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Influence of Bending Stress on Microstructure of Tempered High Chromium Steel

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Transformation plasticity is an irreversible strain observed when metallurgical transformation occurs under small external stress lower than the yield stress of the weaker phase. This paper is devoted to an experimental analysis of that phenomenon in high chromium steels. The article deals with the results of the investigation of steel microstructure during bending at 520 °C temperature for 15 min, 30 min or 1 h. The tests were carried out using the specimens made from steel X12, X12Ф1 (GOST 5950-73) and 95X18 (GOST 5949-75), which were exposed to the bending stress (210 MPa or 450 MPa) during tempering. The methods of self-deformations, digital metallography, eddy currents and X-ray analysis were used. There was determined different influence of compression and stretch stress on the tempering transformations: the segregation of carbon and chromium from the solid solution, the dissociation of austenite, second martensitic transformation. There was indicated that these processes are also related to steel hardening temperature, which defines the structural and chemical composition of the steel.

Keywords: transformation plasticity, hardening, tempering, self-deformation, high chromium steel.

INTRODUCTION

An externally stressed specimen in the process of a phase transformation may show a significant nonlinear behavior, which is known as transformation plasticity [1 – 5]. Even under an externally applied load stress with the corresponding equivalent stress being small in relation to the "normal" yield stress of the material, plastic deformation occurs.

The first pioneering steps to explain transformation plasticity were taken by G. W. Greenwood and R. H. Johnson [6]. They investigated the transformation process driven by cooling/heating for a specimen subjected to a constant, even low load stress.

The earlier papers on transformation plasticity including the ones by J. B. Leblond [7], deal only with this phenomenon during the hardening, and not include any tempering effect. The hardened steel has temporal increased plasticity during tempering, too. The plasticity, related to the phase and structural transformations, in our days discovers its involvement in many scientific works [2, 3, 8 – 10]. During the transformation plasticity the elastic stress relax, thus the sizeable plastic deformations of articles may occur. The acting stress makes the microstructure of tempered steel inhomogeneous. The volume changes, nascent in such steel, decrease the precision and endurance of articles.

Several scientists investigate the influence of acting stress on the microstructure of tempered steel, but recently no general opinion is found. There was obtained by J. Ch. Videau [11] the dependence of the transformation plasticity norm on the applied load direction. It was observed that this norm is maximum for pure tension, lower for a combination tension + torsion, lower again for a combination compression + torsion and minimum for pure compression. Therefore, the results of L. Taleb [3] do not show any obvious difference between the values of transformation plasticity obtained under tension and compression.

The aim of our work was to determine the influence of compression and stretch stress on the microstructure of high chromium steel during tempering. Because of severe service conditions (high temperature, stress, corrosion, irradiation, etc.), alloy steels for the various utility industries must be sufficiently resistant to microstructural degradation. Therefore, the stability of the microstructure is one of the fundamental requirements concerning the industrial applicability of alloy steels [12]. The microstructural stability of martensitic high chromium steels is achieved by heat treatment consisting of austenizing, hardening and high-temperature tempering.

EXPERIMENTAL

The high chromium steel X12 X12Ф1 and 95X18 was used for the experiments (Table 1). From this steel the specimens with rectangular cross-section were made with the dimensions 6 mm × 8 mm × 100 mm from hot rolled pivot ∅14 mm or hot rolled band along the rolling direction. The specimens were hardened choosing the optimal hardening schedule (Table 1).

The influence of bending stress on the structural transformations of steel was investigated using the equipment, described in the earlier work [13]. In this equipment the specimens were loaded by the certain load and heated in the electrical furnace. Pending the heating the elastic deflections of loading and unloading and deflection of transformation plasticity were measured to within ± 0.01 mm. The temperature of specimen was measured using welded chromel – alumel thermocouple with wire of 0.3 mm thickness. Investigating by the self-deformations method, the specimen, extracted from the furnace after tempering, was cooled in the measuring

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Table 1. The chemical composition and heat treatment schedule of steel

Steel grade (GOST)	Chemical composition, %					Hardening schedule		
	C	Cr	V	Si	Mn	*T*, °C	Retained austenite, %	Hardness, HRC
X12	2.13	12.38	–	0.38	0.29	1050	48 – 50	59 – 60
						1100	97 – 98	51 – 53
						1150	100	50 – 51
X12Ф1	1.42	11.57	0.70	0.30	0.40	1000	15 – 17	59 – 62
						1050	29 – 32	61 – 62
						1100	61 – 63	52 – 57
95X18	0.97	18.20	–	0.55	0.55	1000	4 – 6	54 – 56
						1050	6 – 10	57 – 59
						1100	20 – 26	59 – 60

equipment, which has 80 mm distance between the supports. The change of the deflection was measured and the kinetic curve was designed. The changes of volume show that the tempering transformations proceed differently in the compressed and stretched parts of specimen. When the transformations pass irregularly, the specimen bends to the one side or opposite because of the volume changes. The value of the volume change shows the quantitative difference of the transformations.

