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Influence of Transformation Plasticity and Bending Stress on the Structure Evolution of Tempered Tool Steel

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The object of examination was tool steel with 1.42 % carbon content alloyed with chromium (about 12 %) and with small amount of vanadium (0.70 %). This work deals with the investigation of tool steel structure evolution under affect of changes of phase chemical composition, stresses, tempering temperature and transformation plasticity. The structure of steel hardened from 1150 °C temperature tool was found consisting from retained austenite, martensite and carbide phase. The specimens from hardened tool steel were bent at 520 °C tempering temperature. Bending stresses were 90 MPa, duration of tempering during bending varied – from 10 minutes to one hour to obtain different degree of steel structure evolution. After tempering and bending for different duration, the specimens were analyzed with X-ray diffraction method. The type of carbides, lattice parameters of the solid solution and carbide phase were determined. XRD examination was performed in the compressed and stretched surfaces of the bent specimen. Different effect of compression and tensile stresses on transformation plasticity of specimens, lattice parameters of steel structure phases (solid solution and carbides) was determined during bending at tempering temperature.

Keywords: steel, structure, tempering, carbides, transformation plasticity, X-ray analysis.

1. INTRODUCTION

Steel X12Ф1 (GOST 5950-73) depends to the ledeburitic class of the steels and has increased fatigue resistance. Its chemical composition is 1.3 % C-12 % Cr-0.8 % V-Fe [1]. This steel is used for manufacturing of cutting tools and stamps that are exploited under the effect of stresses, especially contact ones, which occur in the work surfaces of the tool. During exploitation, the work surfaces are compressed from every side. Also, the tools are affected by bending and torsion stresses. Deformation and micro plastic flow of the tool surface may occur even in the steel with martensitic structure and high content of carbides because of great stresses and increased temperature. The changes in tool material occurring in even thin layers of the working surfaces as a result of influence of complex stresses and increased temperature may prove to be critical. Martensitic or trostitic structure of tools is metastable, thus, when temperature increases and transformation plasticity proceeds, considerable changes of material properties may occur [2 – 4]. Fragmentation of martensite performs very rapidly and the properties of material change more markedly than in the case of coagulation of carbides that compose about 13 % – 15 % in the steel with such chemical composition [1].

The deformation and micro plastic flow of tool material is more significant when steel structure has retained austenite. Because of high hardening temperatures, the structure may contain even 90 % of retained austenite [5], though, some literature sources deal with the data that the steel containing more than 1 % carbon and 12 % chromium may have purely austenitic structure when the temperature of hardening is 1100 °C – 1150 °C [6].

The retained austenite is not stable even after tempering and may fragment during the exploitation of tool because of several reasons [1]:

- About 2 % – 5 % of retained austenite fragments through all volume after long-lasting aging at 20 °C temperature. The more the structure contains retained austenite, the more this component of the structure undergoes fragmentation.
- During cooling at below zero temperature the transformation also proceeds through all volume. For example, 80 % – 90 % of retained austenite may fragment at –60 °C temperature.
- And the third, the most interest to us reason are stresses. Even inconsiderable stresses of 40 MPa – 50 MPa magnitude can raise the fragmentation of retained austenite. In this case, the transformation proceeds only in very small layers of the surfaces, approximately 0.5 mm of thickness.

These complex processes depending on chemical structure of steel, temperature of hardening and tempering, duration of heating, stresses and other acting factors, are investigated in many works of scientists that are the most interested with the tests of low carbon stainless steel [7 – 10]. The carbide $M_{23}C_6$ with the cubic face centered lattice is the main carbide in the structure of this steel, while the carbide phase of the structure of high carbon steel X12Ф1 is mainly composed from M_7C_3 with hexagonal lattice [11]. Because of the complex form of the lattice, the evolution of this carbide under the effect of temperature, duration and content of carbon and chromium is investigated less. The lack of information is the most detectable in the research of the formation of carbide M_7C_3 particles affected by various stresses.

