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Experimental analysis of transformation plasticity and stress relaxation of carbon spring steel during tempering

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1. Introduction

Transformation plasticity is a significantly increased plasticity during a phase change. For an externally applied load for which the corresponding equivalent stress is small compared to the normal yield stress of the material, plastic deformation occurs. This definition can be found in the very recent works [1, 2]. In several works transformation plasticity is called transformation induced plasticity (TRIP effect) [1-4] or transformation superplasticity [5, 6].

Transformation plasticity is generally considered as the anomalous plastic strain observed when metallurgical transformation of steel (austenite → martensite) occurs under an external applied stress even much lower than the yield stress of the weaker phase [7].

Many investigations of transformation plasticity are based on finite elements method (FEM) [8-10]. The principal part of the scientific works is based on the research of transformation plasticity that is caused by martensitic transformation during quenching [11-13]. In order to get the information of not alloyed carbon steel behaviour we have chosen structural steel containing various amount of carbon for the possibility of comparison. Also, we decided to perform bending test that allows obtaining compression and tensile strain at the same time. Furthermore, the bending as the gentle type of loading is more acceptable for quenched tool steel with high hardness.

Heat treatment of steel is an essential technology to enhance the strength, wear resistance, durability of articles, but dimensional distortion always occurs during this process especially during quenching [10]. The distortion of hardened steel articles could be corrected during tempering by fixing their form into the stamps or other special devices. Therefore we have chosen the bending tests during tempering because of practical use of transformation plasticity phenomenon. The investigation of stress relaxation during transformation plasticity of tempering is included for the possibility to apply this effect practically.

2. Testing procedures

The as-received material was a wrought carbon steel rod with the diameter of 12-14 mm. The chemical composition of the alloys is listed in Table 1.

The grades of investigated steel (GOST 1050-88):

- 45 – structural steel with average quantity of carbon up for a wide appliance (equivalent C45 EN 10083-1);
- 65, 85 – tool steel usable for springs (equivalent C65, C85 EN 10083-1).

The specimens were machined from the original rod along the longitudinal direction, in the form of 6×8×100 mm^3 bar. For hardening the specimens were heated in protective ambience of $CO_2 + CO + N_2$ and then cooled. Schedule of hardening and hardness (Rockwell hardness C) of hardened specimens is given in Table 2.

Experiments of transformation plasticity were carried out with special device [14]. Hardened specimen was put down in the device and then loaded. The value of bending stress was 450 MPa. According to the appropriate tempering transformations, the typical temperatures of tempering were picked: 185°C, 275°C, 370°C and 420°C. At 185°C temperature the tempering of martensite proceeds, retained austenite resolves at 275°C, and 370-420°C temperature is the end of carbon segregation from the martensite.

The temperature of specimen was measured using welded chromel-alumel thermocouple with the wire of 0.3 mm thickness. Pending the heating the elastic deflections of loading y_e and unloading y_n and deflection of transformation plasticity y_{tp} were measured to within ± 0.01 mm.

Table 1

Chemical composition of steel (wt.%)

Steel grade GOST 1050-88	C	Mn	Si	Cr	Ni	S	P	Cu	Fe
45	0.47	0.61	0.30	0.04	0.04	0.007	0.014	0.04	balance
65	0.63	0.51	0.24	0.12	0.04	0.014	0.013	0.04	
85	0.81	0.33	0.21	0.18	0.24	0.015	0.020	0.19	

Table 2

Steel hardening schedule and hardness received after hardening

Steel grade GOST 1050-88	Hardening temperature,°C	Heating duration, min	Cooling agent	HRC (after hardening)
45	840	15	Water	56-58
65	830		Water	60-62
85	820		Oil	58-60

