THERMO-MECHANICAL TREATMENT OF FORGED PRODUCTS OF Ti-V-B MICROALLOYED STEEL

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Abstract

The work presents research results of the influence of thermo-mechanical treatment via forging on microstructure and mechanical properties of newly elaborated microalloyed steel containing 0.31%C, 1.45%Mn, 0.033%Ti, 0.008%V and 0.003%B. Conditions of forging with the method of thermo-mechanical treatment were developed basing on the analysis of precipitation kinetics of MX interstitial phases in a solid solution, plastometric examinations and investigations of the kinetics of supercooled austenite phase transformations. Applied thermo-mechanical treatment allows obtaining fine-grained microstructure of austenite during hot-working and production of forged parts, which acquire advantageous set of mechanical properties and guaranteed crack resistance after controlled cooling from finishing plastic deformation temperature and successive tempering. Forgings produced with the method of thermo-mechanical treatment, consecutively subjected to tempering in the temperature range from 550 to 650°C, reveal the values of YS0.2 equal from 954 to 878 MPa, UTS from 1040 to 939 MPa, KV -40 from 50 to 69 J and hardness ranging from 330 to 300 HB.

Keywords: microalloyed steels, thermo-mechanical treatment, forged elements, mechanical properties, cracking resistance

1. INTRODUCTION

Thermo-mechanical processing is an energy-saving technology used for production of rolled and forged products, integrating hot-working with heat treatment, usually hardening. Production of machine parts from forgings requires application of machining methods. It reduces possibility of production of high-strength forged parts from alloy constructional steels which due to considerable content of carbon and alloying elements increasing hardenability are difficult to be machined mechanically, quenched and tempered, by reason of relatively high hardness. Microalloyed constructional steels consisting of about 0.3%C and 1.5%Mn and microadditions of Nb, Ti, V and N in an amount of 0.1% and B in an amount up to 0.005% have good machining properties in this state. Metallic microadditions in the appropriately adjusted temperature range of plastic working form with nitrogen and carbon dispersive particles of MX interstitial phases with NaCl cubic lattice, reducing grain growth of statically, dynamically or metadynamically recrystallized austenite. Fine-grained recrystallized austenite undergoes transformation into fine-acicular martensite during hardening of products in properly selected temperature of plastic working finish, making a significant contribution to the strengthening of products and improvement of their crack resistance, also in the state after high-temperature tempering [1-5]. Fine-grained steels are characterized with decreased hardenability and for this reason they can be used for machine parts with relatively small cross-section. Hardenability of such steels can be improved through introduction of boron microaddition, which impact is effective only in a dissolved state in solid solution. The desired effect can be achieved solely in case of steels with high metallurgical purity, considering that this element, due to its high chemical affinity for oxygen and nitrogen, forms B2O3 oxide in liquid metal transiting into slag and bonds in a stable BN nitride in solid state [6,7]. Although BN nitride dissolves in solid solution, it requires application of high austenitizing temperatures; such
temperatures also lead to dissolution of AlN and dissolution of the part of MX phases of microadditions introduced into steel. It’s usually the cause of disadvantageous grain growth and deterioration of ductility.

Conditions for the production of unalloyed and alloy steel forgings are selected taking into account the durability of forging tools. This principle also applies in case of production of microalloyed steel forgings with the method of controlled forging and thermo-mechanical treatment. However, in this case the conditions for charge heating should be adjusted to the stability of MX interstitial phases of microadditions introduced into steel, without admission to austenite grain growth. High rate of plastic working during forging, also on presses, and short intervals between successive impacts of a hammer, do not create favourable conditions for the course of static recrystallization of austenite and grain refinement of this phase. Therefore, steels assigned for forgings consist usually of few microadditions, including Ti which forms TiN and TiC phases with highest stability and Nb or V and N, which NbC and VN phases, precipitating in austenite in the vicinity of plastic working finish temperature, effectively reduce grain growth of \( \gamma \) phase after static recrystallization is finished. Exclusive introduction of Ti in concentration exceeding the optimum is disadvantageous for the reason that initially precipitating TiN and TiC dispersive particles undergo coagulation at high temperature and demonstrate susceptibility to cracking under dynamic loads [8].

