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Structure of X11MnSiAl17-1-3 steel after hot-rolling and Gleeble simulations

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ABSTRACT

Purpose: The aim of the paper is to compare results after thermo-mechanical simulation using Gleeble 3800 and hot-rolling on LPS module of high-manganese austenitic X11MnSiAl7-1-3 steel.

Design/methodology/approach: The hot-working behaviour was determined in continuous, 4- and 8-stage compression tests performed in a temperature range of 850 to 1100°C by the use of the Gleeble 3800 thermo-mechanical simulator and LPS module for semi-industrial hot rolling. The comparison between two processes has been established based on microstructure research and X-ray diffraction analysis.

Findings: It was found that austenite microstructure with numerous annealing twins in the initial state was obtained. 4-stage compression tests were realized in the temperature range from 850 to 1050°C with the true strain 4x0.23. 8-stage compression test were performed in the same temperature range and with true strain of 0.4 in the first deformation, and 0.25 and 0.2 in the following deformations. The multi-stage compression examination gives the possibility to refine the austenite microstructure. Based on this research hot-rolling on LPS module in the temperature range from 1100°C to 850°C was realized. Based on microstructures research were found that this process is not perfect due to longer intervals between successive passes and inability to control the temperatures of following passes.

Practical implications: The obtained stress-strain curves relationship and microstructure after Gleeble simulations can be useful in determination of power-force parameters of hot-rolling for thin sheets to obtain fine-grained austenitic microstructures.

Originality/value: The hot-working behavior and microstructure evolution in various conditions of plastic deformation for new-developed high-manganese austenitic steels were investigated.

Keywords: High-manganese steel; Hot-working; Thermo-mechanical simulation; Hot-rolling

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MATERIALS

1. Introduction

The automotive industry based on the internal combustion engine had been developing since 1888, when the Austrian engineer and inventor Siegfried Marcus built the first vehicle that complies with all the basic features of the car. Development of the automobile industry took off in 1912, when Henry Ford launched the first mass series production of the Model T at its factory in Detroit. The automotive industry has always developed on several levels: on the one hand, were designed and refined engine, the other worked on the materials from which they were made not

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only mechanical systems but also car bodies. While at the beginning the most important criterion for the selection of materials for the car bodies was the greatest corrosion resistance and low cost, while in the last twenty years, manufacturers have begun to put increasing emphasis on vehicle safety. Vehicle safety is ensured by different systems of active and passive safety. Active safety ensure all kinds of sensors designed to minimize the likelihood of an accident (supporting systems ABS, EBS, ASR, ESP, etc.) and passive safety are responsible for all of the factors to reduce the damage caused by the already occurring accidents/collisions such as the structure of the body (rigid passenger cage, suitable buffers, controlled crush zones, strengthening doors and side walls), the shape of the bodywork (no protruding parts, rounded body panels parts), seat belts, airbags, adjustable head restraints, etc. [1-5].

In recent years, car producers began to think, how the material from which the car body is formed can increase the safety of passengers in the vehicle when it will be a road collision. Following this line a modern materials have been developed for car bodies that are characterized by a large reserve of strength, so that in the case of an car accident components made from these steels deform and absorb impact energy. This properties can be achieved with proper selection of chemical composition and manufacturing technologies, which guarantee obtaining the structure allowing for obtaining connections of favorable strength and plastic properties of steel. These new developed materials are austenitic high-manganese steel [6-15,22-24]. Since steels for modern car body are not the cheapest materials, so in order to reduce their total cost, the manufacturing process should be simplified in order to compensate for the high costs of materials, such as reducing the number of deep drawing operations or stages of heat treatment [2]. To optimize the production process of these steel are carried out intensive laboratory investigations to simulate its behave during thermo-forming and hot-rolling [16-21].

The purpose of this paper is to compare results after thermo-plastic deformation of high-manganese austenitic steels on Gleeble 3800 thermo-mechanical simulator and LPS module for semi-industrial simulation of hot rolling.

2. Materials and experimental procedure

Investigations were carried out on high-manganese steel X11MnSiAl17-1-3 containing 17.55% Mn, 1.17% Si, 3.29% Al. 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 steel was chosen in order to obtain the structure of the austenitic matrix.

Investigated ingots with a mass of 25 kg were prepared in a laboratorial vacuum arc furnace of the type VSG-50 from Balzers. Casting of ingot took place in atmosphere of argon intended for cast-iron ingot mould, round with a swage, converging downwardly with internal dimensions: bottom - ∅122 mm, top - ∅145 mm, h = 200 mm - without the swage (with the swage - 300mm) (Fig. 1). After casting the ingot head solidify during 60 min, and then the oven was opened and further cooling of ingot in the form 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 in a range between 1200 and 900°C. The ingot body was subjected to forging - its head and feet were cut off at the height of 3 cm to the place which contraction cavity was reached.

