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Hot-working behaviour of high-manganese austenitic steels

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Materials

ABSTRACT

Purpose: The work consisted in investigation of newly elaborated high-manganese austenitic steels with Nb and Ti microadditions in variable conditions of hot-working.
Design/methodology/approach: Determination of processes controlling strain hardening was carried out in continuous compression test using Gleeble 3800 thermo-mechanical simulator.
Findings: It was found that they have austenite microstructure with numerous annealing twins in the initial state. Continuous compression tests realized in the temperature range from 850 to 1050°C with the strain rate of $10s^{-1}$ enabled determination of yield stress values and values of ε_{max} deformations – corresponding to maximum flow stress. It was found that initiation of dynamic recrystallization requires true strain equal at least 0.29. Holding of steel after plastic deformation allowed determining the progress of recrystallization in the function of isothermal holding time. Determined half-times of recrystallization at 900°C after deformation with 25% of reduction are equal 32 and 17s for 27Mn-4Si-2Al-Nb-Ti and 26Mn-3Si-3Al-Nb-Ti steel, respectively. Several-stage compression tests with true strain of 0.29 permit to use dynamic recrystallization for shaping fine-grained microstructure of steel in the whole range of deformation temperature. Decreasing true strain to 0.23 limits the course of dynamic recrystallization to two first deformation cycles. In two final cycles of deformation, as well as in the whole range of hot-working realized with true strain of 0.19 – dynamic recovery is the process controlling strain hardening.
Practical implications: The obtained microstructure – hot-working conditions relationships and stress-strain curves can be useful in determination of power-force parameters of hot-rolling for sheets with fine-grained austenitic structures.
Originality/value: The hot-working behaviour and microstructure evolution in various conditions of plastic deformation for new-developed high-manganese austenitic steels with Nb and Ti microadditions were investigated.
Keywords: High manganese steel; Hot-working; TWIP-effect; Dynamic recrystallization; Static recrystallization

1. Introduction

The beginning of XXI century has brought a development of new groups of steels to be applied for sheets in automotive industry. From the aspect of materials, this development has been accelerated by strong competition with non-metal aluminium and magnesium alloys as well as with composite polymers, which meaning is successively increasing. From the aspect of ecology, an essential factor it is to limit the amount of exhaust gas emitted into the environment. It's strictly connected to the fuel consumption, mainly dependant on car weight and its aerodynamics. Taking into consideration increased quantity of accessories used in modern cars, decreasing car's weight can be achieved solely by optimalization of sections of sheets used for bearing and reinforcing elements as well as for body panelling parts of a car. Application of sheets with lower thickness preserving proper tautness requires using sheets with higher mechanical properties, however keeping adequate formability. Steels of IF and BH type with moderate mechanical properties and high susceptibility to deep drawing were elaborated for elements of body panelling [15]. The highest application possibilities belong to DP-type steels with ferritic – martensitic microstructure. Their mechanical properties can be formed in a wide range, controlling participation of martensite arranged in ferritic matrix. Sheets made of these steels are widely used for bearing and reinforcing elements [2]. In comparison to steels with ferritic microstructure they are characterized by high value of hardening exponent n, what decides about their strong strain hardening during sheet-metal forming [13].

Nowadays, 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. In this aspect, TRIP-type steels (TRansformation Induced Plasticity) with ferritic-bainitic microstructure with retained austenite are further direction of the development. Martensitic transformation of retained austenite into martensite occurs during forming, what leads to additional hardening of a ready part and to increase of total and uniform elongation [10]. Additionally, gradual transformation of austenite into martensite causes that coefficient of deformation is maintained at high level up to much higher range of deformation than in case of DP steels [8]. It creates possibilities of employing high deformations during manufacturing process without anxiety of excessive wall thinning of elements or cracking [5].

Benefits deriving from taking advantage of retained austenite in TRIP-type steels have captured attention of materials engineers to steels with homogeneous austenite microstructure. Although TRIP effect can be achieved in Cr-Ni austenitic steels [9], they are too expensive for their application in automotive industry. Therefore, intense researches on high-manganese austenitic steels have been performed in recent years. Apart from 15-30%Mn they also contain 0.03-0.2%C, 1-3%Si, 1-3%Al [7]. Mechanical properties of these steels depend on structural processes present during cold plastic deformation, which in turn are the derivative of stacking fault energy of austenite [6]. In case it's equal from 12 to 20 mJm^{-2}, partial transformation of austenite into martensite occurs making use of TRIP effect [11]. Values of SFE from 20 to 60 mJm^{-2} determine intense course of mechanical twinning connected to TWIP effect (TWinning Induced Plasticity) [16]. Making use of these phenomena allows to shape mechanical properties of steels in a wide range, i.e. $YS_{0.2}$=250-400 MPa, UTS=500-1000 MPa, UEl=30-70%. Moreover, strong strain hardening causes that the value of incremental exponent of deformation is maintained at high level up to the range of deformation wider than it is for TRIP-type steel with ferritic-bainitic matrix [3]. The set of mechanical properties predisposes discussed steels for parts absorbing impact energy applications, as well as for parts with complex shape, generally fabricated in several operations.

