ISSN 1392–1320 MATERIALS SCIENCE (MEDŽIAGOTYRA). Vol. 9, No. 3. 2003

Investigation of Kinetic Plasticity of High Chromium Steel during Tempering

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Received 12 October 2002; accepted 02 March 2003

This article presents the results of the investigation of the kinetic plasticity of hardened high chromium steel during tempering at 210 °C – 520 °C temperatures. The researched steel contains 0.19 % – 2.13 % carbon and 12 % – 18 % chromium. The hardening temperatures are chosen from 950 °C till 1100 °C. After the investigation was carried out, the dependence between the content of carbon, temperature of hardening and tempering, normal bending stresses was found. An influence of chromium on steel tempering character was determined. The results of the work may be used for the development of technology of hardening and smoothing of articles and tools.
Keywords: high chromium steel, kinetic plasticity, hardening, tempering, deflection.

1. INTRODUCTION

The hardened steel is very hard and brittle, but for the short time during the tempering it can be very plastic. This phenomenon is very interesting theoretically and practically, but it is researched insufficiently.

It is known, that hardened steel becomes kinetically plastic during the first tempering. When the steel has more retained austenite, it becomes plastic also during cooling, when the second martensitic transformation occurs [1].

The kinetic plasticity is related with the content of carbon in steel [2, 3]. It is determined, that kinetic plasticity increases with the increasing of the content of carbon in the solid solution – martensite. Also, during the tempering up to 375 °C temperature, two intensifications of kinetic plasticity appear: at 200 °C – 270 °C temperature, when carbon strongly precipitates from martensite and retained austenite [4], and at 320 °C – 375 °C temperature, when the carbides Fe_3C form from Fe_xC. The plastic deformation of hardened steel before tempering has an influence on carbon precipitation from the martensite and forming of carbides [5].

The hardened high chromium steel has a complex microstructure: solid solution - martensite alloyed by chromium and saturated with carbon and retained austenite, and also, special carbides Cr_7C_3 or $Cr_{23}C_6$, dependently on carbon content. On changing the tempering temperature very different amount of carbides dissolves, the chemical composition of solid solution and relation of quantities of martensite, retained austenite and not dissolved carbides change.

Chromium reduces the diffusion of carbon atoms in steel, thus, the damping of the martensite tempering and the coagulation of carbides occur. When the tempering temperature is high enough (> 450 °C), the diffusion of chromium atoms is possible. All that is related with the structural transformations [4, 6 – 8]. Retained austenite of high carbon and chromium steel dissociates during tempering at 400 °C – 550 °C temperature [8, 9]. Chromium and carbon precipitate partly from the retained austenite, the special carbides form and the temperature M_S increases. Thus, the secondary martensite transformation is possible during cooling. It was noticed [1], that these processes induce significant increase of plasticity, but they were not researched sufficiently well.

The aim of this work is to research the character of the kinetic plasticity of high chromium steel during tempering.

2. EXPERIMENTAL

The bending specimens of steel 20X13, 40X13, 95X18 and X12, made from a hot rolled bar of ∅ 14 mm – 16 mm diameter, were used for the investigation according to the method described in the work [2]. The chemical composition and hardening schedule of the specimens is given in Table 1.

Steel X12 is distinguished for the high heterogeneity of carbides - this very affects mechanical properties of the steel. Using specimens, cut from the hot rolled strip of 10 mm × 100 mm section dimensions, we investigated the influence of carbide orientation on steel kinetic plasticity. We have compared kinetic plasticity of specimens cut along and across section of the strip. The heterogeneity of carbides of this mentioned steel is 3 degree according to GOST 5950-63.

During the investigation, the hardened specimens were tempered at 210 °C, 410 °C, 500 °C and 520 °C temperature on holding 60 min. or 240 min. Normal bending stresses of 188 MPa and 416 MPa were used. During the tests the indicator measured the deflection of the specimens with accuracy of 0.01 mm at chosen ranges of time. The curve of the heating was written down.

During tempering at higher temperatures, without kinetic plasticity, the creep due to temperature of steel is possible during structural transformations. To evaluate this creep, a part of researched steel specimens were tempered at temperature higher on 40 °C – 100 °C, than at the selected tempering temperature, and then turned for testing.

