INVESTIGATION OF PLASTIC DEFORMATIONS OF CARBURIZED ALLOY STEEL DURING HEAT TREATMENT

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Abstract : *The article deals with the investigation of plastic deformations of carburized medium carbon stainless steel after quenching and tempering. After carburization the specimens were heated at 1020 °C temperature and then air quenched. At the process of air quenching the specimens were bent within the temperature dropping interval approximately from 550 °C to room temperature. The bending caused tension or compression in different parts of the specimen, so interstitial distortion was formed. As the bending stress was much lower than the yield stress, the specimen didn't bend during the first minutes of experiment, and then started bending during the martensitic transformation (transformation plasticity effect). The curved quenched specimens then were tempered at temperatures 200, 300, 400, 500, 600 and 700 °C for 1 hour and the deflection of specimen after each tempering was measured.*
The results showed different influence of tension and compression on transformations occurring in steel during quenching and tempering. The tempering temperature effect on self-deformation of curved specimen was revealed.

KEYWORDS: STEEL, TRANSFORMATION PLASTICITY, DEFORMATION, QUENCHING, TEMPERING, MICROSTRUCTURE

1. Introduction

Steel 40X13 (GOST 5632-72) containing 0.4 % carbon and 13 % chromium is medium carbon stainless steel of martensitic class and is often used as corrosion resistant steel in production of plastic injection moulds, springs, bearings and other products that work under the fatigue conditions [1, 2]. On purpose to reach the best mechanical properties of this steel it has to be hardened and double or triple-tempered as during tempering large volumes of secondary carbides precipitate [3]. The resistance to fatigue and wear of steel 40X13 can be increased by thermo-chemical treatment, i. e. by carburizing or nitriding [4-6].

Surface carburizing of specimens gives rather multiplex microstructure: at the very surface the microstructure composes of matrix (pearlite and ferrite) and different amount of surplus carbides dependent on the degree of carbon saturation. During quenching of the carburized specimens, the martensite transformation at the lower carbon core begins considerably earlier (M_s = 270°C) comparing to the transformation inside the carburized surface (M_s < 200°C) [7]. When austenite transforms into martensite, the relative volume increases less at the lower carbon core and signally more at the carburized surface. These transformations proceed great internal stress causing distortions of carburized steel parts due to thermal stresses, volume changes, transformation plasticity, etc. [8-10]. Usually, the steel 40X13 is called as “not much inclined to deformation” during heat treatment [11], however, such precise products as moulds or tools have to maintain especially high precision of the form and parameters. Since the working temperature of some parts can be elevated (tools, moulds), it is important for them to maintain the stable parameters during exploitation. Increased temperature may stimulate such processes as diffusion of carbon and alloying elements, self-tempering of martensite, dissociation of retained austenite, precipitation of carbides and other transformations causing the self-deformation and loss of a stable form [12].

This work was mainly focused on the investigation of plastic properties of carburized specimens of steel 40X13 during air quenching and tempering. The plastic deformation due to transformation plasticity occurred during air quenching was analysed and the phenomenon of self-deformation of the curved specimens after tempering was investigated. This article is the continuous work of the further research based on carburized steel plastic behaviour during heat treatment [13, 14].

2. Material and methodology

Material used for the experimentation was steel 40X13 (GOST 5632-72) with chemical composition listed in Table 1. The critical temperatures of steel 40X13 are presented in Table 2. Table 3 shows the dependence of mechanical properties of steel at elevated temperatures.

