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The influence of hot-working conditions on the structure and mechanical properties of forged products of microalloyed steel

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ABSTRACT

Purpose: Results of the effect of thermomechanical processing conditions on the microstructure, mechanical properties and crack resistance are included in the present work. 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 undercooled austenite phase transformations.

Design/methodology/approach: Light microscopy and transmission electron microscopy techniques were used to reveal the microstructure of samples obtained as a result of the thermomechanical forging. Mechanical properties and hardness tests as well as resistance to cracking using Charpy V samples at room and lowered temperature were carried out.

Findings: 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 $YS_{0.2}$ equal from 994 to 939 MPa, UTS from 1084 to 993 MPa, KV^{-40} from 77 to 83 J and hardness ranging from 360 to 310 HBW.

Research limitations/implications: 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 at decreased temperature with the method of thermo-mechanical treatment.

Practical implications: The applied thermomechanical forging conditions can be useful for elaboration of an industrial forging technology for selected forged elements of microalloyed steels with high strength and guaranteed crack resistance.

Originality/value: Thermomechanical forging conditions for a new-developed microalloyed steel were established.

Keywords: Microalloyed steels; Thermo-mechanical treatment; Forged elements; Crack resistance

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PROPERTIES

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 [1-7].

Niobium is one of the most frequently added microalloying elements because of its strong effect on the improving microstructure and mechanical properties of steels. The state of niobium (in solution or in precipitate), determined by the reheating temperatures, can affect the recrystallization, the grain growth and the $\gamma \rightarrow \alpha$ transformation of austenite [8-10]. For example, the recrystallization and grain growth of austenite is significantly suppressed by the precipitation of NbC prior to the $\gamma \rightarrow \alpha$ transformation. In addition, coarse NbC particles can be preferred sites for ferrite nucleation. In particular, the control of the austenite recovery and recrystallization is an important part of the grain refinement technique in the modern thermo-mechanical controlling process [11]. The addition of Nb to a steel is considered to have three primary effect [12-14]: (i) as an inhibitor of austenite grain coarsening during reheating, (ii) suppression of austenite recrystallization prior to the $\gamma \rightarrow \alpha$ transformation through the strain-induced precipitation of NbC and (iii) precipitation hardening from the NbC in the low temperature transformation step of the thermo-mechanical process. The strongest contribution to the strengthening is the refinement of the final microstructure (essentially ferrite grain size), which accounts for 80-90% of σ_y. A key role of the precipitates is to provide dispersion strengthening, which is often generated in microalloyed steels by NbC, VC or Nb(C,N) or V(C,N) particles, depending on whether N is added or not, with less than 20 nm in size [15-17]. Special attention has also to be paid to vanadium microalloying addition. This elements is easily added to liquid steel and its solubility during reheating is very high. The strengthening effect is enhanced as nitrogen is also added in solution [18,19]. Vanadium provides grain refinement of austenite by carbonitride V(C,N) precipitation in ferrite during cooling.

The final microstructure and mechanical properties thus strongly depend on the chemical composition, the controlled hot-working parameters and the cooling conditions to which the steel is subjected. High strength, good ductility and good formability are developed in steel products during manufacturing processes and to this goal properly balanced quantities of microalloying additions and suitable thermo-mechanical processing schedules have to be carefully applied [20,21].

Controlled forging. Nowadays, the prevalence of die forged components for various branches of industry, including automotive, mining and agricultural machinery, is produced from microalloyed steels with ferritic-pearlitic microstructure. These steels contain up to approximately 0.55% C, up to 2% Mn, up to 0.8% Si and microadditions of Nb up to 0.06%, V up to 0.15%, Ti up to 0.02% and N up to 0.025%. High mechanical properties of forged elements ($YS_{0.2}$ equal to about 550 MPa, UTS up to about 900 MPa and KV up to approx. 30 J) is achieved through adequate selection of forging conditions, i.e. temperature of charge heating and temperature of plastic deformation. However, strain distribution and strain rate during production of complex shape die forgings is difficult to control.

Excessive grain growth of austenite should not be allowed during charge heating to forging. Deformation at high rate and short duration intervals for moving produced part from one die impression to another do not create convenient conditions for complete course of static recrystallization, allowing grain refinement of austenite grains. Forgings produced under such conditions, free-air cooled from the temperature of plastic working finish, admittedly obtain high strength as a result of strong precipitation hardening and overestimated fraction of pearlite, but also low crack resistance [5]. For instance, the temperature of charge heating to forging of steel, containing approximately 0.3% C and up to 0.05% Nb, should not exceed 1100°C. However, higher heating temperature of the charge can be used for steels with Ti, V and N [20] and Ti, Nb and N microadditions, in which TiN nitrides, Ti(C,N) carbonitrides and TiC carbides dissolve in solid solution at much higher temperature and limit the growth of austenite grains; less stable NbC, V(C,N) and VC secondary phases, precipitating in the vicinity of the phase transition temperature range of plastically deformed austenite, cause precipitation hardening of steel.

Controlled forging technology is also used for production of low-carbon steel forgings for carburizing with microadditions of Nb and B. Dispersive NbC particles restrict the growth of austenite grains during prolonged carburizing or high-temperature cyanide hardening, furthermore, boron improves the hardenability of fine-grained steels. Fine-grained microstructure of low-tempered martensite with dispersive NbC particles in carburized surface layer formed during the heat treatment, results in increase of fatigue strength of machine parts and wear resistance in the conditions of sliding friction.

A considerable portion of technological scrap material connected with trimming of forgings and costs of mechanical working of forged machine components decide about preferential production of closed-die forgings. This creates the need to supply the charge with desired geometric characteristics and dimensional tolerance, without surface defects and other faults. Such possibilities are offered by continuous steel casting and careful rolling of ingots with appropriate working rate, especially under conditions of controlled rolling.

