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Microstructure forming processes of the 26Mn-3Si-3Al-Nb-Ti steel during hot-working conditions

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Properties

ABSTRACT

Purpose: The influence of hot-working conditions on microstructure evolution of new-developed 26Mn-3Si-3Al-Nb-Ti high-manganese steel was investigated.

Design/methodology/approach: The force-energetic parameters of hot-working were determined in continuous and multi-stage compression test performed in temperature range of 850 to 1100°C using the Gleeble 3800 thermomechanical simulator. Evaluation of processes controlling work-hardening were identified by microstructure observations of the specimens compresses to the various amount of deformation (4x0.29, 4x0.23 and 4x0.19).

Findings: The investigated steel is characterized by high values of flow stresses from 250 to 430 MPa. Increase of flow stress along with decrease of compression temperature is accompanied by translation of ε_{max} strain in the direction of higher deformation. 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 and a deciding influence on a gradual microstructure refinement has statical recrystallization.

Research limitations/implications: To determine in detail the microstructure evolution during industrial rolling, the hot-working schedule should take into account real number of passes and higher strain rates.

Practical implications: The obtained microstructure – hot-working relationships can be useful in the determination of power-force parameters of hot-rolling and to design a rolling schedule for high-manganese steel sheets with fine-grained austenitic structures.

Originality/value: The hot-deformation resistance and microstructure evolution in various conditions of hot-working for the new-developed high-manganese 26Mn-3Si-3Al-Nb-Ti austenitic steel were investigated.

Keywords: High-manganese steel; Thermo-mechanical processing; Compression test; Recrystallization; Grain refinement

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1. Introduction

In the last few years attention of automotive industry is focused on modern high-strength steels, which allow to decrease the weight of different elements of vehicles, what is directly connected with lowering fuel consumption and limiting of harmful exhaust gas emission. Presently, the most advanced steels predicted to be used for the most challenging car components with a complex shape and absorbing energy in crash events are high-manganese austenitic TRIP/TWIP steels [1-6].

High-manganese austenitic steels consist of 15 to 30% of manganese, from 0.02 to 0.1% of carbon and about 3% of aluminium and 3% of silicon, among others, in order to decrease density which for this group of steels is about 7.3 g/cm^3. The function of silicon and aluminium is solution hardening of the steel, and carbon is an element that stabilizes austenite. These steels achieve profitable group of mechanical properties, i.e. (ultimate tensile strength) UTS = 600÷900 MPa, (yield strength) $YS_{0.2}$ = 250÷450 MPa, (uniform elongation) UEl = 35÷80% which strongly depends on chemical composition, especially concentration of Mn [2,3,7]. Mechanical properties of high-manganese austenitic steels also depend on structural processes present during cold plastic deformation, which in turn are the derivative of stacking fault energy of austenite [3]. Silicon and aluminium have also influence on the stacking fault energy of austenite, deciding about a type of deformation mechanism during plastic deformation. In case stacking fault energy (SFE) is equal from 12 to $20mJm^{-2}$, partial transformation of austenite into martensite occurs making use of TRIP effect (Transformation Induced Plasticity) [4]. Values of SFE from 20 to $60mJm^{-2}$ determine intense course of mechanical twinning connected to TWIP effect (TWinning Induced Plasticity) [7].

Developing production technology of high-manganese austenitic steels require knowledge about their behaviour during hot plastic strain. There is a shortage of sufficient information content in science publication. There are only a few papers related with behaviour of Fe-Cr-Mn, Fe-Mn and Fe-Mn-Al steels during hot plastic deformation [8-11]. Initial investigations on high-manganese steels containing silicon and aluminium showed that new-developed steels are characterized by high values of flow stresses but at relatively low values of strain ε_{max} corresponding to maximum values of flow stress [12-16]. Hamada et. al. [8,9] were found that maximal flow stress at a temperature of 1100°C for 25Mn steel occurs for ε_{max} = 0.17, what allows to refine the steel microstructure by the use of the dynamic recrystallization. Increasing concentration of Al caused displacement ε_{max} to a value about 0.28. Moreover steel which contains Al has a higher plastic flow stress then 25Mn steel. Application of thermo-mechanical treatment consisting in immediate cooling of steel from a finishing temperature of multi-stage hot-working in controlled conditions [14] should also allow to form a fine-grained microstructure of new-developed C-Mn-Si-Al steel containing Nb and Ti microadditions. To develop rolling procedures, it is important to reflect real temperature-strain hot-working conditions and also to determine the microstructure evolution in successive stages of hot plastic deformation. It's foreseen that structure diversification after different kind of thermo-mechanical treatment should have influence on behaviour of that group of steels in further cold plastic strain conditions.

