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Microstructure evolution of high-manganese steel during the thermomechanical processing

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ABSTRACT

Purpose: The aim of the paper is to determine the influence of hot-working conditions on microstructure evolution of new-developed high-manganese austenitic steel.

Design/methodology/approach: The hot-working behaviour was determined in continuous and multi-stage compression tests performed in a temperature range of 850 to 1100°C by the use of the Gleeble 3800 thermomechanical simulator. The processes controlling work hardening and removing it were identified by microstructure evolution observations in successive stages of compression with the amount of true strain 4x0.29, 4x0.23 or 4x0.19.

Findings: The investigated steel is characterized by high values of flow stresses from 250 to 450 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 σ-ε curves can be useful in determination of power-force parameters of hot-rolling and to design a rolling schedule ensuring a fine-grained microstructure of high-manganese steel products.

Originality/value: The microstructure evolution in various conditions of hot-working for the new-developed high-manganese Mn-Si-Al-Nb steel was determined.

Keywords: Materials, Metallic alloys; High-manganese steel; Thermo-mechanical processing; Compression test; Dynamic recrystallization; Static recrystallization

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MATERIALS

1. Introduction

One of the present priorities of automotive industry is to use modern high-strength steels, allowing to decrease the weight of different elements of vehicles, what is directly connected with lowering fuel consumption and environment pollution. Conducted presently scientific projects are directed to a development of multiphase structure steels, enabling to obtain both high strength and ductile properties [1, 2]. The high plasticity is possible to achieve by strain-induced martensitic transformation (TRIP – Transformation Induced Plasticity) of retained austenite with a fraction of about 15% [3, 4]. High energy-absorbing ability of suitably formed profiles of multiphase steels creates high prospects of using these components for controlled body crushing zones [5, 6]. The improvement of passive safety – being one of the challenges for car producers – decides that multiphase steels are a modern determinant of the automotive branch development.

Beneficial features of strain-induced martensitic transformation from a point of view of energy absorption and manufacturing the elements with a complicated shape decided that a subject of interest are also steels with a uniform austenitic structure, susceptible to the improvement of mechanical properties using strain-induced transformation as well [7-12]. The economic-acceptable in a group of austenitic steels are high-manganese alloys, evolving in three directions meeting the needs of automotive industry in a very wide range. The first group of steels containing up to 0.1%C and with manganese concentration from 15 to 20% and various concentration of Si and Al is designed from a point of view of application of a TRIP-effect, linked to martensitic transformation of austenite during cold plastic deformation [7-9]. The second group of steels with manganese concentration above 25% is designed with taking into account possibly highest ductile properties and use of intense mechanical twinning (TWIP – Twinning Induced Plasticity) for matrix hardening [10-12]. The third group of steels with increased up to around 0.5% concentration of carbon, and variable concentration of Mn, Al and Si is characterized by TRIPLEX-type microstructure with various fractions of austenite, ferrite and fine-dispersive precipitations of κ carbide [13, 14].

Numerous works concerning high-manganese steels are connected with their behaviour in conditions of cold plastic deformation [8-12]. It was found that processes influencing the structure and mechanical properties of high-manganese alloys depend on the stacking fault energy (SFE) of austenite, dependent on a chemical composition of the steel and deformation temperature [7, 10]. It was found that mechanical twinning is deciding mechanism about final properties of alloys with $20<SFE<60\ mJm^{-2}$. Decreasing the SFE from 20 to 12 mJm^{-2} results in improving the ductility of the steel by the TRIP-effect [7-10]. Strain-induced martensitic transformation and mechanical twinning are main determinants of obtained mechanical properties, which are in a wide range: UTS = 500–800 MPa, $YS_{0.2}$ = 250–400 MPa, UEl = 30–80% [7, 11-13]. The essential influence on obtained mechanical properties has also a strain rate [8].

To develop the manufacturing methods, it is also important to determine the flow behaviour of steels under hot-working conditions. However, there are only a few papers concerning the behaviour of Fe-Cr-Mn, Fe-Mn and Fe-Mn-Al steels during hot plastic deformation [15, 16]. 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 [17-19]. This behaviour is favourable for a structure refinement by the use of dynamic recrystallization. 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.