Thermomechanical forging. Elements forged in dies with the method of thermo-mechanical treatment of toughening low-alloy steels with microadditions of Ti, Nb and V and N or B gain higher mechanical properties, especially crack resistance, compared with forgings with ferritic-pearlitic microstructure. This method involves plastic deformation of steel in the conditions of controlled forging with successive quenching of forgings directly from the temperature of forging finish, preferably after the $t_{0.5}$ time necessary to produce 50% fraction of statically recrystallized austenite. Direct hardening after the $t_{0.5}$ time at the temperature of forging finish limits the heat treatment of forged parts only to high-temperature tempering. As per example, components forged from 25GVN steel, containing 0.25% C, 1.3% Mn, 0.1% V and 0.020% N with microstructure of upper bainite, produced by the thermomechanical forging with application of the $t_{0.5}$ time, obtain: $YS_{0.2}$ > 650 MPa, UTS > 900 MPa, TEl > 12 %, KV > 45 J and hardness ranging from 280 to 290 HBW. Relatively low hardness of elements forged with the method of thermo-mechanical treatment and successively subjected to high-temperature tempering, does not hinder their mechanical processing due to carbon concentration limited to 0.3%. In special cases, similarly as during conventional toughening, there is a necessity of straightening and stress relief annealing of forged parts prior to mechanical processing.

The results of research of mechanical properties of low-alloyed 0.2C-1.5Mn steel containing Nb microaddition, subjected to thermomechanical forging are presented in [22]. Samples with a diameter of 18 mm and a length of 60 mm after holding at the temperature of 1250°C were subjected to forging in a temperature range from 1200 to 1100°C, and then immediately quenched in water. Specimens machined in such a way revealed: UTS strength of approx. 1057 MPa, TEl elongation of about 13% and KV of approximately 35 J.

Very high mechanical properties at desired hardness (245 HBW), allowing realization of material removing processes, were achieved for steel researched by Rasouli et al. [23]. In the work, the effect of cooling rate on microstructure and mechanical properties of 30MSV6 grade microalloyed steel, containing 0.3% C, 1.54% Mn and microadditions of V, Ti and N, was determined. Specimens with a diameter of 9 mm and a length of 15 mm, after austenitizing at the temperature of 1250°C for 5 minutes, were cooled to the temperature of plastic deformation (925°C), at which they were held for 2 minutes and successively subjected to upsetting at the rate of 0.1 s^{-1} using 50% draft degree. After upsetting, samples were cooled with the rate of 3, 7 and 15°C/s. Samples cooled directly from the temperature of plastic deformation finish demonstrated yield point of 765, 1072 and 1195 MPa, respectively and UTS strength of 1141, 1468 and 1535 MPa.

The research results of the influence of forging with the method of thermo-mechanical treatment on the microstructure and mechanical properties of 0.1C-Mn-Mo-Nb microalloyed steel have been presented in [24]. The work comprised a comparison of mechanical properties and crack resistance of investigated steel subjected to forging using thermo-mechanical treatment and high-temperature tempering with the properties of the same steel forged conventionally and successively subjected to classical quenching and tempering. Specimens cooled in water directly from the temperature of forging finish, after high-temperature tempering demonstrated the value of $YS_{0.2}$ of about 910 MPa, UTS equal about 1164 MPa, while those forged and then subjected to toughening - $YS_{0.2}$ of about 820 MPa, UTS of about 930 MPa, wherein crack resistance of samples produced in those variants was similar and was equal 60 J. Conducted study revealed full suitability of steel to production of forged machine components with the method of thermomechanical forging.

Interesting results of research of mechanical properties of HSLA constructional steel subjected to thermomechanical processing through forging have been presented in [25]. The object of examination was 38MnSiVS6 grade steel containing 0.36% C, 0.56% Si, 1.35% Mn and 0.08% V. Samples produced with the method of thermomechanical treatment presented high mechanical properties ($YS_{0.2}$ of about 550 MPa, UTS of about 800 MPa, TEl of about 22% and RA of about 55%) at relatively low hardness at 230 HBW, advantageous for machining.

Ghosh at el. [26] have presented the results of the impact of cooling rate after forging on microstructure and mechanical properties of HSLA-type steel with Nb and Ti microadditions. An ingot with 50 x 50 mm cross-section, after austenitizing at the temperature of 1200°C for 2h, was subjected to forging in a temperature range from 1100 to 1050°C and from 850 to 800°C, using 50% draft degree each time, and then cooled at the rate of 0.68, 1.15 and 35°C/s. Specimens of studied steel formed in such a way presented: $YS_{0.2}$ of about 738, 784 and 835 MPa, UTS equal approx. 841, 859 and 929 MPa and crack resistance at the temperature of -40°C equal 196, 161 and 155 J, respectively, after cooling from the temperature of forging finish with the rate of 0.68, 1.15 and 35°C/s.

Similar investigative issues have been described in [27], using two microalloyed steels containing 0.35% C: steel A - with V microaddition in a concentration of 0.1% and steel B - with Ti and V microadditions in a concentration of 0.04 and 0.08%, respectively. Specimens after austenitizing at the temperature of 1200°C were subjected to forging in a temperature range from 1100 to 1000°C and consecutively cooled to room temperature at different cooling rates (1.5 and 10°C/s). Higher mechanical properties, independently from the cooling rate, were found for the A steel. Yield point of A steel samples produced in the conditions of thermomechanical treatment was equal from 615 to 660 MPa, while for those from the B steel - from 590 to 605 MPa. However, significant differences applied to crack resistance. Distinctly higher crack resistance (KV of about 42÷48 J) was noted for specimens obtained from Ti and V microalloyed steel (B steel) when comparing to the A steel (KV of approx. 13÷27 J).

Analysis of the literature data unequivocally shows the benefits of application of microalloyed steels and controlled cooling of elements from the temperature of forging finish. Introduction of thermomechanical treatment not only ensures high strength and crack resistance of forgings but also reduction of costs by eliminating needless operations of heat treatment and elementary work time.

2. Material and methodology

The study was performed on newly elaborated microalloyed steel, assigned for production of forged machine parts with high strength and crack resistance, through the method of thermomechanical treatment. The investigated steel contains 0.28% C, 1.41% Mn, 0.29% Si, 0.008% P, 0.004% S, 0.26% Cr, 0.11% Ni, 0.22% Mo, 0.025% Al and Nb, Ti, V and B in the amount of 0.027, 0.028, 0.019 and 0.003%, respectively.

Investigated steel melts, weighing 100 kg, were done in VSG-100 type laboratory vacuum induction furnace, produced by PVA TePla AG. In order to modify non-metallic inclusions, mischmetal (~50% Ce, ~20% La, ~20% Nd) in the amount of 2 g/1 kg 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 300 MN of force.

