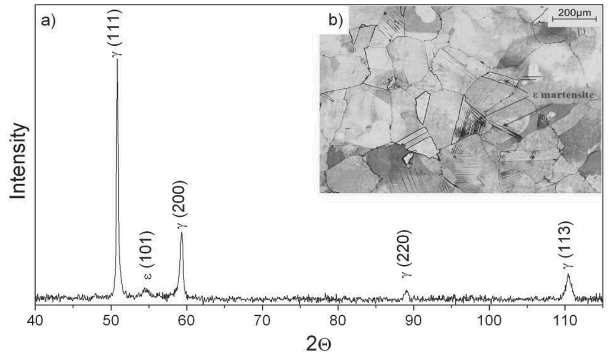


Fig. 3. X-ray diffraction pattern (a) and the austenite structure with many annealing twins and parallel ε martensite plates of the investigated steel 27Mn-4Si-2Al-Nb-Ti in the initial state (b)

Stress-strain curves of steels 26Mn-3Si-3Al-Nb-Ti, 27Mn-4Si-2Al-Nb-Ti plastically deformed during multi-stage compression are presented in Fig. 4. Application of true strain equal 0.29 during four-stage compression creates possibility in the course of dynamic recrystallization, what is indicated by peaks that can be distinguished on σ-ε curves – especially for deformations realized at temperature of 1100 and 1050°C. After decreasing deformation temperature to 950 and 850°C, maxima on σ-ε curves are present for a value of true strain nearly 0.29. The maximum flow stress values after last deformation at temperature 850°C are 380 MPa and 400MPa, respectively for steels 26Mn-3Si-3Al-Nb-Ti and 27Mn-4Si-2Al-Nb-Ti. These values are much smaller compared to obtained during continuous compression [13-18]. Decrease of true strain to 0.23 leads to a change of the course of σ-ε curves (Fig. 4). In order to compare the curves course, the strain axis was interrupted. A shape of the curves during deformation in a temperature range of 1100-1050°C and true stress values are comparable to that obtained after higher strain applying. Moreover, the applied strain is sufficient to initiate a course of dynamic recrystallization.