In the aspect of strength properties improvement, optimalization of chemical composition from the point of view of using Nb, Ti and V microadditions and formation of fine-grained microstructure of products in the controlled process of thermo-mechanical treatment can appear to be the most interesting [20, 21]. The mentioned elements which during hot-working in properly selected conditions form dispersive nitrides, carbonitrides and carbides, are the cause of additional precipitation strengthening what has a particular meaning for steels with austenitic matrix and relatively low yield point. Moreover, precipitating on dislocations in plastically hot-deformed austenite they impede grain growth of recrystallized austenite what favours the forming of fine-grained microstructure [20-22].

2. Experimental procedure

Investigations were carried out on high-manganese austenitic steel containing 0.04%C, 27.5%Mn, 4.18%Si, 1,96%Al and microadditions of Nb=0.033% and Ti=0.009%. The concentration of impurities is very low: P=0.002% and S=0.017%. Melts were realized in the Balzers VSG-50 inductive vacuum furnace. Ingots with a mass of about 25kg were submitted open die forging on flats with a width of 220 mm and a thickness of 20 mm. Then, cylindrical samples ∅10x12mm were made. In order to determine the influence of temperature on a grain growth of steel, samples were solution heat-treated in water from the austenitizing temperature in a range from 900 to 1100°C.

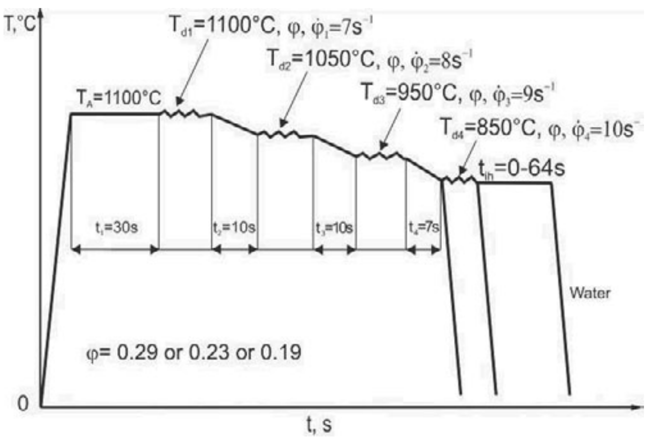

Fig. 1. Parameters of the multi-stage compression test realized in the Gleeble simulator

Determination of processes controlling work hardening was carried out in continuous axisymetrical compression test using the Gleeble 3800 thermo-mechanical 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). The multi-stage deformation was also realized by compression in the Gleeble 3800 simulator. To eliminate welding of sample with a die and decrease the friction on die – sample contact surface, very thin tantalic foil covered with lubricant based on nickel was introduced between the contact surfaces. Identification of microstructure evolution was performed through quenching of samples 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 of 850°C.

Metallographic investigations of specimens along with the determination of grain size and fraction of recrystallized austenite were performed on LEICA MEF4A optical microscope. The fraction of recrystallized austenite was metallographically defined in the distance of 1/3 of radius from a centre of the sample. In order to reveal the austenitic structure, samples were etched in an aqueous solution of nitric and hydrochloric acids. The identification of phase composition of the steel in the initial state was achieved by using X-ray phase analysis with help of X'Pert PRO diffractometer and X'Celerator strip detector. The lamp with Co anode working at 40 kV voltage and 30mA current was used.

3. Results and discussion

The new-developed steel has a $\gamma + \varepsilon$ microstructure in the initial state (Fig. 2).

