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Low Carbon Chromium Steel Transformation Plasticity during Tempering

Rasa KANDROTAITĖ-JANUTIENĖ[1*], Juozas ŽVINYS[2]

[1]*Department of Engineering Graphics, Kaunas University of Technology, Kęstučio 27, LT-44025, Kaunas, Lithuania*
[2]*Department of Metals Technology, Kaunas University of Technology, Kęstučio 27, LT-44025, Kaunas, Lithuania*

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The transformation plasticity of low carbon chromium steel was studied experimentally. The studied material was two-phase stainless steel with martensite base containing approximately 1 % of ferrite. The results of transformation plasticity of stainless steel were compared with the results of steel transformation plasticity of similar chemical composition (except chromium content). After quenching bending tests were performed at various temperatures ranging from 420 °C to 650 °C for 1 hour. The specimens of investigated steel were exposed to the bending stress (90 MPa) during heating for tempering. Also, the transformation plasticity of both types of steel after a long-term tempering at 700 °C temperature for 24 h, 48 h and 120 h was investigated. First results show that the transformation plasticity of investigated steel depends on the structural and chemical composition that undergoes changes with varying tempering temperature and tempering duration. Carbon and chromium precipitation from the solid solution and formation of carbides has significant influence on the mechanical behavior of steel during tempering.
Keywords: transformation plasticity, tempering, low carbon stainless steel, martensite transformation.

INTRODUCTION

Transformation plasticity of steel is a phenomenon when materials show high ductility without sharp necking when the various internal phase transformations occur. When small external stress is applied on steel articles under thermal conditions, these articles possess high internal stresses and deform superplasticaly with an average strain rate, which is proportional to the applied stress and is much faster than the isothermal creep rate. This phenomenon is also known as superplasticity [1, 2] or transformation induced plasticity (TRIP) [3 – 6].

Transformation plasticity of steel may occur during phase transformations that proceed during heat treatment – quenching or tempering. Transformation plasticity takes place due to several reasons. Primarily, it is influenced by internal stresses that come from different sources [4]: the internal stresses resulting from the incompatible transformation strain accompanying martensitic phase transition; and the internal stresses associated with plastic flow of product and parent phase due to dislocation motion. The continuum mechanics model by Greenwood and Johnson [7] evaluates the initial strain that is related to the average volume mismatch between the two phases during the transformation. The relation between phase volume mismatch is also widely described in [8].

The main part of the scientific works is based on the research of transformation plasticity that is caused by martensitic transformation during quenching [4, 9]. Experimental methods that have been reported in the literature include X-ray diffraction [2, 4, 10 – 13], optical microscopy combined with image analysis [11, 14], scanning electron microscopy [2, 12, 13, 15], dilatometry [16], and magnetic measurements [10].

The investigations of the transformation plasticity of steel were performed mainly during tensile stress tests [2], plastic deformation [17] or thermo mechanical tests [14]. For example, Maehara [17] showed a single result obtained with Cr-Ni-Mo alloyed steel that was solution treated at 1300 °C for 30 min followed by a 50 % cold rolling operation. In this case the elongation attained a value around 1000 % for an initial strain at 900 °C.

Other important object of the investigations is the influence of alloying elements on the transformation plasticity. At first, such alloying elements as Cr, W, Mo, V, Co and Si block the diffusion of carbon in the α-solution and further, they intensify interatomic binding [18]. There were found some scientific works that deal with the carbides forming in steel during tempering [12, 19], but there is a lack of the ones that present the direct interest of the influence of alloying elements on the transformation plasticity.

Our tested material was steel containing chromium that finds wide application in industry. We have tested two types of Cr-Ni alloyed steel containing similar content of carbon and nickel but very different content of chromium. The obtained results inspired further investigations of the transformation plasticity of chromium alloyed steel that is related with the precipitation of carbides during tempering under bending stress.

EXPERIMENTAL

Investigated material was 14X17H2 grade stainless steel and 12XH3A grade alloyed structural steel (GOST 5950-73). The materials were chosen due to the similar content of carbon and nickel but different content of chromium. This allowed evaluating the influence of chromium on the transformation plasticity of Cr-Ni alloyed steel.