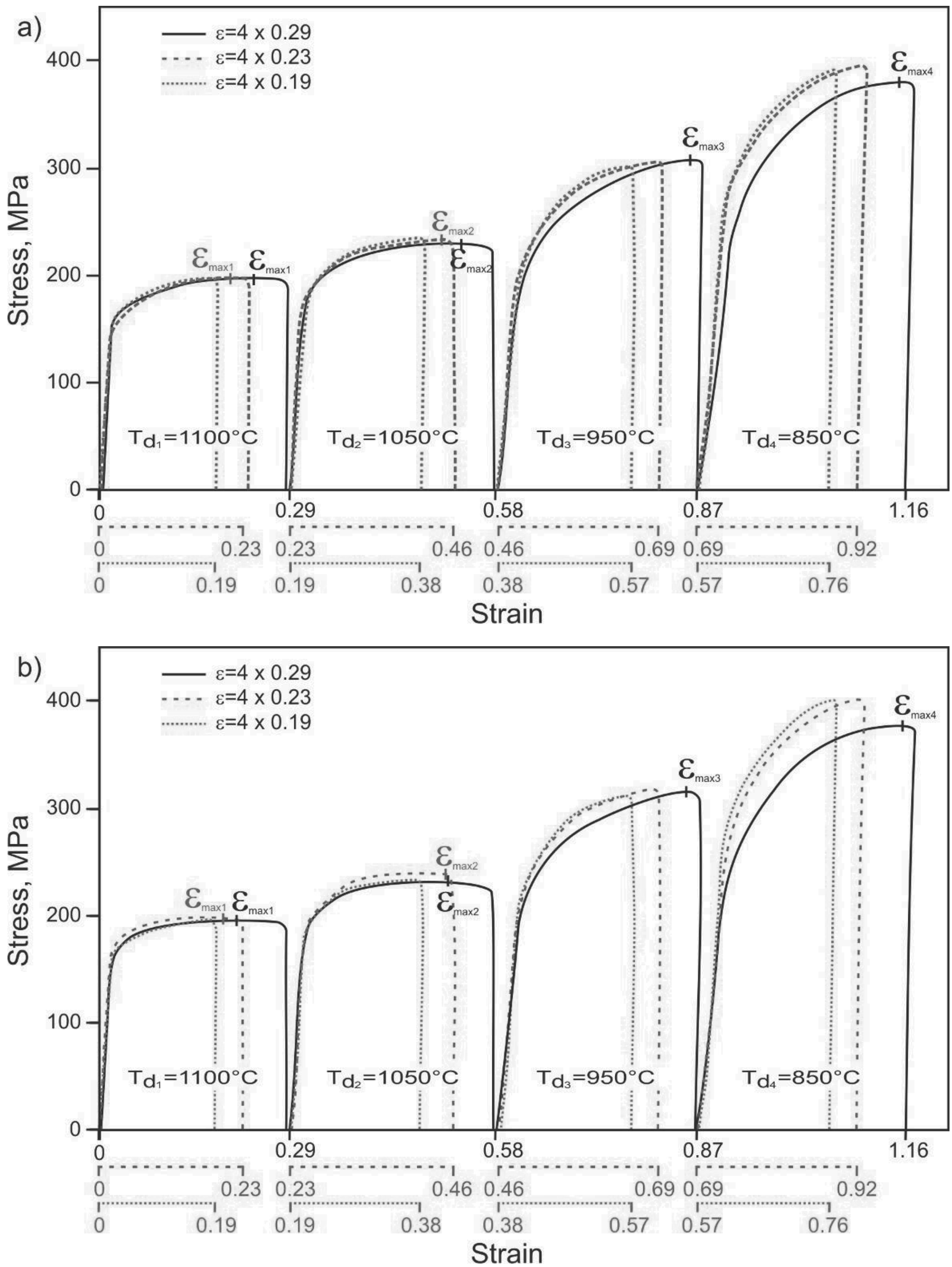


Fig. 4. Stress - strain curves of the 26Mn-3Si-3Al-Nb-Ti (a) and 27Mn-4Si-2Al-Nb-Ti (b) steel after the multi-stage compression of the axisymetrical specimens deformed with the true strain 4x0.29, 4x0.23 and 4x0.19 in a temperature range from 1100 to 850°C; the strain axis was interrupted for the true strains of 4x0.23 and 4x0.19 in order to compare the stress - strain curves with that deformed with the true strain 4x0.29

However, decreasing the compression temperature to 950°C causes that the flow stress is slightly higher and the applied strain value is too low to initiate dynamic recrystallization. Thus, process controlling a course of hot-working at 950°C is a dynamical recovery. A decrease of true strain to 0.19 causes that dynamic recovery is the process controlling strain hardening in the whole temperature range of deformation. Analysis of stress-strain curves of steels 26Mn-3Si-3Al-Nb-Ti and 27Mn-4Si-2Al-Nb-Ti plastically deformed during multi-stage compression were confirmed by metallographic investigations and presented in detail in earlier publications [14-18]. The best conditions for a gradual grain refinement occur after four-stage compression with the true strain of 4x0.29 in hot-working conditions controlled by dynamic recrystallization in a whole temperature deformation range. The steels solutioned directly after deformation is characterized by a mixture of fine, recrystallized grains and some fraction of dynamically recovered grains with a mean diameter of about 10 μm. Completing recrystallization in all the deformed grains requires isothermal holding of the specimen for 32 s at 850°C. Decreasing the true strain to 4x0.23 and 4x0.19 changes a main mechanism controlling a course of work hardening from dynamic recrystallization to dynamic recovery. Due to slow progress of static recrystallization, the isothermal holding of the specimens at 850°C for 32 s results in a small fraction of recrystallized austenite and a larger size of flattened, statically recovered grains.

On the basis of analysis of thermo-mechanical treatment carried out in continuous axisymetrical compression test and multi-stage compression test using the Gleeble 3800 thermo-mechanical simulator allowed to work out a schedule of three different variants of hot-rolling for each of investigated steels 26Mn-3Si-3Al-Nb-Ti and 27Mn-4Si-2Al-Nb-Ti (Fig. 5).