The aim of this work was to examine the evolution of structure of the steel X12Ф1 depending on tempering temperature, duration of heating and bending stresses

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using the effect of transformation plasticity. The bending stresses were chosen because of the possibility to determine influence of compression and tension on various transformations of tempering at the same: fragmentation of martensite and retained austenite and precipitation of special carbides from the saturated solid solution.

2. EXPERIMENTAL

Steel X12Ф1 (GOST 5950-73) (equivalent without molybdenum X155CrVMo12-1 DIN EN ISO 4957:2001-02) was used for the experiments. Its chemical composition is listed in Table 1. Bending specimens of (6×8×100) mm^3 size were made from the raw steel strip with parameters (10×100) mm^2. The specimens were heated 30 minutes at 1150 °C temperature in protective environment and then were quenched in oil. The initial structure after quenching was composed from ~(85–90) wt. % retained austenite, a small part of martensite and not dissolved excess carbides M_7C_3; hardness after quenching was (33 – 35) HRC. After hardening, the specimens were bent during tempering at 520 °C in the special device described in [12]. The bending stress was 90 MPa. The curve of plastic deflection on condition of transformation plasticity was determined during the bending test. Plastic deflection was measured with an indicator within 0.01 mm. To study structure evolution, the tempering with bending was stopped after heating duration of 10, 15, 30, 45 and 60 minutes.

Table 1. Chemical composition of steel X12Ф1 (number of certificate of manufacture 747, 2001-09-25)

Amount of element, wt. %							
C	Mn	Si	Cr	Mo	V	S	P
1.42	0.40	0.30	11.57	0.17	0.70	0.010	0.018

X-ray powder diffraction (XRD) data were collected using a diffractometer DRON-6 operating at 35 kV and 20 mA and equipped with a single crystal graphite flat monochromator for transmission only narrow $CuK_α$ wave length ($λ = 0.15405$ nm). Diffraction patterns were recorded in scanning mode with 0.02° steps of $2θ$ and counting time of 5 s per step. The equipment was calibrated by corundum $α$-Al_2O_3 (99.9 %) standard. Silicon powder standard has been added to the analyzed steel sample for zero error correction of obtained X-ray diffraction pattern. Qualitative phase identification was performed using PDF-2 data base [13] and computer program PowderCell [14] was used for precision lattice parameters measurements. In order to eliminate induced stresses and micro-deformations, which cause XRD peak broadening, the surface layer of steel samples was removed by the electrolytic etching. Power supply 1621A BK Precision was used for electrolytic etching, which lasted for 2 hours at (130 – 150) mA/cm^2 current densities in 5 % hydrochloric acid solution. Then surface was washed by warm distilled water.

The XRD analysis allowed identify the type of phases, content of retained austenite, the parameters of lattice of martensite and carbide M_7C_3 at the compressed and stretched surfaces of specimen.

3. RESULTS AND DISCUSSION

The specimens of steel X12Ф1 were quenched from very high temperature (1150 °C) seeking to dissolve the carbides and to obtain maximum saturation of the solid solution with carbon and alloying elements. XRD analysis of hardened specimens identified some low intensity peaks of carbides M_7C_3 – the temperature close to the melting point is required for the complete dissolution of excess carbides [15]. After hardening from 1150 °C temperature, the structure has approximately 3 % of the excess carbides and the concentration of carbon in the solid solution is increased until 0.9 %. The amount of retained austenite after hardening was obtained about 85 % – 89 % using magnetic method and specifying by X-ray analysis. The X-ray diffraction patterns have showed the peaks of martensite, but their intensity was very low.

The tempering at 520 °C temperature of such quenched steel produces the precipitation of carbon and alloying elements (chromium) from the saturated solid solution (retained austenite and martensite), formation of new special carbides and slow growing of the already formed ones [16]. The temperature M_s of retained austenite increases when it looses a part of carbon and chromium content, thus the cooling after tempering evokes its fragmentation to martensite (the secondary martensitic transformation). These processes are also under the different influence of compression and tensile stresses that was generated during the bending of specimen.

The obtained kinetics of specimen deflection during tempering is presented at Fig. 1.

