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Investigation of Transformation Plasticity of Tempered High Chromium Steel During Quenching

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The transformation induced plasticity (TRIP) phenomenon was first discovered in highly alloyed Cr, Ni and Mo steels. The microstructure of such steels contained significant amounts of retained austenite, which transformed to martensite during subsequent straining resulting in both high strength and toughness of steel. However, large addition of alloying elements make the steels more expensive and, hence, subsequent research efforts were directed at obtaining the TRIP effect in more cost effective compositions utilizing optimum termomechanical processing. Steel products, when hardened, deform and change its shape and measurements. On removal of deformation by flattening, special devices and technologies must be used, so expenditure of the labor increases. Steel after hardening is strength but brittle, however during transformation it is plastic for a short time, so at this moment it is a possibility to flatten curved products. Transformation plasticity of steel especially during tempering transformations investigated not so much that is why not so wide used in the practice.

Keywords: high chromium steel, deflection, tempering, transformation plasticity.

1. INTRODUCTION

Transformation induced plasticity (TRIP) effect is used for production of steels with high strength and high formability. The remarkable strength to ductility balance results form strain-induced transformation of retained austenite to martensite during plastic deformation [1 – 2].

The TRIP steels possess a multiphase microstructure consisting of ferrite, bainite and significant amount of retained austenite. The austenite is metastable at room temperature and is likely to transform to martensite during straining. The amount, morphology and stability of the retained austenite control mechanical properties of the TRIP steel. The formability improves with increasing volume of retained austenite [3].

Unique property of steel like material with crystal structure is anomaly high plasticity at the time of phase and structural changes it is known for 50 years already. This phenomenon more widely was investigated and tested for chromium-nickel TRIP steels and low carbon low alloyed steels during martensitic transformation [4 – 6].

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.

Heating for subsequent tempering of hardened steel, phenomenon of the transformation plasticity also is observed for certain times [7]. There are defined two regions of the transformation plasticity: low-temperature ($T < 450$ °C), when carbon precipitates from the over saturated solid solution and cementite composes, and high-temperature ($T > 450$ °C), when diffusion of chromium, iron and carbon atoms goes on and special carbide compose in the structure of high chromium steel.

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Especially on hardening for the secondary hardness high chromium die steel can possess big amounts of retained austenite. It is determined [7 – 8] that on quenching after tempering the steel Cr12Mo at the temperature of 520 °C during secondary martensitic transformation steel is in a state of transformation plasticity.

It is very important in the theoretical and practical aspects, when it is a need to select the technological regimes of heat treatment of precise tools. More comprehensive studies aren't carried out and described in the works of over authors. Consequently the objective of our research work is to investigate the influence of the tempering regimes on the transformation plasticity of high chromium steel during quenching.

2. EXPERIMENTAL

2.1. Test procedure

Two grades (according to Russian standard GOST) of high chromium steels Cr12 and Cr12V1 are chosen for the experiments. The chemical composition and hardening regimes are given in the Table 1. Chromium content in these steels is the same, but carbon content differs, in addition steel of grade Cr12V1 contains vanadium. The matrix of steel Cr12 after hardening at the temperature of 1100 °C is almost austenitic.

Hardened test pieces are tempered at temperature of 520 °C and are held in the electric furnace for 1 h; after holding are carried out into the special device and loaded under the load, which creates normal bending strains of 600 N/mm^2. Elastic and elastic-plastic deflections are registered at choice time intervals until test piece reaches room temperature. Temperature of test pieces is measured using weld to thermocouple made of chromel-aliumel and quantity of the non-magnetic phase after hardening and after tempering is defined using ballistic device BY-3.

Table 1. Chemical content of the steel and the regimes of the hardening

Grade according to GOST	Alloying elements, %			Hardening regimes				HRC	A_R [5], %
	C	Cr	V	T_1 [1], °C	T_2 [2], °C	t [3], min	quenching [4]		
Cr12	2.13	12.38	0.04	850	1050	4	S – A	65	46 – 49
				850	1100	4	S – A	50	95 – 96
Cr12V1	1.38	11.57	0.70	850	1100	4	S – A	61 – 62	49 – 54

[1] First heating at the temperature T_1 and holding for 4 min in the smelted salt 70 % $BaCl_2$ + 30 % NaCl;
[2] Second heating at the temperature in the smelted salt 97 % $BaCl_2$ + 2.8 % MgF_2 + 0.1 % of magnesium poliboride;
[3] Isothermal quenching at the temperature of 390 °C in the salt and holding for 1 min; after that in the still air;
[4] S – salt mixture for isothermal quenching KNO_3 + NaOH; A – air;
[5] A_R – quantity of non-magnetic phase after hardening.

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 [5]:

$$E_{tp} = \frac{P \cdot l^3}{48 \cdot I_x \cdot y_{tp}}, \text{ N/mm}^2, \quad (1)$$

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:

$$E_{etp} = \frac{P \cdot l^3}{48 \cdot I_x \cdot (y_e + y_{tp})}, \text{ N/mm}^2, \quad (2)$$

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.