Furthermore, martensitic-feritic type steel 14X17H2 and low alloyed steel 12XH3A are used for the important precise articles that are hardened or carburized. The articles need to be smoothened after heat treatment, i. e. the deformations of hardening have to be removed. The characteristics of transformation plasticity become essential.

*Corresponding author. Tel.: +370-686-96288; fax.: +370-37-323461.
E-mail address: *raskand@ktu.lt* (R. Kandrotaitė Janutienė)

Table 1. The chemical composition of steel

Steel grade (GOST 5950-73)	Chemical composition, %									
	C	Cr	Ni	Si	Mn	S	P	Cu	Mo	V
14X17H2	0.16	16.92	2.14	0.19	0.34	0.01	0.02	0.11	0.07	0.05
12XH3A	0.14	0.77	2.90	0.22	0.42	0.02	0.02	0.12	–	–

The material was provided as hot forged 16 mm and 15 mm round bars. The chemical composition of the investigated steels is shown in Table 1.

From this steel the specimens with rectangular cross-section were made with the dimensions (6×8×100) mm. Tested steel was hardened choosing the optimal quenching schedule: the specimens of steel 14X17H2 were treated at 1025 °C for 15 min followed by oil quenching; the specimens of steel 12XH3A were treated at 860 °C for 15 min followed by oil quenching.

Bending stress tests were performed using the equipment, described in the work [20]. In this equipment the specimens were loaded by the certain load (90 MPa) and heated in the electrical furnace. While heating the elastic deflections of loading and unloading and deflection of transformation plasticity were measured within ±0.01 mm accuracy. The temperature of specimen was measured using welded chromel-alumel thermocouple of 0.3 mm thickness. The tempering temperatures were 420 °C, 500 °C, 550 °C, 600 °C and 650 °C. A part of specimens were tempered without load at 700 °C for 24 h, 48 h and 120 h and then bended at certain temperature.

For the comparison of the experimental results, the annealed specimens of both steels were tested at the same conditions.

Some notations [20] are used for presentation of the results: y_{TP} – deflection of transformation plasticity of the specimen; E_{TP} – modulus of the transformation plasticity of steel.

RESULTS AND DISCUSSION

The received curves of plastic deflection of hardened specimens are very different by its value and kinetics after bending at 420 °C – 650 °C tempering temperatures (Fig. 1, 2). During the first 4 – 6 minutes of heating in the furnace the specimens of steel 14X17H2 bend more violently than the specimens of steel 12XH3A (Fig. 3). When the specimen temperature is lower than 450 °C, at this period the precipitation of carbon from the martensite occurs initiating the transformation plasticity. The concentration of chromium in the martensite of steel 14X17H2 is 22 times higher than one in steel 12XH3A. So, the inhibitory influence of chromium on the segregation of carbon causes the differences of transformation plasticity.

On the tempering at 420 °C temperature, the specimens of steel 14X17H2 bend at most during the first 5 minutes of heating. Later they start to straighten. After 30 minutes the specimens start bend backwards (Fig. 1). This phenomenon may be explained by the effect of volume differences in the tempered steel.