The majority of conducted researches is focused on optimalization of chemical composition of high-manganese steels and investigation of their behaviour during cold-working [7]. Taking into account dependence of SFE on temperature, plastic strain realized using different ways of load application takes place both in decreased and increased temperature [11]. Tests of dynamic strain, simulating the conditions of road collision, have also a substantial meaning [6]. However, developing the technology of production of high-manganese austenitic steels requires knowledge about their behaviour during hot-working. There is a shortage of sufficient information in science publications. In the work [14], the influence of initial grain size and deformation parameters on plasticity characteristics obtained in hot torsion tests for 18Cr-8Ni and 18Cr-17Mn-0.5C steels was investigated. It was found that Cr-Mn steel characterizes with much higher intensity of strain hardening than Cr-Ni steel, which makes more difficulties during plastic deformation. Higher intensity of strengthening of the steel with addition of manganese causes occurrence of maximal flow stress for smaller ε_{max} value. It gives opportunity for the refinement of structure by dynamic recrystallization. This phenomenon was investigated by Hamada et. al. [12] in 25Mn and 25Mn3Al steels in a temperature range from 900 to 1100°C. It was found that maximal flow stress at a temperature of 1100°C for 25Mn steel occurs for $\varepsilon_{max} = 0.17$.

Application of thermo-mechanical treatment consisting in immediate cooling of products from a finishing temperature of hot-working in controlled conditions should increase mechanical properties [4]. Introduction of Nb and Ti microadditions to steels could be the reason for additional strain hardening of high-manganese steels and allows forming a fine-grained microstructure in successive hot-working stages.

2. Material and experimental procedure

Investigations were carried out on two high-manganese austenitic Mn-Si-Al steels containing Nb and Ti microadditions (Table 1). Melts were realized in the Balzers VSG-50 inductive vacuum furnace. Ingots with a mass of 25 kg were submitted open die forging on flats with a width of 220 mm and a thickness of 20 mm. Then, cylindrical samples ∅10x12 mm were made. Preliminary tests consisted in solution heat treatment of the specimens from a temperature of 900°C and hot upsetting at temperatures of 900 and 1000°C up to a true strain of 0.29 and 0.50. To investigate a recrystallization progress, the specimens were held at the deformation temperature up to 64 s (Fig. 1). Upsetting was carried out using the PMS 50 eccentric press with a strain rate of about $30s^{-1}$.

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

In order to determine σ-ε curves high-temperature compression tests in the temperature of 850, 950 and 1050°C with $10 s^{-1}$ strain rate were performed. Work-hardening curves were assigned using DSI Gleeble 3800 thermomechanical simulator. The specimens were inserted in a vacuum chamber, where they were resistance-heated. Tantalum foils were used to prevent sticking and graphite foils as a lubricant. The evaluation of processes controlling the course of work-hardening was done through microstructure freezing of samples deformed in the temperature of 850°C and 950°C, to the engineering strain equal 20, 25, 40 and 60% (it corresponds to a true strain of 0.23, 0.29, 0.5 and 0.91, respectively).

Depending on application of loads possible in specific rolling mill and designed course of deformation sequences, it's essential to determine stress - deformation curves for different values of reduction. In purpose of mentioned above, the sequences of true deformations for successive variants of deformation were equal: 4x0.19, 4x0.23 and 4x0.29. The deformation was realized by compression also in the Gleeble 3800 simulator (Fig. 2).

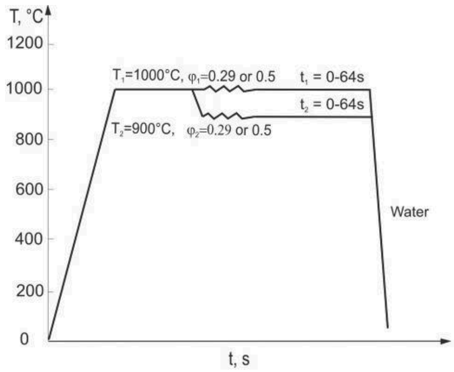

Fig. 1. Parameters of the preliminary hot upsetting tests

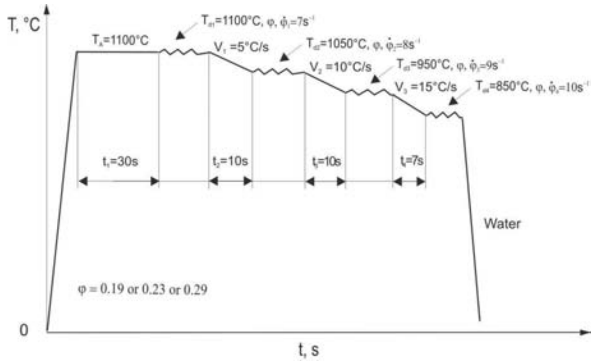

Fig. 2. Parameters of the multi-stage compression test realized in the Gleeble simulator

Metallographic tests of samples along with the determination of grain size and portion of recrystallized austenite fractions 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 austenite grain boundaries, samples were etched in nitric and hydrochloric acids mixture in 2:1 proportion.

