DEVELOPMENT OF AUSTENITE MICROSTRUCTURE OF HSLA-TYPE STEEL DURING HOT-WORKING

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Abstract

The paper investigates the influence of hot-working parameters on the course of thermally activated dynamic and static processes in HSLA (High Strength Low Alloy) constructional steel, containing 0.17 % C, 1.37 % Mn and microadditions of Nb, Ti, V in the amounts of 0.025 %, 0.004 % and 0.019 %, respectively. In order to determine the stess - strain curves and the kinetics of recrystallization of plastically deformed austenite, the Gleeble 3800 thermomechanical simulator was used. Specimens were tested in the temperature range from 900 to 1000°C, at the deformation rate of 3 s^{-1}. Microstructure of primary austenite was revealed after two-stage compression of samples with given strain, with isothermal holding for the period from 0.2 s to 120 s; the activation energy of plastic deformation process of examined steel was determined. Obtained research results will allow to develop the technology of HSLA type microalloyed steel metal plates with the method of thermomechanical treatment - recrystallization controlled rolling.

Keywords: HSLA-type steels, thermomechanical treatment, austenite, dynamic recrystallization

1. INTRODUCTION

Knowledge of recrystallization rate as a function of temperature and size of grains formed during this process in steel, previously plastically deformed under given conditions, has an essential meaning for the design of industrial technologies of hot working, ensuring manufacture of metallurgical products not only with correct geometric form, dimensional tolerances and surface finish, but also with required mechanical properties. This applies, in particular, to multi-pass rolling of constructional steels, during which the softening of strain hardening in the intervals between final roll passes and during cooling of products from the finish temperature of this treatment occurs as a result of static recovery and static recrystallization [1-4].

Particularly useful technology of metallurgical products with high mechanical properties, assigned in a wide range for HSLA-type microalloyed steels, is a method of thermomechanical processing which integrates hot working with direct controlled cooling of products from the finish temperature of this treatment or after isothermal holding for $t_{0.5}$ (s) time [5-7]. The methods of thermomechanical processing are energy-saving ways of producing, for example, weldable plates with high strength and guaranteed crack resistance at reduced temperature, pipes, long shaped products, forgings and other, omitting expensive heat treatment or its limitation only to tempering or ageing, e.g. in case of steel with copper [8, 9].

The aim of the presented paper was to investigate the influence of hot-working parameters on the course of thermally activated dynamic and static processes in HSLA (High Strength Low Alloy) constructional steel.

2. EXPERIMENTAL PROCEDURE

The research was done on low-carbon toughening steel, containing (in wt. %): 0.17 C - 1.37 Mn - 0.26 Si - 0.012 P - 0.001 S - 0.24 Cr - 0.05 Ni - 0.48 Mo - 0.019 V - 0.025 Nb - 0.004 Ti - 0.059 Al - 0.004 N - 0.002 B.

Plastometric tests were carried out in Gleeble 3800 thermomechanical simulator, on axisymmetric samples with diameter of 10 mm and length of 12 mm. In order to determine the stress - strain curves and activation energy of plastic deformation process, continuous compression tests were performed on samples to the actual strain 1. Specimens were resistance heated under vacuum at the rate of 3 °C·s^{-1} up to the temperature of 1,150 °C, held at the temperature for 30 s and cooled to the temperature of deformation equal 1,100 °C; 1,050 °C; 1,000 °C; 950 °C and 900 °C. Compression of samples was carried out at a strain rate of 3 s^{-1}. The activation energy of the plastic deformation process Q (kJ·mol^{-1}) was calculated using the Energy 4.0 software [10].

In order to determine recrystallization kinetics of plastically deformed austenite, discontinuous compression tests of samples with applied two-stage plastic deformations ($\varepsilon_1 = \varepsilon_2 = 0.2$) were performed in a temperature range from 900 to 1,100 °C with isothermal holding of specimens between deformations for 0.2 s, 0.5 s, 2 s, 5 s, 10 s, 20 s, 60 s, 90 s and 120 s. Samples after the second deformation were cooled in water. The degree of strain hardening softening (softening fraction X (%)), was determined basing on the dependence:

$$X = \frac{(\sigma_1 - \sigma_2)}{(\sigma_1 - \sigma_0)} \tag{1}$$

where:

σ_0, σ_1 - the stresses necessary to initiate plastic strain and its value at the moment of its finish in the first stage of deformation, respectively,

σ_2 - the stress necessary to initiate plastic strain in the second stage of deformation after Δt (s) time passed between those stages.