Conditions of hot processing and cooling after its finish, allowing to obtain desired mechanical properties of forgings, were selected taking into consideration [28-30]:

- analyses of the kinetics of MX-type interstitial phases precipitation in a solid state,
- research of the influence of austenitizing temperature on γ phase grain size,
- 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,
- examination of the kinetics of strain hardening (recrystallization) softening of plastically deformed austenite in mentioned conditions,
- research of the kinetics of phase transformations of undercooled austenite.

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, 60 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).

The schema used for open die forging of flat bars with the method of thermomechanical forging and conventional method is presented in Fig. 1.

Metallographic investigations of specimens hardened after plastic deformation under mentioned conditions and after high-temperature tempering were done in Leica MEF 4A light microscope. Samples for testing were etched in nital, whereas in order to reveal prior austenite grain boundaries - etching in saturated aqueous solution of picric acid with addition of $CuCl_2$ at the temperature of 60°C temperature was applied. The measurement of prior austenite grain size was performed with the use of Leica Qwin software. Microstructure observations of thin foils were done in TITAN80-300 FEI ultra high resolution scanning transmission electron microscope (S/TEM), at accelerating voltage of 300 kV. Identification of chemical composition of dispersive precipitations was determined with the use of energy dispersion spectrometer EDS (Edax).

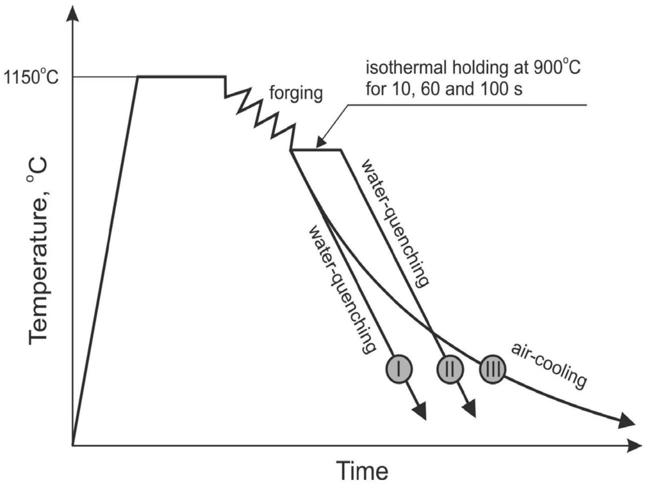

Fig. 1. Schematic of forging of flat samples with the thermomechanical (variants I and II) and conventional methods (variant III)

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. 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.

3. Results

The investigation of prior austenite grains of specimens taken from sections of flat bars quenched in water from the temperature of forging finish after 10, 60 and 100 s from plastic deformation finish revealed that the microstructure of steel in such state is fine-grained. Austenite grains with average diameter of approximately 20 μm were revealed in the microstructure of steel quenched in water from the temperature of 900°C after isothermal holding for 10 s. While partially recrystallized austenite microstructure, consisting of equiaxial grains of austenite and very fine statically recrystallized grains (Fig. 2), was obtained for a forging isothermally held at the temperature of forging finish for 60 s prior to water-quenching. Very fine recrystallized grains are distributed on grain boundaries and on the contact of grains of γ phase, due to highest strain concentration in those areas during plastic working. Average diameter of austenite grains obtained in such conditions is equal around 13 μm.

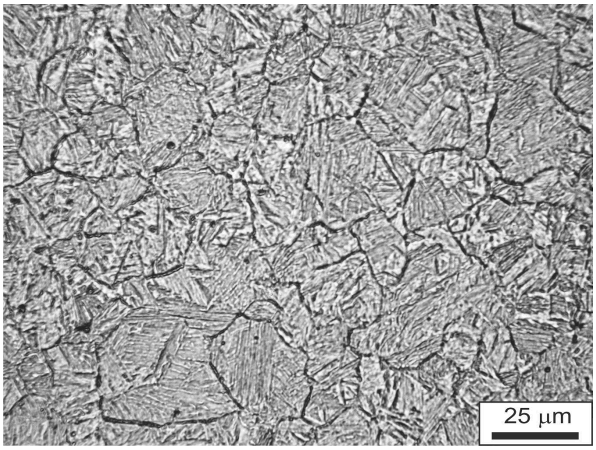

Fig. 2. Microstructure of prior austenite of steel quenched in water directly from the temperature of forging finish (900°C), after isothermal holding at this temperature for 60 s; II variant of thermo-mechanical treatment

Increase of isothermal holding time of flat bar sections at the temperature of forging finish to 100 s results in slight growth of γ phase grains. Metallographic examinations of samples cut from flat bar sections produced according to the I variant of thermomechanical treatment, i.e. quenched in water immediately after plastic deformation finish, revealed that microstructure of steel in this state consists of fine-lath martensite (Fig. 3). Segments produced according to the I variant of thermomechanical treatment, subjected successively to tempering in a temperature range from 550 and 650°C, demonstrate microstructure of high-tempered martensite with dispersive precipitations of carbides (Fig. 4). Specimens coming from a flat bar section obtained according to the II variant of thermomechanical treatment and according to the III variant, i.e. after forging with successive air cooling and toughening, have similar microstructure, both in quenched and tempered state.

Analyses of microstructure of thin foils in a transmission electron microscope revealed that microstructure of steel, hardened directly from the temperature of forging finish after plastic deformation finish, consists of lath martensite, often with curved laths with faults (Fig. 5), as a result of an impact of uneven distribution of dislocation density in strongly plastically deformed austenite. The presence of dispersive (Ti,Nb)C carbides, locating themselves mainly on boundaries of martensite laths (Fig. 6) was revealed in martensite with diversified spatial orientation of individual laths. The presence of retained austenite (Fig. 7), occurring in the form of thin films (with the thickness from 7 to 21 nm) between laths of martensite was also revealed in the microstructure of studied steel. Kurdiumow-Sachs crystallographic relationship was found between retained austenite and martensite.