2. Experimental procedure

The examinations were performed on new-developed high-manganese austenitic 26Mn-3Si-3Al-Nb-Ti steel, containing Nb and Ti microadditions (Table 1). Melts were prepared in the Balzers VSG-50 vacuum induction furnace. After homogenization at 1200°C for 4 h, in order to remove the segregation of Mn, ingots with a mass of 25kg were submitted for open die forging on flats with a width of 220 mm and a thickness of 20 mm. Then, cylindrical machined samples ∅10x12mm were made. In order to determine the influence of temperature on a steel grain growth, samples were solution heat-treated in water from the austenitizing temperature in a range from 900 to 1100°C.

Table 1.
Chemical composition of the investigated steel

26Mn-3Si-3Al-Nb-Ti				Mass contents, (%)			
C	Mn	Si	Al	P	S	Nb	Ti
0.065	26.0	3.08	2.87	0.004	0.013	0.034	0.009

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 $10s^{-1}$. Depending on loads possible to apply in specific rolling schedules, it is important to determine σ-ε curves for various values of reduction. In purpose of mentioned above, the sequences of true strains for successive variants of deformation were equal: 4x0.29, 4x0.23 and 4x0.19 (Fig. 1). Multi-stage compression tests were also carried out using Gleeble 3800 thermomechanical simulator. The specimens were inserted in a vacuum chamber, where they were resistance-heated. Tantalum foils were used to prevent sticking of sample with a die and graphite foils as a lubricant. Identification of microstructure evolution was performed through samples quenched in water in successive stages of deformation and after isothermal holding the samples for the time up to 64s in a temperature of finishing deformation (850°C).

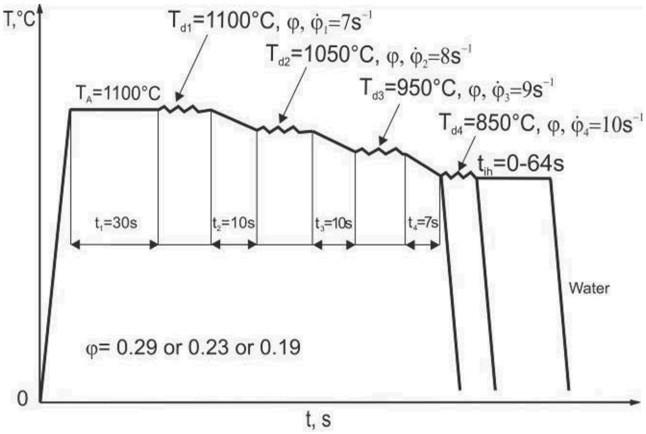
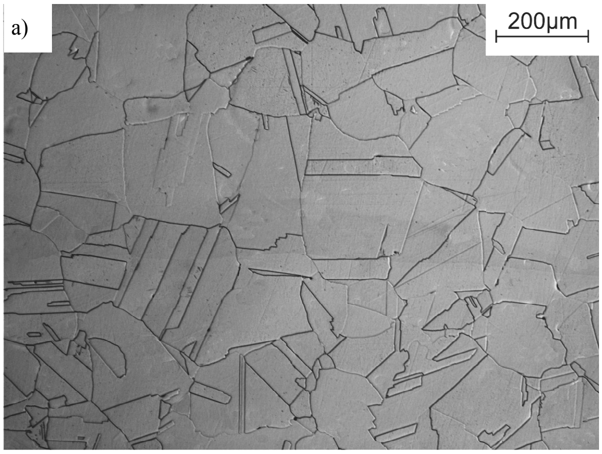


Fig. 1. Parameters of the multi-stage compression test realized in the Gleeble simulator

Metallographic examination of samples with specification of grain size and mass of recrystallized austenite fraction were carried out on light microscope LEICA MEF4A. Mass of recrystallized austenite fraction was determined in the area of 1/3 radius from the centre of the sample. In order to disclose austenite grain boundary, samples etched in mixture of nitrous and hydrochloric acid in proportions 2:1 and in mixture HNO_3, HCl and H_2O in proportions 2:2:1. 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

The new-developed steel in the initial state is characterized by homogeneous microstructure of austenite with a grain size equal approximately 100 µm, in which numerous annealing twins can be identified (Fig. 2a). Single-phase microstructure of the steel is confirmed by X-ray diffraction pattern in Fig. 2b.



