INFLUENCE OF PLASTIC DEFORMATION CONDITIONS ON RECRYSTALLIZATION KINETICS OF Nb-Ti-V MICROALLOYED STEEL

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Abstract

The paper presents the results of the plastometric tests for the new-developed microalloyed steel containing 0.28%C, 1.41%Mn, 0.027%Nb, 0.028%Ti, 0.019%V and 0.003%B. The investigated steel is assigned to production of forged elements for the automotive industry by thermo-mechanical treatment. Continuous and double-hit compression tests were performed using the Gleeble 3800 thermomechanical simulator. The activation energy of the hot plastic deformation of the steel was determined on the basis of continuous compression of the specimens. The samples were investigated at the temperature range from 900°C to 1100°C and strain rate of 1, 10 and 50s\textsuperscript{-1}. The study covers the effect of softening during two following deformations for different interpass time.

Keywords: microalloyed steels, thermo-mechanical treatment, dynamic recovery, dynamic recrystallization, static recrystallization, softening kinetics, activation energy

1. INTRODUCTION

The pursuit of lower production cost is a basis for implementation of economical technologies of products made of constructional alloy steels with the methods of thermo-mechanical treatment. These methods consist in plastic working conducted in conditions adjusted to their chemical composition and the type of introduced microadditions with subsequent direct hardening of parts from the temperature of plastic deformation finish or after particular time specified. This allows reducing expensive heat treatment of products exclusively to tempering [1-6].

Hardening of products from the temperature of plastic working, directly after plastic deformation finish, usually does not assure expected functional properties, especially when it’s about products of steels containing elements with high chemical affinity for carbon. It’s connected with the influence of high density of dislocations on martensitic transformation and precipitation of dispersive carbides of alloying components and microadditions on these lattice defects in plastically deformed austenite prior to transformation start. Moreover, high density of dislocations in supercooled austenite and the presence of dispersive carbides make growth of products of martensitic transformation difficult and lead to decrease of hardenability. This impact, resulting in a decrease of concentration of carbon and alloying elements in martensite at significant participation of dispersive carbides, decides that hardness of steel quenched directly from plastic working finish temperature is relatively high, however, quickly decreases along with the increase of tempering temperature at simultaneous decrease and broadening of secondary hardenableness effect. Hence austenite, plastically deformed under given temperature and strain rate conditions, should be at least 50% recrystallized prior to hardening in order to avoid this disadvantageous impact of high density of dislocations and precipitation, with their participation, of carbides. It can be achieved through isothermal holding of products at plastic working finish temperature for the $t_{0.5}$ time - necessary to form 50% fraction of recrystallized austenite. The time substantially depends on chemical composition of steel [7-9] and can be determined basing on a research of kinetics of strain hardening decay (kinetics of austenite recrystallization). It can also be evaluated with the use of various modelling dependences regarding $t_{0.5}$ time, which are set together in the literature [10-14]. Verification of calculations can be performed experimentally basing on
metallographic observations of hardened specimens after $t_{0.5}$ passed after plastic deformation finish, revealing grain boundaries of primary austenite through etching.

2. EXPERIMENTAL PROCEDURE

The research was performed on new elaborated microalloyed steel. Chemical composition of steel (Table 1) was designed taking into consideration the production of forged machine elements with energy-saving method of thermo-mechanical processing.

Table 1. Chemical composition of the investigated steel (mass contents, %)

<table>
<thead>
<tr>
<th>Steel designation</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td>28MnTiNbVB</td>
<td>0.28</td>
<td>1.41</td>
<td>0.29</td>
<td>0.008</td>
<td>0.004</td>
<td>0.25</td>
<td>0.10</td>
<td>0.22</td>
</tr>
</tbody>
</table>

Investigated steel melts, weighing 100kg, were done in VSG-100 type laboratory vacuum induction furnace, produced by PVA TePla AG. Furnace charge consisted of ARMOCO, 04JA grade iron and alloy additions, mainly in the form of pure metals (Mn, Cr, Ni, Mo, Cu, Ti and Al) and ferroalloys (FeV, FeNb and FeB) as well as non-metallic additions (C and Si). In order to modify non-metallic inclusions, mischmetal (~50%Ce, ~20%La, ~20%Nd) in the amount of 2g/1kg of steel was used. Casting was performed in atmosphere of argon through heated intermediate ladle to quadratic section cast iron hot-topped ingot mould: top – 160/bottom – 140 mm x 640 mm. In order to obtain 32x160 mm flat bars, initial hot plastic working of ingots was performed implementing the method of open die forging in high-speed hydraulic press, produced by Kawazoe, applying 300MN of force. Heating of ingots to forging was conducted in gas forging furnace. The range of forging temperature was equal 1200÷900°C, with interoperation reheating in order to prevent the temperature of the material to drop below 900°C. Ingot bodies were subjected to forging without feedheads which were cut off during forging.