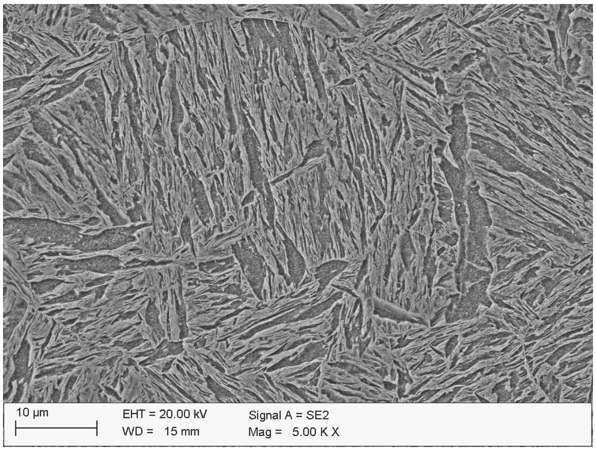

Fig. 3. Martensitic microstructure; I variant of thermo-mechanical treatment: 900°C/water

Similar morphology of lath martensite was found for steel coming from a flat bar section obtained according to the II variant of thermomechanical forging. Laths with different width and quite diversified orientation around particular crystal zone are present in packs of martensite. Some of martensite laths disclose fragmentation caused by an impact of subgrain boundaries with considerable crystallographic misorientation angle on their growth, and other reveal curvilinear grain boundaries and variable width. As in previous case, the presence of (Ti,Nb)C and (Ti,Nb,V)C dispersive carbides (Fig. 8) with variable sizes in the range from 50 to 100 nm was revealed in martensite.

Microstructure of steel hardened in a conventional way after austenitizing of samples at the temperature of 900°C consists also of lath martensite with dispersive (Ti,Nb)C carbides.

Forgings produced in both variants of thermomechanical processing and forgings quenched conventionally from the temperature of 900°C demonstrate quite diversified microstructure after tempering in a temperature range from 550 to 650°C. Microstructure of specimens taken from flat bar sections, quenched directly after forging finish, after tempering at the temperature of 550°C, consists of tempered martensite with precipitations of granular and lamellar Fe_3C particles, distributed inside of grains and on lath boundaries. Lamellar and granular precipitations, formed in such conditions, fulfil with the matrix spatial dependences established by Bagariacki. Increase of tempering temperature leads to coagulation of cementite. The M_3C lamellar precipitations retain privileged spatial orientation with ferrite, while coagulated granular particles of this phase reveal random crystallographic orientation in respect to the matrix.

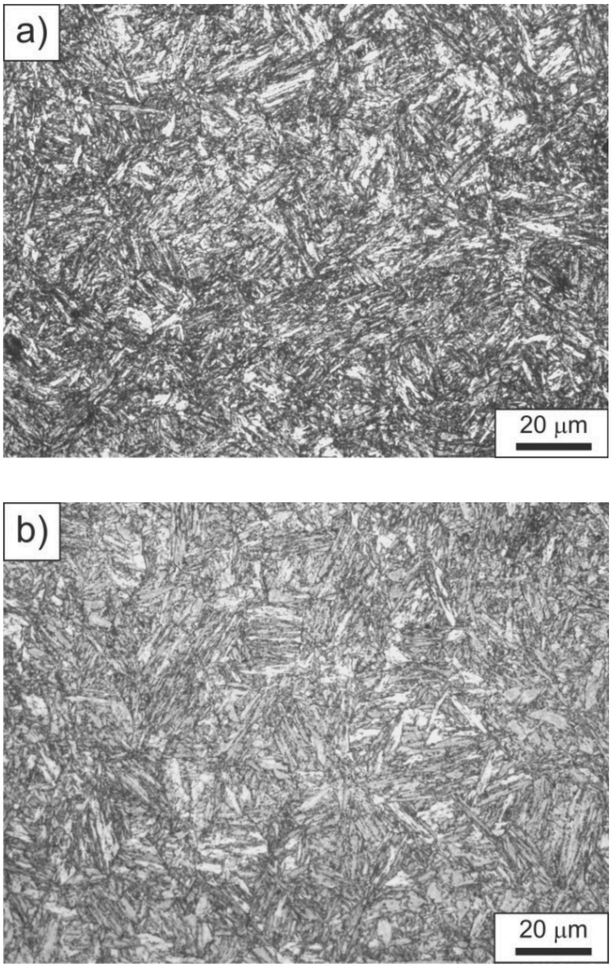

Fig. 4. High-tempered martensite; I variant of thermo-mechanical treatment: 900°C/water; tempering temperature: 550°C (a) and 650°C (b)

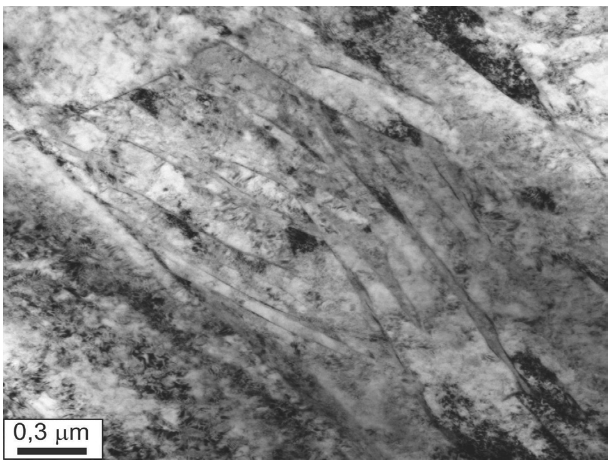

Fig. 5. Lath martensite structure; I variant of thermo-mechanical treatment: 900°C/water

Samples taken from a forging produced in the II variant of thermomechanical treatment have similar microstructure in tempered state. In this case, in microstructure of the steel tempered at the temperature of 550°C there are thin lamellar precipitations of Fe_3C on lath boundaries, while inside of laths of recovered ferrite - dispersive lamellar particles of the phase with privileged spatial orientation with matrix (Fig. 9). Lamellar precipitations transform into granular Fe_3C particles, distributed on lath boundaries and on subgrain boundaries of recovered ferrite, along with increase of tempering temperature.

Microstructure of steel subjected to conventional toughening also consists of tempered martensite with dispersive particles of cementite.