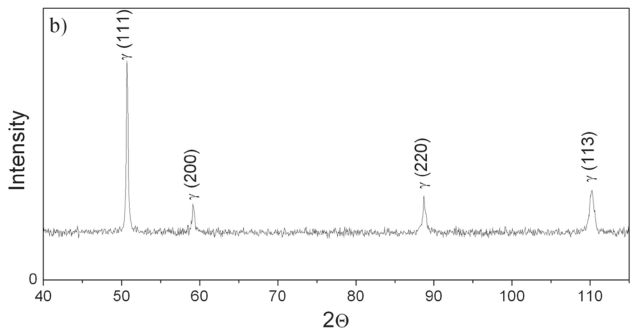


Fig. 2. Austenitic microstructure with numerous annealing twins of the 26Mn-3Si-3Al-Nb-Ti steel in the initial state (a) and X-ray diffraction pattern (b)

Starting points for microstructure analysis of specimens that were plastically hot-deformed in variable conditions are microstructures of steel subjected to solution heat treatment from a temperature range of 900 to 1000°C. The steel possesses fine-grained microstructure of austenite with grain sizes from 12 to about 22 µm up to temperature of 1000°C (Fig. 3). Further increase in solutioning temperature to 1100°C results in a rapid grain growth up to about 50 µm. The fine-grained microstructure is due to the advantageous influence of dispersive particles of (Nb,Ti)(C,N) limiting the steel grain growth, what was investigated elsewhere [15]. Moreover, numerous annealing twins can be observed in the microstructure (Fig. 3).

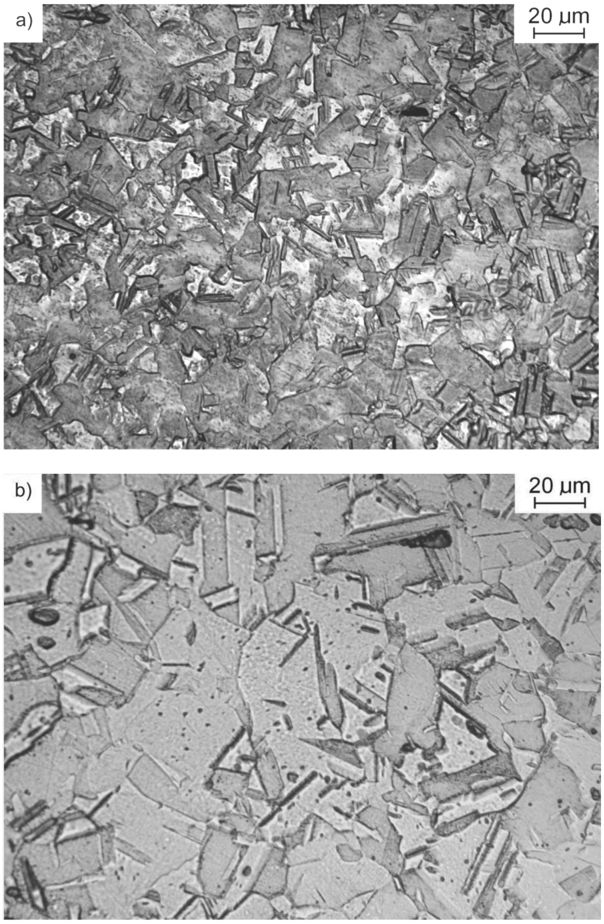


Fig. 3. Austenitic structures of the steel 26Mn-3Si-3Al-Nb-Ti after solution heat treatment from a temperature: a) 900°, b) 1000°C