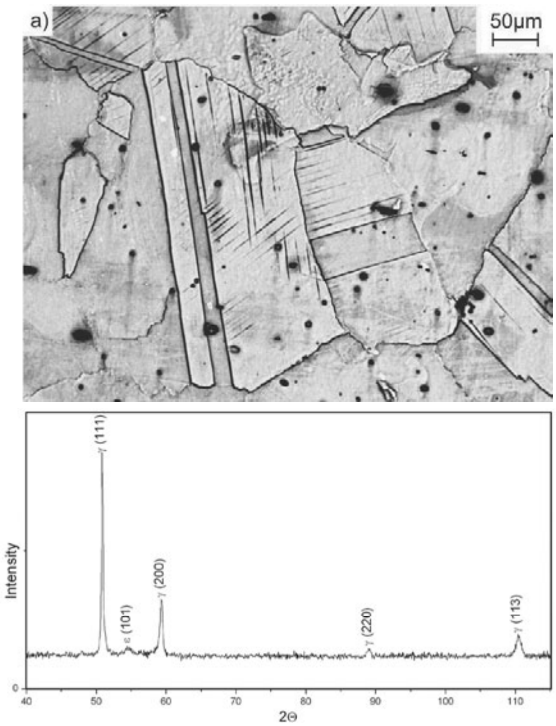

Fig. 2. Austenitic structure with annealing twins and ε martensite plates of the 27Mn-4Si-2Al-Nb-Ti steel in the initial state (a) and X-ray diffraction pattern (b)

The austenite grain size equals from 70 to 100μm, in which numerous annealing twins can be identified (Fig. 2a). Moreover, a result of high manganese concentration is the presence of some fraction of non-metallic inclusions. Diphase microstructure of the steel is confirmed by X-ray diffraction pattern in Fig. 2b. The presence of ε martensite can be a result of increased concentration of Si in relation to Al, oppositely influencing SFE of austenite. Parallel lamellas of martensite ε are hampered by both grain boundaries and annealing twins boundaries.

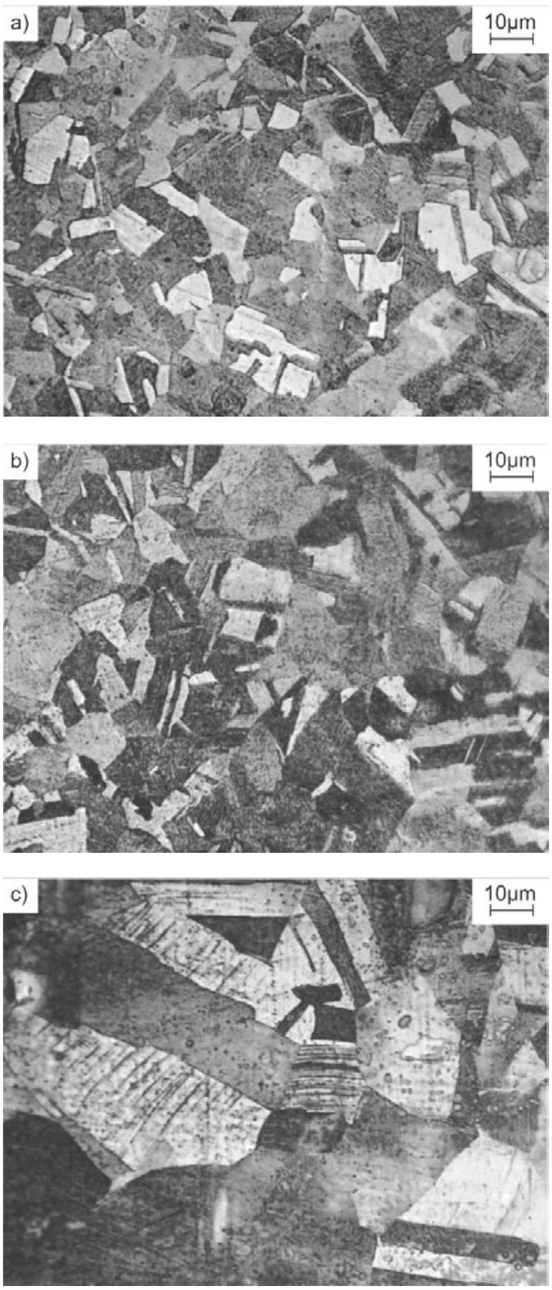

Fig. 3. Austenitic structures of the steel after solution heat treatment from a temperature: a) 900°, b) 1000°C, c) 1100°C

Starting point for microstructure analysis of specimens that were plastically hot-compressed in variable conditions are microstructures of steel subjected to solution heat treatment from a temperature range from 900 to 1100°C. The steel possesses fine-grained microstructure of austenite with grain sizes from 10 to about 17μm up to temperature of 1000°C (Fig. 3a, b). Further increase in solutioning temperature to 1100°C results in a rapid grain growth up to about 50μm (Fig. 3c). This behaviour is connected with a total dissolution of NbC particles above 1000°C, what was investigated elsewhere [19]. Moreover, numerous annealing twins can be observed in the microstructure and some fraction of ε martensite plates (Fig. 3).