We used various methods: self-deformations, metallography, X-ray diffraction analysis using X-ray diffractometer DRON UM2 and eddy currents for the research of the steel structure. The methods of self-deformations and eddy currents are described in work [14]. The radiation used was CuK$_{\alpha}$. For the metallographic investigations we used the original digital metallographic equipment [14].

RESULTS AND DISCUSSION

Tempering with deforming improves performance of steel: resistance to macro and micro plastic deformations, the proportion and elastic limits, resistance to relaxation, etc. Because of the stress, the dislocations form and redistribute, which bring influence on migration of carbon and chromium to the dislocations and formation of carbides. Acting stress changes the shape of carbides, their orientation and distribution in matrix. Formed by the external load stress field relates with the stress fields, which form by segregated disperse carbides. The form of carbides and their distribution have to make sure the minimum of the elastic energy of all the system [15]. Therefore, the morphology of the segregated carbides depends on the direction of acting stress.

The transformation plasticity of deformed pending the tempering specimens depends on the chemical composition of steel solid solution and phase structure, which is formed by different hardening schedule. This is evident in Fig. 1. Rising hardening temperature and the concentration of carbon and chromium in the solid solution, two stages of transformation plasticity are evident progressively. These stages are related to the increasing of plastic deformation.

The method of self-deformations highlighted great differences of the second martensitic transformation in the compressed and stretched part. There was determined that steel X12Ф1 specimens, bent at 520 °C temperature for 15 minutes and tempered at 520 °C temperature for 1 hour without load, started smooth intensively during cooling, when the temperature decreased below 265 °C. This phenomenon is caused by the second martensitic transformation, proceeding in the compressed part of the specimen when the volume has increased. When the temperature lowers till 125 °C, the direction of self-deformation changes – the second martensitic transformation occurs in the stretched part of specimen (Fig. 2). The compression and stretch stress, acting pending the first tempering, and the plastic deformation had different influence on the segregation of carbon and chromium from the retained austenite. These processes were passed more in the compressed part of the specimen than in the stretched one. This is confirmed by sufficiently high difference between the temperatures $M_{S_{cp}}$ and $M_{S_{st}}$.

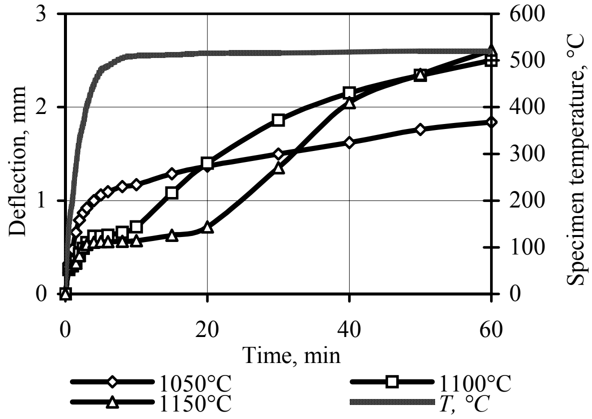


Fig. 1. Influence of hardening temperature on the kinetics of steel X12 deformation at 520 °C temperature (bending stress 210 MPa)

Hardened from 1150 °C temperature the steel X12 has austenite, the primary carbides Cr_7C_3 and a little bit of martensite in its structure. After such treatment bending the specimen at 520 °C temperature for 30 minutes, some needles of martensite occur in the compressed part (Fig. 3, a), while in the stretched part some areas of tempered