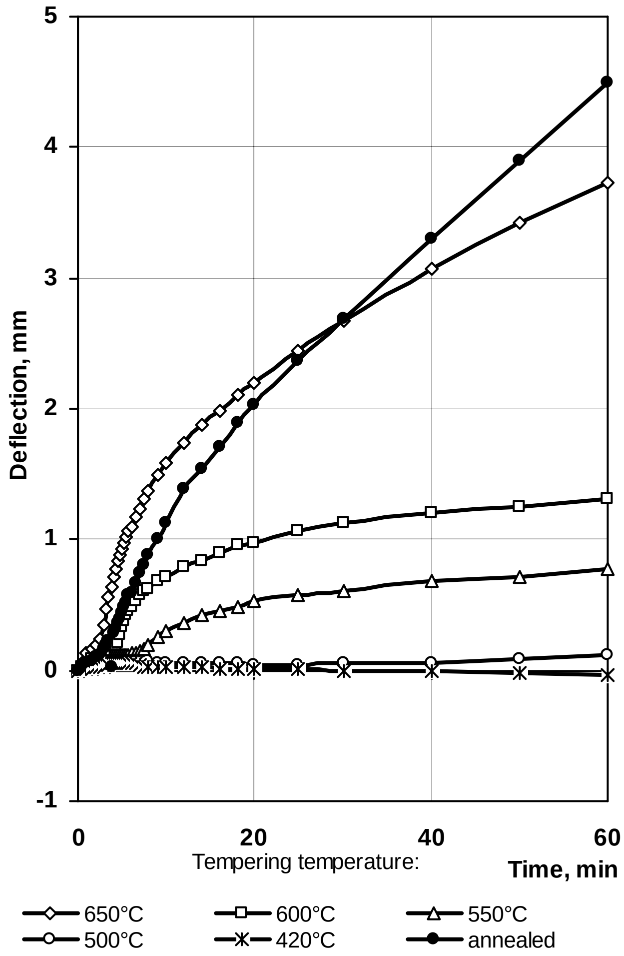

Fig. 1. Kinetics of deflection of steel 14X17H2 specimens during tempering at 420 °C – 650 °C temperatures

During tempering the volume decreases when the atoms of carbon precipitate from martensite. This deformation of specimen shows more intensive decrease of volume in the stretched part of specimen than in the compressed one after 5 minutes of heating. Carbon precipitation from martensite proceeds very apace [21] and coincides with the heating till the tempering temperature. Slow decrease of volume in the stretched part of specimen indicates that the tensile stress blocks the carbon precipitation from martensite (in low-carbon steel). After 4 – 6 minutes of heating the specimens of steel 14X17H2 start bend intensively, especially at 550 °C – 650 °C temperatures. At these temperatures the intensive diffusion of C, Fe, Cr atoms occurs and the special carbides $(Cr, Fe)_{23}C_6$ form and coagulate. There are two formation mechanisms of chromium carbides [22]:

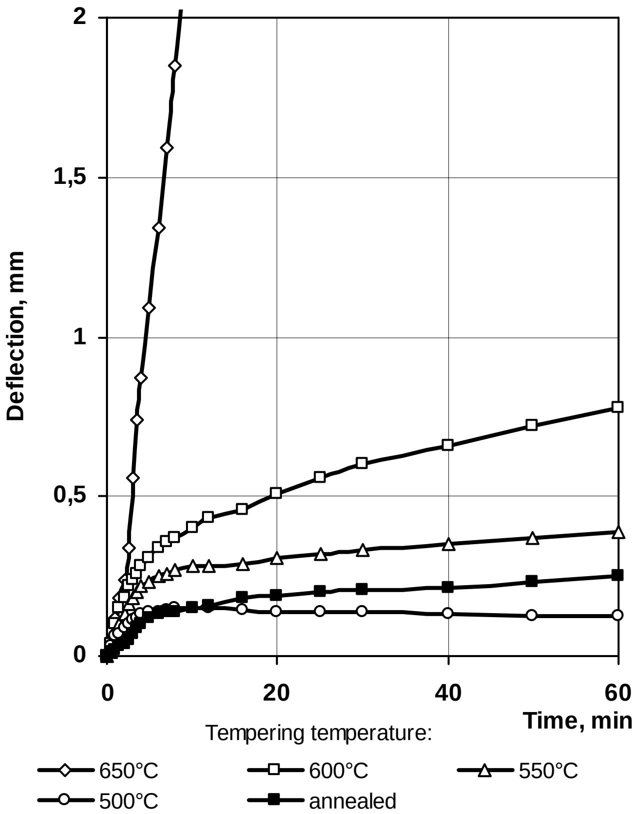

Fig. 2. Kinetics of deflection of steel 12XH3A specimens during tempering at 500 °C – 650 °C temperatures

a) over the alloyed cementite (Fe, Cr)$_3$C (in situ)

$$(Fe, Cr)_3C \rightarrow Fe_3C + Cr_{23}C_6;$$

b) directly in the solid solution when formed at the low temperatures alloyed cementite dissolves in the α-solid solution and its atoms of carbon participate in the formation of special carbides.