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>
<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>31MnTiB</td>
<td>0.31</td>
<td>1.45</td>
<td>0.30</td>
<td>0.006</td>
<td>0.004</td>
<td>0.26</td>
<td>0.11</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>Nb</td>
<td>Ti</td>
<td>V</td>
<td>B</td>
<td>Cu</td>
<td>Al</td>
<td>N</td>
<td>O</td>
</tr>
<tr>
<td></td>
<td>−</td>
<td>0.033</td>
<td>0.008</td>
<td>0.003</td>
<td>0.20</td>
<td>0.040</td>
<td>0.0043</td>
<td>0.0006</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 ARMCO, 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.

Conditions of hot processing and cooling after its finish, allowing to obtain desired mechanical properties of forgings, were selected taking into consideration:

- analyses of the kinetics of MX-type interstitial phases precipitation in a solid state [9],
- research of the influence of austenitizing temperature on \( \gamma \) phase grain size [10],
- investigation of the process of hot-working of steel with the method of continuous compression of specimens at the rate of 1, 10 and 50 s\(^{-1}\) in a temperature range from 1100 to 900°C [11],
- examination of the kinetics of strain hardening (recrystallization) softening of plastically deformed austenite in mentioned conditions [12],
- research of the kinetics of phase transformations of supercooled austenite [13].

Obtained research results were used to develop two variants of forging with the method of thermo-mechanical treatment of flat bars with 160x32 mm cross section into 14 mm thick flat bars, in the
temperature range of 1100 to 900°C at the strain rate equal 3 s\(^{-1}\), applying 50% of draft. The charge for forging was heated up to 1150°C and held at the temperature for 45 minutes. In the first variant, segments of flat bars were hardened in water directly from the temperature of forging finish. While in the second variant, flat bars were isothermally held at the temperature of 900°C for 10, 30 and 100 s after forging finish and prior to hardening in water. Directly after quenching, obtained flat bars sections were subjected to tempering at the temperature of 550 and 650°C for 1 h. Moreover, in order to compare the microstructure and mechanical properties of flat bars produced with the method of thermo-mechanical treatment, selected segments of flat bars were air-cooled after forging finish and successively subjected to conventional heat treatment, i.e. quenching in water from the austenitizing temperature proper for the steel, i.e. 900°C and tempering in the same conditions as the segments of flat bars obtained in both variants of thermo-mechanical treatment (variant III).

Metallographic investigations of specimens hardened after plastic deformation under mentioned conditions were done in Leica MEF 4A light microscope. With the aim to reveal grain boundaries of prior austenite, etching in saturated water solution of picric acid with addition of CuCl\(_2\) at the temperature of 60°C was applied. The measurement of prior austenite grain size was performed with the use of Leica Qwin software. Morphological details of structural constituents of the steel were carried out in ZEISS - SUPRA 35 high-resolution scanning electron microscope, applying the accelerating voltage equal 20kV and magnification in a range from 100 to 15000x. Hardness measurements were performed with the use of Brinell method.

In order to investigate the influence of implemented thermo-mechanical treatment and in particular the conditions of isothermal holding of forged flat bars on mechanical properties, static tensile test was carried out. The study was conducted on INSTRON 1115 universal testing machine. The tests were performed on samples with a diameter of 8 mm and a gauge length of 40 mm. Impact testing at room temperature and at -40°C was carried out on the Charpy pendulum machine with initial energy of 300 J, using V-notch specimens with cross-section of 8x10 mm. At least 3 samples taken from flat bars produced applying each treatment variant were used with the aim to test mechanical properties and crack resistance.

3. RESULTS AND DISCUSSION

Metallographic studies of specimens taken from flat bars obtained using the II variant of thermo-mechanical treatment revealed that investigated steel is characterized with fine-grained microstructure of primary austenite. Such microstructure was obtained as a result of isothermal holding of forgings for the time assuring the smallest size of recrystallized austenite grains. The time at the temperature of 900°C is equal 30 s and a mean diameter of austenite grains is equal about 12 \(\mu\)m (Fig. 1a). The microstructure of fine-acicular martensite obtained under such conditions is presented in Fig. 1b.