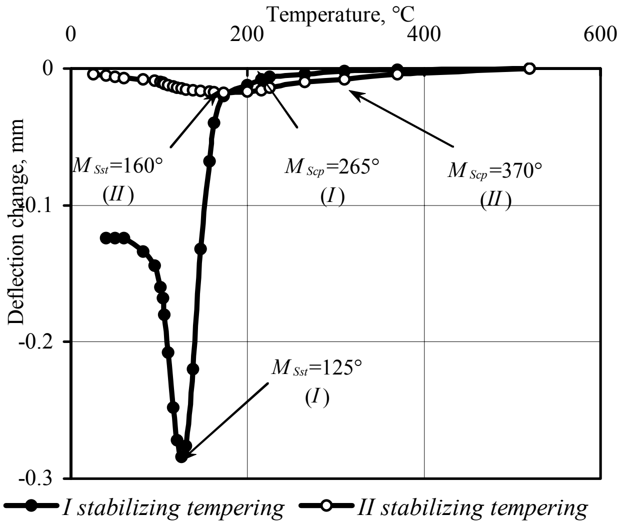


Fig. 2. Kinetics of self-deformation of steel X12Ф1 during the cooling after the stabilizing tempering at 520 °C temperature for 1 h (hardening temperature 1100 °C, bending duration 15 min, bending stress 450 MPa): $M_{S_{cp}}$ is temperature of the start of second martensitic transformation in the compressed part of the specimen, $M_{S_{st}}$ - in the stretched part of the specimen

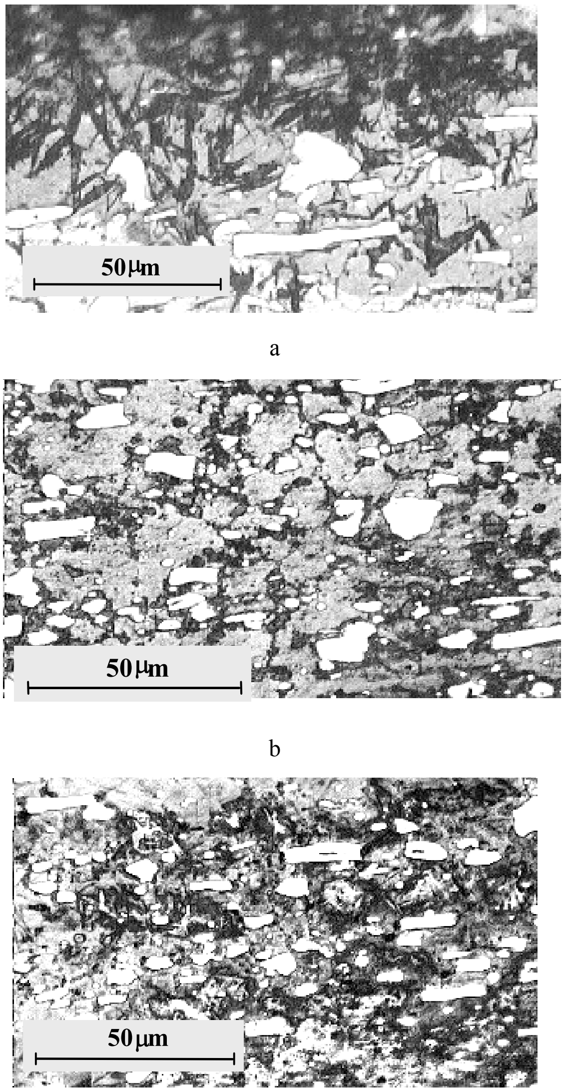
martensite are shown (Fig. 3, c). This demonstrates that the compression stimulates the fissure of austenite, and the stretch actuates the tempering of martensite. There was determined by the digital metallography method that in the compressed part of the specimen the amount of formed martensite is bigger more than 10 % than in the stretched part. This affirms that the compression stimulates the fissure of retained austenite. The differences of microstructure, formed by acting stress, may cause the self-deformation of the articles.

In the microstructure of the compressed and stretched parts of hardened from 1100 °C and tempered at 520 °C for 30 minutes steel X12 specimens (Fig. 4), the needles of martensite are visible. A little of martensite needles is observed also in not deformed part of the specimen. This shows that less alloyed by chromium austenite is less stabile, therefore these conditions of tempering are sufficient that the structure was prepared for martensitic transformation. Acting stress sustains this effect.

After tempering at 520 °C for 1 hour, the needles of martensite are observed particularly in the compressed and stretched parts of the specimens.

X-ray analysis defined that in the steel X12 specimen, hardened from 1150 °C and bent at 520 °C, saturated by carbon and chromium solid solutions of iron – austenite and tempered martensite, special chromium carbides with iron (Cr, Fe)$_7$C$_3$ and alloyed with chromium cementite (Fe, Cr)$_3$C have been formed.