***Table 1**. Chemical composition of steel 40X13 according certification of producer No. 747, 2001 09*

Element, wt.%						
C	Si	Mn	Cr	P	S	Fe
0.38	0.32	0.35	12.89	0.020	0.010	Rem

***Table 2.** Critical temperatures of steel 40X13* [7]

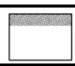
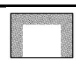
A_{c1}, °C	A_{c3}, °C	A_{r1}, °C	M_s, °C
820	870	780	270

***Table 3.** Mechanical properties of steel 40X13 at elevated temperatures* [7]

Test temperature, °C	$R_{p0.2}$, MPa	R_m, MPa
1030-1050 °C, air quenching, tempering 530 °C, 2 h		
20	1420	1670
410	1310	1360
470	960	1130
510	980	1070
1050 °C, air quenching, tempering 600 °C, 3 h		
20	890	1120
200	810	940
300	710	900
400	670	780
500	470	520
600	255	300

The steel rods were used for manufacturing of the specimens of rectangular cross-section and measurement of 100 × 8 × 6 mm^3. The specimens were carburized at 930°C temperature 6 hours placed in the hard carburizer for the purpose to get approximately 1 mm of carburized surface depth. Three schema of carburizing were chosen that are presented in the Table 4. Not carburized surfaces were protected by silicate glue film.

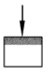
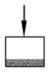
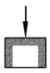
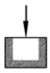
***Table 4.** Schematic view of carburized specimens*

Marking of carburized specimen type	A	B
Schematic view		
Comment	One carburized surface	Three carburized surfaces

The specimens were austenized for air quenching at 1020 °C temperature in an environment of protective gas of $N_2 + CO + CO_2$. For the investigation of steel plasticity during transformations, the austenized specimen was placed in the special testing device for bending [14] and air quenched. At the set temperature the specimen was loaded by bending load generated bending stress of 100 MPa and not exceeded yield strength $R_{p0.2}$ of steel at the certain temperature (table 3) then, the plastic deflection of specimen was measured with accuracy of 0.01 mm until the temperature of specimen reached room temperature (RT). The range of bending temperatures was from 550 °C to RT. The temperature 550 °C is an approximate temperature at which the specimen is placed in testing device and bending starts. This temperature was indicated by chromel-alumel thermocouple.

The influence of stress type on transformations proceeding inside the material was investigated as well. The position of specimens was varying as table 5 presents. The purpose of this was either to compress, or to stretch the carburized part of specimen.

Table 5. Schematic view of bending of carburized specimens

Marking of bending schema	A1	A2	B1	B2
Schematic view (arrow shows the direction of bending)				

After air quenching and bending the specimens were tempered at different temperatures for 1 hour: 200, 300, 400, 500, 600 and 700 °C. Then the change in deflection of specimen was measured observing the effect of self-deformation as well.

After quenching and tempering the samples were tested for heat treatment quality. Universal hardness meter VERZUS 750CCD for Rockwell hardness measurement was used.

The microstructure of specimens was investigated by monitoring with the laser analyzer LMA Carl Zeiss using a video camera YCH15. Following thermal or thermo-mechanical treatment, the samples for optical analysis were carefully cut off by METKON MICRAcut125 low speed precision cutter, then ground and polished by Lam Plan machine using diamond suspension of 1 μm grain size, and finally etched in 3% Nital solution.

3. Results and discussion

3.1. Evaluation of structure of steel 40X13 after carburizing

The microstructures of the carburized specimens exhibit different phase composition at the core and at the surface. The microstructure of the core consists of ferrite, pearlite and here and there hardly visible carbides (Fig. 1). The carburized surface of about 1 mm in depth was found to be rich of iron-chromium carbides that possibly are $M_{23}C_6$ [2, 15] or M_7C_3 as the surface contain higher carbon content than the core [16] (Fig. 2).

At the temperature of quenching – 1020 °C, the microstructure of the specimen was austenite with not dissolved carbides as its temperature A_{c3} is 870 °C (table 2).