3. Results and discussion

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 temperature of 900°C (Figs. 3, 4). Both steels possess fine-grained microstructure of austenite with grain sizes equal approximately around 14μm. Moreover, numerous annealing twins can be observed in the microstructure.

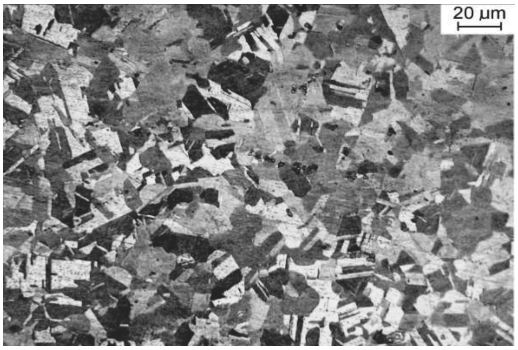

Fig. 3. Austenitic structure of the 27Mn-4Si-2Al-Nb-Ti steel after solution heat treatment from a temperature of 900°C

Fig. 4. Austenitic structure of the 26Mn-3Si-3Al-Nb-Ti steel after solution heat treatment from a temperature of 900°C

Microstructure development of 27Mn-4Si-2Al-Nb-Ti steel, solution heat treated from temperature of 850 or 950°C, after application of specified reduction, as well as σ-ε curves obtained in continuous compression test are presented in Fig. 5a-h. It arises from Fig. 5a that the steel is characterized by values of yield stress equal from 240 to 450 MPa in investigated range of temperature. These values are considerably higher than they are for conventional C-Mn steels as well as for Cr-Ni and Cr-Mn austenitic steels [14]. It proves high strain hardening, which is probably caused by high Mn concentration in the steel. Additionally, the increase of flow stress is influenced by Si and Al additives as well as Nb and Ti microadditions. Decrease of strain temperature by around 100°C results in increase of flow stress by around 100 MPa. 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. However, it's characteristic, that after strong strain hardening, peaks of ε_{max} are present for relatively low deformation values, i.e. from 0.23 to 0.48. It creates convenient conditions for using dynamic recrystallization for refinement of microstructure, what is confirmed by fine-grained microstructure of steel, solution heat treated from the temperature of 950°C after true strain of 0.5 (Fig. 5b). Decrease of true strain to 0.29, close to ε_{max} deformation in Fig. 5a, also leads to the initiation of dynamic recrystallization (Fig. 5c). Nevertheless, further decrease of reduction to 20% (true strain equal 0.23) is too low for initiating dynamic recrystallization (Fig. 5d). In such conditions, microstructure of steel is composed of dynamically recovered austenite grains elongated in the direction of plastic flow with size comparable to the sample solution heat treated from temperature of 900°C.