All specimens were tempered at 520 °C temperature and were bent under the load that causes 90 MPa stresses, but the duration of the test was different. As the transformations of tempering depend on the duration of heating, the changed structure of specimens was fixed by stopping of heating and bending after 10, 15, 30, 45 and 60 minutes. The analysis of specimen deflection during heating shows, that at the first minutes the bending of specimen is very intensive and may be explained by the transformation plasticity phenomena occurred during the precipitation of carbon from solid solution (because only diffusion of carbon is available when the heating temperature is less than 450 °C). Different specimens, in spite of their the same steel grade, hardening and tempering conditions, show different values of plastic deflection during transformation plasticity (Fig. 1), probably, because of a little difference between their phase composition after hardening (e. g., amount of retained austenite varies in the range of 5 %).

The formation of chromium carbides begins at 425 °C temperature (the most intensive it is at 650 °C temperature) [8]. All these processes may proceed at the same time or one transformation may begin when other one is not past. Some literature sources deal with the information that the fragmentation of martensite in chromium steel is fully finished after one hour heating at 735 °C temperature [17], and the formation of carbide M_7C_3 begins at 300 °C – 400 °C [1], but not only above 425 °C as the scientific work [8] affirms. To all these disagreements also the influence of stresses is added.

During the bending of specimen we have compression at the upper part of specimen and tensile stresses at the bottom part. When the specimen is heated for one hour, the decrease of deflection is obtained at the time intervals of 4 – 6 and 35 – 40 minutes. The same tendency of deflection kinetics remains even after stopping of experiment after different durations. XRD analysis has allowed explaining this phenomenon by determining the amount of retained austenite at compressed and stretched surface of specimen (Fig. 2). The picture shows that the stretched layers contain more retained austenite than the compressed ones. Consequently, we have assumption that tensile stresses stop the fragmentation of retained austenite. From the other side, may be the compression stimulates this transformation? To have more evidence, other tests and experiments are required, for example, dilatometer and following XRD analysis, undoubtedly.

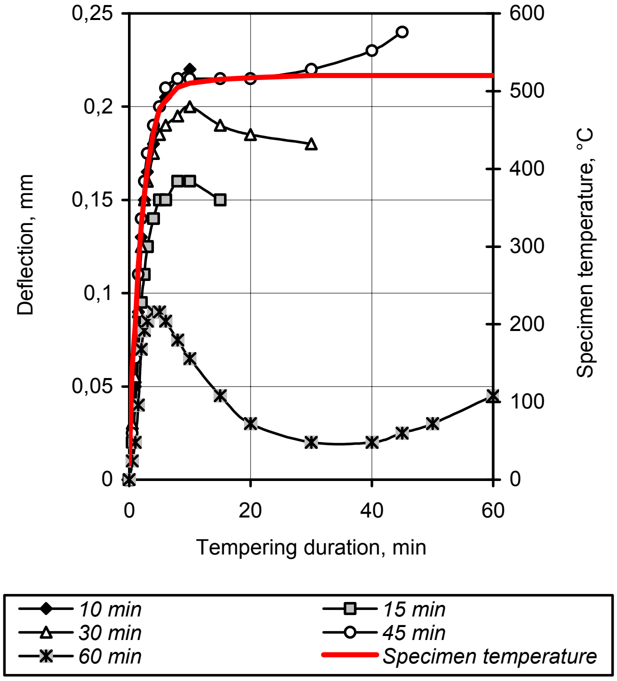


Fig. 1. Kinetics of specimen deflection depending on the duration of tempering during bending at 520 °C temperature under the condition of transformation plasticity

Returning to the Fig. 1, the decrease of specimen deflection shows that for some time the specimen is straightening. The reason could be slower precipitation of carbon and chromium from solid solution (that is composed from ~85 % austenite) in the stretched layers comparing with the same process in the compressed part of the specimen. The volume of solid solution is decreased when it looses carbon and chromium atoms. This decrease is more intensive in the compressed layers than in the stretched ones. The specimen begins straightening. During cooling from tempering temperature we have two different M_s temperatures of stretched and compressed layers that have differently saturated by carbon and chromium solid solution. The retained austenite of compressed part of specimen has lost more carbon and chromium and its M_s temperature has increased more, so, during cooling, the bigger part of austenite has fragmented into martensite comparing with the stretched layers.