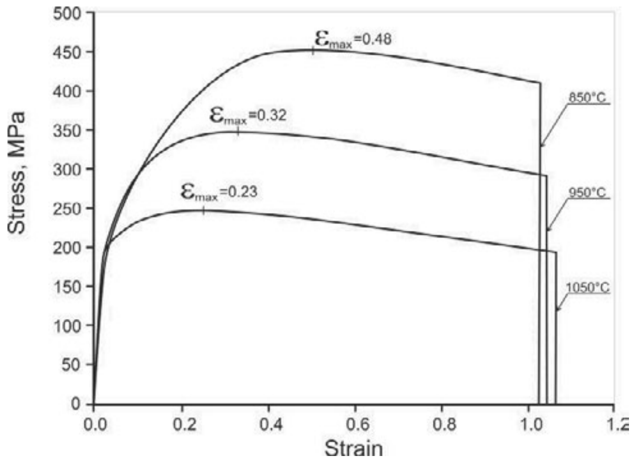

Fig. 4. Influence of the temperature on a shape of σ-ε curves for the specimens compressed with a strain rate of $10s^{-1}$

Continuous compression tests allowed determining the range of flow stress of investigated steel in a temperature range from 1050°C to 850°C. It arises from Fig. 4 that flow stress is equal from 250 to 450MPa. These values are considerably higher than they are for conventional C-Mn steels [23] and for Cr-Ni and Cr-Mn austenitic steels [16]. Increase of flow stress along with decrease of compression temperature is accompanied by translation of ε_{max} strain in the direction of higher deformation. High stress values are a result of strengthening effect of high content of Mn, Si and Al. It arises from Fig. 4 that the initiation of dynamic recrystallization in a temperature range up to 950°C requires a relatively small strain value of about 0.3, often applied in rolling schedules. Lowering the deformation temperature to 850°C results in a considerable increase of the critical strain to about 0.48. However, earlier results [17-19] showed that the structure refinement due to dynamic recrystallization initiation is possible to occur already after the true strain of about 0.3.

Results of the multi-stage compression test carried out according to the scheme in Fig. 1 are the stress-strain curves presented in Fig. 5. Application of true strain equal 0.29 during cyclic deformation 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 (Fig. 5). After decreasing plastic deformation temperature, maximum on σ-ε curves is present for maximum value of true strain (0.29). 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 at the temperature of 950°C and cooling of a sample for 7s to the temperature of 850°C, the steel is characterized by uniform, metadynamically recrystallized microstructure of austenite with grain size of about 30μm (Fig. 6a).