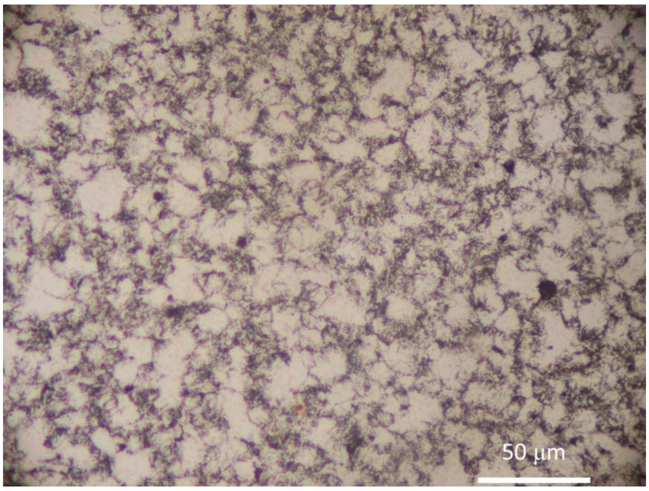


Fig. 1. *Core of carburized specimen of 40X13 steel*

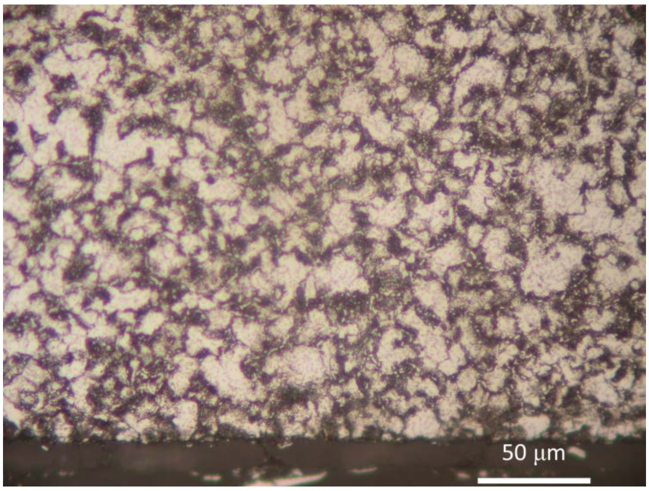


Fig. 2. *Carburized surface of steel 40X13 specimen*

3.2. Investigation of transformation plasticity of steel 40X13 specimens during air quenching

Carburized steel specimens were austenized in the furnace at 1020 °C temperature in an environment of protective gas of $N_2 + CO + CO_2$. Then the specimen was withdrawn from the furnace and placed into bending device. The specimen was loaded after 45 seconds starting from the very beginning of air quenching and the temperature of the specimen was 590-595 °C. The bending stress was 100 MPa and it was clear, that this value was much lower than the yield stress of austenite of steel as it caused just elastic deflection which was not increasing until the martensitic transformation started (Fig. 3). The Fig. 3 shows that the martensitic transformation of bent specimens started approximately after 2-3 min of cooling and when temperature dropped until 310-320 °C. As M_s of steel 40X13 is 270 °C, the higher temperature of martensitic transformation start could be related with stresses occurred inside the specimen and the formed martensite could be named as “stress-assisted martensite” [17, 18]. So, in generally, the stresses, even low, stimulate martensitic transformation of steel.

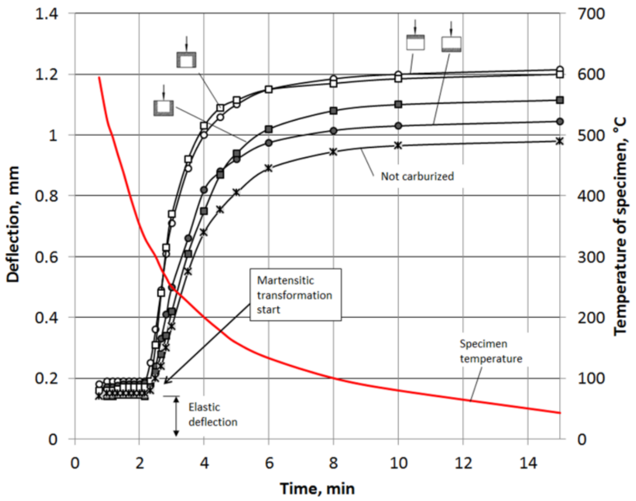
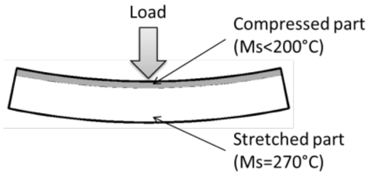