3. ANALYSIS AND RESULTS

During tempering of high chromium steel at 500 °C – 520 °C temperature, two kinetic plasticity ranges were observed. The plastic deflections of these ranges were signed by y_v' and y_v''. During tempering at 200 °C – 400 °C

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Table 1. Chemical composition and hardening schedule of steel

Steel grade	Chemical composition, %				Hardening schedule		
	C	Cr	Si	Mn	T, °C	Retained austenite, %	HRC
20X13	0.19	12.71	0.23	0.29	950; 1000; 1050; 1100	3 – 16	47 – 59
40X13	0.38	12.89	0.32	0.35	950; 1000; 1050; 1100	5 – 22	47 – 59
95X18	0.97	18.20	0.55	0.55	950; 1000; 1050; 1100	5 – 24	53 – 60
X12	2.13	11.57	0.30	0.44	950; 1000; 1050; 1100	9 – 65	58 – 62

Annotation. The specimens were heated in the smelted salts: I – heating till 840 °C for 4 min. in $BaCl_2 + NaCl$ salts; II – heating till the hardening temperature for 4 min. in $BaCl_2 + MgF_2$ salts; III – isothermal cooling till 380 °C in the bath of $KNO_3 + NaOH$; IV – final cooling in air

temperature (Fig. 1, 2), only the first plastic deflection y_v' was obtained. It is related with the precipitation of carbon from solid solution, formation and coagulation of cementite. The kinetic plasticity is as bigger as steel has more carbon: tool steel X12 is more plastic for 1.5 – 2.5 times than stainless steel 20X13, 40X13 and 95X18.

During tempering of stainless steel at 407 °C temperature, it was noticed, that the specimens after 5 minutes heating, when their temperature reaches 360 °C, stop bending, then they begin smoothing (Fig. 2). This is characteristic for steel, which is hardened from low temperatures. Such phenomenon, when the specimen deforms conversely to the direction of the bending force, may be explained by the structural transformations of different intensities and structural stresses that appear due to the changes of volume. The deformation of the specimen contrariwise to the bending direction, allows to suppose, that the tension stresses induce the precipitation of carbon atoms from the lattice of martensite. As concerns this reason, the volume of steel lessens more in the stretched part of the specimen than in compressed part of this one. If the structural stresses were bigger, than the load stresses, the deformation would be negative. According to its value Δy the force that produces such deformation may be calculated:

$$\Delta y = -\frac{Pl^3}{48 I_x E_T} \ . \tag{1}$$

According to (1):

$$-P = \frac{48 I_x E_T \Delta y}{l^3} \ , \tag{2}$$

where E_T is the elasticity modulus of researched steel at the temperature of test, calculated according to the deflection of unloading; I_x is the inertia moment of specimen, mm^4; l is the distance between supports when specimen is bended by concentrated force.

Table 2. Deflection change of specimen after 5 minutes tempering, when the temperature of specimen reaches 357 °C, till 60 minutes. Tempering temperature 407 °C; maximum normal bending stresses 416 MPa

Steel grade	Hardening T, °C	Deflection y_i, when time is		Deflection change Δy at 5′– 60′		Deformation conversely to force direction	
		5 minutes	60 minutes	mm	%	P, kgf	σ, MPa
20X13	950	0.16	0.08	–0.08	–50.0	–22.0	–76
	1000	0.23	0.17	–0.06	–26.0	–16.0	–56
	1050	0.32	0.26	–0.06	–19.0	–16.0	–56
	1100	0.48	0.42	–0.06	–12.5	–15.5	–54
40X13	950	0.21	0.20	–0.01	–5.0	–2.7	–9
	1000	0.25	0.23	–0.02	–8.0	–5.4	–18
	1050	0.40	0.45	+0.05	+12.5	–	–
	1100	0.65	0.71	+0.06	+9.0	–	–
95X18	950	0.20	0.24	+0.04	+20.0	–	–
	1000	0.19	0.11	–0.08	–42.0	–22.0	–76
	1050	0.32	0.38	+0.06	+19.0	–	–
	1100	0.51	0.58	+0.07	+14.0	–	–
X12	950	0.52	0.60	+0.08	+15.0	–	–
	1000	0.65	0.70	+0.05	+8.0	–	–
	1050	0.81	0.86	+0.05	+6.0	–	–
	1100	1.12	1.23	+0.11	+10.0	–	–