In order to determine the effect of temperature and strain rate as well as time of isothermal holding between two stages of deformation on changes of flow stress, strain hardening and degree of softening, plastometric tests were carried out with the use of GLEE BLE 3800 device, allowing to compress specimens according to established program. Axisymmetrical samples with 10 mm in diameter and 12 mm in length were used for the purpose of research. Continuous compression tests of samples up to true strain equal $\varepsilon=1$, applying graphite-tantallic washers reducing friction between end faces of specimens and anvils, were performed in order to evaluate $\sigma$-$\varepsilon$ curves and activation energy of plastic deformation. Specimens were resistance heated in vacuum at a rate of 3°C/s to a temperature of 1150°C, held at the temperature for 30 s and cooled to programmed deformation temperature equal 1100, 1050, 1000, 950 and 900°C. Compression of specimens was realized at a strain rate of 1, 10 and 50 s$^{-1}$. Activation energy of plastic deformation process was calculated using ENERGY 4.0 software. Part of samples subjected to true strain equal 0.2, 0.4 and 0.8 was cooled in water in order to freeze their microstructure and to identify processes which control the course of strain hardening. So as to determine kinetics of recrystallization of plastically deformed austenite, discontinuous compression tests of samples with applied deformation were performed in a temperature range from 900 to 1100°C with isothermal holding of specimens between successive deformations for 2 to 100 s. In order to reveal grains of primary austenite, metallographic observations of samples cooled in water directly after plastic deformation for applied value of strain and successive etching of metallographic specimens was conducted in OPTON, AXIOVERT 405M light microscope, with magnification ranging from 100 to 800x. Metallographic specimens were prepared according to axis of a sample, in a distance of 1/3 of radius from the centre of a sample.
3. RESULTS AND DISCUSSION

The analysis of the process of hot plastic deformation of 28MnTiNbVB steel was conducted in the temperature range from 900 to 1100°C and at the cooling rate of 1, 10 and 50 s\(^{-1}\), allowed to define the impact of compression parameters on the course of strain hardening curves, determined in the function of flow stress - strain (Fig. 1). In the initial stage of compression, substantial increase of flow stress, as a result of increasing density of dislocations generated in this process, can be observed on strain hardening curves in the range of strain hardening \(\varepsilon < 0.1\). In the next stage of compression, at strain increased from \(\varepsilon = 0.1\) to \(\varepsilon = \varepsilon_m\), slight increase of stress takes place up to attaining maximum value of flow stress. This indicates that thermally activated processes, causing partial decay of emitted dislocations, occurs along with formation of new dislocations during the plastic deformation. For the strain equal \(\varepsilon_m < \varepsilon < 1.0\), the curves of strain hardening are characterized with gentle decrease of flow stress up to the value of state equilibrium between processes of strain hardening and its decrease in the result of the course of thermally activated processes.

During compression of investigated steel at the rate of 10 s\(^{-1}\) at the temperature of 900°C, the value of \(\sigma_m\) is equal 246 MPa and is present at the strain equal \(\varepsilon_m = 0.527\). The increase of deformation temperature up to 1100°C at this strain rate leads to a decrease of stress to the value of 134 MPa. The \(\varepsilon_m\) value, corresponding to maximum flow stress at this temperature, is equal 0.384.

![Fig. 1. Influence of the plastic deformation temperature (a) and strain rate (b) on a shape of \(\sigma-\varepsilon\) curves](image)

The analysis of the form of curves obtained in the compression test allows to state that in the studied range of hot deformation parameters, the decrease of strain hardening is caused by the process of continuous dynamic recrystallization. This is also confirmed by the results of evaluation of activation energy of plastic deformation process of examined steel. Determined activation energy of plastic deformation process is equal \(Q = 379.95 \text{ kJ} \cdot \text{mol}^{-1}\). Obtained value of activation energy is substantially higher than activation energy of self-diffusion, 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 studied steel is controlled by dynamic recrystallization.

Exemplary microstructures of primary austenite of water-quenched samples from the temperature of 900°C, after applied logarithmic strain of 0.4 and 0.8 at the strain rate of 10s\(^{-1}\), are presented in Fig. 2. Examined steel after austenitizing at the temperature of 1150°C and compression performed at 900°C is characterized with austenite grains with the average size ranging from 25 to 65 \(\mu\text{m}\). Fine-grained microstructure of austenite is a result of the presence of NbC stable carbides essentially inhibiting grain growth of this phase.