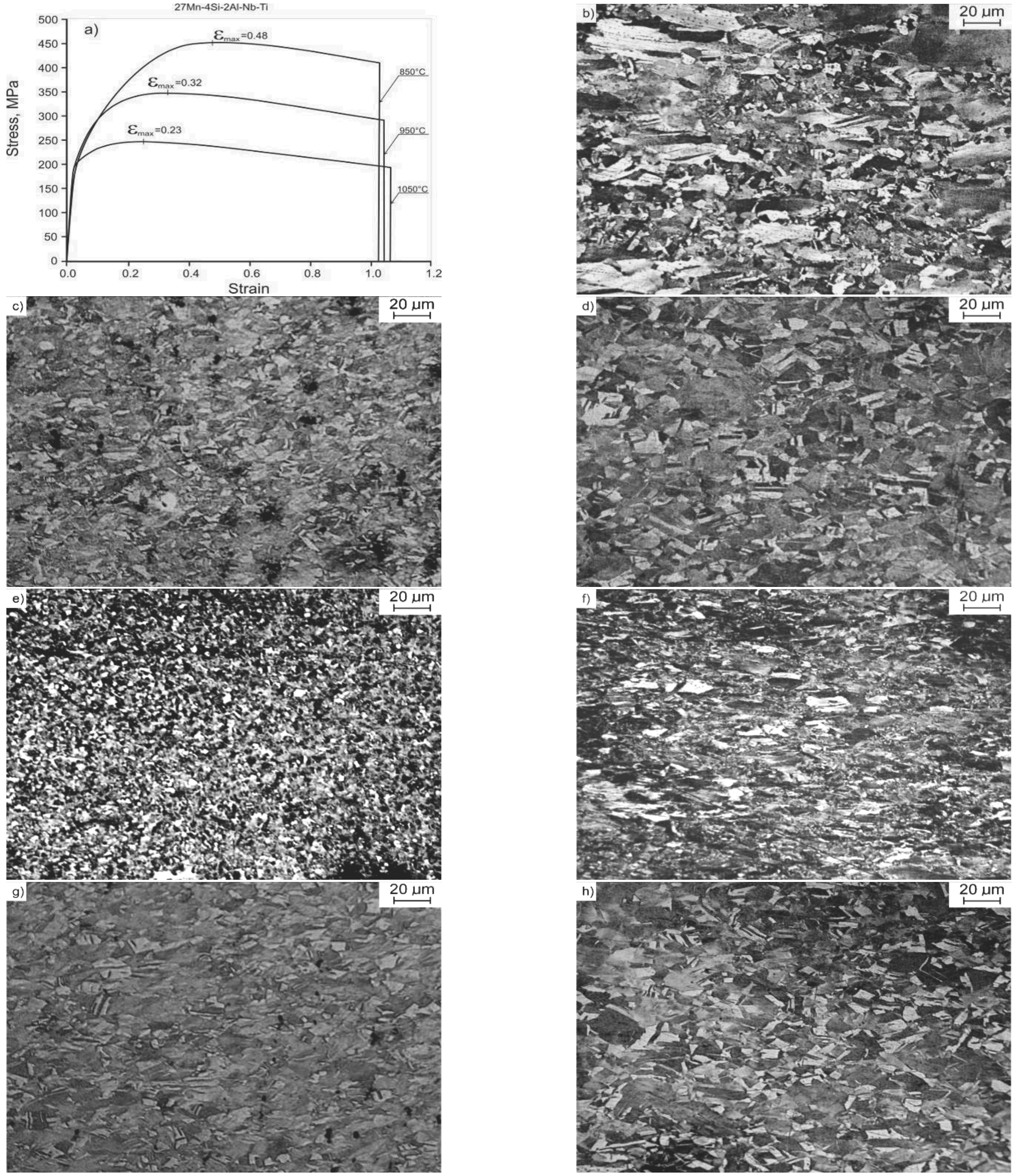

Fig. 5. Evolution of the microstructure of 27Mn-4Si-2Al-Nb-Ti steel compressed to a various strain: a) σ-ε curve; b) T = 950°C, ε = 0.5; c) T = 950°C, ε = 0.29; d) T = 950°C, ε = 0.23; e) T = 950°C, ε = 0.91; f) T = 850°C, ε = 0.5; g) T = 850°C, ε = 0.29; h) T = 850°C, ε = 0.23