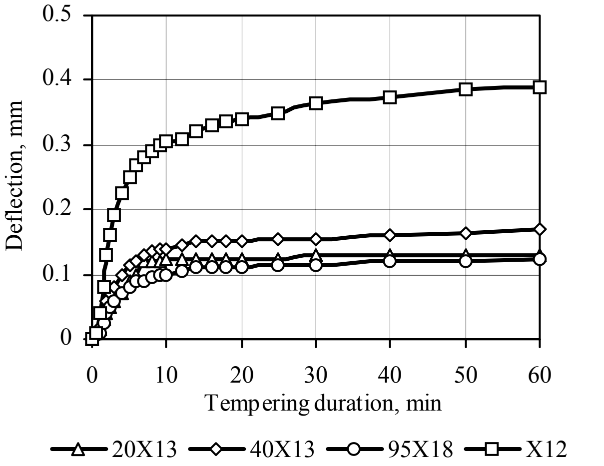

Fig. 1. Deflection of the specimens at tempering temperature 210 °C. Hardening temperature 1050 °C, normal bending stresses 416 MPa

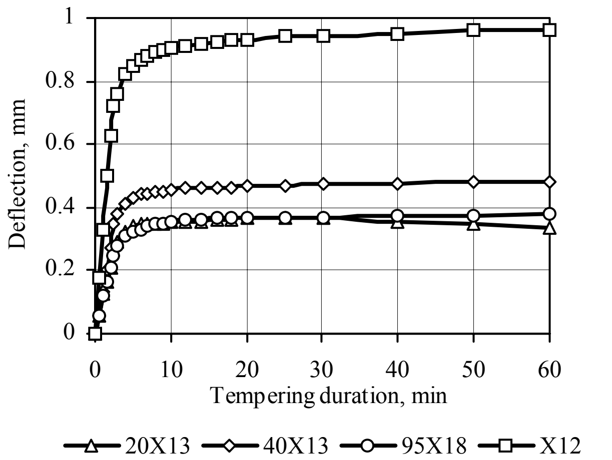

Fig. 2. Deflection of the specimens at tempering temperature 407 °C. Hardening temperature 1050 °C, normal bending stresses 416 MPa

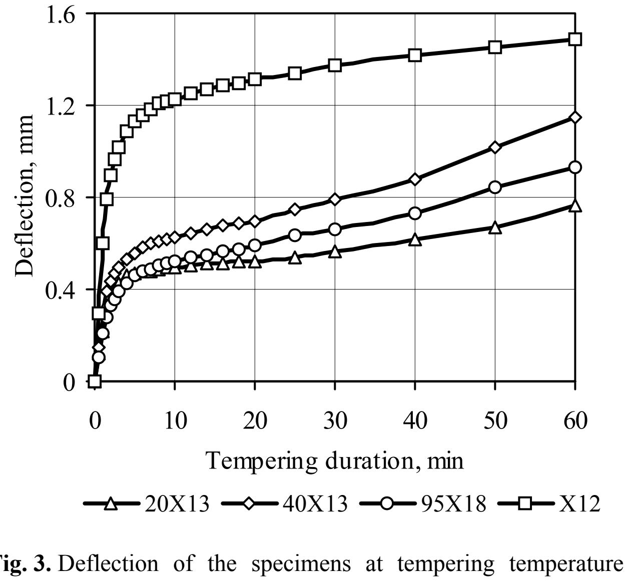

Fig. 3. Deflection of the specimens at tempering temperature 500 °C. Hardening temperature 1050 °C, normal bending stresses 416 MPa

The value of the structural stresses σ_s may be calculated according to [8]:

$$\sigma_s = -\frac{Pl}{4W}k , \tag{3}$$

where $k = 1.2$ is the coefficient calculating resistance moment of the specimen, when the deformation is elasto-plastic. The results of calculation are presented in Table 2.

On tempering of high chromium steel at temperature higher than 450 °C, the second increase of plasticity, which is signed by y_v'', occurs. This is characteristic especially for stainless steel. Fig. 3 shows, that during the first 10 minutes tempering at 500 °C while the specimens of steel 20X13 hardened from 1050 °C heats up till 490 °C, deflection y_v' reaches 0.44 mm value. Deflection does not change until 25-th minute of heating, then the specimens start to bend and until 60-th minute of heating the deflection y_v'' reaches 0.16 mm value that is 37 % of the value of deflection y_v'. In this period the specimens of steel 95X18 and 40X13 are more plastic, because their deflection increases accordingly on 67 % and 82 %, while the deflection of steel X12 specimens – only 13 %.

