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Analysis of the Plasticity of Secondary Martensitic Transformation of High-Speed Steel during Tempering

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Abstract: - The paper presents the results of transformation plasticity of high speed steel during secondary martensitic transformation. Tempering temperatures starting from 540 °C up to 600 °C were chosen for investigation. The different floor to floor times from 5 min to 2 h help to evaluate influence of plastic deformation and intensity of transformation plasticity. Transformation plasticity of steel was estimated by extent of the plastic deflection y_{tp}, which was measured on a given test piece when secondary martensitic transformation goes on, and by modulus of transformation plasticity E_{tp}, which can be calculated for a given material under the conditions of transformation. The results show that high-speed steel is in the state of transformation plasticity during secondary martensitic transformation. It is possible to restore tools of high-speed steel that were distorted after hardening, during quenching after first tempering.

Key-Words: - Transformation plasticity, plastic deflection, non-magnetic phase, high-speed steel, secondary martensitic transformation, Modulus of transformation plasticity.

1 Introduction

Although high-speed steels have been known and used for a century, they are still one of the main materials used for the production of tools for machining as well as for cold working. In spite of a rapid development of contemporary tool materials such as sintered carbides, special ceramic materials or extremely hard materials, i.e. boron nitride and diamond, high-speed steels are still commonly used, owing to their satisfactory hardness, ductility and good machinability in soft-annealed state [1].

In order to prolong the service life of tools secondary hardening mechanism has been studied. The results show that high-speed steels can be hardened remarkably by secondary hardening to meet the hardness requirements. Secondary hardening is related to the transformation of the residual austenite into martensite and the precipitation of fine and disperced Mo_2C and VC [2].

Stress-dependent phase transformations (SDPT) and transformation-induced plasticity (TRIP) of steel are some of the reasons for distortion of workpieces. Investigation and modeling of SDPT and TRIP in the framework of thermal treatment are very active fields of research [3]. Using the results obtained under constant temperature and loading it is possible to test the material behaviour under time-dependent conditions. This information can be integrated in complex models on material behaviour in order to simulate the behaviour of work-pieces in real situations such as heat treatment example.

During mechanical loading, the austenite undergoes a displacive phase change and transforms into martensite. This transformation is accommodated by plastic deformations in the surrounding matrix. Experimental results show that the presence of austenite typically enchances the ductility and strength of the steel [4].

The transformation of austenite to martensite is fundamental to the hardening of carbon steels. This transformation plays an important role for the mechanical behavior of low-carbon ferrous alloys containing about 10 vol. % retained austenite. Results show [5] that a homogeneous microstructure and the absence of initial blocky martensite ensure long deformation paths. At the same time, tensile data reveal only a small influence of deformation parameters on the ultimate strength.

Relaxation of internal strains goes on being in the state of transformation plasticity; huge hardening deformations are possible, when internal strains or stresses of external character are acting. It is possible easy to change shape of the product acting it in the right direction.

2 Problem Formulation

Fine tools made of high-speed steels: drills, cutter mills deform and distort during hardening. The main thing that stimulates large plastic deformations is transformation plasticity of steel during martensitic transformation [6 – 8]. This unique property of the steel may be successfully used for flattening of the products, e.g. on quenching of the drills between rotating shafts in the hardening automatic machine. Otherwise tools made of high-speed steel can be flattened during tempering on heating to the desirable temperature, when steel is in the plastic state [9] for a limited time or on quenching of the products after tempering, when secondary martensitic transformation go on. The latter phenomenon was noticed 30 years before, but was not more wide studied [9]. The main object of this work is to determine influence of tempering regimes to plasticity of secondary martensitic transformation.

2.1 Parameters of transformation plasticity

Transformation plasticity of steel is estimated by extent of the plastic deflection y_{tp}, which is measured on a given test piece when secondary martensitic transformation goes on, and by modulus of transformation plasticity E_{tp}, which can be calculated for a given material under the conditions of transformation.

Modulus of transformation plasticity defines the relation between acting load P and plastic deflection of double supported beam for the given materials and under the given condition and can be calculated using an expression [8]:

$$E_{tp} = \frac{P \cdot l^3}{48 \cdot I_x \cdot y_{tp}} \tag{1}$$

where: P is the load acting to the center part of the test piece, N; l is the distance between bending supports, mm; I_x is the inertia momentum of the test piece, mm^4; y_{tp} is the deflection of transformation plasticity during second martensitic transformation, mm.