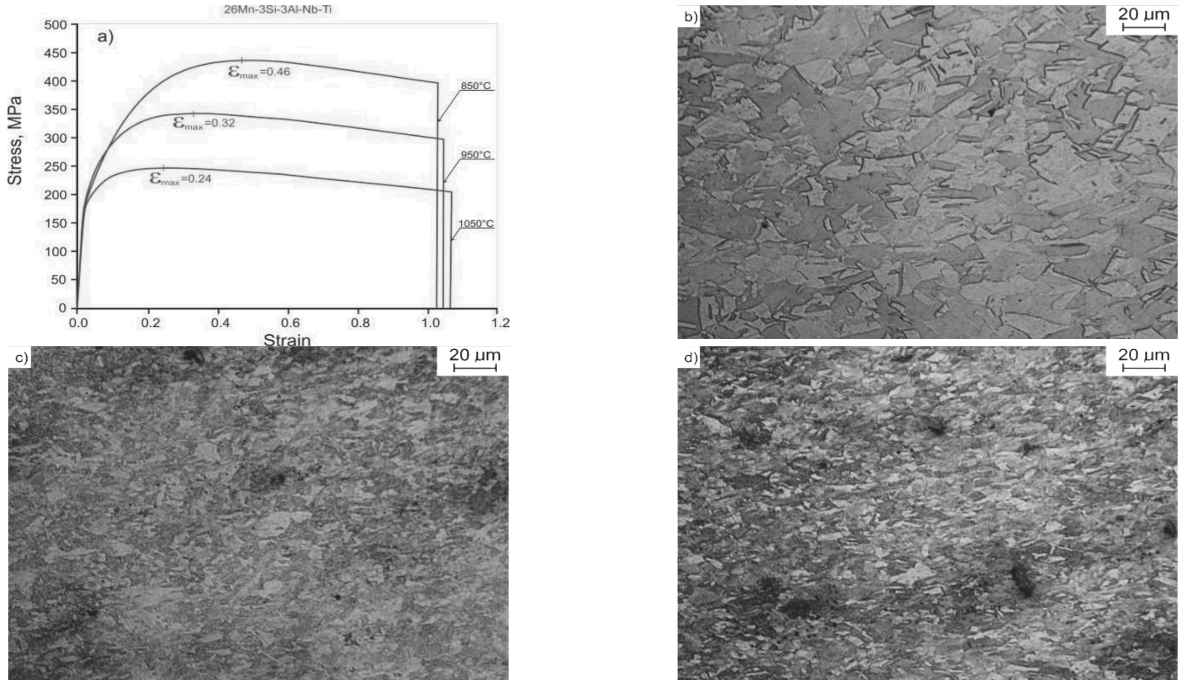

Fig. 6. Evolution of the microstructure of 26Mn-3Si-3Al-Nb-Ti steel compressed to a various strain: a) σ-ε curve; b) T = 850°C, ε = 0.23; c) T = 850°C, ε = 0.29; d) T = 850°C, ε = 0.5

After decreasing compression temperature to 850°C, fully recrystallized microstructure of austenite with grain size of approximately 3µm was achieved through application of true strain equal 0.9 (Fig. 5e). Decrease of reduction to 40% results in obtaining microstructure of recrystallized grains of austenite uniformly distributed in matrix of dynamically recovered grains with sizes slightly smaller than for the strain temperature of 950°C (Fig. 5f). Decrease of true strain to 0.29 is sufficient for initiation of dynamic recrystallization also for the deformation temperature of 850°C (Fig. 5g), although the value of ε_{max} is equal 0.48. It's in accordance with data presented in [1], in which it was stated that the initiation of dynamic recrystallization can occur at critical deformation value ε_{cd}=(0.5-0.85)ε_m. Solution heat treatment from temperature of 850°C after true strain of 0.23 doesn't cause grain refinement of microstructure as a result of dynamic recrystallization. Microstructure of steel is composed of slightly deformed grains of dynamically recovered austenite (Fig. 5h).

The σ-ε curves together with microstructures of 26Mn-3Si-3Al-Nb-Ti steel solution heat treated from the temperature of 850°C and specified reduction are presented in Fig. 6a-d. The course of σ-ε curves is almost identical as in case of steel discussed above (Fig. 6a). It refers both to the values of flow stresses and values of ε_{max} deformations. It can be observed in Fig. 6a that the only difference derives from slightly lower values of flow stress for the strain temperature of 850°C, what can be caused by lower solution hardening of aluminium when compared to silicon, which concentration is twice smaller than in 26Mn-3Si-3Al-Nb-Ti steel. Similarly as for the second steel, true strain equal 0.23 is too low for initiating dynamic recrystallization (Fig. 6b), which occurs after increasing true strain to 0.29 (Fig. 6c). Still, significant microstructure refinement requires application of deformation equal 0.5 (Fig. 6d).

Intervals between individual roll passes, in which thermally activated processes removing strain hardening occur, have particularly essential meaning for microstructure refinement in case of deformations realized in industrial conditions in range of reduction up to 25%. The development of microstructure of 27Mn-4Si-2Al-Nb-Ti steel isothermally held at the deformation temperature with different reductions is shown in Fig. 7a-i. For example, Figures 7a-c present microstructures of austenite of samples held for 4, 16 and 64 s after true deformation of 0.29 at temperature of 900°C. Holding of steel for 4 s practically doesn't cause any microstructure changes when comparing with a sample solution heat treated directly from the temperature of 850°C and analogical reduction. Dynamically recovered austenite grains elongated in the direction of plastic flow with small participation of metadynamically recrystallized grains are present in a great majority (Fig. 7a). Increase of holding time of steel to 16s results in significant microstructure refinement as a result of metadynamic recrystallization progress, which doesn't require any incubation period, as it does in case of static recrystallization (Fig. 7b). The course of static recrystallization of dynamically recovered grain regions leads to recrystallization of steel in over 80% after finishing of 64 s time (Fig. 7c). In case of possibility of applying 40% reduction, adequate stages of metadynamic and static recrystallization are being shortened in time (Fig. 7d, e), what results in obtaining fully recrystallized microstructure of the steel after 64 s of isothermal holding (Fig. 7f). Average size of recrystallized austenite grains is equal approximately 5 µm. Possibilities of application of higher deformations with cause of lower loads are available along with increase of plastic strain temperature up to 1000°C. Development of microstructure of specimens isothermally held, deformed in such temperature to true strain equal 0.5 is presented in Fig. 7g-i. After 4s the participation of metadynamically recrystallized grains is higher than it is in case of samples deformed at 900°C. They are mainly located at the boundaries of dynamically recovered austenite grains with bigger size than for the temperature of 900°C (Fig. 7g). The difference between sizes of dynamically recovered grains decays together with elongation of isothermal holding time of samples to 16s, in the result of intense course of dynamic recrystallization (Fig. 7h). Holding of steel in the deformation temperature for 64s causes gradual increase of recrystallized grains sizes (Fig. 7i).