The tests of transformation plasticity were accomplished by bending steel specimens. At the moment of loading, the particular stress has produced elastic deflection of the specimen on condition that the value of certain stress would not be higher than 40% of yield strength of the steel. At that time, temperature of the specimen was not higher than 40-50°C and the value of elastic deflection y_e of loading was measured. The hardened steel specimen was bent elastically, put into the tempering furnace and started to bend intensively during the heating. The increasing of plastic deformation of heated specimen is determined by transformation plasticity and decreased Young's modulus when the stress is constant. The values of transformation plasticity deflection y_{tp} at all tempering duration, and elastic deflection during unloading y_n were measured. The total deflection of specimen is the sum of elastic and plastic deflections

$$y_{ep} = y_e + y_{tp} \tag{1}$$

During unloading we had constant value of the decrease of deflection of unloading y_n. The remained plastic deflection of cooled specimen is

$$y_p = y_{ep} - y_n \tag{2}$$

3. Results and discussion

When hardened steel specimen is placed into the furnace, it starts bending rapidly, though chosen tensile stress is less than yield strength. The curves of specimens' deflection show (Fig. 1) that the plastic deflection of various carbon steel specimens increases during tempering. The specimens of all investigated steel grades bend mostly during the first 5-10 minutes. Over the last 50 minutes of tempering, the plastic deformation of specimens is gradually decreasing. The big difference of transformation plasticity of different carbon steels is met through all the tempering duration.

The plastic deformation of steel specimens during tempering can be explained by the diffusion of carbon atoms in the martensite matrix. Carbon atoms are small interstitial ones in metal and they diffuse through the lattice by interstitial mechanism from one interstitial site to the adjacent interstitial site [1, 2, 4, 7]. Motion of carbon atoms generates the stress in the lattice that is summed with the external stress and thus large plastic deformations occur in the steel specimens. More carbon is in the steel, the higher degree of supersaturation of solid solution (martensite), the greater metastability of microstructure and also the bigger plastic deformations during tempering occur (Fig. 1).

The presence of the phenomenon of transformation plasticity is described very demonstratively by Fig. 2. For that part of the experiment two groups of the specimens were investigated. The first group was of the hardened specimens with the structure of high metastability degree that was turned to the experiment of bending during tempering (Fig. 2, the curves with black points). Other specimens were hardened then tempered at 370°C without loud, cooled and eventually bended at the certain temperature of tempering (Fig. 2, the curves with white points).

It is known [15], that at the temperature of 350-400°C, the process of carbon saturation from the solid solution-martensite terminates fully, the interruption of coherence occurs and the formation of cementite (ε-$Fe_xC \rightarrow Fe_3C$) proceeds. Therefore the degree of metastability declines considerably and the result is the absence of plastic bending of the specimens during tempering. Furthermore, the mentioned figure presents high intensity of the tempering transformation at the period of 200-300°C temperature: decomposition of martensite and retained austenite and the formation of carbides.

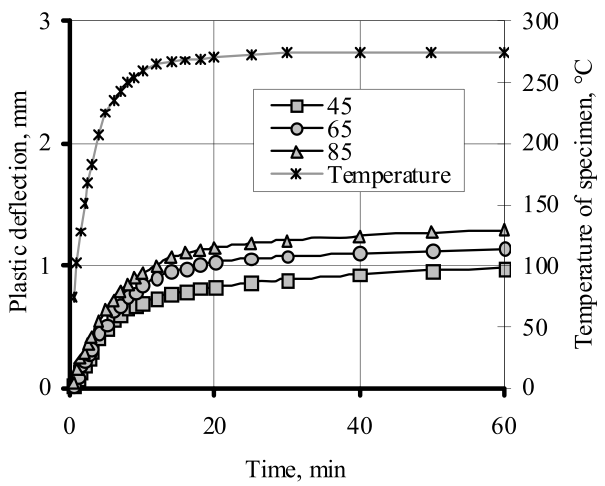

Fig. 1 Relationship between transformation plasticity deflection and carbon content. Normal bending stress 450 MPa, tempering temperature 275°C, tempering duration 1 hour