Stress-strain curves obtained in continuous compression tests is presented in Fig. 4. This test allowed determine the range of flow stress of investigated steel in a temperature range from 1050°C to 850°C. It arises from Fig. 4 that the steel 26Mn-3Si-3Al-Nb-Ti is characterized by values of flow stress equal from 250 to 430 MPa in investigated range of temperature. These values are considerably higher than they are for conventional C-Mn steels and for Cr-Ni and Cr-Mn austenitic steels [10]. It proves high work-hardening, which is caused by high Mn concentration in the steel. Additionally, the increase of flow stress is influenced by Si and Al as well as Nb and Ti microadditions. Increase of flow stress along with decrease of compression temperature is accompanied by translation of ε_{max} strain in the direction of higher deformations. It is characteristic, that after strong strain hardening, peaks of ε_{max} are present for relatively low strain values, i.e. from 0.24 to 0.46. It creates convenient conditions for using dynamic recrystallization for refinement of microstructure. Initiation of dynamic recrystallization in a temperature range up to 950°C requires a relatively small strain value of about 0.32, often applied in rolling schedules. Lowering the deformation temperature to 850°C results in a considerable increase of the critical strain to about 0.46.

Stress-strain curves of the steel plastically deformed according to the scheme shown in Fig. 1 are presented in Fig. 5. Application of true strain equal 0.29 during multi-stage compression creates possibility of 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, maximum on σ-ε curves is present for a maximum value of true strain (0.29). The values of flow stress in the range of deformation temperature from 1100 to 950°C are comparable with values obtained in continuous compression test. Cyclic deformation and a partially recrystallization between successive deformations result in a much faster maximum on the σ-ε curve for the fourth deformation compared to the curve obtained at a temperature of 850°C in the continuous compression test (Fig. 5). Microstructures of steel in the successive deformation stages and after its finish corresponding to σ-ε curves are put together in Fig. 6a-f. After deformation of the specimen at a temperature of 1050°C and subsequent cooling for 10s corresponding to the interpass time, the steel is characterized by uniform, metadynamically recrystallized austenite microstructure with a grain size of about 40 μm (Fig. 6a). Lowering the deformation temperature to 950°C and the time of 7s for cooling the specimen to 850°C results in much smaller fraction of metadynamically recrystallized grains located in a matrix of statically recovered grains (Fig. 6b). A partial removal of work-hardening through metadynamic recrystallization that occurs during the interval between third and fourth deformation is a result of significant decrease of flow stress noted for the last deformation realized at the temperature of 850°C (Fig. 5), compared to the curve obtained in the continuous compression test (Fig. 4). Additionally, cyclic deformations as well as the course of partial recrystallization cause much faster achievement of maximum on σ-ε curve for the fourth deformation when comparing to continuous compression at the temperature of 850°C.

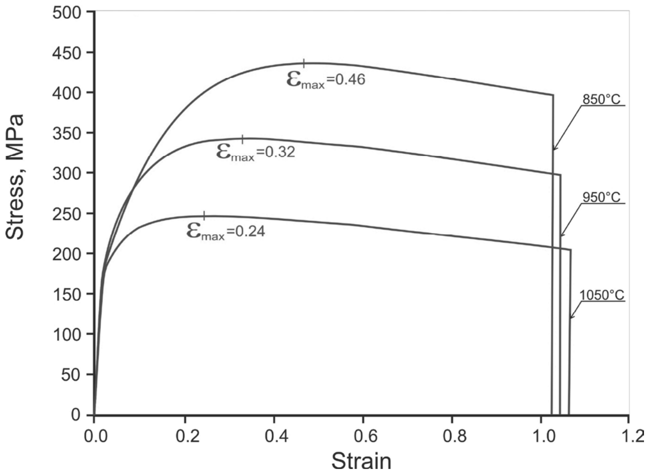


Fig. 4. Influence of the temperature on a shape of σ-ε curves for the specimens compressed with a strain rate of $10s^{-1}$