During tempering of high chromium steel 95X18 at 520 °C temperature, the plastic deflection y_v'' increases till 300 % – 450 % of y_v' value after 60 minutes. In the same conditions the deflection of steel X12 specimens reach only 44 % of y_v' value (Fig. 4). After 1 hour endured test, the specimens of steel 95X18 still bend intensively, therefore at the further test of the specimens deforming during tempering the duration was prolonged till 4 hours. The results of tests are presented in Fig. 5. They show, that the deflection y_v'' increased on 1.7 – 2.7 times after further 3 hours tempering. The specimens, hardened from 950 °C temperature and tempered 3 times at 560 °C temperature for 2 hour, bend the least. Steel after such treatment has stable microstructure (HRC 41 – 43). We may propose that the specimen, bent at 520 °C temperature for 4 hours, bends till 0.6 mm only because of creep. This composes about 25 % of the value of deflection comparing to the deflection of the specimen, tempered for the first time at the same conditions. Martensite of steel 95X18, hardened from 1100 °C temperature, has about 11 % chromium and 0.25 % carbon [10]. After the multiple tempering at 560 °C tempering, the hardness of steel is HRC 47 – 50 and the

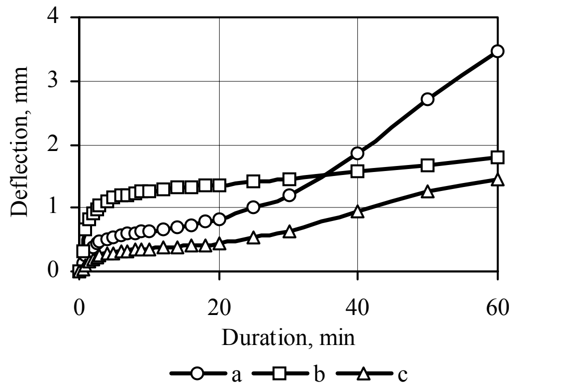

Fig. 4. The deflection of specimens at 520 °C tempering for 1 hour. Hardening temperature 1050 °C: a – 95X18, 416 MPa; b – X12, 416 MPa; c – 95X18, 188 MPa

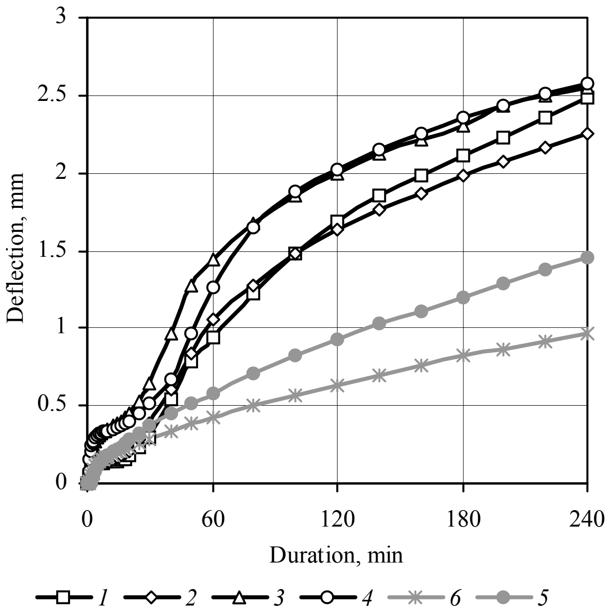

Fig. 5. The hardening temperature and tempering duration influence on deflection of steel 95X18 specimens. Tempering temperature 520 °C; normal bending stresses 188 MPa: 1 – 950 °C; 2 – 1000 °C; 3 – 1050 °C; 4 – 1100 °C; 5 – 950 °C, 560 °C × 1 h × 3 times; 6 – 1100 °C, 560 °C × 1 h × 3 times