Discussed microstructure of steel, both in hardened and tempered state, significantly affects mechanical properties of flat bar sections obtained in both variants of thermomechanical treatment. Results of investigation of mechanical properties and impact energy of Charpy V samples, taken from forgings produced in accordance to applied variants, are put together in Table 1. The data presented in this table show that the flat bar section quenched in water directly from the temperature of forging finish (I variant of thermomechanical treatment), demonstrates the following properties after tempering at the temperature of 550°C: $YS_{0.2}$ of about 973 MPa, UTS of about 1057 MPa, TEl of about 13.5% and RA of about 51.5%.

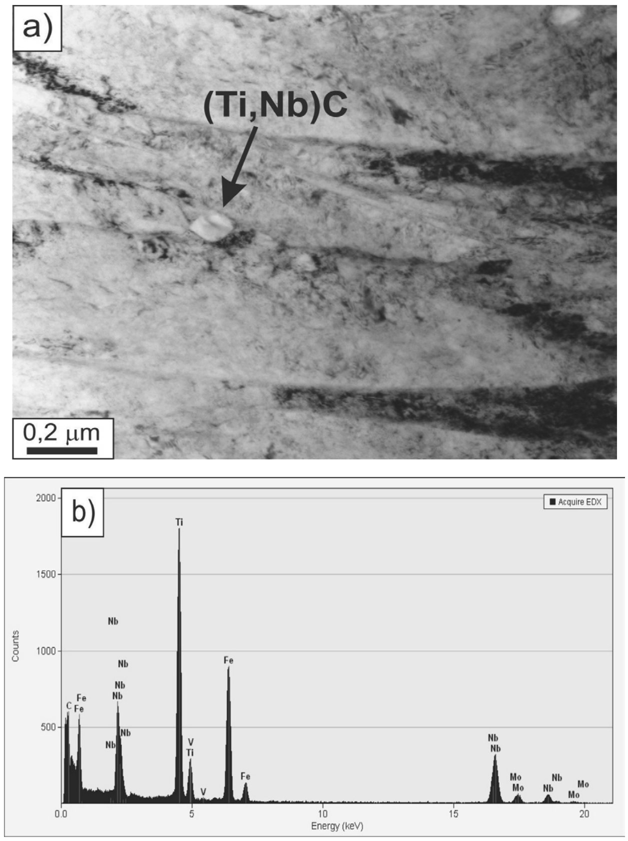

Fig. 6. The carbide of the approximate formula $(Ti_{0,67},Nb_{37})C$ at boundaries of martensite laths (a); EDS spectrum (b); I variant of thermo-mechanical treatment: 900°C/water

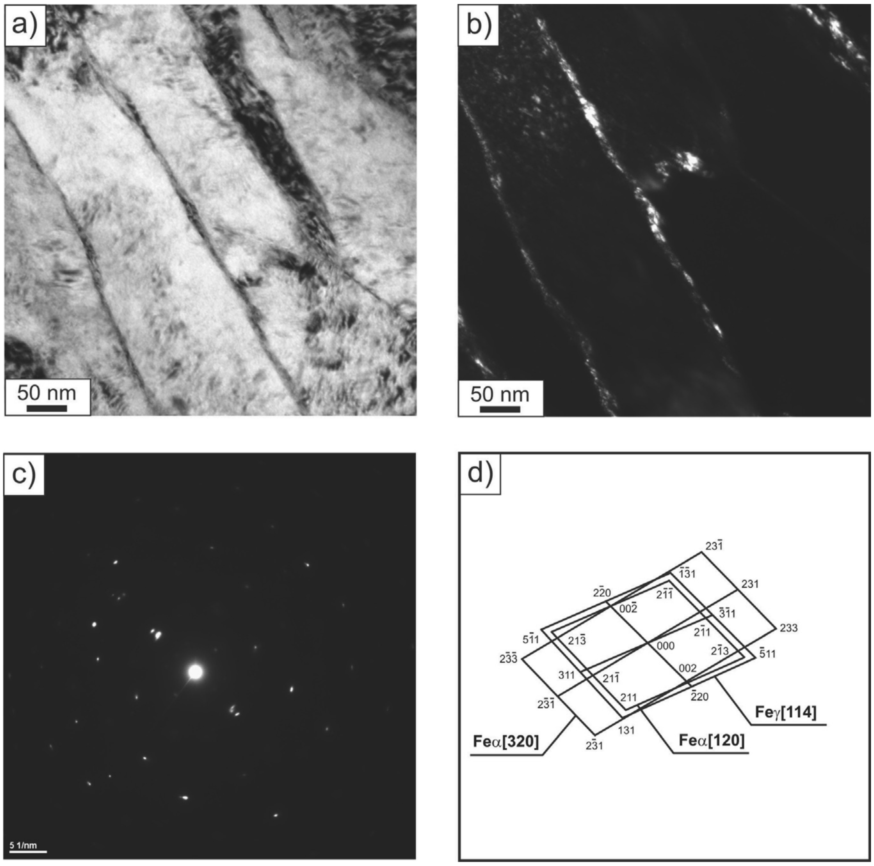

Fig. 7. Retained austenite as films located between martensite laths: a) bright field image, b) dark field image from (220) Feγ, c) diffraction pattern, d) solution of the diffraction pattern from fig. c; I variant of thermo-mechanical treatment: 900°C / water