The special carbides are not formed in steel 12XH3A that consists of low content of chromium. So, at 550 °C – 600 °C temperatures, the specimens of such steel bend intensively only during the first 5 – 10 minutes until the carbon precipitation from martensite (saturated solid solution) occurs and dispersive alloyed cementite (Fe, Cr)$_3$C forms.

During the tempering at 650 °C the plasticity of hardened specimens is very high, furthermore, the deflection of steel 12XH3A specimens after 20 minutes is about 2.4 times higher than that of steel 14X17H2 specimens (Fig. 3). The opposite results were obtained during bending experiments at 650 °C temperature of annealed specimens of both steel grades with the structure formed at the metallurgy factory after hot rolling (Table 2, Fig. 4). The deflection of steel 14X17H2 specimens was 13.5 times higher than that of steel 12XH3A specimens.

Comparing the deflections of hardened (y_H) and annealed (y_A) specimens, there was obtained:

a) steel 12XH3A $\rightarrow y_H/y_A = 29.5$;

b) steel 14X17H2 $\rightarrow y_H/y_A = 0.9$

This comparison shows that annealed steel 12XH3A has a stable microstructure: ferrite slightly alloyed with

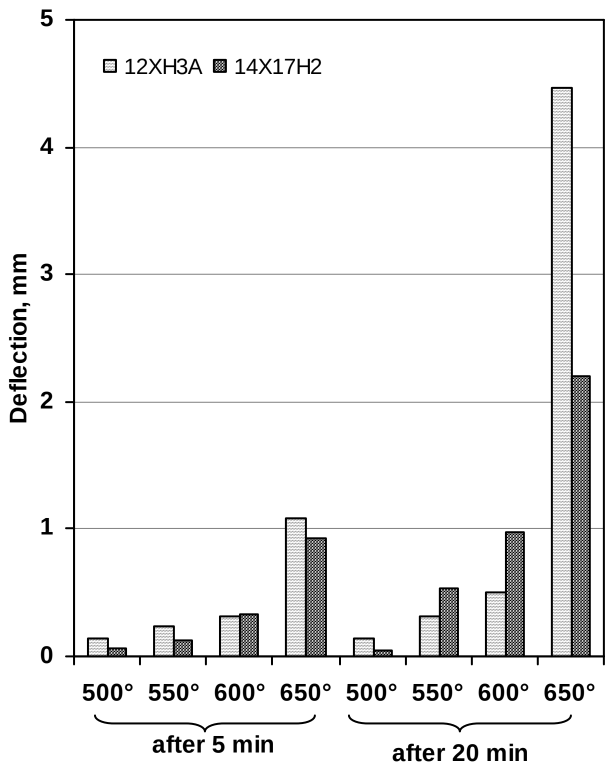

Fig. 3. Comparison of plastic deflection of steel 14X17H2 and steel 12XH3A specimens in process of bending experiments at various tempering temperatures: after 5 min of bending and after 20 min of bending. Bending stress 90 N/mm^2

Table 2. Influence of structural state on the characteristics of steel plasticity on tempering at 650 °C temperature for 30 minutes. Bending stress 90 N/mm^2

Structural state	$y_{14X17H2}/y_{12XH3A}$	12XH3A			14X17H2		
		y_H/y	y, mm	E_{TP}, N/mm^2	y_H/y	y, mm	E_{TP}, N/mm^2
Annealed	13.50	29.5	0.20	100320	0.90	2.70	7430
Hardened	0.41	–	5.90	3400	–	2.42	8290
Hardened and tempered 700 °C × 24 h	2.54	4.54	1.30	15430	0.73	3.30	6080
Hardened and tempered 700 °C × 48 h	2.72	3.39	1.74	11530	0.51	4.73	4240
Hardened and tempered 700 °C × 120 h	5.03	6.05	0.95	21120	0.49	4.93	4070

Note. y – deflection of transformation plasticity of specimen, mm.