Determining *a* and *c* parameters of martensitic lattice by XRD analysis, it is evident that precipitation of carbon from martensite proceeds during all heating, because the tetragonality of martensite decreases all heating time (Fig. 3) as it was determined in scientific work [17]. The values of *a* and *c* parameters of martensite lattice were determined after different durations of heating at 520 °C temperature under the stress effect. It was obtained that the degree of tetragonality of martensite is a little bit less at the compressed layers, at least until 45-th minute. So, we can make an assumption that compression stimulates the fragmentation of martensite, i. e. the precipitation of carbon.

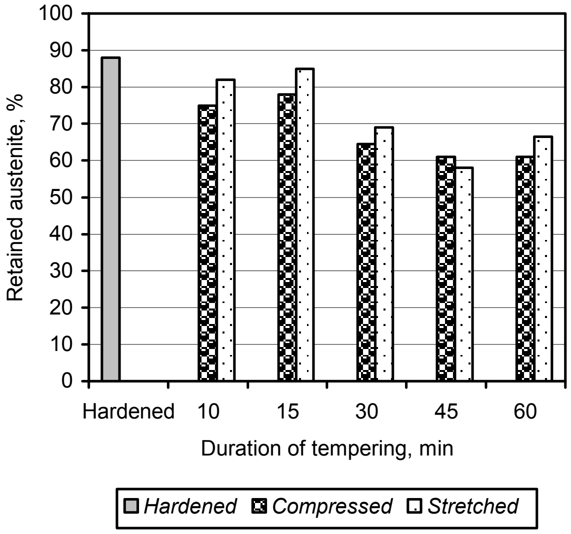


Fig. 2. Influence of stresses on the fragmentation of retained austenite in the compressed and stretched surface of specimen at 520 °C tempering temperature