Conducted research of the influence of applied variant of processing as well as tempering temperature on the hardness of 31MnTiB steel flat bars revealed that the highest hardness – 330 HB – is demonstrated by forging formed according to the II variant of thermo-mechanical treatment with application of isothermal holding at the temperature of forging finish for 30 s prior to water hardening, then subjected to tempering at the temperature of 550°C. Increase of tempering temperature of the flat bar segment formed under such conditions up to 650°C results in a mild decrease of hardness to about 320 HB. The lowest hardness was revealed in case of segments of flat bars cooled in open-air from the temperature of forging finish. The hardness of flat bars obtained in such conditions after tempering in the temperature range from 550 to 650°C changes from 300 to 270 HB.
Fig. 1. Microstructure of prior austenite (a) and lath martensite (b) of steel hardened in water directly from the temperature of forging finish (900°C), after isothermal holding at the temperature for 30 s; II variant of thermo-mechanical treatment.

Microstructure of investigated steel, both in hardened and tempered condition, has a major influence on mechanical properties of flat bars segments produced in both variants of thermo-mechanical treatment, subjected successively to tempering at the temperature of 550 and 650°C. This applies to YS₀.₂ yield strength, UTS strength, TEI elongation and RA necking set in the static tensile test at room temperature, as well as to the impact energy of Charpy V samples at room temperature (KV) and at -40°C (KV⁻⁴⁰).

Conducted research revealed that the segment of the flat bar made from 31MnTiB steel, obtained in the first variant of thermo-mechanical treatment applying direct water hardening after forging finish at the temperature of 900°C, demonstrates the value of YS₀.₂ equal about 954 MPa, UTS strength of about 1040 MPa, TEI elongation of around 14%, RA necking of approximately 55% and KV and KV⁻⁴⁰ impact energy of 66 and 50 J, respectively (Fig. 2). Increase of tempering temperature up to 650°C results in mild decrease of mechanical properties and improvement of ductility of steel.

Enhanced set of mechanical properties in tempered state under examined conditions was noted for forgings produced according to the second variant of thermo-mechanical processing using isothermal holding at the temperature of forging finish for 10, 30 and 100 s prior to quenching in water. Partial recrystallization of plastically deformed austenite speaks that segments of flat bars formed in such conditions show, after tempering in the studied temperature range, mechanical properties comparable with the properties of those produced in the first variant of thermo-mechanical treatment, but significantly higher crack resistance. As per example, KV and KV⁻⁴⁰ impact energy of specimens taken from the segment of the flat bar obtained according to the second variant of thermo-mechanical treatment with the use of isothermal holding for 30 s at the temperature of 900°C prior to quenching in water, after tempering at the temperature of 550°C is equal 82 and 60 J, respectively, and after tempering at the temperature of 650°C – 93 and 69 J, respectively. Whereas the value of YS₀.₂ in this range of tempering temperature decreases from 993 to 925 MPa.

Studies carried out to compare the impact of conventional heat treatment (variant III) on mechanical properties of samples taken from the section flat bar cooled in the open air from the temperature of forging finish and successively tempered in the same conditions as flat bar sections, formed according to the first and the second variant of thermo-mechanical processing, revealed that the steel in this state demonstrates slightly decreased mechanical properties and significantly reduced crack resistance (Fig. 2).
CONCLUSIONS

Performed investigations showed that thermo-mechanical treatment conducted under conditions that ensure production of fine-grained microstructure of austenite before quenching and subsequent tempering gives studied steel better set of mechanical properties and, in particular, considerably greater resistance to cracking as compared with the state after open air cooling from the temperature of plastic working finish. The greatest set of mechanical properties and crack resistance was obtained for forging formed according to the II variant of thermo-mechanical treatment with the use of isothermal holding at the temperature of forging finish for 30 s prior to water quenching. Section of the flat bar obtained in such conditions reveals the following properties after tempering in the temperature range from 550 to 650°C: YS from 993 to 925 MPa,
UTS from 1061 to 978 MPa, TEI from 13.4 to 14.6\%, RA from 53.7 to 60\%, KV from 82 to 93 J and KV\textsuperscript{40} from 60 to 69 J.

Obtained hardness values for examined steel in hardened state after thermo-mechanical treatment and successive high-temperature tempering should not cause difficulties in the process of mechanical treatment of forged parts.

Executed analyses of mechanical properties, crack resistance and hardness in quenched and tempered state revealed full usability of elaborated microalloyed steel for production of forged machine parts with high strength and crack resistance, also in decreased temperature with the method of thermo-mechanical treatment.

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LITERATURE