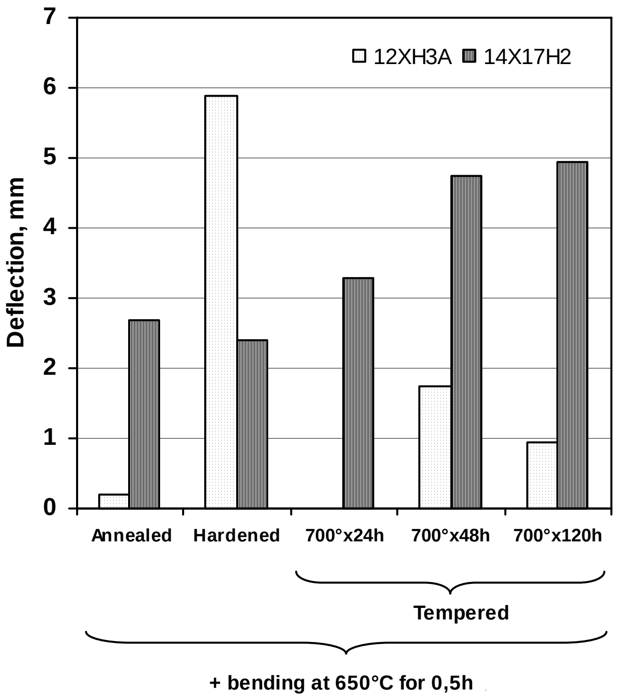

Fig. 4. Influence of structural state of steel on plasticity during tempering at 650 °C. Bending stress 90 N/mm^2

chromium and alloyed cementite (Fe, Cr)$_3$C). The deflection of such steel specimens at 650 °C temperature was minimal when bending stress was 90 N/mm^2.

The microstructure of annealed steel 14X17H2 consists of high alloyed ferrite with chromium and the carbides $Me_{23}C_6$ (the content of nickel is similar in the both grades of steel, so, it can be taken the view that the influence of nickel on structural transformations is comparable). Such structural transformations occur in high chromium steel: formation of special carbides Me_7C_3, $Me_{23}C_6$, increase of chromium content in these carbides by expulsion of iron atoms, e. g.:

$$(Cr, Fe)_{23}C_6 \rightarrow Cr_{23}C_6$$

In the low carbon chromium steels (of type 14X17H2) also the formation of δ-ferrite, i. e. FeCr phase formation proceeds. These processes pass very heavily and may continue thousands of hours [23]. Exactly this fact allows making an assumption that such high plasticity of annealed steel 14X17H2 at 650 °C temperature is related to the above mentioned processes.

This assumption was confirmed during testing of hardened specimens and tempered for 24 – 120 hours at 650 °C temperature. The plasticity of steel 12XH3A reached maximum value after hardening. After tempering at 700 °C the plasticity decreased with the increasing of heating duration, but remained higher than plasticity of annealed steel (Fig. 5). The specimens of steel 14X17H2 behave contra wise: the plasticity increased with the increasing of heating duration at 700 °C temperature (Fig. 6).

Actually in this case when the specimens were treated according to schedule 500 °C × 1 h + 700 °C × 24 h, plasticity was higher for 20 % as comparing with the specimens treated at 420 °C × 1 h + 700 °C × 24 h. The plasticity of hardened steel 14X17H2 was greater only at the beginning of heating. After 30 minutes the plastic