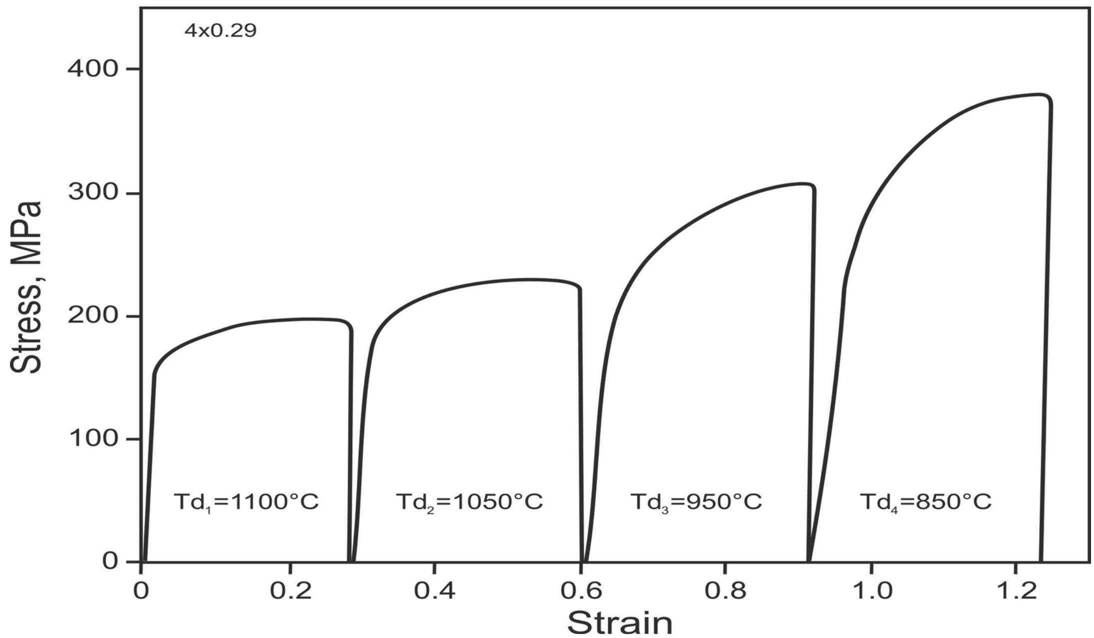


Fig. 5. Stress - strain curves after the multi-stage compression test of the axisymetrical specimens deformed with a true strain 4x0.29 in a temperature range from 1100 to 850°C