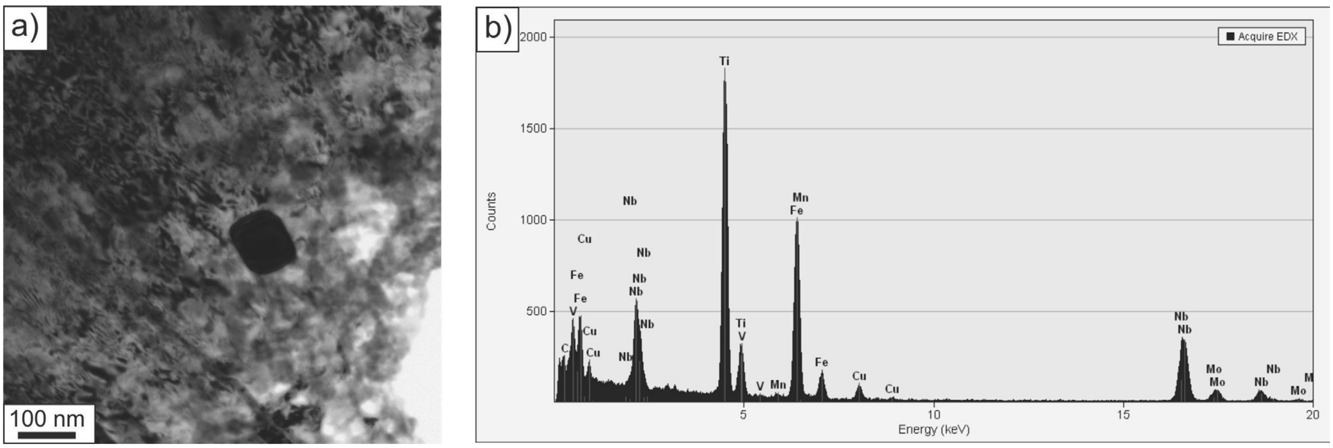

Fig. 8. Carbide (Ti,Nb,V)C in the martensite (a); EDS spectrum (b); II variant of thermo-mechanical treatment: 900°C/60s/water

Flat bar sections obtained according to the II variant of thermomechanical processing reveal higher mechanical properties and distinctly higher crack resistance in tempered state, however, the best set of mechanical properties and crack resistance was noted for forging isothermally held at the temperature of 900°C for 60 s prior to hardening in water. The section of a flat bar obtained in such conditions reveals the following properties after tempering in the temperature range from 550 to 650°C: $YS_{0.2}$ from

994 to 911 MPa, UTS from 1084 to 974 MPa, KV from 95 to 109 J and KV^{-40} from 77 to 83 J.

Flat bar sections air cooled after forging, successively subjected to toughening (III variant) demonstrate the lowest mechanical properties and crack resistance. Properties of the flat bar section formed in such conditions, after tempering in the investigated temperature range, are as follows: $YS_{0.2}$ from 854 to 793 MPa, UTS from 895 to 830 MPa, TEl from 14.5 to 17.8%, RA from 58.4 to 62.5 %, KV from 56 to 69 J and KV^{-40} from 38 to 49 J.

Conducted examinations of the influence of applied variant of processing as well as tempering temperature on hardness revealed that the highest hardness - of approximately 360 HBW - is demonstrated by a forging formed according to the II variant of thermomechanical treatment with application of isothermal holding at the temperature of forging finish for 60 s prior to water-quenching, then subjected to tempering at the temperature of 550°C. Increase of tempering temperature for a forging formed under such conditions up to 650°C results in a mild decrease of hardness to about 330 HBW. 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 a temperature range from 550 to 650°C, changes from 330 to 280 HBW.

Fracture of Charpy V specimen taken from a forging obtained according to the I variant of thermomechanical treatment, subjected to tempering at the temperature of 650°C, after examination of impact resistance at the temperature of +20°C, is presented in Fig. 10. Performed observations revealed that samples taken from forgings produced in such conditions have ductile fracture with numerous craters and voids and small amount of non-metallic inclusions on the fracture surface. Fractures of specimens after impact resistance testing, taken from forgings produced according to the II variant of thermomechanical treatment (Fig. 11), and obtained according to the III variant of processing, i.e. subjected to conventional forging with free air cooling of forgings and successive toughening, have similar nature.

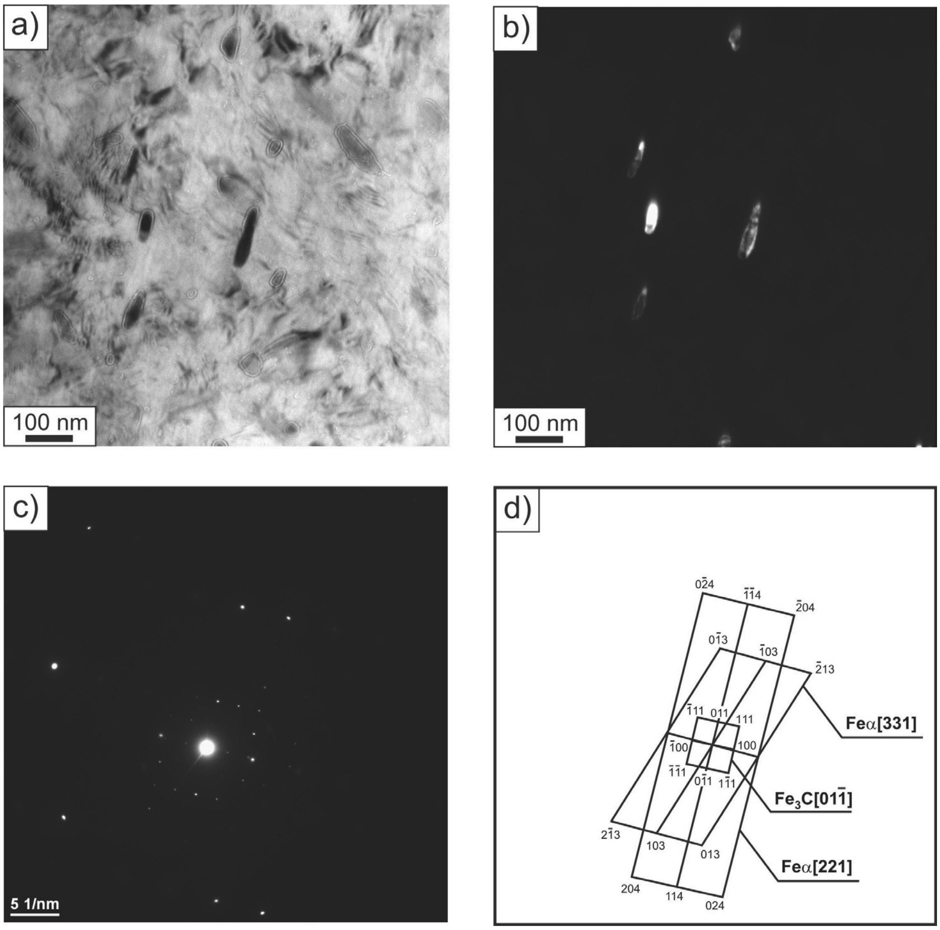

Fig. 9. Disperse plate precipitations of Fe_3C inside recovered ferrite laths: a) bright field image, b) dark field image from (110) Fe_3C, c) diffraction pattern, d) solution of the diffraction pattern from fig.c; II variant of thermo-mechanical treatment: 900°C/60s/water; tempering temperature: 550°C