Recrystallization kinetics of plastically deformed austenite was described with the use of the Johnson-Mehl-Avrami equation [11]. Metallographic observations of samples, cooled in water after two-stage plastic deformation, were performed on LEICA MEF4A light microscopy in the range of magnifications from 100 to 500x. Etching into primary austenite grain was carried out in saturated aqueous solution of picric acid at the temperature of 70 °C.

3. RESULTS AND DISCUSSION

Conducted continuous compression tests of samples performed at a strain rate of 3 s^{-1} allowed to determine the influence of plastic deformation temperature in a range from 1,100 to 900 °C on the form of stress - strain curves and ε_m (-) strain, corresponding to the maximum value of yield stress (see **Figure 1**), and hence to estimate strain necessary to initiate dynamic recrystallization of austenite ($\varepsilon_{cd} \approx 0.8 \cdot \varepsilon_m$) under investigated conditions. The data presented in **Figure 1** shows that along with temperature decrease, strain values ε_m move towards larger strains.

Decreasing the temperature of plastic deformation from 1,100 °C to 900 °C leads to increase of maximum yield stress σ_m from 118 MPa to 209 MPa and the strain ε_m from 0.26 to 0.69. The analysis of the form and the course of curves obtained in the compression test allows to state that in the studied range of hot plastic deformation parameters the decrease of strain hardening is caused by the process of dynamic recrystallization.

Determined activation energy of plastic deformation process of investigated steel is equal Q = 397 kJ·mol^{-1}. Comparable values of plastic strain activation energy for HSLA-type microalloyed steels with similar chemical composition were obtained in [12-14]. The value of activation energy of hot-working obtained for investigated steel is substantially higher than activation energy of selfdiffusion (creep), when the processes which control the course of plastic deformation are dislocation climbing and formation of subgrains. It means that the process of plastic deformation of the investigated steel is controlled by dynamic recrystallization.

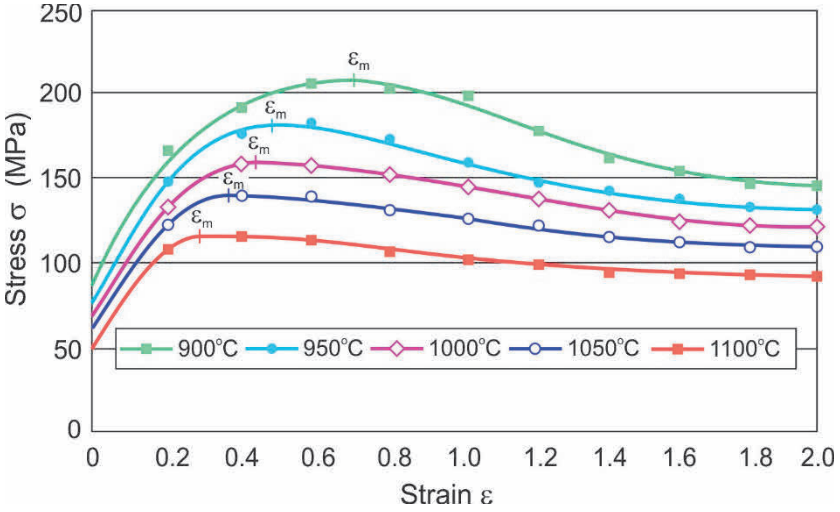

Figure 1 Influence of plastic deformation temperature on a shape of stress - strain curves

Conducted discontinuous compression tests of specimens at given strain revealed, according to expectations, that there is a partial and even complete softening of strain hardening during isothermal holding between two stages of deformation, depending on strain temperature and the time of isothermal holding. It's a consequence of the course of static recovery and static recrystallization. Detailed data on the kinetics of austenite recrystallization in the intervals between two stages of plastic strain at the rate of 3 s^{-1}, comparable to the deformation rate used in the rolling process of plates, is shown graphically in **Figure 2**.