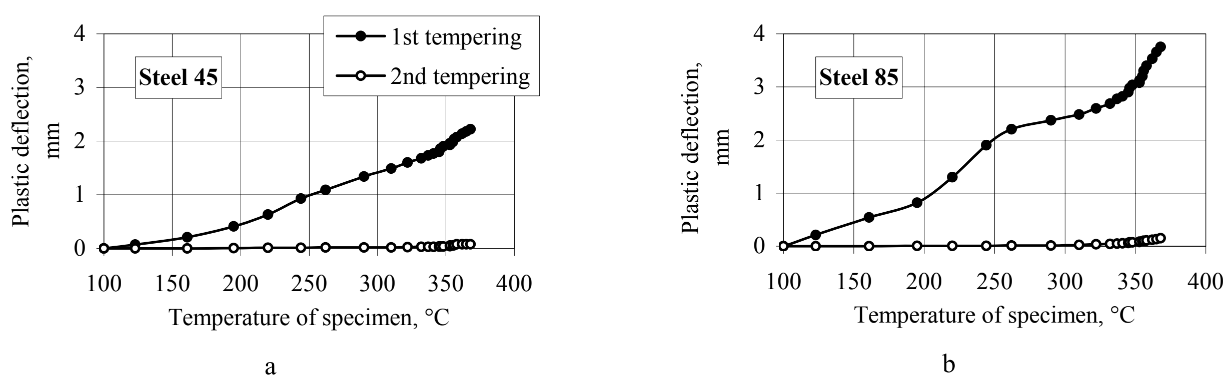

Fig. 2 Dependence of transformation plasticity deflection on stability of steel structure. Tempering temperature 370°C, normal bending stress 450 MPa: a - grade 45 steel; b - grade 85 steel

The phenomenon of transformation plasticity can be used practically. During hardening the deformations or splits occur because of the stress when the articles are cooled. This is characteristic for carbon steel, which is cooled in water. There are several methods how to reduce the hardening deformations. One of them is the improving during the transformation plasticity of tempering. The curved article is bent to the reverse direction and turned to heating. The transformation plasticity occurs and elastic stress relaxes.

The relaxation properties of carbon spring steel were researched with the same transformation plasticity device. The specimens were bent for the fixed value of deflection y_e, and heated in the furnace. The hardened steel is brittle and the specimen brakes if it is bent for more than 0.5 mm, thus, the elastic deflection of 1.5 mm value was reached after 3 stages during heating: the specimen was bent for 0.5 mm when its temperature has reached 70°C, 1.0 mm deflection – at 150°C and 1.5 mm deflection – at 170°C. The fixed elastic deflection y_e, deflection of unloading y_n and retained plastic deflection were measured.

The elastic stress relaxes because of the transformation plasticity and a part of the fixed elastic deflection y_e becomes plastic y_{tp}. Not relaxed elastic deflection is calculated as the deflection of unloading y_n. The deflection of unloading y_n decreases when tempering temperature and the content of carbon increase.

Steel relaxation properties may be evaluated by relative relaxation coefficient K_r

$$K_r = \frac{y_p}{y_e} \tag{3}$$

where y_p is retained plastic deflection, mm; y_e is fixed deflection of a specimen bent elastically before heating, mm.

The experiments proved that the relaxation coefficient of carbon steel depends on the degree of tempering and the content of carbon. The values of elastic and plastic deflections of the specimens show that the relative coefficient of relaxation K_r increases when tempering temperature and the content of carbon rises (Fig. 3). Higher values of K_r are obtained for grade 65 and 85 steel at 185-275°C temperatures, when intensive separation of carbon atoms from the lattice of martensite occurs and the carbides Fe_3C form. The values of the coefficient of relaxation are presented in Table 3.

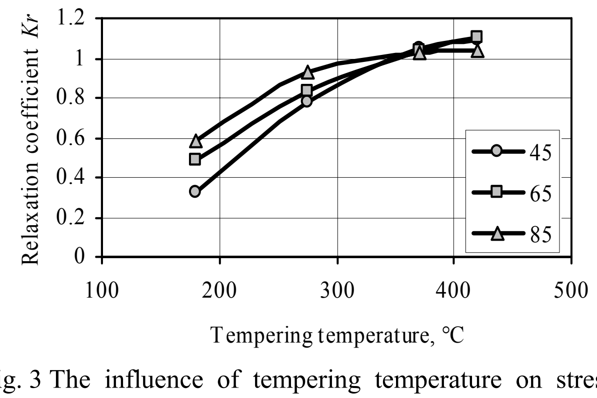

Fig. 3 The influence of tempering temperature on stress relaxation. Tempering duration 1 hour

The tensile stress and compression has different influence on the processes of tempering, especially on the volume changes. The compression has bigger effect on this process and the volume of compressed layer diminishes more, thus the greater values of coefficient K_r were obtained for steel with high carbon content and at higher temperatures of tempering (Table 3).