Elastic-plastic state of the material under the given condition characterizes modulus of the elastic-plastic state E_{etp} that can be expressed:

$$E_{etp} = \frac{P \cdot l^3}{48 \cdot I_x \cdot (y_e + y_{tp})} \tag{2}$$

where: P is the load acting to the center part of the test piece, N; l is the distance between bending supports, mm; I_x is the inertia momentum of the test piece, mm^4; y_e is the elastic deflection of the test piece, mm; y_{tp} is the deflection of transformation plasticity during second martensitic transformation, mm.

Elastic deflection of the test piece can be calculated using expression:

$$y_e = \frac{P \cdot l^3}{48 \cdot E_T \cdot I_x} \tag{3}$$

where: l is the distance between bending supports, mm; E_T is Young's modulus at temperature of 420 °C, N/mm^2; I_x is the inertia momentum of the test piece, mm^4; P is the load acting to the center part of the test piece, N.

Using Young's modulus of speed steel we can calculate elastic deflection of the test piece y_e = 1.115 mm. Plastic deflection of the test piece at the moment of the loading can be calculated:

$$y_p = y_{ep} - y_e \tag{4}$$

where: y_{ep} is the elastic-plastic deflection of the test pieces on loading, mm; y_e is the elastic deflection of the test piece, mm.

3 Problem Solution

Bending test pieces (6 x 8 x 100 mm) were made of hot rolled bar of broadly used tungsten-molybdenum high-speed steel P6M5 (grade according Russian standard GOST 19265). Test pieces were heat treated according such a schedule: hardening with heating up to the 850 °C into the smelted salt for a 4 minutes, final heating up to the 1220 °C for a 4 minutes with subsequent isothermal cooling up to the 380 °C for a 1 minute, cooling in the air. Rockwell hardness of hardened test pieces was 65 – 66 HRC, quantity of non-magnetic phase (retained austenite) was 19 – 21 %.

Ordinary temperature for the tempering of high-speed tool steel 560 °C, temperature of accelerated tempering 600 °C and intermediate temperatures 540 °C and 560 °C were chosen for experiments. Holding time in such temperatures was from 5 min up to 2 h, test pieces were carried out into the device of transformation plasticity testing and were loaded under the load of P = 2160 N forming the biggest normal tensile strains σ_1 = 800 MPa. It makes about 25 % of tensile strength of hardened high-speed steel P6M5. Temperature of the test pieces were measured using weld to thermocouple made of chromel-aliumel; a deflection of the test pieces was tested with 0.01 mm accuracy using indicator and was recorded at choice intervals of the time. Quantity of non-magnetic phase (retained austenite) was registered using ballistic testing machine before and after the tempering. Temperature of secondary martensitic transformation M_S'.was determined according beginning of the plastic deformation of the test pieces.

The test piece after holding in the furnace at the tempering temperature for a certain time carries out into the testing device and in 30 s loads applying tensile stress. The test piece in such a state cools up to the room temperature that reaches during 12 – 15 min. Loaded test piece bends elastically and remains in this state until reaches temperature of secondary martensitic transformation M_S'. At the beginning of the transformation the test piece plastically bends intensively till transformation goes on (Fig. 1). An intensity of transformation plasticity and size of plastic deformation depend on the holding time at the tempering temperature.

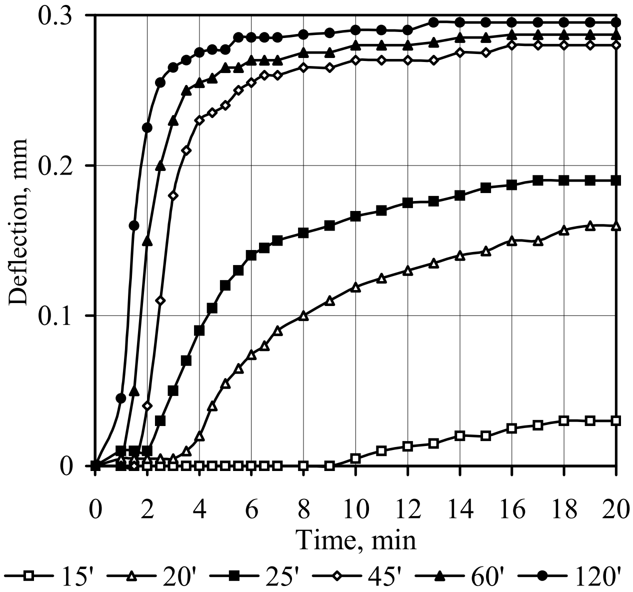

Fig. 1 Kinetics of transformation plasticity cooling after tempering at 560 °C.

The biggest effect of plasticity is obtained after tempering at 560 °C when holding time is 60 min (Table 1). Further increasing of the holding time until 120 mm doesn't change the plasticity.