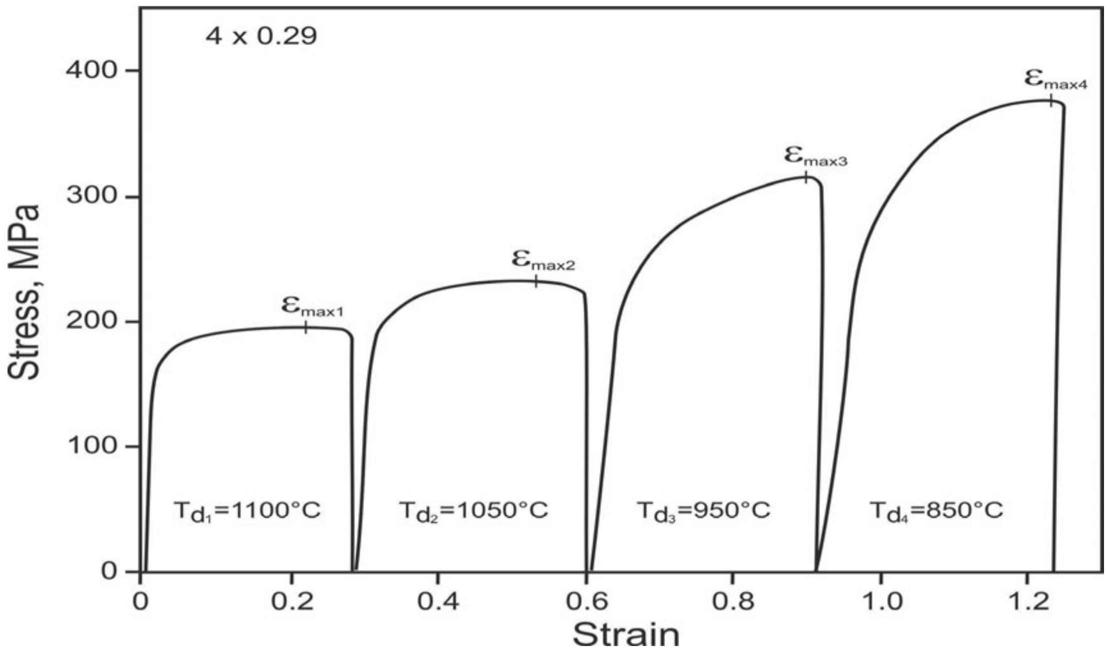

Fig. 5. Stress - strain curves after the multi-stage compression test of the axisymetrical specimens deformed with a true strain 4x0.29 in a temperature range from 1100 to 850°C