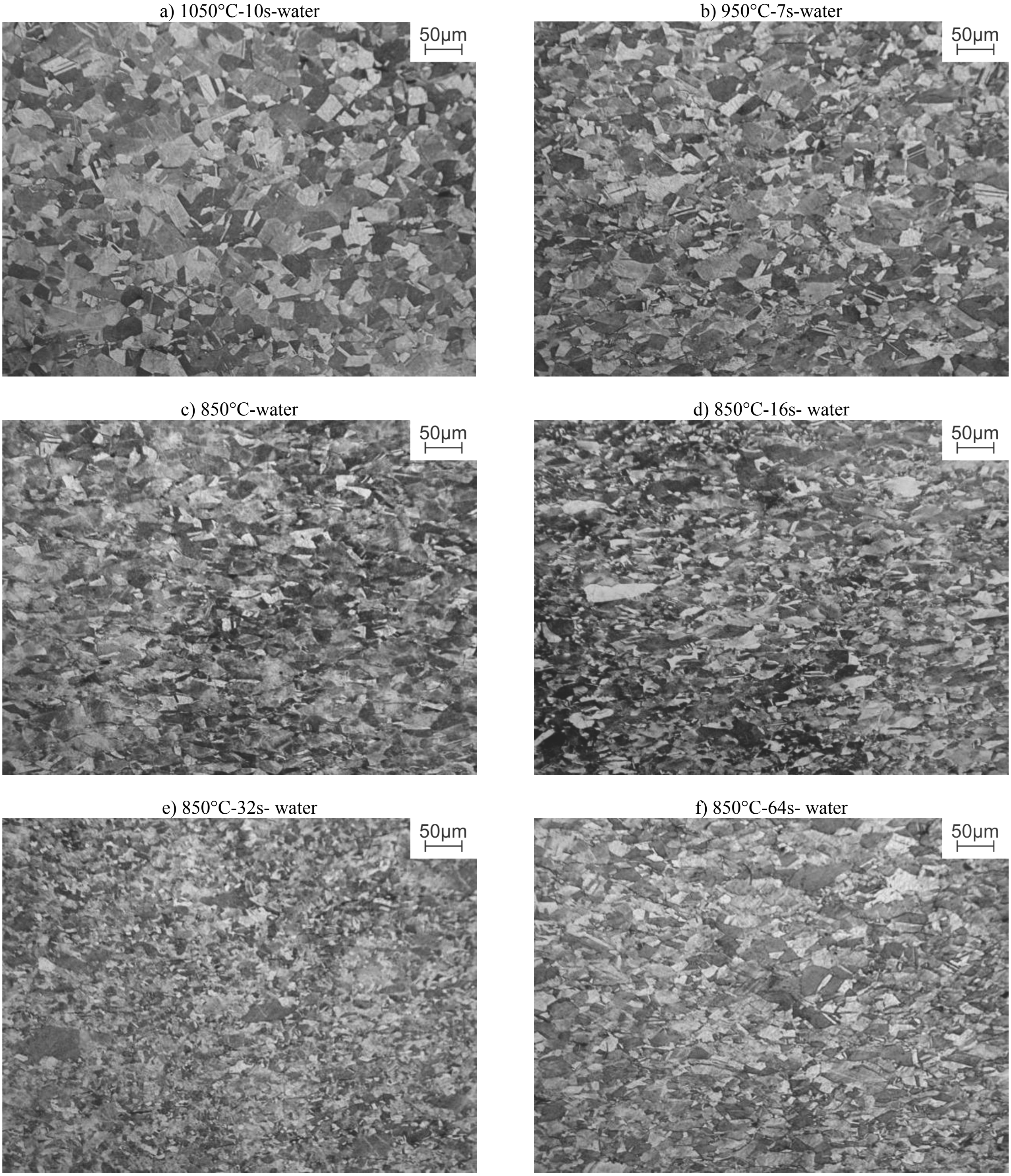


Fig. 6. Austenitic structures obtained after solutioning the steel in successive stages of the hot-working for the specimens compressed to a true strain 4x0.29 and isothermally held for the time from 0 to 64s: a) metadynamically recrystallized grains during the interval between second and third deformation, b) metadynamically recrystallized grains during the interval between third and fourth deformation, c) initiation of dynamic recrystallization, d) grain refinement due to metadynamic and static recrystallization, e) fine statically recrystallized austenite grains, f) grain growth as a result of metadynamic recrystallization