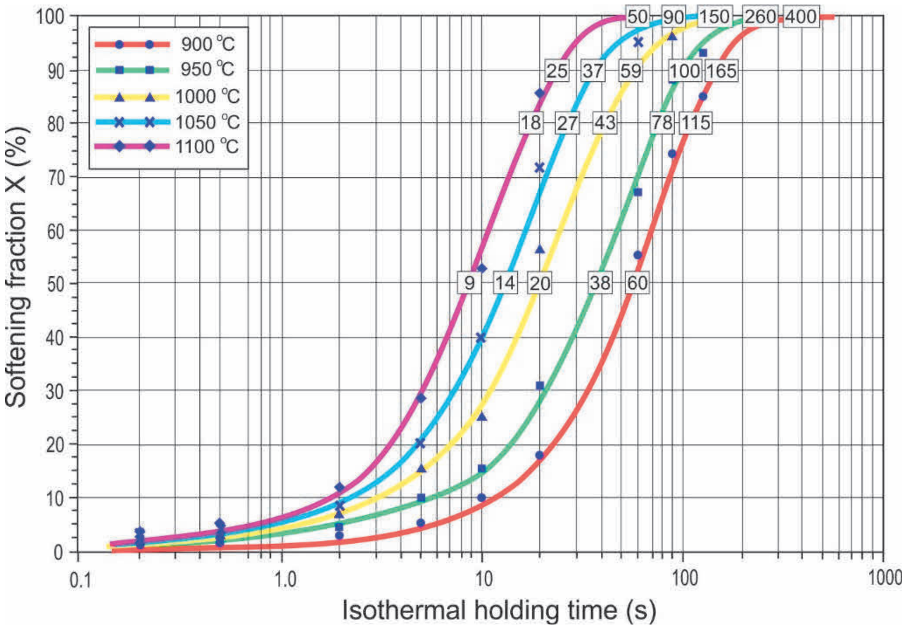

Figure 2 Effect of the test temperature on the softening fraction of plastically deformed austenite

It can be concluded from the data summarized in **Figure 2**, that inhibiting effect of the constituents introduced into the steel on the course of recovery process and static recrystallization of austenite is particularly effective after lowering the temperature of plastic deformation to 900 °C. At this temperature, dissolved in solid solution, there is Cr, Mo and partially vanadium microaddition, while Nb and Ti microadditions are bound into carbides and carbonitrides. The time of complete recrystallization of austenite t_R (s) at the temperature of 1,100 °C is equal 50 s and extends to 400 s at the temperature of 900 °C. In turn, the time $t_{0.5}$, required to form 50 % fraction of recrystallized austenite of steel deformed in the same temperature range, increases from 9 s to

60 s. Increase of time of recovery and static recrystallization of austenite is a result of synergistic effect of segregation of atoms dissolved in solid solution and MX-type dispersive particles of interstitial phases.

Metallographic examinations of samples quenched in water after two-stage plastic deformation in the temperature range from 900 °C to 1,000 °C for a given value of strain equal to 0.2 and isothermally held for 0.2 s to 120 s, revealed good correspondence with the course of the recrystallization kinetics curves. It was found that the size of recrystallized austenite grains depends significantly on the temperature of deformation and the time of isothermal holding. Austenite microstructure of specimens compressed at the strain rate of 3 s^{-1} at the temperature of 900 °C, after isothermal holding for 10 s to 120 s is shown in **Figure 3**.