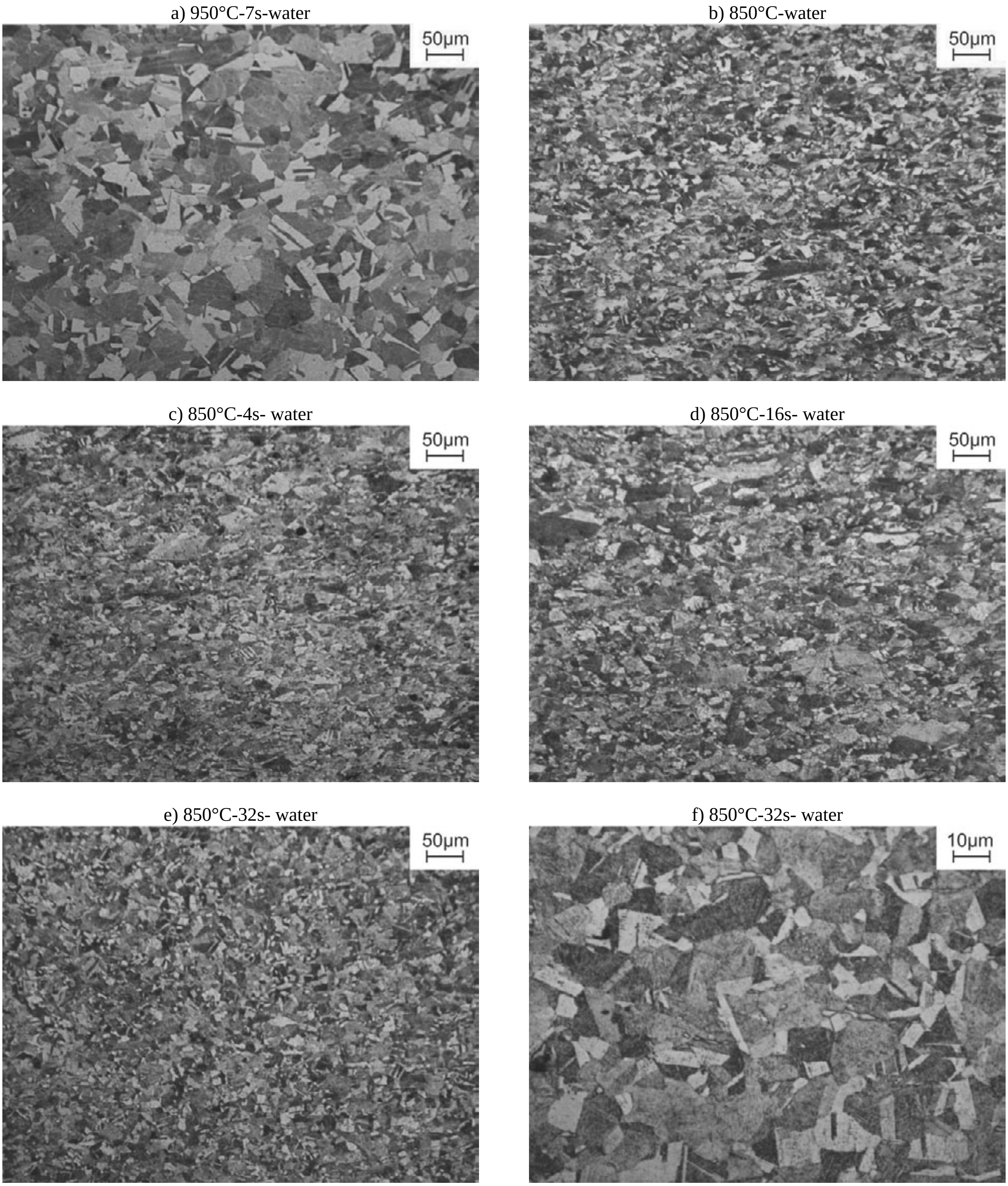

Fig. 6. Austenitic structures obtained after solutioning the steel in successive stages of the hot-working for the specimens compressed to a true strain 4x0.29 and isothermally held for the time from 0 to 64s: a) metadynamically recrystallized grains during the interval between third and fourth deformation,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