Table 1.
Results of mechanical properties and impact fracture energy using Charpy V samples after the thermomechanical forging and successive tempering (variant I and II) and conventional forging and successive toughening (variant III)

Variant	Forging conditions				Tempering temperature °C	Mechanical properties				Impact energy	
	Charge heating temperature, °C	Finish of forging temperature, °C	Isothermal holding time, s	Cooling medium		$YS_{0.2}$ MPa	UTS MPa	TEl %	RA %	KV J	KV^{-40} J
I	1150	~900	-	water	550	973	1057	13.5	51.5	69.3	55.0
			-	water	650	909	976	14.0	52.0	81.7	68.6
II	1150	~900	10	water	550	967	1063	13.6	49.6	91.6	71.3
			10	water	650	892	958	14.5	52.7	99.0	79.7
			60	water	550	994	1084	14.3	50.9	95.0	77.3
			60	water	650	911	974	15.1	50.2	108.7	82.6
			100	water	550	988	1077	13.0	49.6	95.7	75.7
			100	water	650	939	993	14.8	51.3	101.3	80.0
III	1150	~900	-	air	550	854	895	14.5	58.4	56.3	37.6
			-	air	650	793	830	17.8	62.5	68.6	49.0

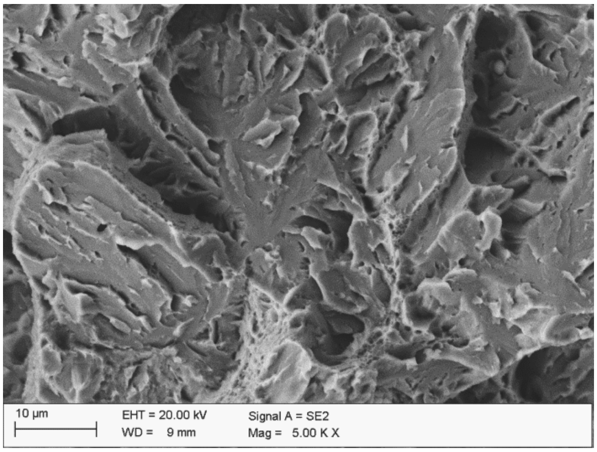

Fig. 10. Ductile fracture with numerous craters and voids after impact test at the temperature of 20°C; I variant of thermo-mechanical treatment; tempering temperature 650 °C

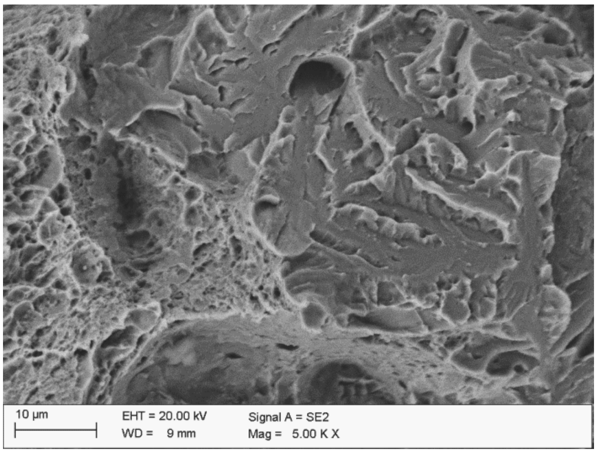

Fig. 11. Ductile fracture with numerous craters and voids after impact test at the temperature of 20°C; II variant of thermo-mechanical treatment: 900°C/60s/water; tempering temperature: 550°C

Dispersive particles of interstitial phases, mainly (Ti,Nb)C carbides (Fig. 12) as well as Ti(C,N) carbonitrides (Fig. 13), were revealed on the fracture surface of Charpy V specimens of studied steel.

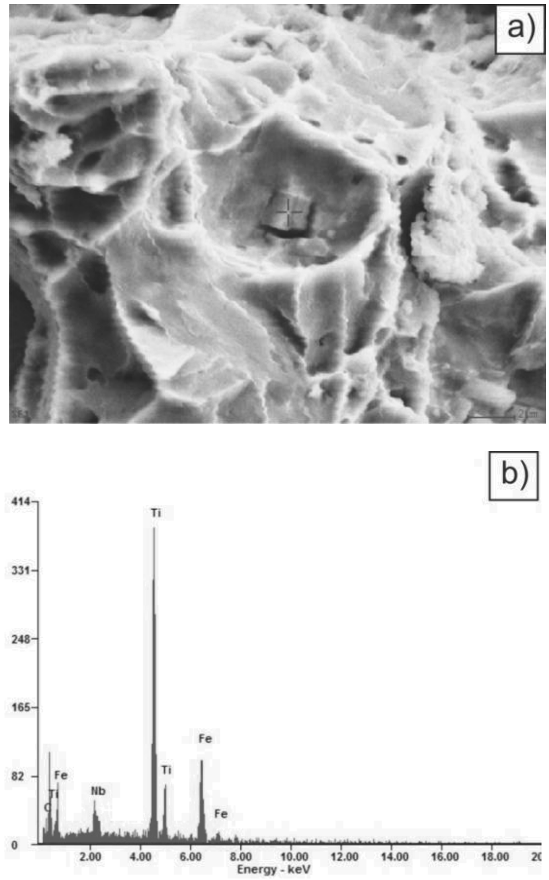

Fig. 12. Carbide (Ti,Nb)C on the fracture surface of the specimen after impact test performed at the temperature of 20°C: a - a view of the particle, b - spectrum of carbide; I variant of thermo-mechanical treatment; tempering temperature: 650 °C