Recrystallization course of 26Mn-3Si-3Al-Nb-Ti steel together with elongation of isothermal holding time, after finish of deformation with 25% of reduction at 900°C is presented in Fig. 8. Analyzing microstructures shown in Fig. 8a-c it can be stated, that the role of metadynamic recrystallization, favouring refinement of microstructure, is also dominant. The curves of recrystallization progress in the function of isothermal holding time are shown in Figs. 9 and 10. It arises from Fig. 9, that participation of recrystallized phase of 27Mn-4Si-2Al-Nb-Ti steel increases along with increasing deformation temperature and increase of reduction.

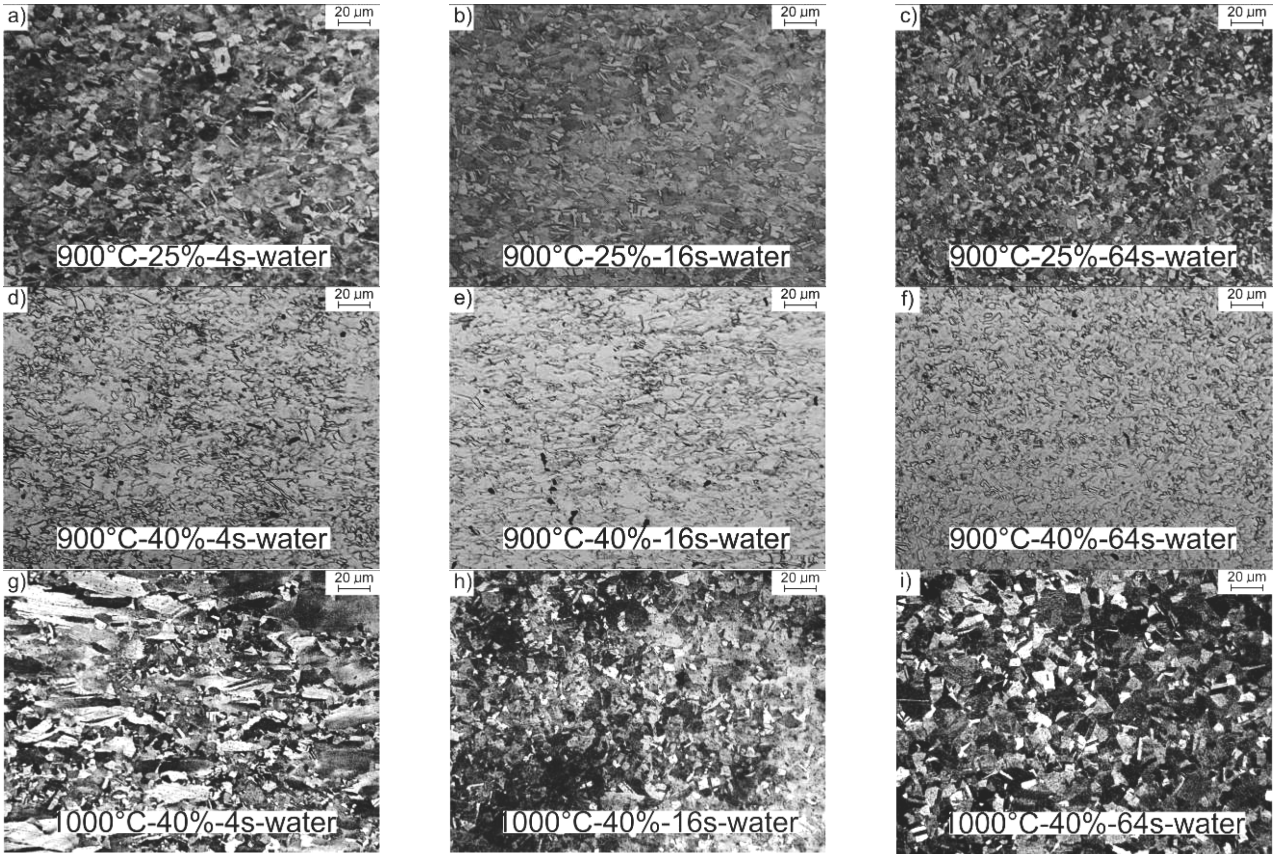

Fig. 7. Microstructure evolution of the 27Mn-4Si-2Al-Nb-Ti steel after isothermal holding for various time for the specimens plastically deformed: a, b, c) at 900°C, $\varepsilon = 0.29$; d, e, f) at 900°C, $\varepsilon = 0.5$; g, h, i) at 1000°C, $\varepsilon = 0.5$