3. RESULTS

Tempered and held for 1 h in the furnace at the temperature of 520 °C test piece is carried out into the transformation plasticity testing device and in 30 s is loaded by a bending load. Temperature of the test piece at this moment is 420 °C.

When test pieces are bent after first tempering, its deflection at the moment of the loading is for 25 – 85 % bigger than after the second tempering (Table 3), when deflection is $y_e = 0.75 – 0.76$ mm. Elastic deflection of the test piece can be calculated using expression:

$$y_e = \frac{P \cdot l^3}{48 \cdot E_T \cdot I_x}; \quad (3)$$

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 high chromium steel with body centered cubic space lattice at the temperature of 420 °C $E_T = 186000$ N/mm^2 [9] we can calculate elastic deflection of the test piece $y_e = 0.72$ mm. Young's modulus of chromium-nickel steel with face centered cubic space lattice – $E_T = 177000$ N/mm^2, elastic deflection of the test piece $y_e = 0.76$ mm. Comparing these results with the testing results it can be noticed that the bigger the quantity of the austenite the lower the yield point σ_y of the steel, i.e. the test piece bend by elastic-plastic deflection y_{ep} and it can be plastically deformed at the temperature interval of 400 – 500 °C. Plastic deflection of the test piece at the moment of the loading can be calculated:

$$y_p = y_{ep} - y_e; \quad (4)$$

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. It should be noted that the test pieces made of steel Cr12 and hardened at the temperature of 1050 °C have big enough creep on loading until cools from 420 °C to the temperature of 350 – 300 °C (Fig. 1).

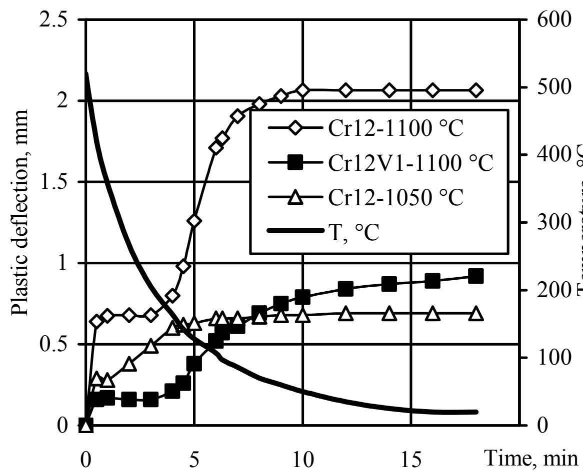

Fig. 1. Kinetics of the plastic deflection changes during cooling after the first tempering

The creep of test pieces made of steel Cr12V1 hardened at the temperature of 1100 °C is negligible. This can be explained by different chromium content, which dissolves in the solid solution.

Plastic deflection of the test pieces, made of steel Cr12 hardened at the temperature 1100 °C, above M_S' temperature is 2 – 3 times higher than plastic deflection of the test pieces with 46 – 54 % of retained austenite.

When temperature of quenched test pieces falls down until temperature of secondary martensitic transformation M_S', phenomenon of transformation plasticity appears, yield point σ_y of the steel reduces and test pieces until now being in the elastic state starts deform plastically (Fig. 1). The biggest plasticity is obtained when test pieces with quantity of the retained austenite from 95 % to 96 % are hardened at the temperature of 1100 °C, and smallest plasticity – when hardening temperature for steel Cr12 is 1050 °C.

Calculated values of modulus E_{etp} and E_{tp} are given in the Table 2.

Table 2. Dependence of modulus of transformation plasticity E_{tp} and modulus of elastic-plastic state E_{etp} on the steel grade and hardening temperature, quenched after tempering and held for 1 h at the temperature of 520 °C

Grade according to GOST	Hardening temperature, °C	E_{tp}, N/mm^2	E_{etp}, N/mm^2
Cr12	1050	427 300	125 200
	1100	93 800	61 300
Cr12V1	1100	177 100	81 600

Experimental data in the Table 3 show that during secondary artensitic transformation after first tempering quantity of retained austenite considerably decreases. After calculation of increased medium deflection during transformation plasticity for a 1 % of the composed martensite it is obtained for the test pieces made of steel Cr12 and hardened at the temperature of 1100 °C:

$$\frac{y_{tp}}{A_R - A_R'} = 0.036\ \frac{mm}{\%}\ , \quad (5)$$

hardened at the temperature of 1050 °C:

$$\frac{y_{tp}}{A_R - A_R'} = 0.001\ \frac{mm}{\%}\ , \quad (6)$$

where: A_R is the quantity of non-magnetic phase after hardening; A_R' is the quantity of non-magnetic phase after first tempering.

For the test pieces made of steel Cr12V1 hardened at the temperature of 1100 °C this relation:

$$\frac{y_{tp}}{A_R - A_R'} = 0.0355\ \frac{mm}{\%}\ . \quad (7)$$

These calculations show that transformation plasticity not only depends on the extent of transformation, but on the chemical content of the solid solution, determined by hardening temperature, as well.