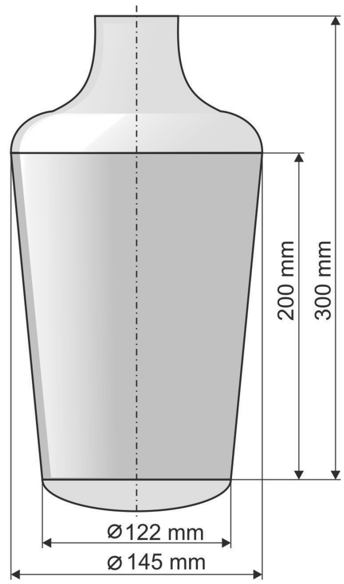


Fig. 1. Ingot scheme of investigated steel

From the pre-forged ingot was prepared test samples. Scheme of material parts are shown on Fig. 2. One of material parts was intended for investigation on Gleeble 3800 thermo-mechanical simulator and the rest of the materials were divided into four equal pieces. Three of them were hot-rolled using LPS module for semi-industrial simulation of hot-rolling. For the purposes of plastomeric investigation on Gleeble 3800 were prepared three types of samples:

- cylindrical Ø10x12mm for continuous compression test (Fig. 3a) with strain rate equal 0.1, 1 and $10s^{-1}$, at temperature: 1050, 950 and 850°C,
- axially symmetric samples 20x35x15mm for 8-stage compression (Fig. 3b) for simulated final roll passes of rolling. Scheme of 8-stage compression is presented on Fig. 4.
- cylindrical Ø10x12mm for 4-stage compression (Fig. 3a) for simulated final roll passes of rolling. Scheme of 4-stage compression is presented on Fig. 5.

For the purpose of hot-rolling simulation using LPS module were prepared three pieces of material 5x185x600 mm which were hot rolled on flat sheets with initial thickness of 22 mm to 6 mm and then finish hot-rolling in four passes to about 2-3 mm thickness sheets. The samples were cooled in three different variants: cooling in water, natural cooling in air, and cooling in water after isothermal holding at the temperature of last deformation 850°C.

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

Steel designation	Chemical composition, mass fraction										
	C	Mn	Si	Al	P_{max}	S_{max}	Ce	La	Nd	O	N
X11MnSiAl17-1-3	0.11	17.55	1.17	3.37	0.002	0.003	0.023	0.007	0.009	0.0003	0.0036

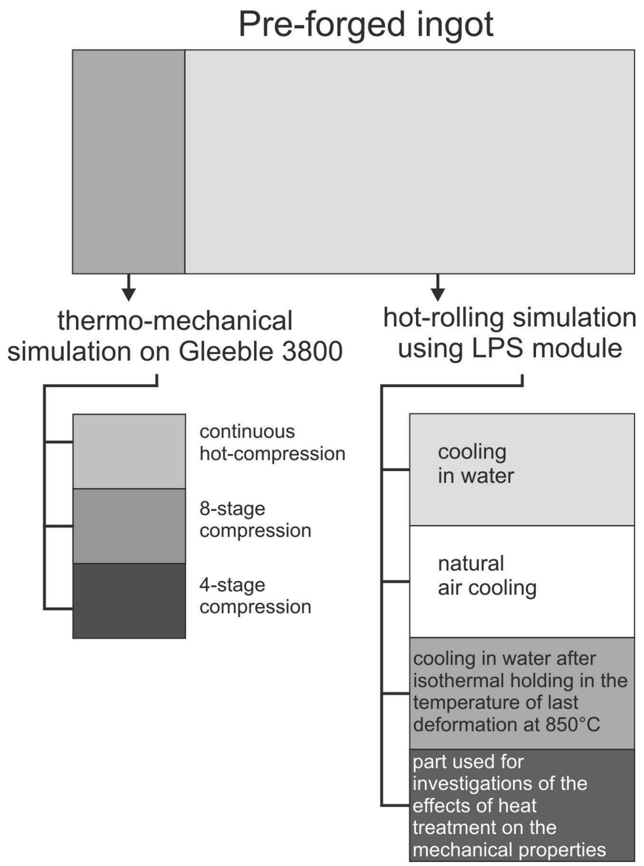


Fig. 2. Scheme of the material selections for specific research tasks

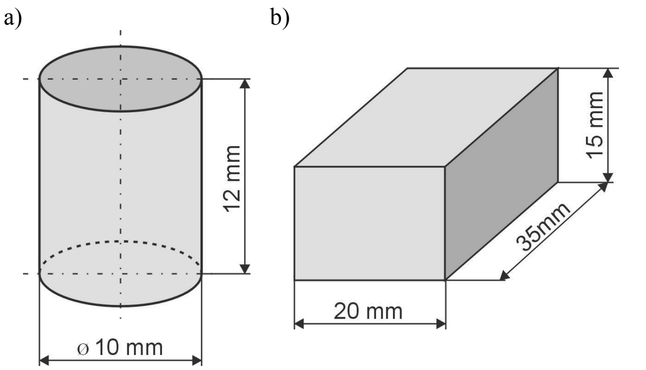


Fig. 3. Scheme of the specimens used for plastomeric investigations on Gleeble tests: a) continuous compression and 4-stage compression tests, b) 8-stage compression test