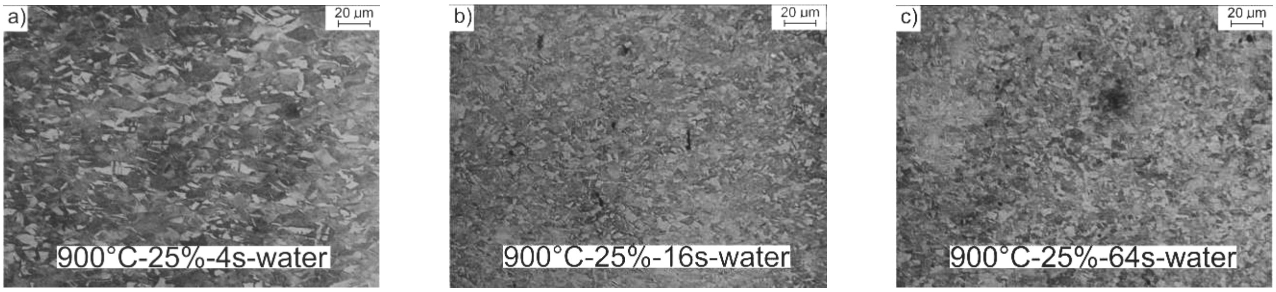

Fig. 8. Microstructure evolution of the 26Mn-3Si-3Al-Nb-Ti steel after isothermal holding for time: a) t = 4s; b) t = 16s; c) t = 64s; for the specimens plastically deformed at 900°C, $\varepsilon = 0.29$

Half-time of recrystallization at the temperature of 1000°C after deformation with 40% of reduction is equal 13s and increases to 18s after decreasing strain temperature to 900°C. Decrease of reduction to 25% results in elongation of $t_{0.5}$ time to 32 s, because of the change of prevailing participation of metadynamic recrystallization – in removing the effects of hardening – on behalf of static recrystallization. Half-times of recrystallization of 26Mn-3Si-3Al-Nb-Ti steel are shorter and are equal – 8, 12 and 17 s, respectively for analogical strain conditions (Fig. 10). It comes from higher participation of metadynamic recrystallization in removing effects of strain hardening, what arises directly from higher portion of dynamically recrystallized grains during plastic strain (Fig. 6c).

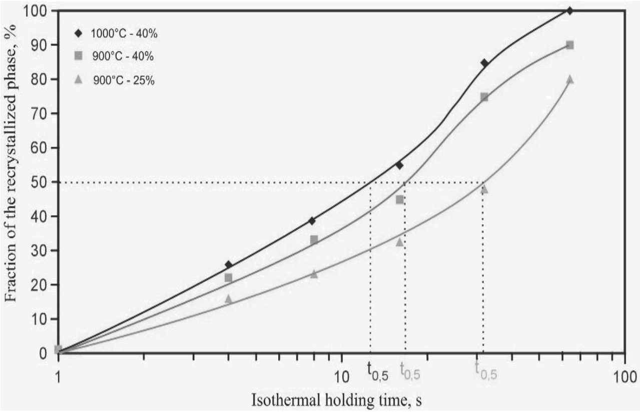

Fig. 9. Progress of recrystallization of the 27Mn-4Si-2Al-Nb-Ti steel isothermally held after plastic deformation in various conditions

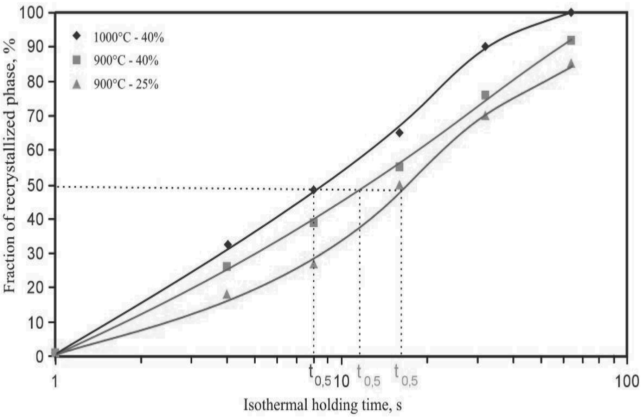

Fig. 10. Progress of recrystallization of the 26Mn-3Si-3Al-Nb-Ti steel isothermally held after plastic deformation in various conditions

Stress-deformation curves of steels plastically deformed according to the scheme shown in Fig. 2 are presented in Figs. 11-13. Application of true strain equal 0.29 during cyclic 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 (Fig. 11). After decreasing plastic deformation temperature, maximum on σ-ε curves is present for maximum value of true strain (0.29). Initiation of dynamic recrystallization at this deformation value is additionally confirmed by microstructures of steels solution heat treated after deformation in analogical conditions of continuous compression (Figs. 3c, 3g, 4c). The values of yield stress in the range of strain temperature from 1100 to 950°C are comparable with values obtained in continuous compression test; however deformation of steel with lower concentration of Si and Mn requires slightly lower pressures. Significant decrease of flow stress is noted for the last deformation realized at the temperature of 850°C (Fig. 11). It's a result of partial removal of strain hardening through metadynamic recrystallization that occurs during the interval between third and fourth deformation. Additionally, cyclic deformation as well as the course of partial recrystallization result in much faster achievement of maximum on σ-ε curve for the fourth deformation when comparing to σ-ε curve of continuous compression at the temperature of 850°C.