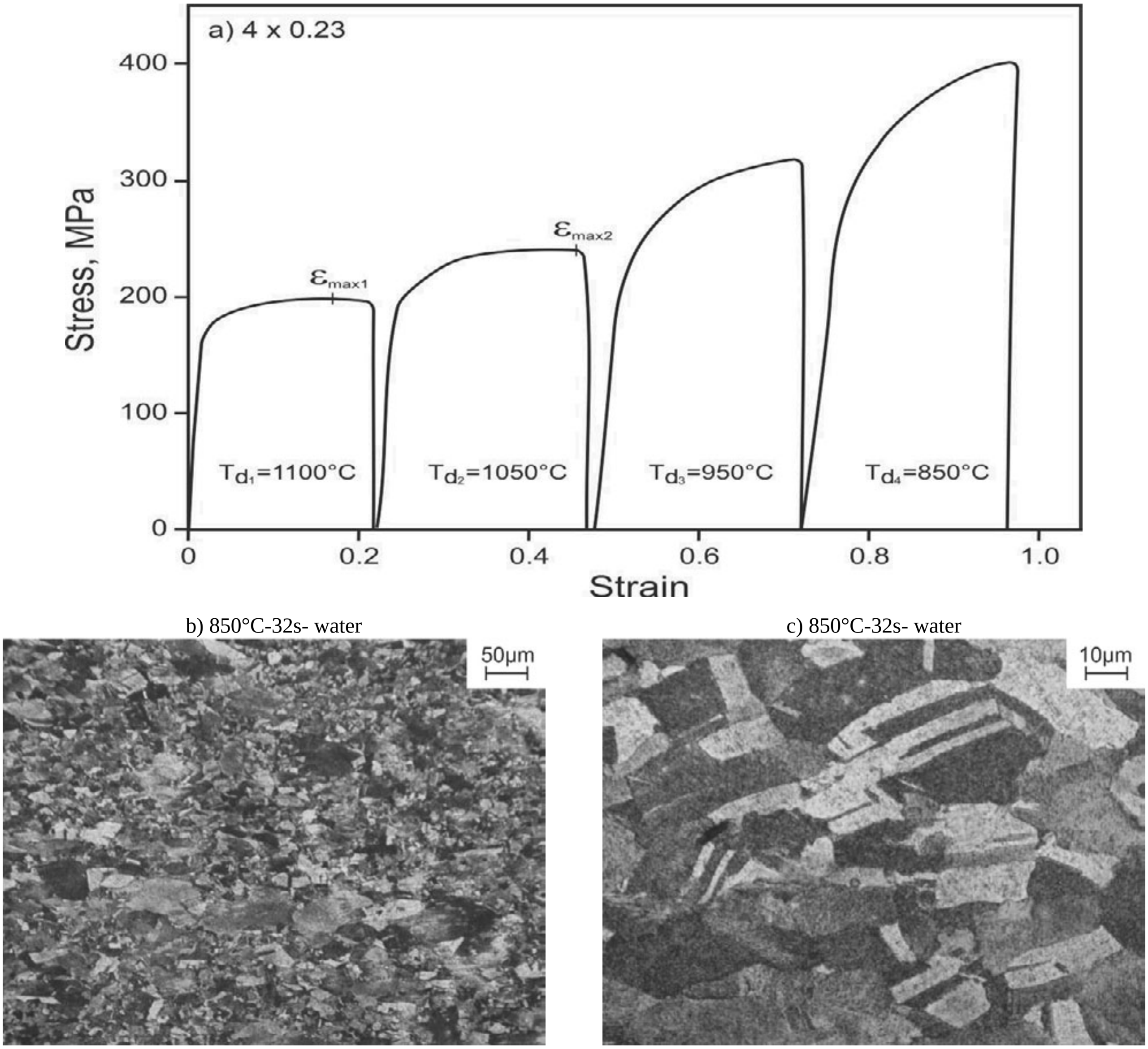

Fig. 7. Stress - strain curves after the multi-stage compression test of the axisymetrical specimens deformed with a true strain 4x0.23 in a temperature range from 1100 to 850°C (a), and statically recrystallized austenitic structures of the steel obtained after solutioning the specimen after isothermal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

Initiation of dynamic recrystallization during the last deformation at 850°C is confirmed by fine-grained austenite microstructure obtained as a result of water-quenching the specimen directly after fourth deformation (Fig. 6b). Isothermal holding of the steel after the deformation at 850°C for 4s does not cause any essential modifications of microstructure. The microstructure consists of fine metadynamically recrystallized austenite grains and larger grains in which the process controlling the work hardening during deformation was just dynamic recovery (Fig. 6c). Increase of isothermal holding time to 16s results in further refinement of the austenite microstructure due to metadynamic recrystallization of fine equiaxial grains and statical recrystallization of elongated dynamically recovered grains (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 10μm (Fig. 6f).

Decrease of true strain to 0.23 leads to changes of the course of stress-strain curves (Fig. 7a). The shape of these curves after deformation at the temperature of 1100 and 1050°C indicates the possibility of initiating dynamic recrystallization. However, decrease of the temperature causes that the process which controls strain hardening is dynamic recovery. Moreover, only partial course of static recrystallization during cooling of the sample between the third and fourth deformation results in increase of flow stress value during the deformation at 850°C to approximately 400MPa.