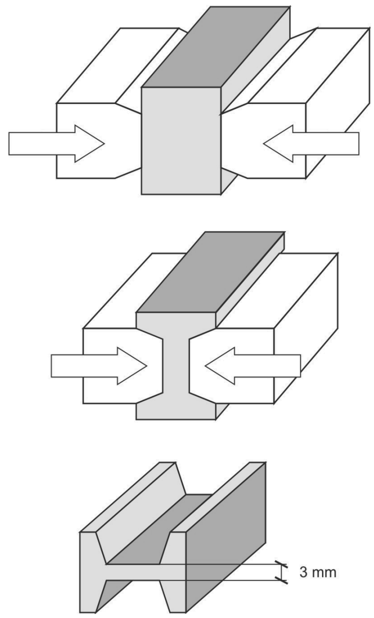


Fig. 4. Scheme of specimen before and after 8-stage compression tests on Gleeble 3800 thermo-mechanical simulator

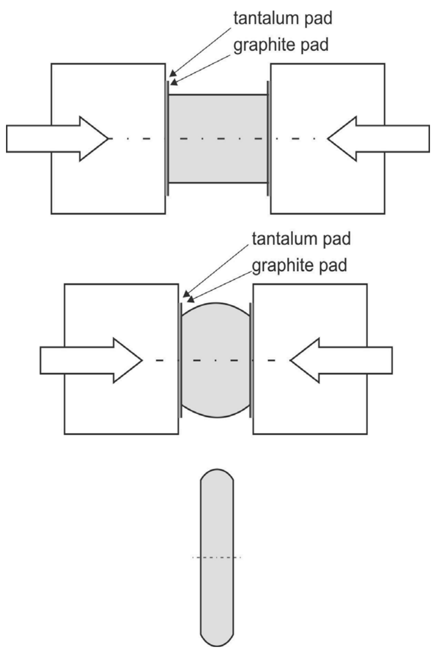


Fig. 5. Scheme of specimen before and after 4-stage compression tests on Gleeble 3800 thermo-mechanical simulator

In order to simulate thermo-mechanical treatment, Gleeble 3800 simulator was used, which allowed for establishing of stress-strain curves of the tested steels at various temperature and strain rate and them influence on processes controlling work hardening of investigated steels. Continuous compressions of samples were made with plastic strain rate equal 0.1, 1 and $10s^{-1}$, in temperature: 1050, 950 and 850°C.

In the second stage of plastometric examination, 8-stage compression process was devised for axially symmetric samples, which simulated final roll passes of hot-rolling. Reduction ratios of plastic deformation rates and intervals times between successive plastic deformation stages were selected taking into account conditions of planned hot rolling on flat sheets with initial thickness of 4.5 mm, rolled down to 3 mm thickness samples. Schematic and parameters of the 8-stage compression test carried out on Gleeble 3800 thermo-mechanical simulator were presented on Fig. 6 (Variants No. I, II and III). In the last stage of plastometric investigation, 4-stage compression test was devised using cylindrical samples which simulated final roll passes of hot-rolling. Reduction ratios of plastic deformation rates and time intervals between successive plastic deformations stages were taking into account the applicable conditions of industrial hot rolling production. Schematic and parameters of the 4-stage compression test were presented on Fig. 7 (Variants No. IV, V and VI). In both cases apart from determining force and energy parameters of the hot plastic deformation, the samples were cooling in water, natural cooling in air, and in water after isothermal holding at the temperature of last deformation 850°C.

Based on the results of plastometric and thermo-mechanical investigations with cylindrical and axially symmetric samples performed on Gleeble 3800 thermo-mechanical simulator optymalization of hot-rolling parameters (temperature, true strain and isothermal holding time) were made. On this basis, the three variants of the hot-rolling simulation were determined (Fig. 8).

Flat sheets obtained by the open die forging method on a high-speed hydraulic press from Kawazoe were hot-rolled in four passes with a thickness of 6 mm. Hot-rolling temperature was in the range from 1150 to 850°C. Temperature difference between the surface and the center of samples did not exceed 2°C. A similar range of temperature differences ie ≤ 2°C was characterized the temperature of the end and middle of samples. Soaking time for the pre-rolling at 1150°C of samples having a thickness of 22 mm was 15 min.

Hot rolling was performed on single-cage reversing hot-rolling mill line for semi-industrial simulation (LPS) module B at the Institute of Ferrous Metallurgy in Gliwice. Diameter of the cylinder was 550 mm, with a linear speed of the rollers 0.74 m/s. The parameters of hot rolling process was developed assuming that the size reduction rates inflicted limit is determined by the strength of the pressure range combat.