According to X-ray analysis, the quantity of retained austenite was determined. This quantity is less in the stretched part than in the compressed part of the tempered specimen. This consists with the results of metallography. Before X-ray analysis, the layers of certain thickness were removed by chemical etching and mechanical polish from the surface of the specimen: *I* – 0.035 mm, *II* – 0.07 mm, *III* – 0.105 mm, *IV* – 0.5 mm and *V* – 1.0 mm, and X-ray analysis was made after each layer removing.



a

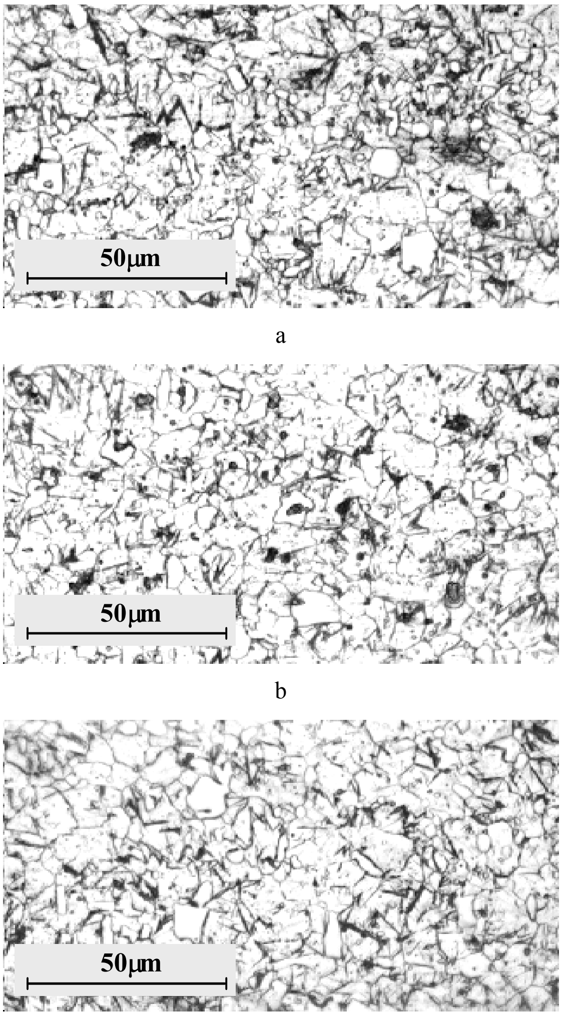
b

c

Fig. 3 Influence of stress on the microstructure of steel X12 (hardening temperature 1150 °C, tempering duration 30 min, bending stress 450 MPa): a – compressed part of specimen; b – not deformed part of specimen; c – stretched part of specimen

X-ray patterns, made after removing the layers of 0.035 mm – 0.105 mm thickness, show the intensive line of austenite and expanded top of line Fe$_\alpha$ (Fig. 5). This is characteristic for the specimens, bent at 520 °C temperature for 30 minutes. This period corresponds with the increased plasticity of steel because of the beginning of intensive diffusion of carbides forming elements (Fig. 1). The lattice is deformed because of the formation of disperse chromium carbides. After 1-hour duration this effect is not observed (Fig. 6).

Investigating the steel 95X18 by eddy currents method, more intensive (5 % – 20 %) signal was observed in the stretched part of the specimen, hardened from 1050 °C or 1100 °C and bent at 520 °C temperature for 1 hour (Fig. 7). This proves, that the stress stimulates the diffusion of chromium, therefore the stretched part of specimen is more tempered. This effect is not observed when hardening temperature is 1000 °C and tempering temperature is lower than 500 °C.



a

b

c

Fig. 4. Influence of stress on the microstructure of steel X12 (hardening temperature 1100 °C, tempering temperature 520 °C, tempering duration 30 min, bending stress 210 MPa): a – compressed part of specimen; b – not deformed part of specimen; c – stretched part of specimen