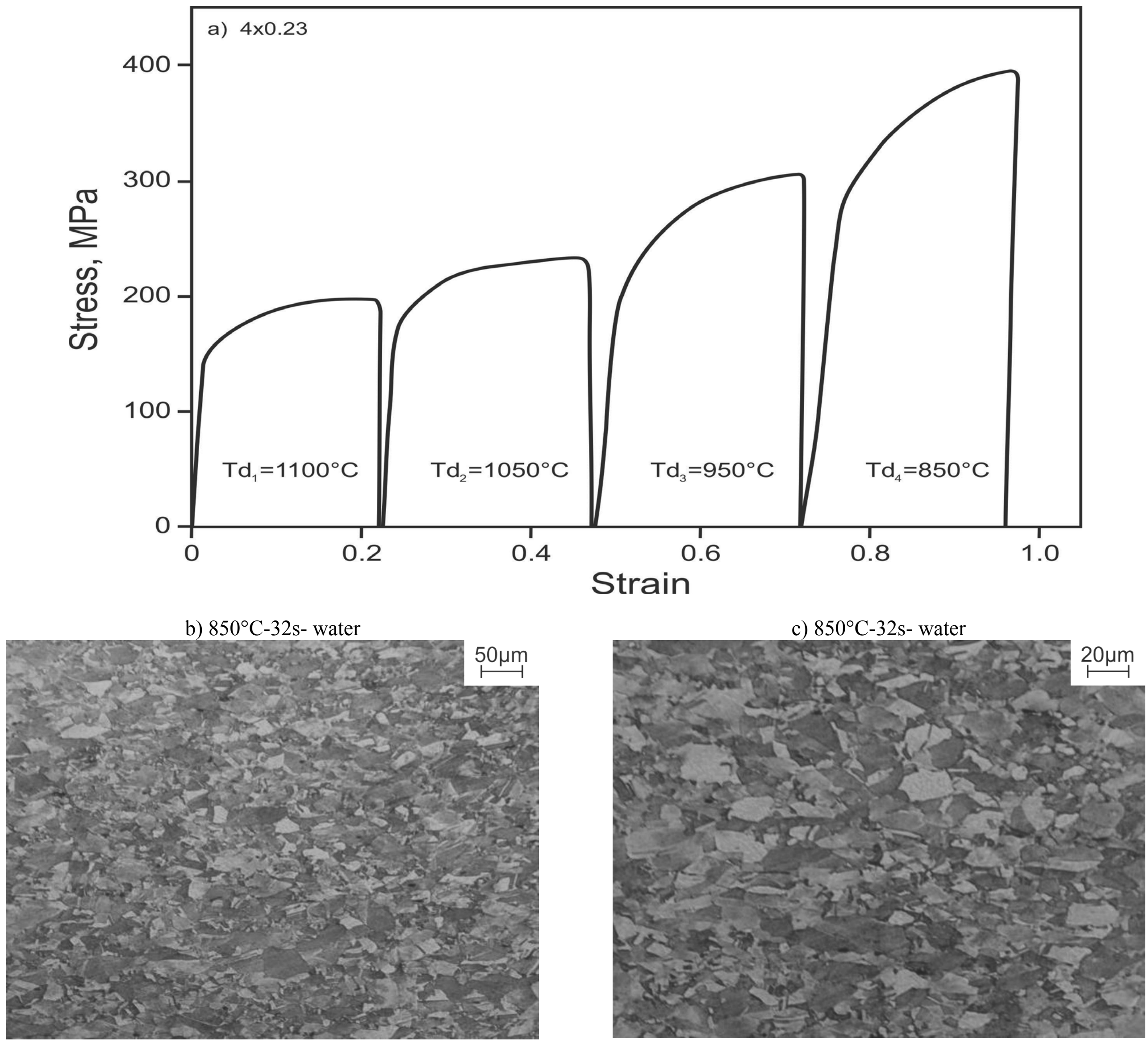


Fig. 7. Stress - strain curves after the multi-stage compression test of the axisymetrical specimens deformed with a true strain 4x0.23 in a temperature range from 1100 to 850°C (a), and statically recrystallized austenitic structures of the steel 26Mn-3Si-3Al-Nb-Ti obtained after solutioning the specimen after isothermal holding the steel for 32s in a last deformation temperature of 850°C (b), (c)

The initiation of dynamic recrystallization during the last deformation at a temperature of 850°C is confirmed by a micrograph in Fig. 6c, showing a partially recrystallized austenite with a grain size of about 20 µm. Isothermal holding of the specimen in a temperature of the last deformation for 16s leads to a remarkably fine-grained metadynamically recrystallized austenite microstructure with a fraction of about 40%, located in the matrix of slightly elongated, statically recovered grains containing numerous annealing twins (Fig. 6d). Further extension of holding time to 32s leads to obtaining almost fully recrystallized microstructure of steel (Fig. 6e) with a mean austenite grain size of about 10 µm. Holding of steel in the deformation temperature for 64s causes gradual increase of recrystallized grains sizes (Fig. 6f)

Decrease of true strain to 0.23 during the multi-stage compression test leads to changes of the course of stress-strain curves (Fig. 7a). 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. 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.