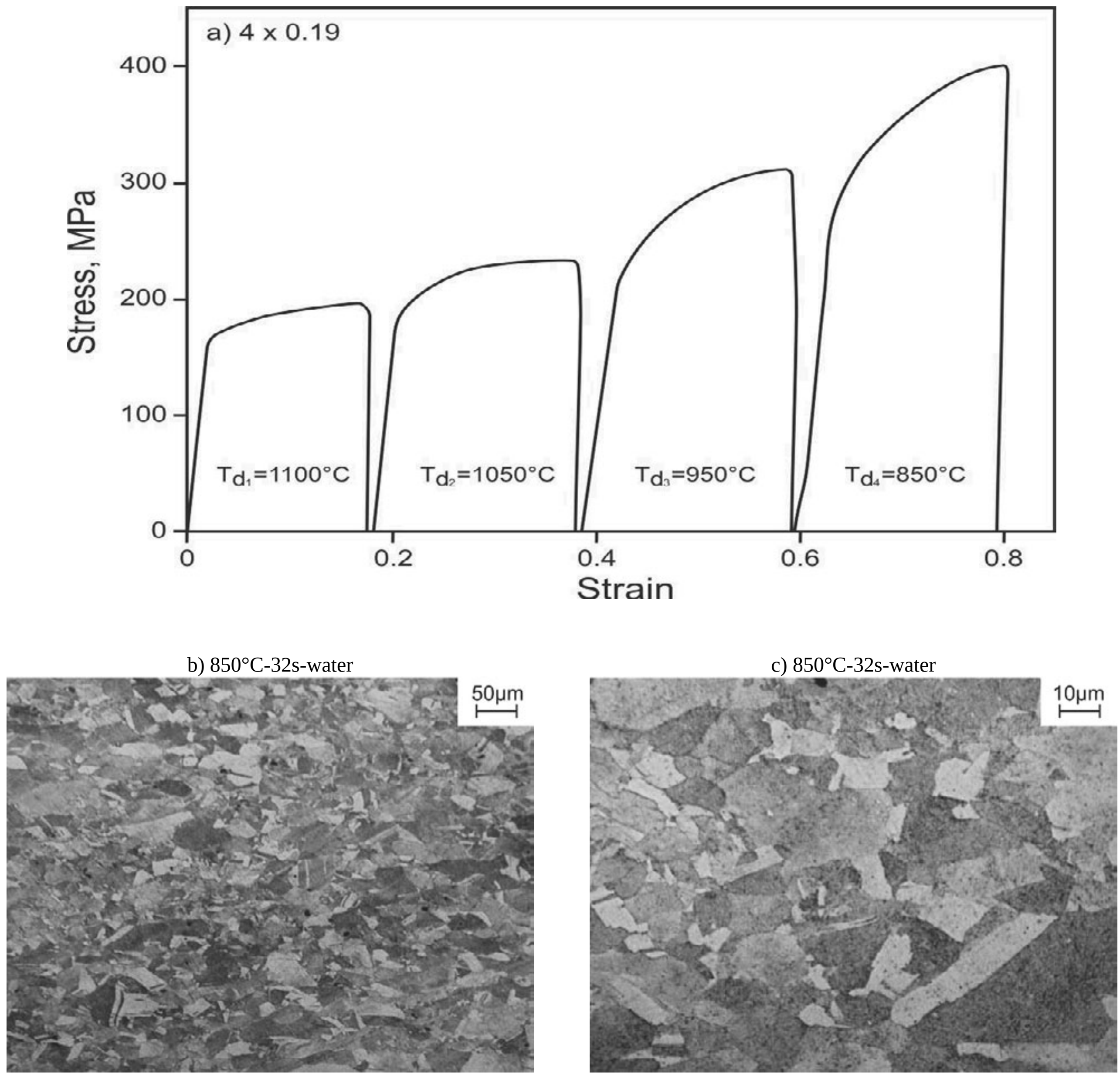

Fig. 8. Stress - strain curves after the multi-stage compression test of the axisymetrical specimens deformed with a true strain 4x0.19 in a temperature range from 1100 to 850°C (a), and austenitic structures of the steel in an initial stage of statical recrystallization obtained after solutioning the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

Obtaining fine-grained austenite microstructure requires holding of the steel after deformation for 32s, during which static recrystallization occurs in about 60% (Fig. 7b). Numerous annealing twins can be observed in the microstructure and a mean statically recrystallized austenite grain is higher compared to the specimen compressed 4x0.29 (Fig. 7c).

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 comparable values of flow stresses. Admittedly, holding of the steel for 32s results in obtaining certain participation of statically recrystallized grains, yet size of both recrystallized grains and statically recovered grains is bigger than after application of true strain equal 0.23 (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

The new-developed steel is characterized by uniform austenite microstructure containing annealing twins and some fraction of ε martensite. 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 continuous compression test showed that the steel possesses relatively high values of flow stress, however with not very high values of ε_{max} strain. It creates possibility of using dynamic recrystallization for obtaining fine-grained microstructure of steel. Taking advantage of dynamic recrystallization are confirmed by multi-stage compression results, in which lowering the flow stress in a range from 20 to 90 MPa dependent on a deformation temperature was observed and decreasing the critical strain ε_{max} to lower values. In case of applying the true strain 4x0.29, the refinement of the austenite microstructure during intervals between successive stages of deformation is caused by metadynamic recrystallization, whereas the fine-grained structure of the steel after the last deformation at a temperature of 850°C is a result of dynamic recrystallization. Further refinement of the microstructure can be obtained by isothermal holding of the steel in a finishing hot-working temperature for about 16s. In case of applying the lower deformations 4x0.23 and 4x0.19 often used in finishing stages of hot-working, the process controlling work hardening is dynamic recovery and a deciding influence on a gradual grain refinement of microstructure has statical recrystallization occurring during intervals between successive stages of deformation and after its finish as well.

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