Due to the rapid process of heat loss by thin metal sheet, transition time between each strain were reduced to a minimum time about 3-5 seconds - which is needed to switch the direction of rolling. Additionally, at both ends of the LPS hot-rolling mill were special thermoses, which allowed less heat transfer to the environment. Its temperature were reached 550°C, which is the maximum possible temperature setting for this type of equipment.

Intervals times between passes were selected to get the required end temperature of hot plastic deformation, which was reached 850°C. Examined hot-rolled sections of steels have dimension 5x185x600 mm. Samples were austenitized at 1150°C for 15 min. End-forming temperature for all variants of the hot-rolling was 850°C.

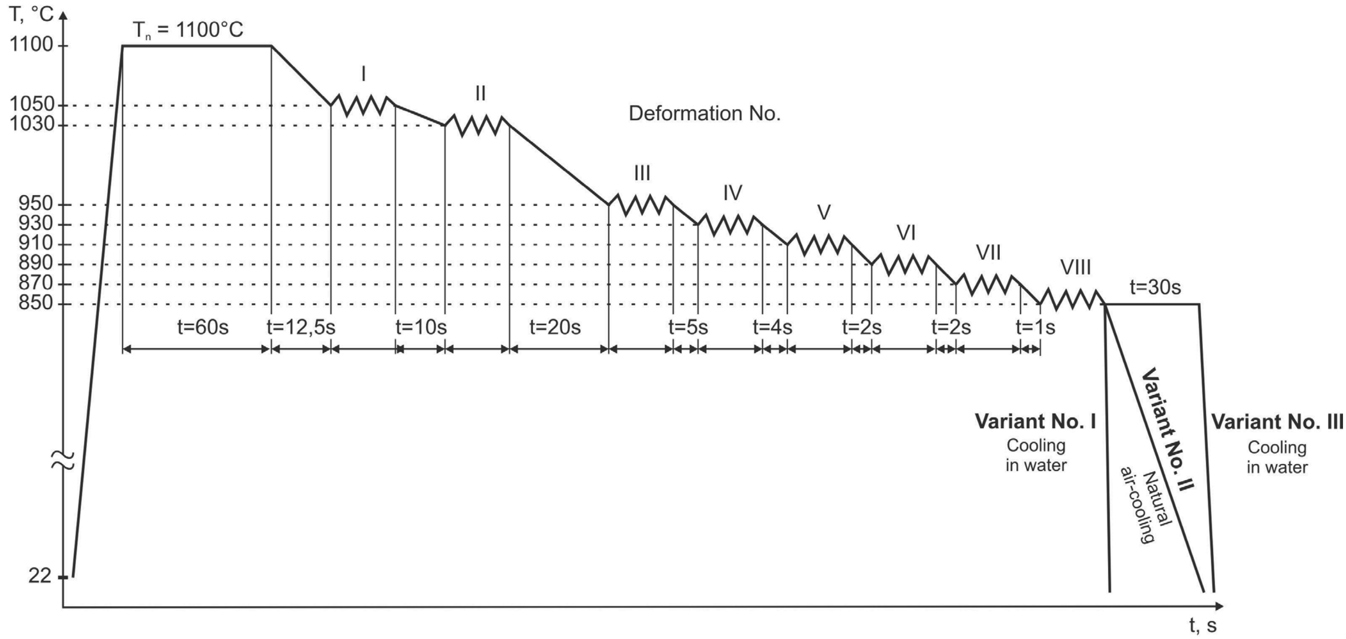


Fig. 6. Schematic and parameters of the 8-stage compression test carried out on Gleeble 3800 thermo-mechanical simulator. T_A - austenitizing temperature, t_{iso} - time of the isothermal holding of specimens at temperature of last deformation - 850°C

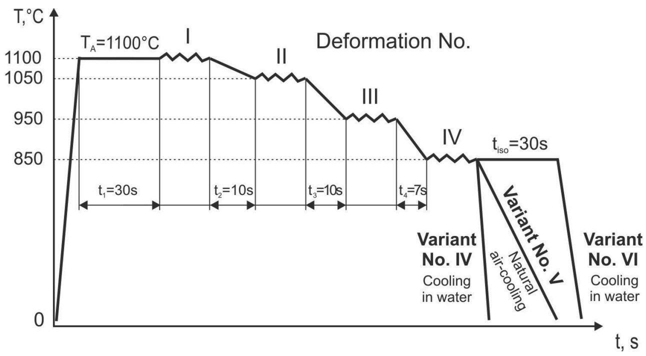


Fig. 7. Schematic and parameters of the 4 -stage compression test carried out on Gleeble 3800 thermo-mechanical simulator. T_A - austenitizing temperature, t_{iso} - time of the isothermal holding of specimens at temperature of last deformation - 850°C