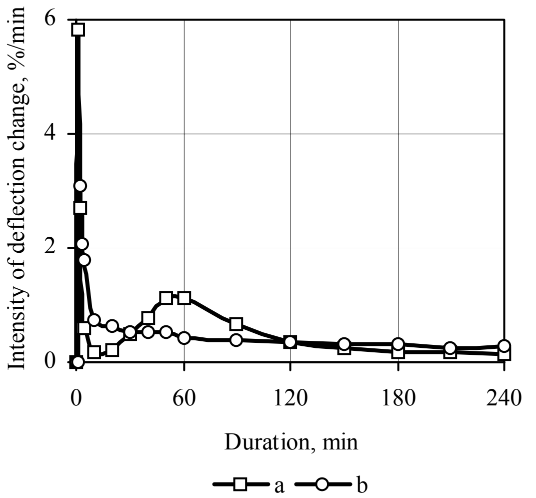

Fig. 6. Intensity of deflection of steel 95X18 specimens, hardened from 1100 °C and bended during tempering at 520 °C temperature for 4 hours: a – tempered for the first time after hardening; b – tempered without load at 560 °C temperature 4 times by 1 hour

plasticity on the repeated tempering is bigger on 37 % comparing with the plasticity of the specimen during the first time tempering.

Evaluation of the absolute (mm/min.) and relative (%/min.) intensities of deflection change shows, that during the first time tempering, the plastic deformation is the most intensive trough the 2 first minutes, while the specimen is heated till 350 °C – 400 °C temperature and the carbon precipitates intensively from the martensite. When the specimen is heated till 500 °C – 520 °C temperature the intensity of plastic deformation increases again and it becomes the biggest after 40 – 60 minutes. Perhaps, at this period the intensive precipitation of chromium atoms from the solid solution, the diffusion of carbon and chromium, the replacement of iron atoms to chromium ones and the formation and coagulation of special carbides $Me_{23}C_6$ appear. Carbon and chromium, dissolved in solid solution – martensite and retained austenite, has a great influence on these processes. During the hardening from 950 °C – 1000 °C temperature, when the special carbides $Me_{23}C_6$ practically do not dissolve, the parameters of the plasticity are the same (Fig. 7). The intensity of deflection change is the biggest one when the specimens are hardened from 1050 °C temperature, and it starts to decrease after hardening from 1100 °C temperature. Perhaps, these processes proceed when the amount of retained austenite (7.5 % when hardening is from 1050 °C temperature) reaches 24 % when hardening temperature is 1100 °C.

Fig. 9 shows, that steel X12 is the most plastic and steel 20X13 has the lowest plasticity, if compared the plasticity of specimens of steel 20X13, 40X13, 95X18 and X12, hardened from 950 °C, 1000 °C, 1050 °C and 1100 °C temperature and tempered at 210 °C – 407 °C temperature. The plasticity of steel decreases with the increasing of hardening temperature. Especially steel 95X18 has high plasticity during tempering at 520 °C temperature.

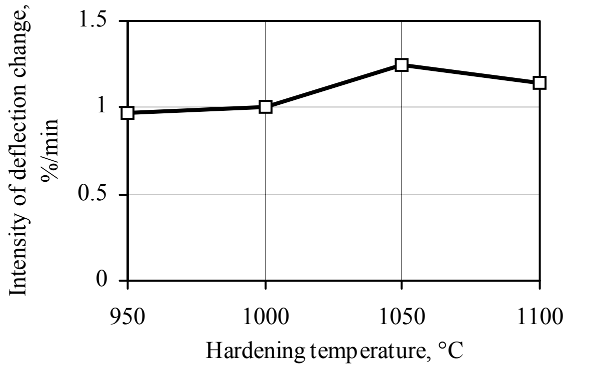

Fig. 7. The dependence between hardening temperature and the maximum intensity of deformation. Tempering temperature 520 °C; normal bending stresses 188 MPa

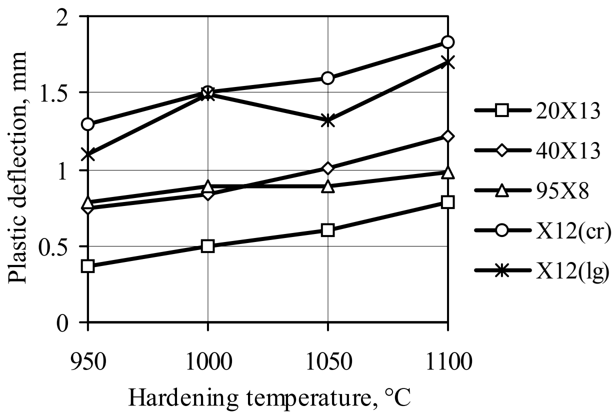

Fig. 8. The influence of hardening temperature on deflection of transformation. Normal bending stresses 416 MPa, tempering temperature 500 °C, duration 60 min