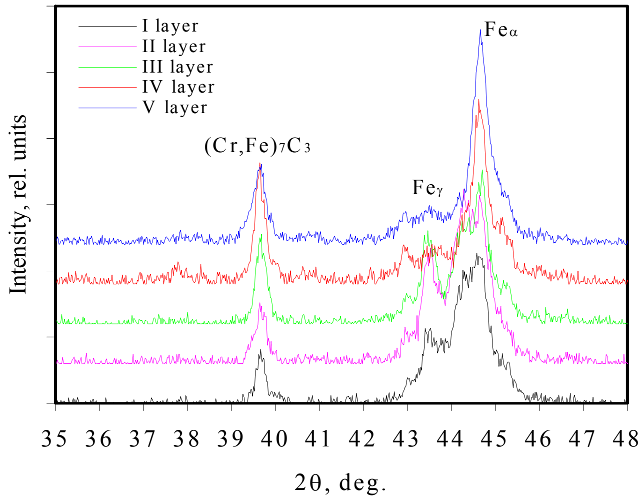


Fig. 5. X-ray diffraction patterns of stretched part of steel X12 specimen (hardening temperature 1150 °C, tempering temperature 520 °C, tempering duration 30 min, bending stress 450 MPa)

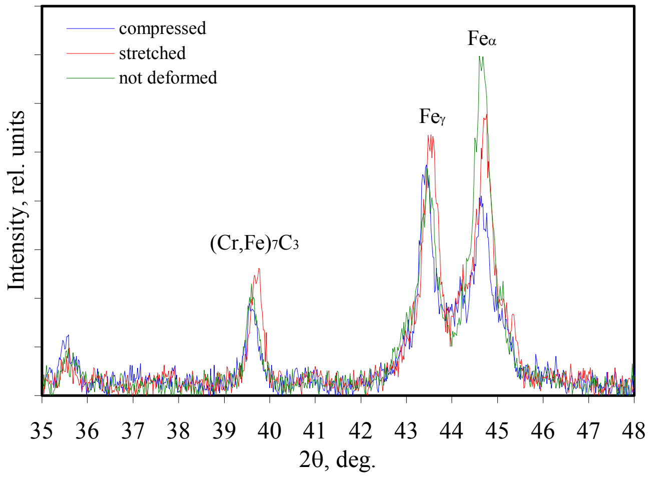


Fig. 6. X-ray diffraction patterns of stretched part of steel X12 specimen (hardening temperature 1150 °C, tempering temperature 520 °C, tempering duration 1 h, bending stress 210 MPa)

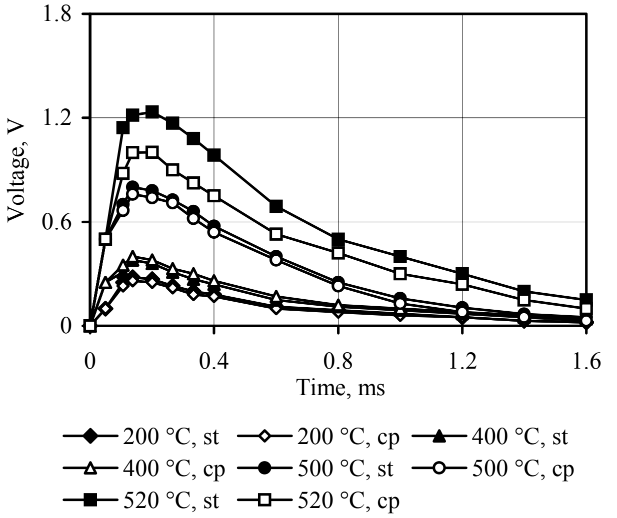


Fig. 7. Kinetics of the voltage of eddy current sensor versus tempering temperatures of steel 95X18 (hardening temperature 1100 °C, tempering duration 1 h, bending stress 450 MPa). Deformation: st – tensile, cp – compression

CONCLUSIONS

1. Hardened steel has temporal increased plasticity during tempering. In the high chromium steel this transformation plasticity occurs in two periods: till 450 °C, when carbon atoms segregates from solid solution, and above 450 °C when the diffusion of chromium, carbon and iron proceeds.
2. The methods of self-deformations and metallography show that compression stimulates segregation of carbon and chromium from retained austenite. Bending steel X12Ф1 specimens, temperature of martensitic transformation start is 265 °C in compressed part and 125 °C – in stretched part of the specimen.

3. X-ray analysis determined that the lattice of second martensite is mostly deformed in 0.03 mm – 0.105 mm depth after tempering at 520 °C temperature for 30 minutes, when the austenite has fissured.
4. The methods of eddy currents and metallography defined that the tensile stress stimulates the tempering of alloyed and saturated with carbon martensite.

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