Fig. 3. *Plastic deformation of specimens of steel 40X13 during air quenching due to transformation plasticity caused by martensitic transformation*

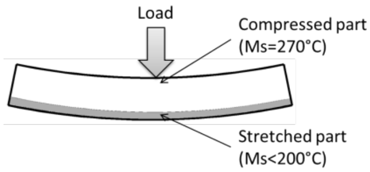
Bending of specimens as the mode of stress type was chosen for the purpose. During bending a half of specimen’s volume is compressed and another part is stretched (Fig.4). We can investigate the influence of stress mode on martensite transformation. So, at the same experiment there are several variables: stress mode and carbon content causing the difference in martensite start temperature.

Compression and tension act differently on martensite transformation and its start. Stresses, in generally, stimulate martensitic transformation, but tension induces it more intensively. That was found in some references [19, 20] and this is also visible in Fig. 3: the plastic deflection of schema A1 is approximately 15 % bigger than the one of schema A2. In the case of schema A1, the austenite of the stretched part has lower carbon content and it transforms to martensite first. During transformation the volume of stretched part increases and elongates. The stresses caused by volume changes summarize with external stresses and exceed the yield strength of material. The result is big plastic deflection. In the case of schema A2, the martensitic transformation starts at first in compressed part and we can see a result: the plastic deflection is less.



A1

a



A2

b

Fig. 4. *Deformation of the specimens according schema A1 and A2 and the position of carburized surface*

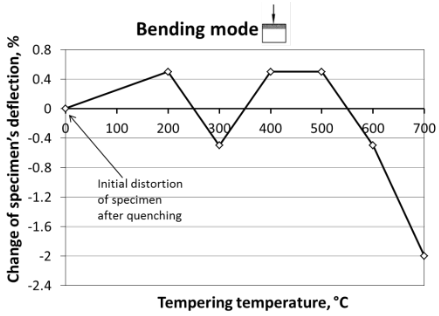
The total plasticity due to martensitic transformation is directly related with carbon content. It is seen clearly comparing the total deflection of not carburized specimens and the carburized ones (Fig. 3). Not carburized specimens have the lowest plastic deflection. The reason of that is not sufficiently revealed yet. Maybe the bigger plasticity of carburized steel could be related with higher carbon content in austenite causing bigger distortion of transformed martensite lattice [21] and, thus, higher stresses that summarize with external ones. However, this assumption requires more experiments and investigation methods.

3.3. Investigation of self-deformation of steel 40X13 specimens during tempering

After bending during air quenching, the curved specimens were tempered at temperatures of 200, 300, 400, 500, 600 and 700 °C for 1 hour. After each tempering the deflection of specimens was measured and the change of deflection comparing with the initial one was calculated. Fig. 5 presents the change of deflection, %.

The steel 40X13 is presented as material not much inclined to deformation [11], however some factors may cause self-deformations of quenched parts during tempering, especially if they have heterogeneous phase structure: different content of retained austenite in carburized and not carburized parts that could be from 6 % to 10 % [22]. The retained austenite transforms into martensite at tempering temperatures of 450-500 °C [2, 11], that may decrease the dimension stability on account of 4 % vol. expansion [8, 10]. Also, the carbide precipitation proceeds during tempering. When tempering temperature increases to 500 °C a large amount of dispersive carbides, mainly $M_{23}C_6$ are precipitated within the steel [2, 10].

The biggest self-deformation of specimens was found at the temperatures started from 400 °C (Fig. 5) that is in a good agreement with the changes of material structure mentioned above. Significant decrease of deflection was determined for all modes of carburizing and bending when temperature was higher than 600 °C. Total self-deformation of specimens was in the range of 1-3 %.