Decrease of true strain to 0.23 leads to a change of the course of σ-ε curves (Fig. 12). Shape of the curves after deformation at the temperature of 1100 and 1050°C indicate possibility of initiating dynamic recrystallization. However, decreasing the temperature causes that dynamic recovery is the process controlling strain hardening. Moreover, only partial course of static recrystallization during cooling of sample between third and fourth deformation results in increasing the value of yield stress during deformation at 850°C. Further decrease of true strain to 0.19 causes that dynamic recovery is the process controlling strain hardening in the whole temperature range of deformation (Fig. 13), at comparable values of yield stress.

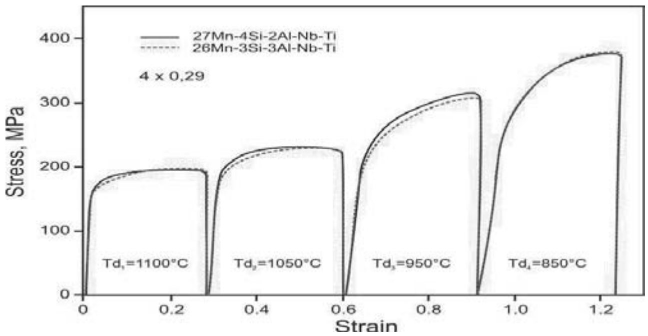

Fig. 11. Stress – strain curves for the specimens plastically deformed 4 x 0.29

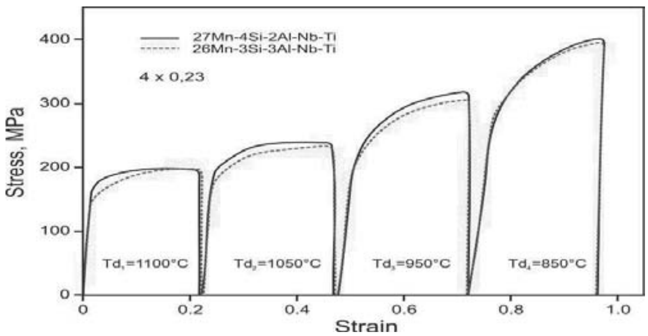

Fig. 12. Stress – strain curves for the specimens plastically deformed 4 x 0.23

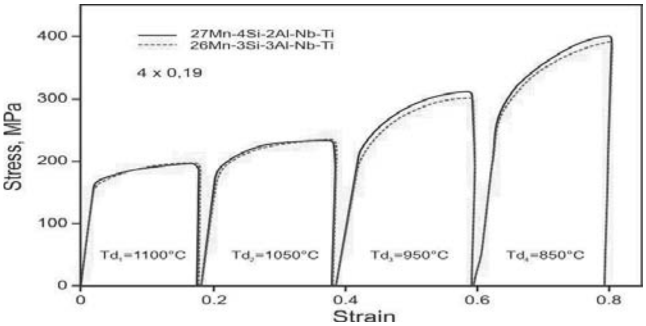

Fig. 13. Stress – strain curves for the specimens plastically deformed 4 x 0.19

4. Conclusions

Elaborated steels are characterized by relatively high values of flow stress, equal from 240 to 450 MPa, however with not very high values of ε_{max} deformation, corresponding to maximum value of yield stress. It creates possibility of using dynamic recrystallization for obtaining fine-grained microstructure of steel. Initiation of dynamic recrystallization in a temperature range from 850-950°C requires approximately 0.29 of true strain. Increase of true strain to 0.5 results in obtaining considerable participation of dynamically recrystallized grains located in the matrix of dynamically recovered austenite. Multi-stage hot compression tests allow stating that investigated steels have comparable values of flow stress. Cyclic deformation as well as partial course of recrystallization result in certain decrease of yield stress value, particularly in the final stage of hot-working. Determined half-times of recrystallization of austenite indicate that in the time of intervals between individual roll passes, partial recrystallization of γ phase should occur, contributing to achievement of fine-grained microstructure of steel. Faster course of metadynamic recrystallization in 26Mn-3Si-3Al-Nb-Ti steel is probably caused by lower total concentration of Si and Mn, when comparing to 27Mn-4Si-2Al-Nb-Ti steel.

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