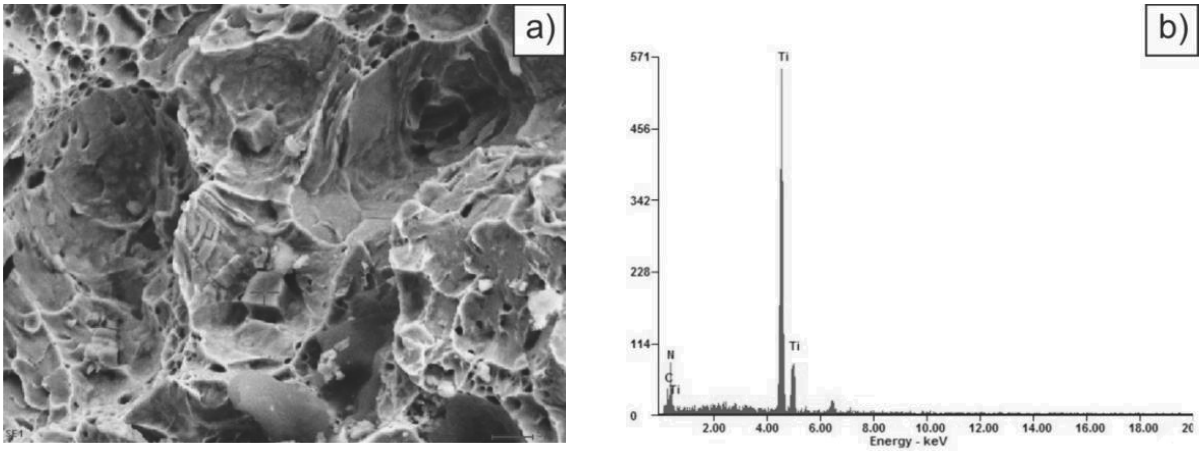

Fig. 13. Titanium carbonitride Ti(C,N) on the fracture surface of the specimen after impact test performed at the temperature of 20°C: a) a view of the particle, b) spectrum of carbonitride; II variant of thermo-mechanical treatment: 900°C/100s/water; tempering temperature: 550°C

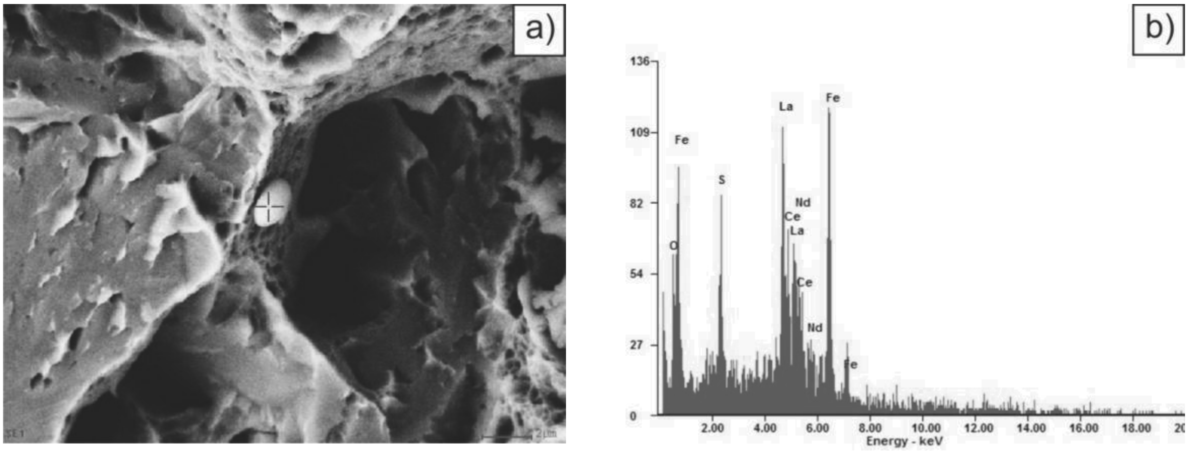

Fig. 14. Oxysulfide type non-metallic inclusion modified with rare earth elements on the fracture surface of the specimen after impact test performed at the temperature of -40°C: a - view of the inclusion, b - spectrum of the inclusion; II variant of thermo-mechanical treatment: 900°C/60s/water; tempering temperature: 550°C

Moreover, the presence of fine, mainly globular oxysulfide inclusions (Fig. 14) was revealed on fracture surface of specimens of examined steel. Qualitative analyses of chemical composition of exposed non-metallic inclusions confirmed effectiveness of applied modification of non-metallic inclusions with rare earth elements, i.e. Ce, La and Nd, in the process of smelting. It's confirmed in spectrograms of analyzed non-metallic inclusions (Fig. 14b), where in addition to spectral lines deriving from S, O and Fe, there are also spectral lines coming from Ce, La and Nd. The presence of spectral lines deriving from Fe in spectrograms is a result of analysis of a certain part of the matrix surrounding non-metallic inclusion.

4. Conclusions

Realized study showed that thermomechanical treatment (variant I and II), performed in conditions which ensure production of fine-grained microstructure of austenite prior to quenching and subsequent high-temperature tempering, gives studied steel a 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 forging finish (variant III). Implemented thermomechanical processing allows to produce forged fabrications obtaining the following properties after controlled cooling from the temperature of plastic deformation finish and subsequent tempering in a temperature range from 550 to 650°C: $YS_{0.2}$ from 994 to 939 MPa, UTS from 1084 to 993 MPa, TEl from 14.3 to 15.1%, RA from 51.5 to 52.7%, KV from 96 to 109 J and KV^{-40} from 77 to 83 J. High strength in such state at high crack resistance, also at decreased temperature, is noteworthy.

The best set of mechanical properties and crack resistance was noted for a forging isothermally held at the temperature of 900°C for 60 s prior to quenching in water, subsequently subjected to tempering at the temperature of 650°C.

Relatively low hardness of steel in state after high-temperature tempering should not cause difficulties during machining of forgings.

Microstructure observations of thin foils using transmission electron microscope revealed that microstructure of steel in quenched state consists of lath martensite with high density of dislocations with considerable amount of dispersive carbides. Dispersive (Ti,Nb)C and (Ti,Nb,V)C carbides revealed in examined steel, forming on dislocations during the plastic deformation, slow down the course of dynamic recovery and possibly also dynamic recrystallization and when hot-working is finished - decrease the rate of recovery and static or metadynamic recrystallization and limit grain growth of recrystallized austenite.

Investigation of fractures of test pieces revealed that regardless of implemented variant of processing, their fracture is ductile with slight amount of globular non-metallic inclusions, mainly oxide-sulfide type, properly modified with rare earth elements.

Obtained research results make it possible to develop industrial technology of forgings with high mechanical properties and guaranteed crack resistance, also at decreased temperature, with the method of thermomechanical treatment.

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