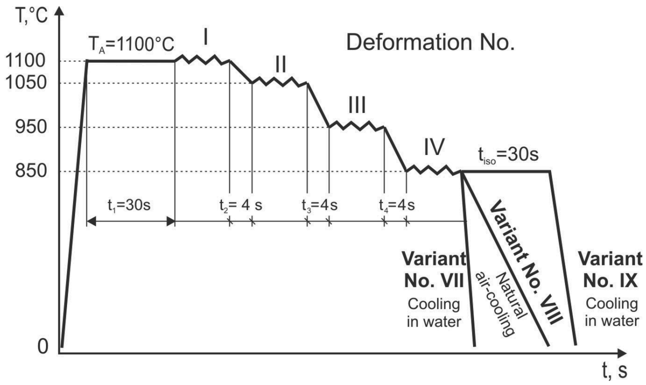


Fig. 8. Schematic and parameters of the multi-stage hot-rolling carried out on single-cage reversing hot-rolling mill line for semi-industrial simulation (LPS) module B at the Institute of Ferrous Metallurgy in Gliwice. T_A - austenitizing temperature, t - time of the isothermal holding of specimens at a temperature of last deformation - 850°C

Metallographic examination was carried out on samples in researched 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 investigated 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 5s 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 tested in low and high strain rate conditions are microstructure in the initial state of the investigated steels. Steel X11MnSiAl17-1-3 is characterized by homogeneous microstructure of austenite with a grain size in range from 150 to 200 μm (Fig. 9). A numerous annealing twins can be observed. Single-phase microstructure was confirmed by X-ray diffraction pattern.

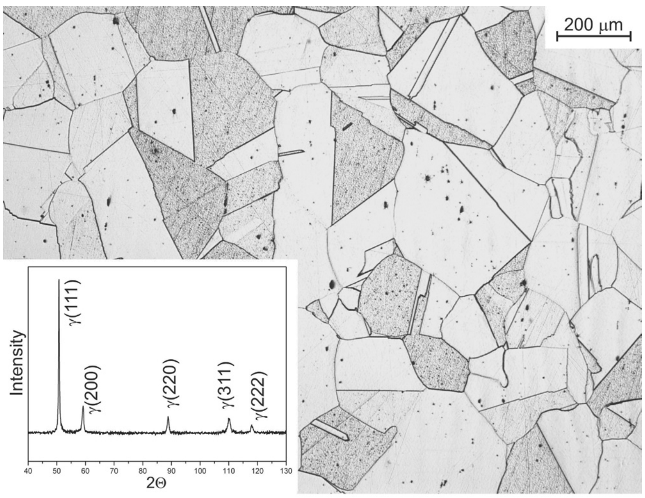


Fig. 9. Structure containing annealing twins and some non-metallic inclusions of austenitic steel X11MnSiAl17-1-3 in the initial state witch X-ray diffraction pattern

The value of ε_{max} of the X11MnSiAl17-1-3 steel determined in continuous hot-compression test in various conditions of temperature and strain rate are shown Table 2. Strain rate has an essential influence on value of flow stress which for investigated steel is equal from 120 to 360 MPa for applied deformation conditions. Increasing temperature of deformation or decreasing strain rate cause decreasing relatively high values of flow stress. 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.

Representative stress-strain curve of steels plastically deformed according to the parameters shown in Fig. 6 is presented in Fig. 10. Multi-stage work-hardening curves of new-developed high-manganese steels can be useful to estimate force-energetic parameters of industrial hot rolling. Insignificant differences between the various variants of thermo-plastic deformation is not the result of the processing variables, because these variants differ only in the variant of cooling after the final step of deformation at a temperature of 850°C. In variant No. I the test sample is cooling in water to freeze the structure of steel. In variant No. II sample was cooled naturally in air, while in the variant No. III, after the final deformation at 850°C the sample was hold isothermally at this temperature and then cooled in water in order to freeze the structure and investigate the effect of static or metadynamic recrystallization progress on mechanical properties of the steel.

Table 2.
The value of ε_{max} and flow stress of the X11MnSiAl17-1-3 steel for different strain rate: 0.1, 1, 10 s^{-1}, and in a temperature: 850, 950 and 1050°C

Starin rate / Temperature	0.1 s^{-1}		1 s^{-1}		10 s^{-1}	
	ε_{max}	flow stress [MPa]	ε_{max}	flow stress [MPa]	ε_{max}	flow stress [MPa]
850°C	0.532	291	0.561	311	0.586	360
950°C	0.498	195	0.528	246	0.453	296
1050°C	0.349	127	0.491	177	0.451	225