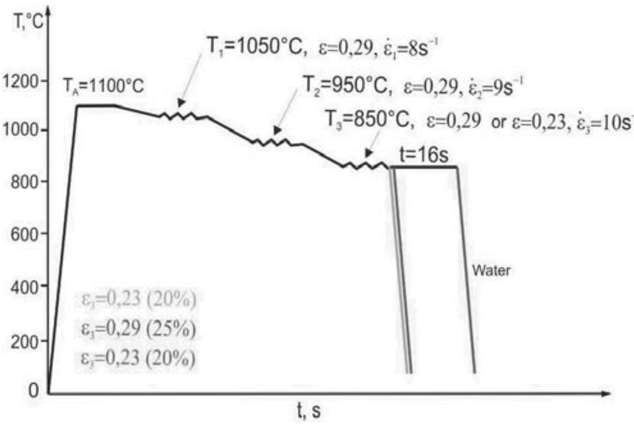


Fig. 5. Parameters of hot-rolling of high-manganese austenitic steels 26Mn-3Si-3Al-Nb-Ti and 27Mn-4Si-2Al-Nb-Ti

Microstructures of the steels in the diffrent deformation stages after hot-rolling are presented in Fig. 8. Solution heat treatment of steels 26Mn-3Si-3Al-Nb-Ti and 27Mn-4Si-2Al-Nb-Ti from the finishing rolling temperature with pass reduction 20% leads to obtaining structure consisted of elongated in the rolling direction dynamically recovered grains (Figs. 8a, d). Increasing the final pass reduction to 25% caused obtaining 20% of dynamically recrystallized grains located on elongated dynamically recovered grains boundaries (Figs. 8b, e). Numerous annealing twins can be observed in the microstructure of both investigated steels. Isothermal holding for 16 s after hot-rolling with final pass reduction 20%, causes that the fraction of statically and metadynamically recrystallized grains occurs in about 30% and is considerably lower than for specimens after hot-working in the Gleeble 3800 simulator due to shortened holding time of steel from 32 to 16s. Statically and metadynamically recrystallized grains are located mainly on boundaries of elongated grains of austenite statically and dynamically recovered, often located also on twins' boundaries (Figs. 8c, f). Repeated recrystallization and corresponding grain refinement causes that the thermo-mechanically processed steels are characterized by uniform structure of γ phase without ε martensite plates (Figs. 6, 7) even in steel 27Mn-4Si-2Al-Nb-Ti (Fig. 7) where certain portion of ε martensite in the initial state was observed (Fig. 3a).

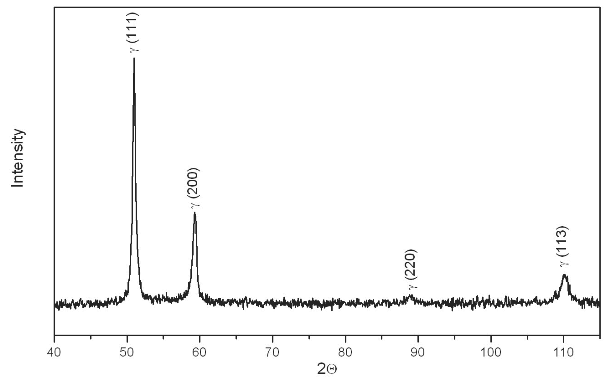


Fig. 6. X-ray diffraction patterns of the steel 26Mn-3Si-3Al-Nb-Ti after hot-rolling