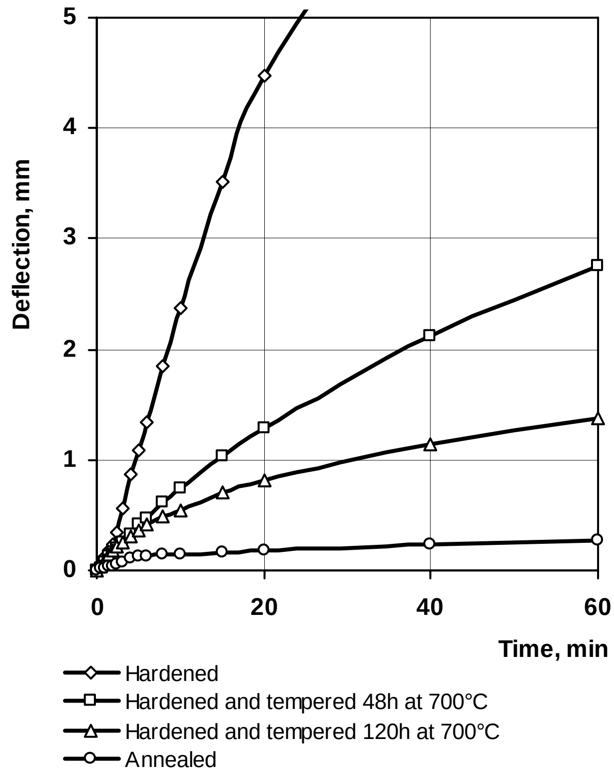

Fig. 5. Dependence of steel 12XH3A plasticity on structural state during tempering at 650 °C temperature. Bending stress 90 N/mm^2

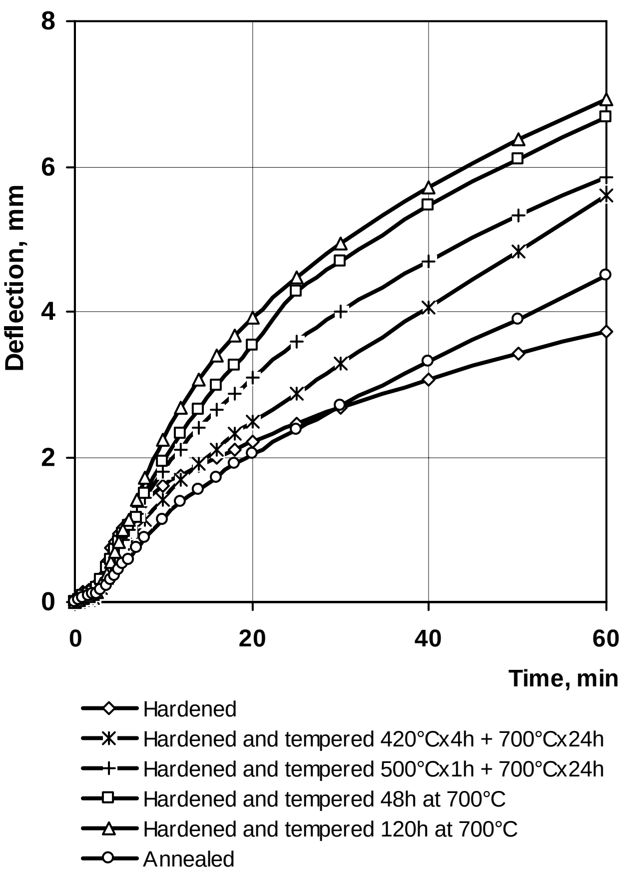

Fig. 6. Dependence of steel 14X17H2 plasticity on structural state during tempering at 650 °C temperature. Bending stress 90 N/mm^2

deflection became less even than the deflection of annealed steel specimens.

CONCLUSIONS

1. During bending of steel 12XH3A and 14X17H2 specimens at 420 °C – 650 °C temperatures the dependence of the plasticity on steel chemical composition, structural state and tempering temperature was obtained. The plasticity of steel was estimated by the value of plastic deflection y_{TP} and modulus of transformation plasticity E_{TP}.
2. During heating of hardened steel 14X17H2 two stages of intensive plastic deformation were found:
   – precipitation of carbon and formation of alloyed cementite at temperature $T \leq 450$ °C;
   – diffusion of all steel consisting elements and formation of special carbides at $T > 450$ °C.

   The second stage was not obtained for hardened steel 12XH3A during heating for tempering.
3. At 650 °C temperature annealed steel 14X17H2 is more plastic for 13.5 times than the annealed steel 12XH3A. The plasticity of hardened steel 14X17H2 is less for 2.5 times than plasticity of steel 12XH3A.
4. During bending at 650 °C steel 14X17H2 has greater plasticity after tempering at 700 °C for 24 – 120 hours than entirely hardened steel. The plasticity increases with the elongation of tempering duration at 700 °C. Conversely, steel 12XH3A hardened and tempered at 700 °C for 48 – 120 hours is less plastic than only hardened on bending at 650 °C. Elongation of heating duration at 700 °C causes the decrease of plasticity.

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