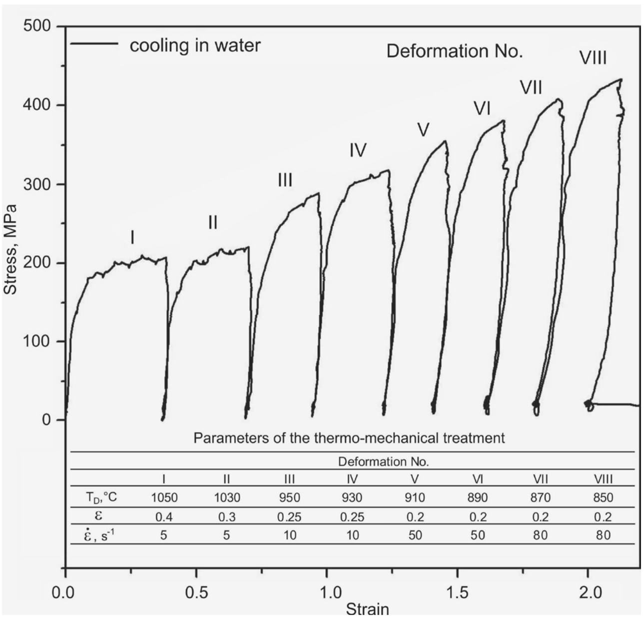


Fig. 10. Representative stress-strain curves of X11MnSiAl17-1-3 steel after 8-stage compression axially symmetrical specimens deformed at temperature range from 1050 to 850°C according to the scheme shown in Fig. 6. Variant no. I - cooling in water

The use of true strain of 0.4 in the first deformation at 1050°C and 0.25 and 0.2 in the following deformation for the tested steel during cyclic compression provides the possibility to dynamic recrystallization and metadynamic in the intervals between the deformations, as indicated by the value of the maximum stress that can be distinguished on the curves σ-ε especially for deformation performed at a temperature of 1050 and 950°C.

For investigated steel X11MnSiAl17-1-3 after reduction temperature of plastic deformation to 950°C and true strain to 0.2 cause that on stress-strain curve maximum value do not occur. The value of the flow stress of the plastic deformation temperature of 1100 to 950°C is comparable to the values obtained in a continuous compression test at a speed of 50 s^{-1}. Cyclic plastic deformation and the course of the partial metadynamic and static recrystallization between various stages of plastic deformation cause obtaining a maximum stress value of ε_{max} for smaller values of deformation curve σ-ε for the last stage of plastic deformation as compared to the continuous compression curve at 850°C.

Some of the typical optical micrographs of high-manganese austenitic X11MnSiAl17-1-3 steel after hot working in the thermo-mechanical simulator Gleeble 3800 are shown in Fig. 11.

Solution heat treatment of X11MnSiAl17-1-3 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 4-stage compression mean grain diameter is about 20-25 μm (Fig. 11a), while after the 8-stage compression standard diameter is much less. 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 5-10 μm (Fig. 11b). The initiation of metadynamic and static recrystallization after the last deformation and subsequent air-cooling leads to obtain mean grain size of about 8-12 μm (Fig. 11c). Isothermal holding of the steel X11MnSiAl17-1-3 after the last deformation at 850°C for 30 s leads to growth of new grains as a result of metadynamic recrystallization and the initiation of static recrystallization (Fig. 11d). Average austenite grain size after this variant of thermo-mechanical treatment is about 15-20 μm. 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 which presents the comparison of a representative diffraction curves after 4- and 8-stage compression tests on the thermo-mechanical simulator using Gleeble 3800 and after hot-rolling performed on semi-industrial simulation (LPS) of hot-rolling. Based on the results of X-ray diffraction was found that the applied thermo-mechanical treatment does not have influence on phase changes.

The results of metallographic examination made on light microscopy on X11MnSiAl17-1-3 steel after semi-industrial hot rolling are shown in Fig. 13. Solution heat treatment after last deformation of the hot rolling with reduction rate equal 20% causes that dynamically recovery austenite grains containing annealing twins elongated in the rolling direction was obtained.