The shortest tempering time at 560 °C is 15 min, when one of the two test pieces already shows beginning of the martensitic transformation and decreasing of the quantity of retained austenite.

Holding time at the tempering temperature influences on level of the secondary martensitic transformation: on increasing the holding time quantity of the retained austenite in the steel decreases. A portion of carbon, tungsten, molybdenum and chromium atoms precipitate at the high tempering temperature from the over saturated solid solution forming dispersed special carbides. When concentration of these components in the austenite decreases, temperature of secondary martensitic transformation M_S' raises depending on the duration of the holding at the tempering temperature (Table 1).

Table 1. Influence of the holding time on the transformation plasticity during tempering at 560 °C

Time, min	After hardening		After tempering		Deflection of the test pieces, mm	
	HRC	A_R, %	HRC	A_R, %	y_{etp}	y_{tp}
15	65.2	19	64.9	10.4	0.84	0.02
20	64.3	18	64.1	4.7	0.99	0.17
22′30″	65	18.8	64.9	7.8	0.98	0.16
25	63.5	19.8	63.4	4.4	1.01	0.19
30	65	20	65.3	1.8	1.03	0.21
45	62.5	18.5	62.9	2	1.08	0.26
60	64	19	64.4	1.3	1.12	0.30
120	64.8	18.4	65.2	1.3	1.115	0.295

Time, min	M_S'		E_{tp}, N/mm^2	E_{etp}, N/mm^2
	t, min	T, °C		
15	8′05″	80	8570000	204000
20	3′08″	197	1008000	173100
22′30″	2′15″	250	1071000	174900
25	2′15″	250	902000	169700
30	1′25″	315	816000	166400
45	1′23″	320	659100	158700
60	1′17″	330	571200	153000
120	1′17″	330	580900	153700

y_{etp} – elastic deflection of transformation plasticity;
y_{tp} – deflection of transformation plasticity;
M_S' – temperature of secondary martensitic transformation;
E_{tp} – modulus of transformation plasticity;
E_{etp} – modulus of elastic-plastic state.

The tempering temperature is very important for the diffusion processes occurring during tempering. Tempering processes at the 540 °C slows down that after 30 min at this temperature quantity of non-magnetic phase decreases just for 4 – 5 %, but plastic deformation of the test pieces does not appear. Plastic deflection of the test pieces after 1 h holding at the 540 °C is for one third smaller than plastic deflection of test pieces tempered at 560 °C.

Opposite processes go on at the higher temperatures, diffusion processes speed up, so at the tempering temperatures of 580 °C and 600 °C martensitic transformation already go on when holding time respectively is 10 min and 7.5 min, but the maximum plastic deflection and decreasing of quantity of non-magnetic phase is obtained when tempered for 45 min and 15 min (Table 2).

Table 2. Influence of the holding time on the transformation plasticity during tempering at 600 °C

Time, min	After hardening		After tempering		Deflection of the test pieces, mm	
	HRC	A_R, %	HRC	A_R, %	y_{etp}	y_{tp}
5	63.5	17	63.1	16.8	0.82	0.00
7.5	63.8	19	63.3	8.8	1.01	0.19
10	64	21	64.5	3.1	1.03	0.21
15	62	18	62.3	1.8	1.06	0.24
20	64.2	20.5	64.8	0.4	1.075	0.255
25	62.5	18.5	62.8	1.3	1.09	0.27

Time, min	M_S'		E_{tp}, N/mm^2	E_{etp}, N/mm^2
	t, min	T, °C		
5	–	–	∞	21000
7.5	3′	218	902000	169300
10	2′15″	262	816000	166400
15	1′45″	310	714000	161700
20	1′30″	333	672000	159400
25	1′30″	333	6347000	157200

y_{etp} – elastic deflection of transformation plasticity;
y_{tp} – deflection of transformation plasticity;
M_S' – temperature of secondary martensitic transformation;
E_{tp} – modulus of transformation plasticity;
E_{etp} – modulus of elastic-plastic state.