Evaluation of the influence of testing temperature on the kinetics of thermally activated processes was enabled by conducted research of recrystallization after two-stage hot compression. Discontinuous compression tests of specimens at given strain revealed, according to expectations, that there is a partial
and even complete decay of strain hardening between two stages of deformation, depending on the strain temperature and the isothermal holding time. It’s a consequence of the course of static recovery and static recrystallization. The impact of atoms of alloying elements, dissolved in solid solution and the presence of dispersive particles of MX-type interstitial phases on a rate of recovery and mobility of recrystallization front, significantly influences kinetics of static recrystallization of studied steel.

Fig. 2. Primary austenite structures of steel water quenched from a temperature of 900°C after the true strain $\varepsilon=0.4$ (a) and $\varepsilon=0.8$ (b) with the strain rate of $10\text{s}^{-1}$.

Data shown in Fig. 3 indicates that inhibiting impact of alloying constituents introduced into steel on the course of recovery and static recrystallization of austenite is particularly effectively noted after decreasing the temperature of plastic deformation and the temperature of isothermal holding to 900°C. At this temperature, there is Mo and microaddition of vanadium present in a solid solution in dissolved state. While at this temperature, microadditions of Nb and Ti are completely bounded into NbC, TiN and TiC [15]. As shown in Fig. 3, the $t_{0.5}$ time, necessary to form 50% fraction of recrystallized austenite at the temperature of 1100°C, is equal approximately 8 s and increases to about 65 s together with decrease of the temperature of plastic deformation to 900°C. Time of total recrystallization of austenite, $t_R$, which varies from about 300 to about 800 s in considered temperature range, elongates even more.

Fig. 3. Effect of the test temperature on the softening fraction of deformed austenite for a investigated steel

In the result of two-stage compression of steel at the temperature of 900°C at the rate of $10\text{s}^{-1}$, diversified grain size of primary austenite, in a range from 25 $\mu$m to 70 $\mu$m, was achieved due to the course of static recovery and static recrystallization. Two-stage deformation of examined steel at the temperature of 1000°C
with the use of isothermal holding from 2 s to 100 s caused a decrease of strain hardening as a result of static recovery (Fig. 4a) and static recrystallization (Figs. 4b–d). In the investigated range of isothermal holding, the average grain size of austenite changes from 14 μm to 60 μm and obtained decrease of strain hardening is equal X = 0.83. Isothermal holding of specimens at the temperature of 1100°C for 2 and 5 s after the first strain equal ε = 0.2 resulted in a decrease of work hardening of steel as an outcome of the course of static recovery and static recrystallization, which determines obtaining the size of primary austenite with average size equal 20 μm and 33 μm, respectively. For the time of isothermal holding equal 10, 50 and 100 s, the fraction of recrystallized grains is equal 63, 83 and 96%, respectively.

**Fig. 4.** Primary austenite grains revealed after two-stage compression tests at the temperature of 1000°C at the rate of 10 s⁻¹ applying breaks between deformations in a range from 2 s to 100 s (a–d)

**CONCLUSIONS**

Continuous compression tests of samples performed at a rate of 1, 10 and 50 s⁻¹ allowed to determine the influence of plastic deformation temperature in a range from 1100 to 900°C on the form of σ–ε curves and εₘ strain, corresponding to the maximum value of flow stress, and hence to estimate strain necessary to initiate dynamic recrystallization of austenite under investigated conditions. The course of σ–ε curves and the values of activation energy indicate that the process of plastic deformation of studied steel is controlled by the course of dynamic recrystallization.

Conducted two-stage compression tests indicated that the time of total recrystallization of austenite in a temperature range from 1100°C to 900°C changes from 300 to 800 s. This means that the complete course of recrystallization of austenite requires long times, unacceptable in the production process of forgings. Therefore, the t₀.₅ time has a greater meaning than tᵣ for technological purposes. Moreover, considerable deformation at high rate and short duration intervals for moving produced parts from one die impression to
another do not create convenient conditions for the course of static recrystallization, enabling grain refinement of austenite grains. Hence, forgings should be isothermally held at the temperature of forging finish prior to hardening for the time necessary to form 50% fraction of recrystallized austenite, which for investigated steel is equal 65 s. Performed hot compression tests will contribute to establishing forging conditions for newly elaborated micro-alloyed steel with the method of thermo-mechanical treatment.

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LITERATURE