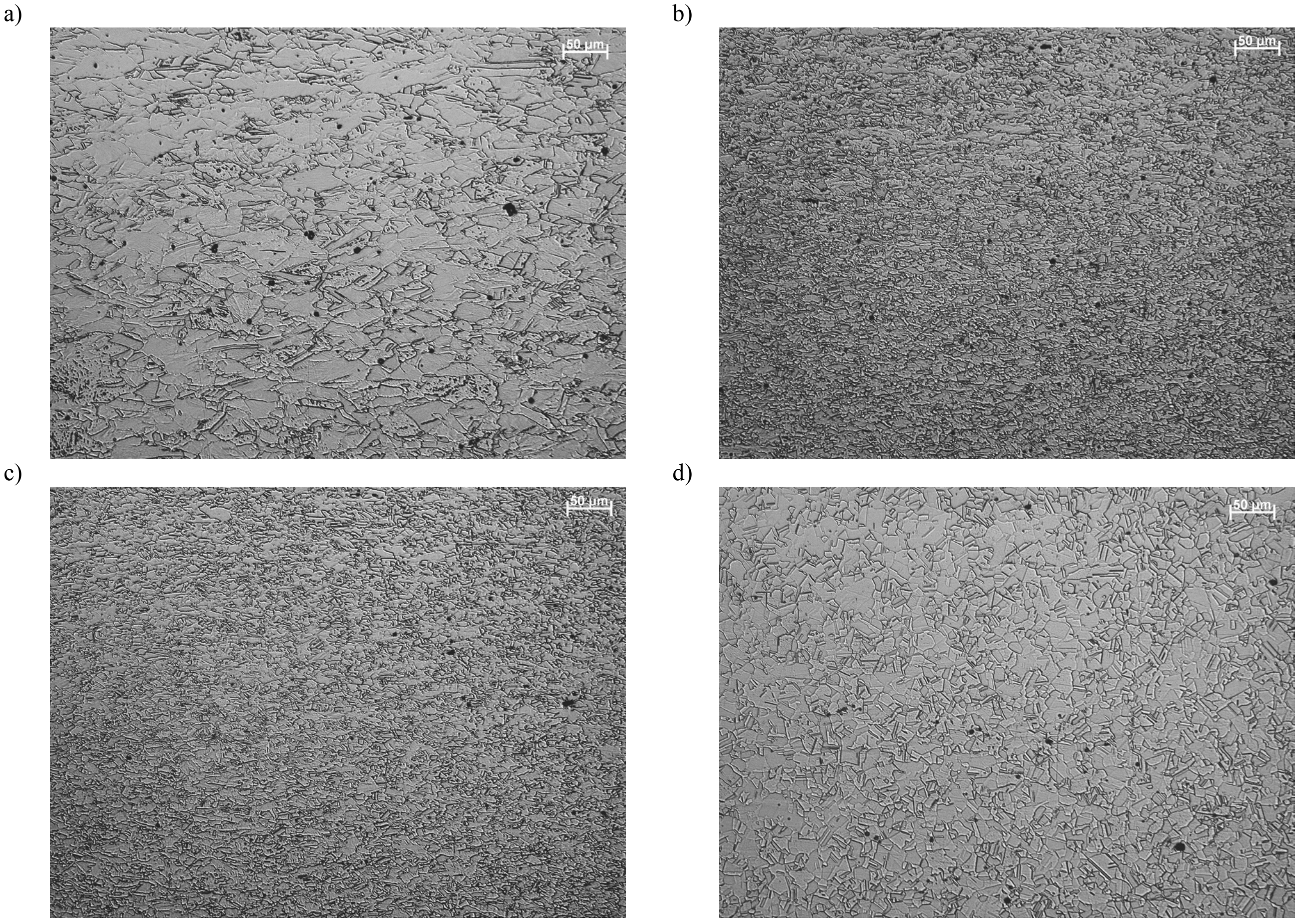


Fig. 11. Structures of high-manganese austenitic X11MnSiAl17-1-3 steel a) after thermo-mechanical treatment according to schedule shown in Fig. 7 and cooling in water from temperature of last deformation at 850°C; b) after thermo-mechanical processing according to schedule shown in Fig. 6 and cooling from temperature of last deformation at 850°C - in water, c) air-cooling, d) in water after isothermal holding 30s at 850°C

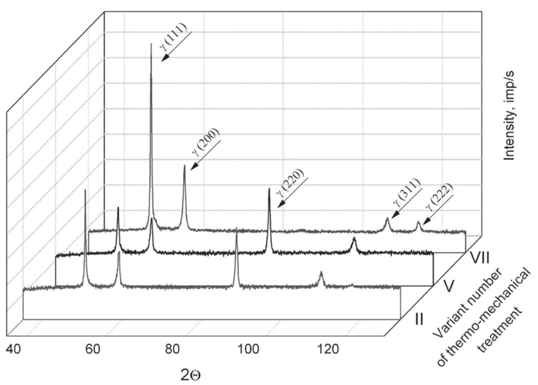
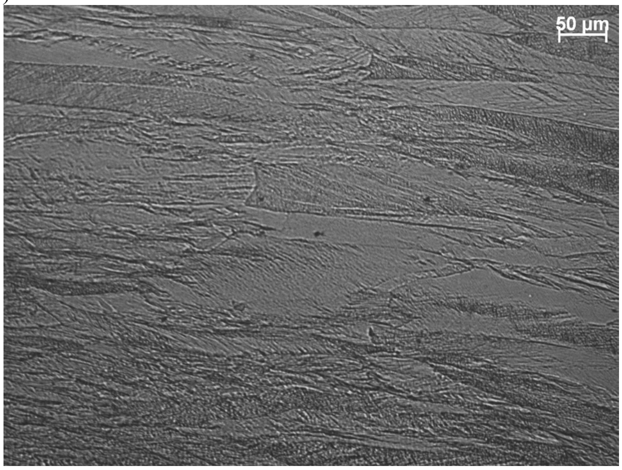


Fig. 12. Comparison of X-ray diffraction pattern after different stages and variants of hot-working

The use of natural cooling in air after the last stage of deformation gives rise of recrystallized fine particles to about 10% mainly statically or metadynamically which are located on the borders of large austenite grains recovered dynamically elongated in the rolling direction. The use of isothermal holding at 850°C for 30 s after last deformation with degree of reduction rate of 20% the participation of statically and metadynamically recrystallized grains is approximately about 20%, which is significantly lower than for samples deformed plastically in the Gleeble simulator. Statically and metadynamically recrystallized grains are located mainly on the borders of elongated austenite grains recovered dynamically, and often situating on the twin border.