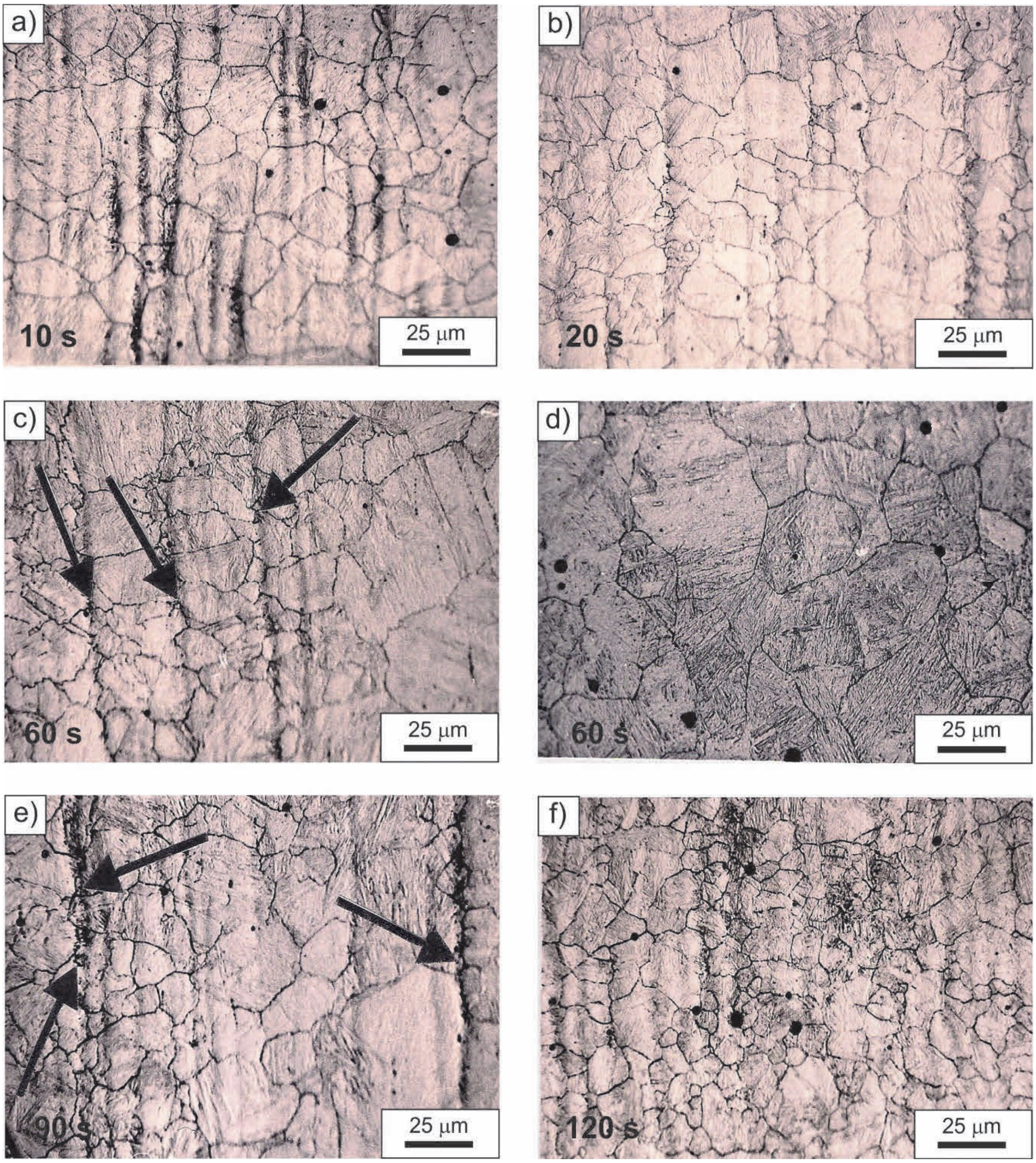

Figure 3 Prior austenite grains revealed after two-stage compression test at the temperature of 900 °C applying time intervals between deformation steps in range from 10 s to 120 s

Performed metallographic observations revealed clear differences in size of austenite grains in the outer zone of samples and in the core, which is the result of heterogeneous deformation distribution on sample cross-section. Moreover, in highly deformed zone of samples, dark bands propagating in the direction of deformation were observed, possibly being deformation (shear) bands formed as a result of inhomogeneous plastic deformation. Similar effects of inhomogeneous deformation were revealed in constructional steels [15-17], as well as in non-ferrous alloys [18] and in pure metals [19, 20]. Diversified size of austenite grains on the cross-section of sample deformed at the temperature of 900 °C after isothermal holding for 58 s (X = 50 %), before quenching in water, is presented in **Figure 3c**. The middle zone of the sample with distinct deformation bands visible in **Figure 3c** exhibits fine grained austenite microstructure with grain size of approx. 15 μm, passing into coarse grain microstructure of this phase with a grain size of approx. 35 μm in the outer zone of the sample (see **Figure 3d**). Extending the isothermal holding time at this temperature to 120 s (X = 85 %) leads to formation of almost completely recrystallized austenite microstructure with grain size of approx. 8 μm with distinct blur effect, revealing the presence of deformation bands (see **Figure 3f**). In some areas of penetration of discussed bands through grain edges, i.e. at the contact points of three grains, there are very fine grains - probably recrystallization nucleuses (arrows in **Figure 3c** and **Figure 3e**). It should be assumed that disclosed bands have high dislocation density and, in interaction with deformation in the edge region of grains, create favourable conditions for formation of recrystallization nucleuses.

CONCLUSIONS

Analysis of the shape and the course of stress - strain curves, obtained in the compression test, allows to conclude that in the examined range of hot plastic deformation parameters the main thermally activated mechanism controlling the process of plastic deformation is dynamic recrystallization of austenite. This is also confirmed by evaluation results of activation energy of plastic deformation process of examined steel.

Compression is a heterogeneous process leading to accumulation of deformation in successive cycles, to formation of shear bands with high dislocation density in austenite, the presence of which provides advantageous conditions for formation of recrystallization nucleuses.

Chemical composition of the steel, particularly the interaction of Mo, Cr, and microadditions of Nb and Ti, decides that thermally activated processes, resulting in softening of strain hardening of austenite after plastic deformation, occur relatively slowly, hence the time $t_{0.5}$, necessary to form 50 % fraction of recrystallized austenite and t_R - complete recrystallization of the phase is long, especially in the lower range part of hot working. Knowledge of t_R and $t_{0.5}$ times is necessary to design steel plates rolling with controlled recrystallization, with complete recrystallization of austenite in the intervals between successive roll passes and formation of at least 50 % fraction of recrystallized austenite after plastic working is done, prior to their hardening from rolling finish temperature.

Obtained research results allow to develop industrial technology of steel plates with high mechanical properties of investigated steel with the method of thermo-mechanical treatment - recrystallization controlled rolling.

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