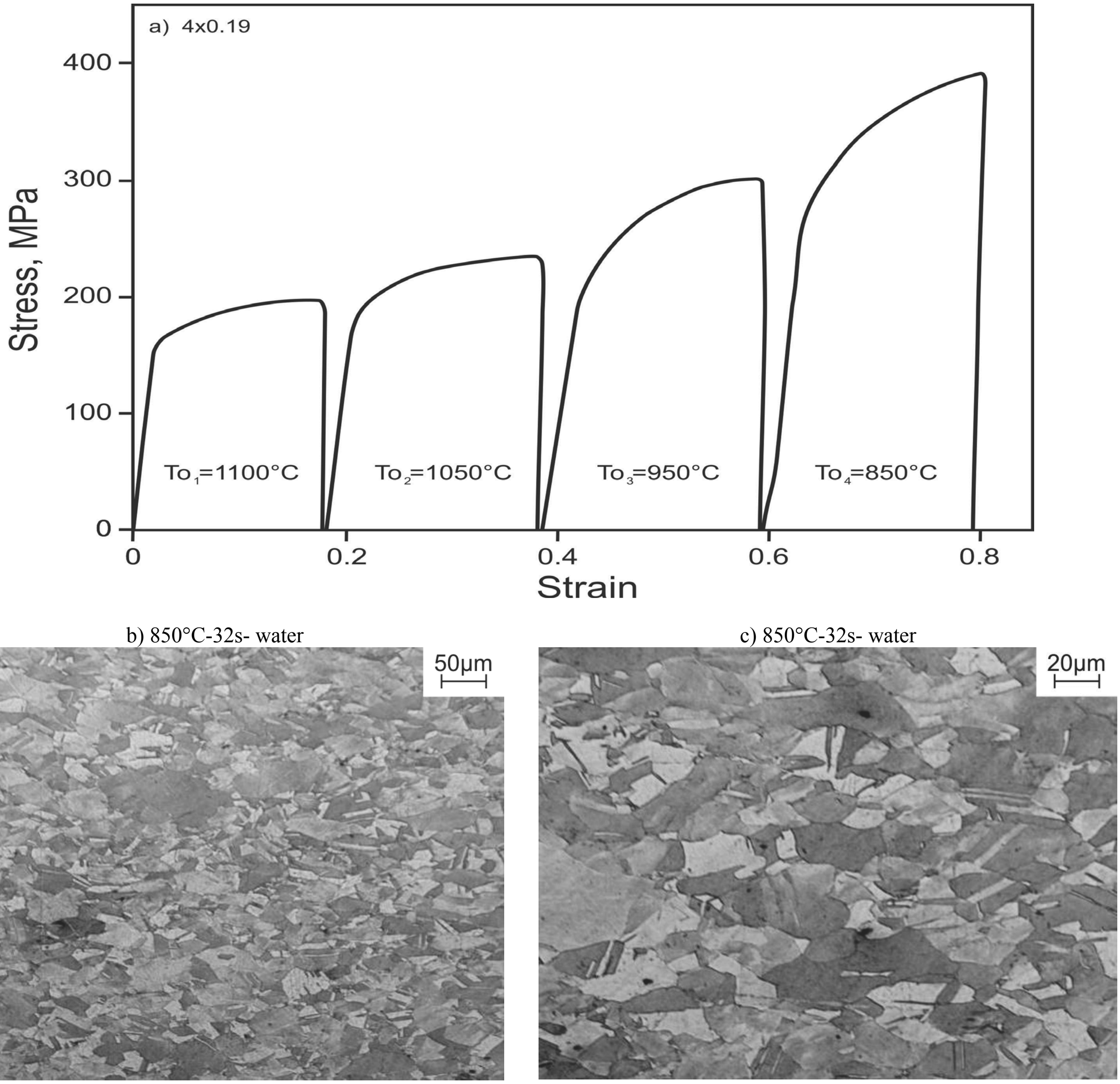


Fig. 8. Stress - strain curves after the multi-stage compression test of the axisymetrical specimens deformed with a true strain 4x0.19 in a temperature range from 1100 to 850°C (a), and austenitic structures of the steel 26Mn-3Si-3Al-Nb-Ti in an initial stage of statical recrystallization obtained after solutioning the specimen after isothermal holding the steel for 32s in a last deformation temperature of 850°C (b), (c)

Because of a lack of dynamic recrystallization in final passes, a refinement of microstructure requires the use of thermally activated, static processes removing work-hardening. For instance, the micrographs in Fig. 7b, 7c show the austenite microstructure of the steel isothermally held for 32 s at 850°C after compression with a true strain of 4x0.23. The fraction of statically recrystallized austenite equals approximately 50% (Fig. 7b). Numerous annealing twins can be observed in the microstructure (Fig. 7c) and a mean statically recrystallized austenite grain is higher compared to the specimen compressed 4x0.29, where a reconstruction of the microstructure was obtained both in static and metadynamic processes (Fig. 6e).

Further decrease of true strain to 0.19 causes that dynamic recovery is the process controlling work hardening in the whole temperature range of deformation (Fig. 8a), at similar values of flow stress in comparison with the specimen deformed 4x0.23. However, the isothermal holding of the specimen for 32s is to short to obtain a desired fraction of recrystallized phase, which equals approximately 20% (Fig.8b). Once again, numerous annealing twins can be observed in microstructure and fine statically recrystallized grains of γ phase are located mainly on boundaries of elongated statically recovered austenite grains (Fig. 8c).

4. Conclusions

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

- The new-developed high-manganese steel is characterized by homogeneous austenite structure with many annealing twins.
- Solutioning the steel does not change its phase composition but has essential effect on a grain size of austenite, which is fine-grained up to a temperature of about 1000°C.
- 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.
- 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 steel 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. The refinement of austenite microstructure proceeds by metadynamic recrystallization.
- 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. A relatively small fraction of recrystallized phase between successive passes is a reason of higher flow stresses up to 400 MPa in a final deformation temperature. 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.

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