Simulation of thermo-plastic deformation using Gleeble 3800 simulator in conditions close to perfect allowed obtaining the refinement of austenite grains. However, hot-rolling made on semi-industrial conditions did not allow for obtaining ideal conditions of temperature and true strain during the following steps, because the fact that rollers in first passes were cold and caused rapid process of heat loss by thin metal sheet. These factors resulted in lack of uniform refinement of the structure of rolled metal sections.

a)



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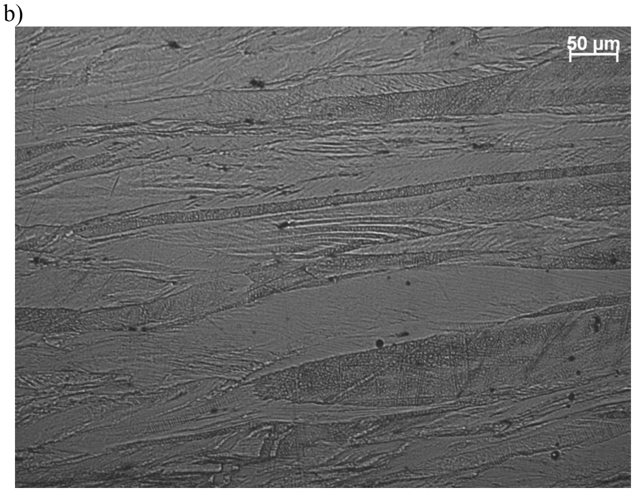

c)

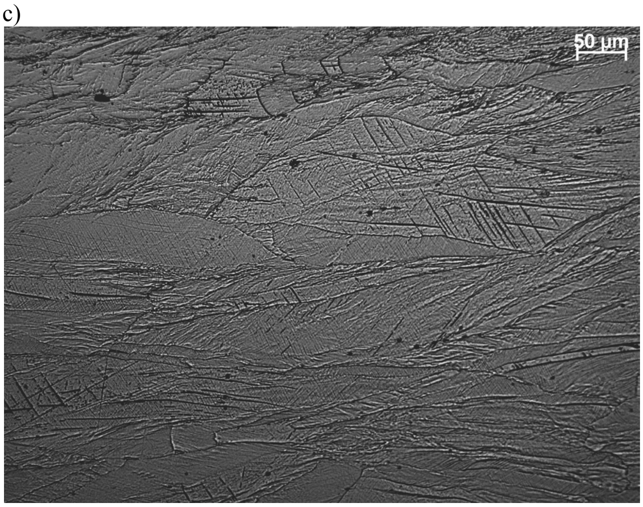

Fig. 13. Microstructures of high-manganese austenitic X11MnSiAl17-1-3 steel after hot-rolling according to schedule shown in Fig. 8, and cooling from temperature of last deformation at 850°C b) in water, c) air-cooling, d) in water after isothermal holding 30 s at 850°C

4. Conclusions

Steel X11MnSiAl17-1-3 in the state after casting is characterized by homogeneous microstructure of austenite with a mean grain size in range from 150 to 200 µm. Continuous compression test on Gleeble 3800 thermo-mechanical simulator proved that elaborated steel is characterized by relatively high values of flow stress, equal from 120 to 360 MPa, and values of ε_{max} deformation come from a range from 0.20 to 0.57, corresponding to maximum value of flow stress. Small values of ε_{max} allow to obtain a fine-grained microstructure due to the dynamic recrystallization.

During 8-stage compression the use of real strain of 0.4 in the first deformation at 1050°C, and 0.25 and 0.2 in the following deformation for the tested steel during cyclic compression provides the possibility to dynamic and metadynamic recrystallization in the intervals between the deformations. Analyzing the results of the study results found that 8-stage compression causes higher grain refinement of investigated high-manganese austenitic steel than in 4-stage compression test.

There also were conducted simulation of hot-rolling and 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 5-10 µm. Solution heat treatment after last deformation of the hot rolling witch reduction rate equal 20% causes dynamically recovery austenite grains containing annealing twins are elongated in the rolling direction was obtained. Statically and metadynamically recrystallized grains are located mainly on the borders of elongated austenite grains dynamic and static recovered, often situating on the twin border.

The fine-grained structure has no influence on a phase composition of steel and should increase mechanical properties during subsequent cold plastic deformations.

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