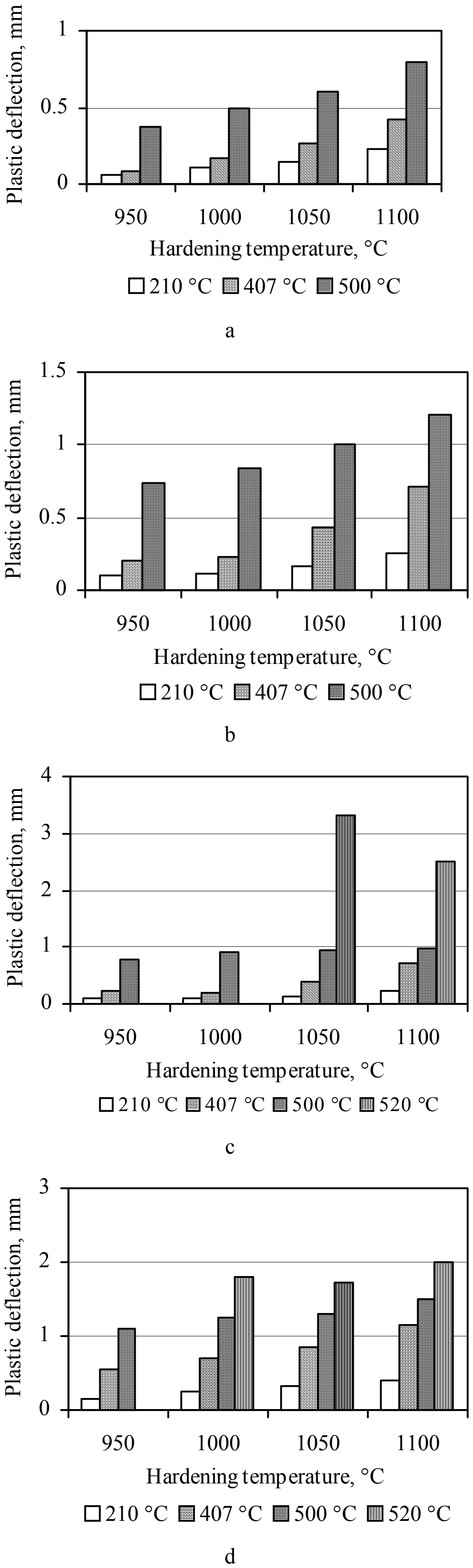

Fig. 9. The influence of hardening and tempering temperatures on plastic deflection of steel specimens during the first tempering. Normal bending stresses 416 MPa, duration 60 min: a – 20X13; b – 40X13; c – 95X18; d – X12

The test, made for investigation of the heterogeneity of carbides in steel X12, showed that the orientation of carbides hasn't any influence on the plasticity of steel during tempering. Comparing the deflections of cross and longitude specimens (Fig. 8), we may suppose, that the cross specimens bent more for 8 % – 9 % than the longitude ones during tempering at 500 °C.

4. CONCLUSIONS

1. Two ranges of temperature, having very high plasticity during the tempering of high chromium steel were determined: 200 °C – 400 °C where intensive precipitation of carbon atoms from martensite appears and temperature higher than 500 °C where the carbides of chromium form.
2. The hardening temperature affects on kinetic plasticity of high chromium steel during tempering: the hardening temperature changes the chemical composition of solid solution and phase structure of steel.
3. At higher than 500 °C temperature, where formation of the chromium carbides occurs, plasticity of steel 95X18 is bigger on 7 – 11 times than during the precipitation of carbon atoms from martensite and Fe_3C formation.
4. Steel 95X18 has the highest plasticity at tempering temperature 520 °C after 40 – 60 minutes.
5. The heterogeneity of carbides slightly affects on the plasticity of steel X12 during tempering at 210 °C – 520 °C temperature.

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Paper presented at the XI International Baltic Conference “Materials Engineering & Tribology - 2002”, November 14 - 15, 2002, Kaunas, Lithuania