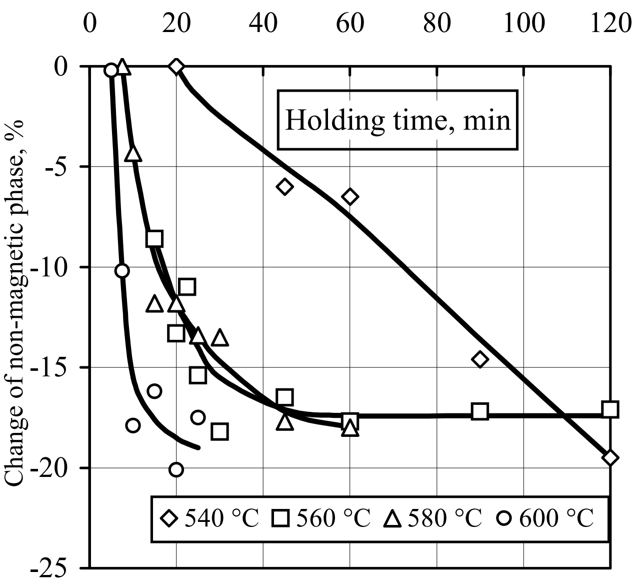

Fig. 2 Influence of tempering temperature and holding time on the variation of the quantity of non-magnetic phase.

Influence of temperature and holding time on the tempering processes of high-speed steel we can characterize by variation of quantity of non-magnetic phase (Fig. 2) and by the dependence of these parameters on the temperature of secondary martensitic transformation M_S' (Fig. 3).

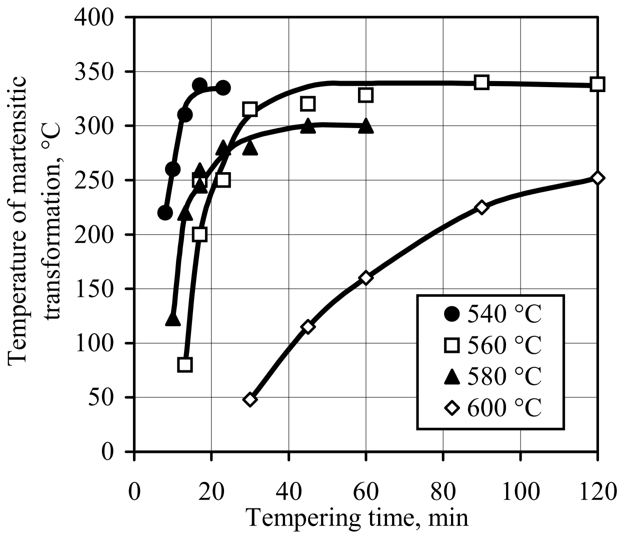

Fig. 3 M_S' dependence on the holding time at the tempering temperature.

According to these data it is possible to specify optimum holding time for high-speed steel that especially important applying tempering at the higher temperatures. The optimum holding times for steel P6M5: at the 540 ° ≥ 120 min, at the 560 °C – 60 min, at the 580 °C – 45 min and at the 600 °C – 15 min.

Figure 4 shows that transformation plasticity is related to secondary martensitic transformation, but there is no linear dependence on quantity of composed martensite.

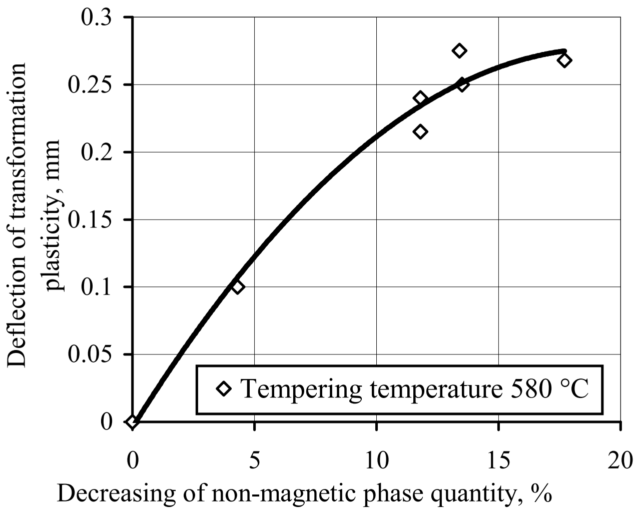

Fig. 4 Dependence of deflection of transformation plasticity on the extent of secondary martensitic transformation.

4 Conclusion

High-speed steel is in the state of transformation plasticity during secondary martensitic transformation. This state can be defined by the size of the plastic deflection and modulus of transformation plasticity E_{tp}.

Transformation plasticity for steel P6M5 is characteristic at 540 – 600 °C and depends on temperature of tempering and holding time.

There is no linear dependence between transformation plasticity and quantity of composed secondary martensite.

It is possible to flatten tools of high-speed steel that were distorted after hardening, during quenching after first tempering, accordingly evaluate kinetics of the secondary martensitic transformation.

The high-speed steel is very broadly used in manufacturing industry. So, the problems concerning cutting tools geometry and distortions shall be minimized. The main target of our research group is to analyze steel behavior during operations of heat treatment and to suggest for manufacturers how to escape above mentioned problems.

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