High chromium die steels hardened for secondary hardness after the first tempering at the temperature of 520 °C can contain sufficiently much retained austenite (Table 3). Portion of carbon and chromium precipitate, temperature of secondary martensitic transformation M_S'' rises (in this case until 360 °C) on repeatedly tempering, and during quenching secondary martensitic transformation goes on and test piece plastically bends intensively (Fig. 2).

If after the second tempering the steel still have about 20 % of the retained austenite it is subjected for third tempering, but quenched after the latest doesn't bend.

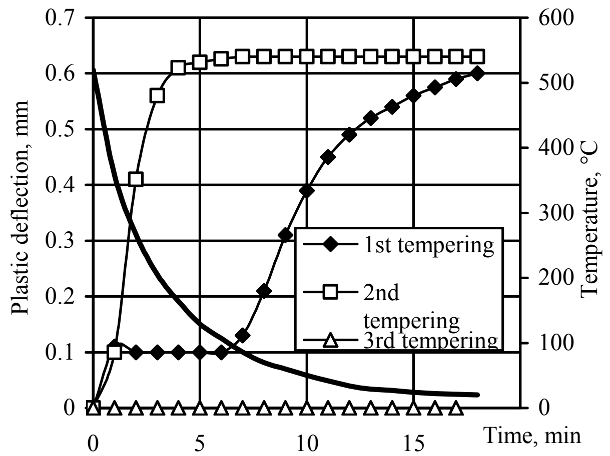

Fig. 2. Kinetics of the transformation plasticity change after repeated tempering and holding for 1 h at the temperature of 520 °C; σ_1 = 600 N/mm^2, steel Cr12V1

Table 3. Variation of elastic-plastic deflection and non-magnetic phase of the test pieces depending on hardening temperature and number of the tempering

Grade according to GOST	Hardening temperature, °C	After I tempering				After II tempering			
		y_{ep} [1], mm	y_p [2], mm	y_{tp} [3], mm	A_R' [4], %	y_{ep}, mm	y_p, mm	y_{vp}, mm	A_R'' [5], %
Cr12	1050	0.88 – 1.01	0.12 – 0.25	0.29 – 0.37	17 – 12	0.81 – 0.86	0.05 – 0.10	0.00	11 – 9
	1100	1.35 – 1.50	0.59 – 0.75	1.02 – 1.85	68 – 43.5	0.76	0.00	0.47	11.7
Cr12V1	1100	0.92 – 0.98	0.16 – 0.22	0.79 – 0.99	38.7 – 24.5	0.75 – 0.76	0.00	0.12 – 0.52	20 – 14

[1] elastic-plastic deflection on loading the test piece;
[2] plastic portion of deflection on loading the test piece;
[3] deflection of the transformation plasticity during secondary martensitic transformation;
[4] quantity of retained austenite after first tempering;
[5] quantity of retained austenite after second tempering.

The same we can state about the test pieces made of steel Cr12 hardened at the temperature of 1050 °C. After the first tempering steel contains from 12 % to 17 % of retained austenite and quenched after the second tempering doesn't bend as well.

In this case extent of plastic deflection (0.51 mm and 0.50 mm) and quantity of the composed martensite (15.4 % and 14 %) after the first and second tempering practically coincide. After the third tempering the test piece absolutely doesn't bend even if 15.5 % of martensite composed during quenching.

Table 4. Dependence of temperature of secondary martensitic transformation M_S on hardening temperature and number of repeated tempering at 520 °C; $\sigma_1 = 600$ N/mm^2

Grade according to GOST	Hardening temperature, °C	M_S' [1], °C	M_S'' [2], °C
Cr12	1050	218 – 285	282
	1100	182 – 150	–
Cr12V1	1100	97 – 182	282 – 360

[1] M_S' – temperature of secondary martensitic transformation after the first tempering;
[2] M_S'' – temperature of secondary martensitic transformation after the second tempering.

According to the curves of deflection variation given in Fig. 1 and Fig. 2 it is determined temperature of the secondary martensitic transformation M_S' and M_S'', which is presented in the Table 4.

It can be seen that this temperature depends on grade of the steel and hardening temperature, but because of strongly expressed segregation of chemical elements that effects on uniformity of tempering processes for individual test piece it is rather different.

3. CONCLUSIONS

1. During secondary martensitic transformation high chromium steel is in a state of the transformation plasticity, which is evaluated by extent of plastic deflection of the test pieces y_{tp} and by modulus of the transformation plasticity E_{tp}.
2. On quenching after tempering at the temperature of 520 °C transformation plasticity depends on the steel grade and on the structural and chemical content of the solid solution, stipulates by heating regimes during hardening.
3. On raising the hardening temperature from 1050 °C to 1100 °C for steel Cr12 transformation plasticity increases 4 times.

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