Table 3

Dependence of relaxation coefficient K_r of carbon steel on tempering temperature

Steel grade GOST 1050-88	Tempering temperature,°C	Deflection, mm		K_r
		y_n	y_p	
45	185	0.91	0.62	0.32
	275	0.56	1.17	0.78
	370	0	1.57	1.05
	420	0	1.63	1.09
65	185	0.90	0.73	0.49
	275	0.26	1.24	0.83
	370	0	1.56	1.04
	420	0	1.65	1.10
85	185	0.65	0.87	0.58
	275	0.22	1.40	0.93
	370	0	1.55	1.03
	420	0	1.56	1.04

As there was mentioned, the transformation plasticity can be used practically to improve deformed hardened articles. E. g., a spring, which has deflection y_m after hardening, is tightened elastically in special device and tempered at typical temperature. Estimating the coefficient of stress relaxation K_r, the fixed deflection y_e required for improving of the spring can be calculated

$$y_e = \frac{y_m}{K_r} \tag{4}$$

Improving the articles with big deformations of hardening, especially the articles of high carbon steel, rather intense force is required that can cause breaks. In that case the force must be increased gradually till the article reaches 150-170°C temperature.

4. Conclusions

The transformation plasticity of hardened steel is related to phase and structural changes during tempering and it depends on chemical composition of the steel. Transformation plasticity was indicated during tempering of carbon steel at 370°C and lower temperature, when carbon separates from the saturated solid solution and cementite forms. The transformation plasticity increases by 4 to 7 times when the tempering temperature rises from 185°C to 420°C and the content of carbon increases from 0.45% to 0.85%. During second tempering of carbon steel at 370°C and lower temperature plastic deflection of the specimens is from 3% to 5% of the plastic deflection as comparing to the deflection of the specimens, tempered for the first time. Elastic stress decreases during tempering because of the transformation plasticity. The stress relaxation coefficient varies from 0.32 to 1.1, depending on carbon content and tempering temperature. Considering the transformation plasticity of hardened steel during tempering and the relaxation properties, it is possible to project the technologies of the improving of geometrical parameters of deformed springs.

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ANGLINIO SPYRUOKLIŲ PLIENO VIRSMINIO PLASTIŠKUMO IR RELAKSACINIŲ SAVYBIŲ TYRIMAS ATLEIDIMO METU

R e z i u m ė

Atleidžiamų išorinės jėgos išlenktų grūdinto plieno bandinių įtempiai relaksuoja dėl virsminio plastiškumo ir gaunama labai didelė plastinė deformacija. Virsminiam plastiškumui ir įtempių relaksacijai tirti buvo parinktos trys anglinio plieno markės, turinčios skirtingą anglies kiekį (0.45%, 0.65% ir 0.85%). Darbe aptariamas virsminio plastiškumo ir įtempių relaksacijos savybių praktinis pritaikymas.

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EXPERIMENTAL ANALYSIS OF TRANSFORMATION PLASTICITY AND STRESS RELAXATION OF CARBON SPRING STEEL DURING TEMPERING

S u m m a r y

The phenomenon of stress relaxation during transformation plasticity of hardened steel at tempering is observed, when an article of hardened steel is impressed by an external force during tempering and the unusually great plastic deformation is obtained. Series of experiments were made for the investigation of transformation plasticity of carbon steel with various content of carbon (0.45%, 0.65% and 0.85%) and the subject of application of transformation plasticity was discussed.

Р. Кандротайте Янутиене, Ю. Жвинис

ИССЛЕДОВАНИЕ ПЛАСТИЧНОСТИ, НАВЕДЕННОЙ ПРЕВРАЩЕНИЕМ И РЕЛАКСАЦИОННЫХ СВОЙСТВ УГЛЕРОДИСТОЙ ПРУЖИННОЙ СТАЛИ ПРИ ОТПУСКЕ

Р е з ю м е

При отпуске закаленных стальных образцов, изогнутых наложенным внешним усилием, напряжения в них релаксируют благодаря пластичности превращения, результатом которой является значительная пластическая деформация. Для исследования отпускной пластичности превращения и релаксации упругих напряжений выбраны три марки углеродистой стали с различным количеством углерода (0.45%, 0.65% и 0.85%). В статье обсуждается возможность исследования пластичности превращения и релаксации напряжений в практических целях.

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