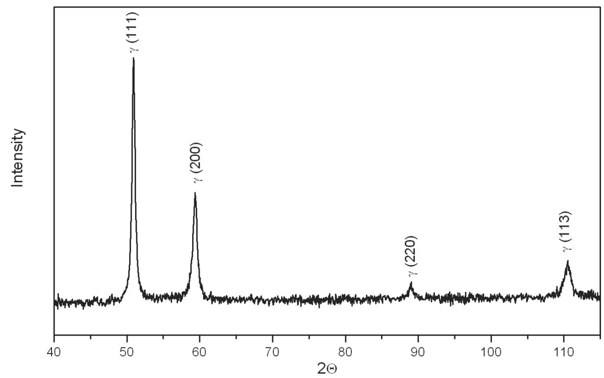
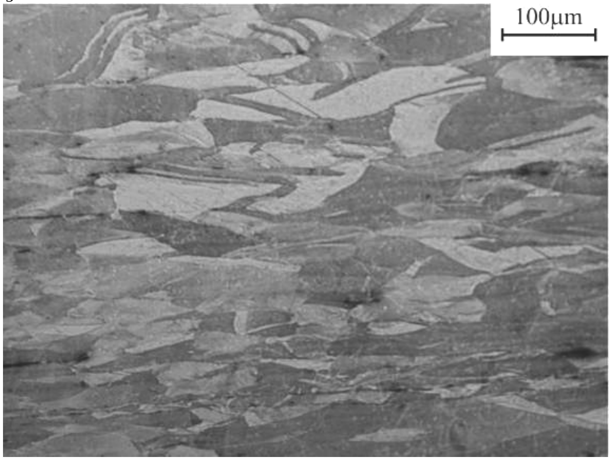
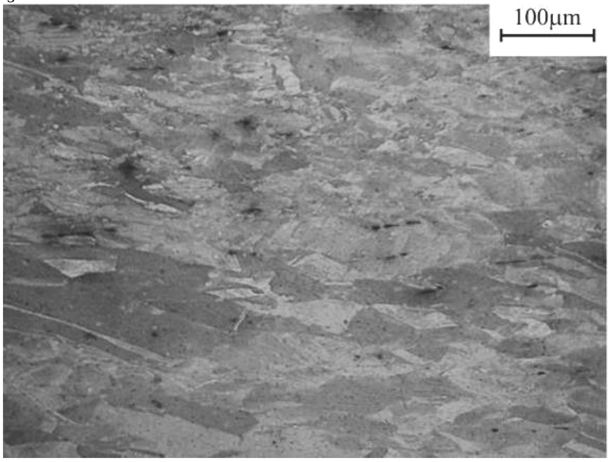


Fig. 7. X-ray diffraction patterns of the steel 27Mn-4Si-2Al-Nb-Ti after hot-rolling