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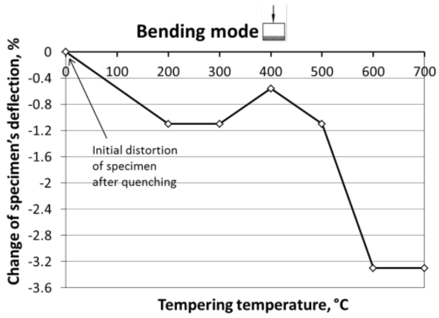

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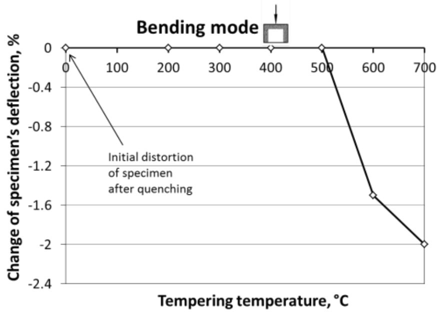
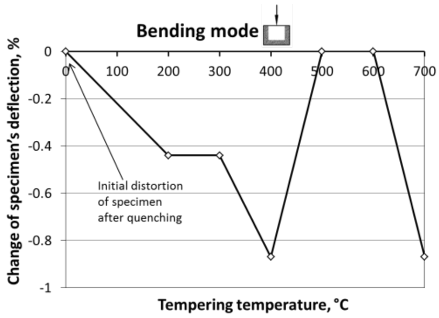


c



d

Fig. 5. *Self-deformation of specimens of steel 40X13 influenced by tempering temperature*

3.4. Investigation of hardness of steel 40X13 specimens during tempering

The Rockwell hardness of specimens was measured at the carburized and not carburized surfaces after quenching and each tempering. A big difference between hardness of carburized and not carburized surfaces was not determined, just slightly bigger values of hardness were showed by carburized ones (Fig. 6). The hardness after quenching was obtained 55-60 HRC for carburized surfaces and 54-59 HRC for not carburized ones.

The secondary hardening due to precipitation of chromium rich $M_{23}C_6$ carbides was determined at 400-500 °C temperatures. As some references stated that the temperature of peak of carbides precipitation was 500 °C [2], hardness increase at 400 °C showed the possible stress effect on stimulation of the carbide precipitation process. The bending stresses increase the content of dislocations and other defects of the material. During the tempering treatment, the diffusion of carbon and alloying elements proceeds to the nearby defects. These segregated areas are preferable sites for small secondary carbide nucleation [3]. Hence, a larger volume of defects provided more driving force for carbide nucleation at lower temperature.

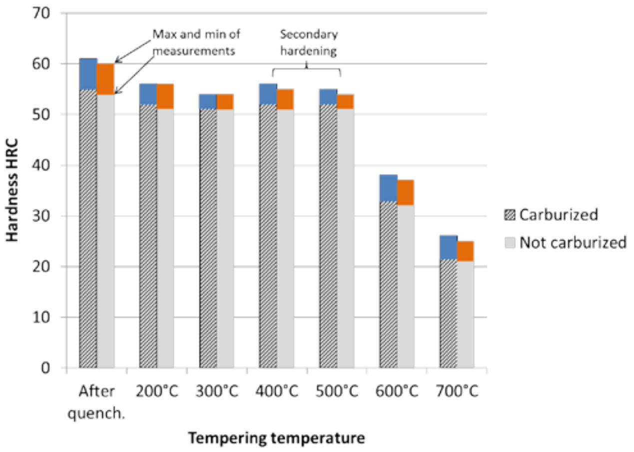


Fig. 6. *Rockwell hardness of specimens of steel 40X13 influenced by tempering temperature*

4. Conclusions

1. It was revealed that external stresses stimulated martensitic transformation, but tension induced it more intensively comparing to compression. The result obtained was the bigger transformation plasticity of specimens of steel 40X13.
2. The total plasticity due to martensitic transformation is directly related with carbon content. Not carburized specimens have the lowest plastic deflection comparing to carburized ones.
3. Self-deformations of bent specimens occur during tempering because of many factors: phase transformations, volume changes, residual stresses, thermal expansion, etc. The highest self-deformations were obtained above 400 °C tempering temperature and were determined of 1-3 %.
4. Secondary hardening of steel 40X13 was determined at 400-500 °C tempering temperatures, i.e. at a little bit higher than found in scientific data, possibly because of the stress effect.

5. Literature

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