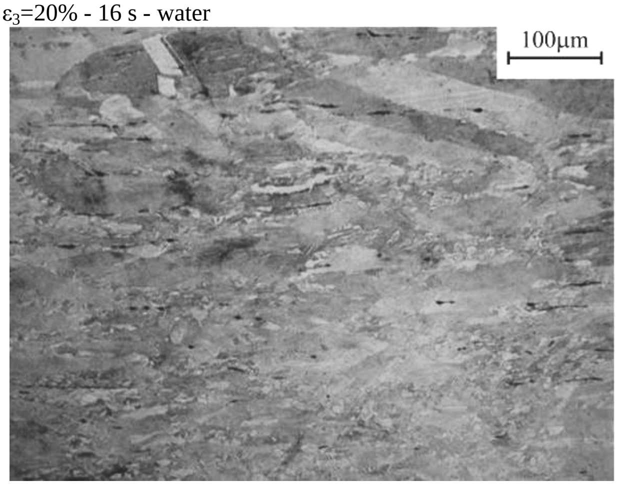
a) ε_3=20% - 0 s - water



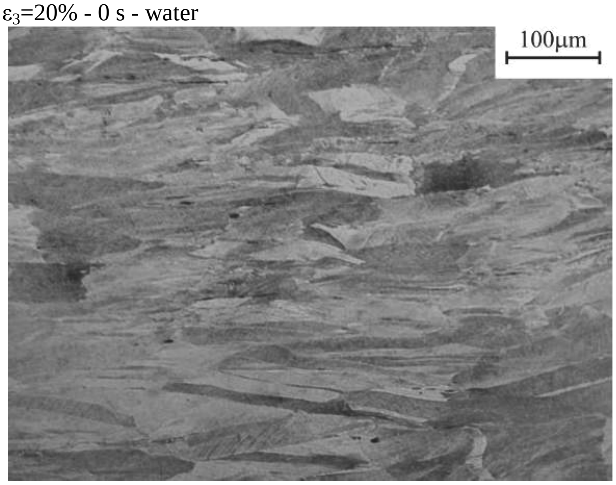
b) ε_3=25% - 0 s - water



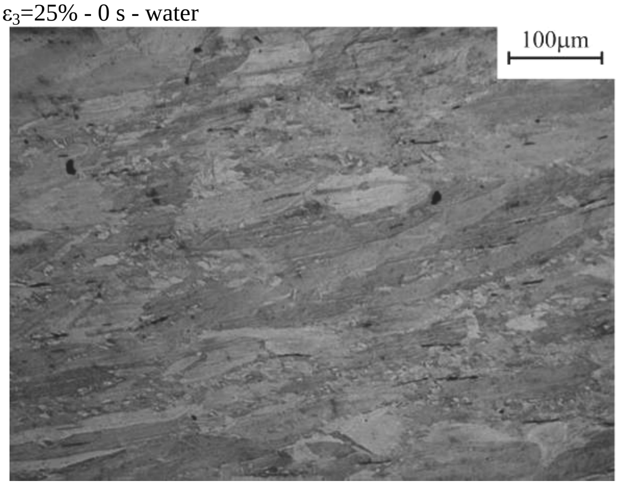
c) ε_3=20% - 16 s - water



d) ε_3=20% - 0 s - water



e) ε_3=25% - 0 s - water



f) ε_3=20% - 16 s - water

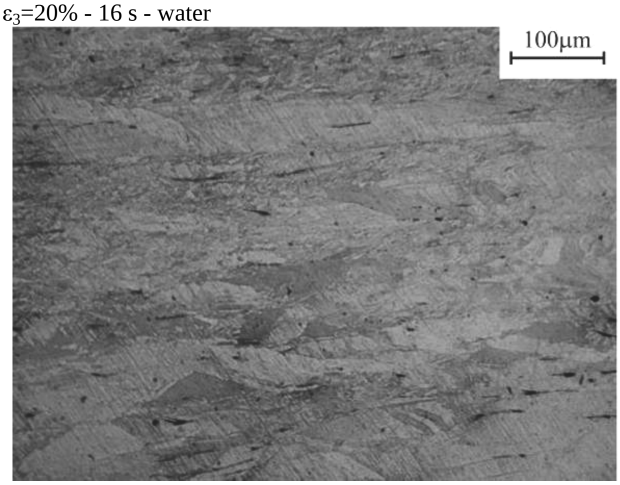


Fig. 8. Austenitic structures obtained after solution heat-treated from a temperature of 850° steels 26Mn-3Si-3Al-Nb-Ti (a-c) and 27Mn-4Si-2Al-Nb-Ti (d-f) at different stages of the hot-rolling for the specimens with final pass reduction a, d) 20%; b, e) 25% and c, f) 20% and isothermally held for 16 s

4. Conclusions

On the basis of the investigations carried out in the initial state and under conditions of the multi-stage compression test and hot-rolling, the following conclusions can be drawn:

- Despite slight difference in chemical composition, brought mainly to concentration of Si and Al, elaborated steels show different microstructure in the initial state. Steel with higher Al concentration has stable microstructure of austenite with annealing twins, while steel with higher Si concentration consists of certain portion of ε martensite in form of plates.
- The hot-working resistance of the steel is much higher in comparison with austenitic Cr-Ni and Cr-Mn steels and slightly higher compared to binary Fe-Mn alloys. The flow stresses are in the range of 200-430 MPa for the applied conditions of hot-working and are up to 40 MPa lower compared to continuous compressions.
- Solution heat treatment of steels 26Mn-3Si-3Al-Nb-Ti and 27Mn-4Si-2Al-Nb-Ti from the finishing rolling temperature with pass reduction 20% leads to obtaining structure consisted of elongated in the rolling direction dynamically recovered grains.
- Solution heat treatment of investigated steels from the finishing rolling temperature with pass reduction 25% caused that main mechanism controlling a course of work hardening is dynamic recrystallization.
- Isothermal holding for 16 s after hot-rolling with final pass reduction 20%, causes that the some fraction of statically and metadynamically recrystallized grains occurs and is considerably lower than for specimens after hot-working in the Gleeble 3800 simulator due to shortened holding time of steel from 32 to 16 s .

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