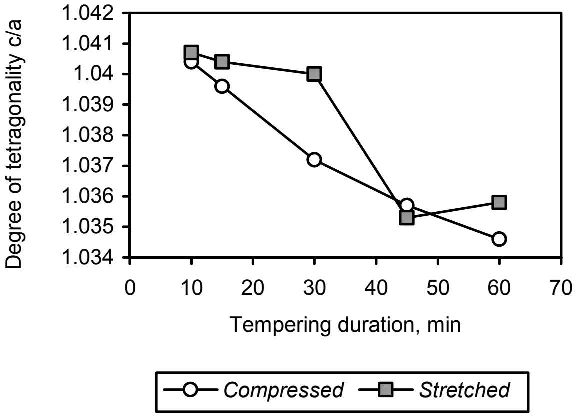


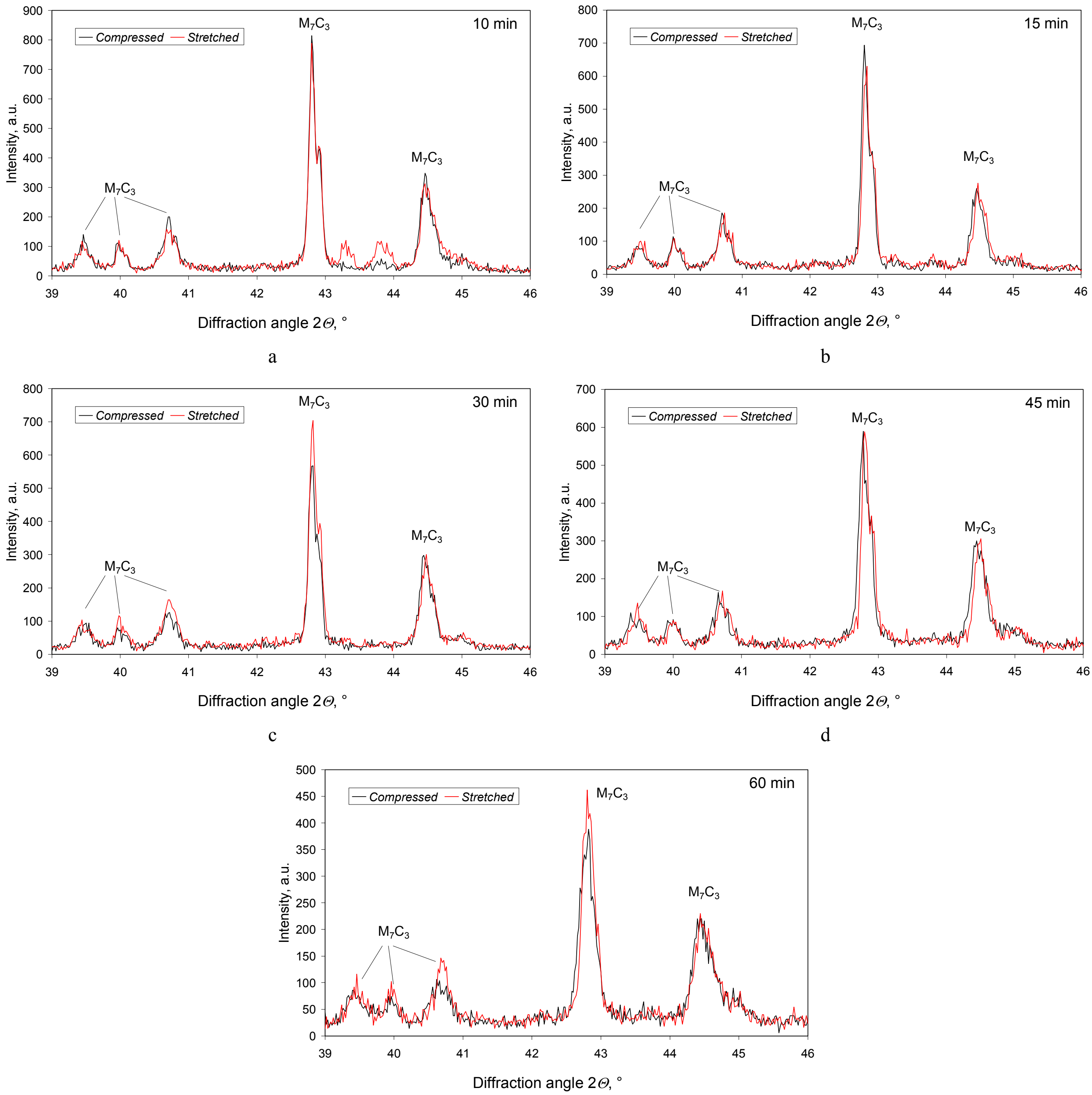
Fig. 3. Influence of compression and tensile stresses on the degree of tetragonality *c/a* of martensite lattice during the tempering at 520 °C temperature

Analyzing influence of stress on the formation of carbides M_7C_3, many questions have raised, at the first place because of the lack of scientific information, second, the differences between the results of compressed and stretched layers are inconsiderable, and thus the minimal inaccuracy of experiment may cause the results of measurement. In spite of this risk, the analysis of X-ray pictures of carbides after different heating time during bending show that the intensity of carbides M_7C_3 peaks has decreased a little bit in the compressed layers after 30-th minute of heating comparing with stretched layers (Fig. 4). This allows the assumption that the formation of carbides is slower and this is in a good agreement with the data of scientific work [10] where the precipitation of bigger carbide particles from the solid solution was determined. However, our X-ray pictures of carbides M_7C_3 show very inconsiderable differences of peak intensity between compressed and stretched layers (Fig. 4), therefore, in the future, more precise methods for the preparing specimens to XRD test, recording X-ray pictures and evaluating obtained results have to be developed.

The investigation of compression and tensile stresses effect on the lattice parameters of carbide M_7C_3 has brought the biggest indeterminations (Fig. 5). In this field there was not found any literature data.

The lattice of carbide Cr_7C_3 is hexagonal, this means that the parameters are $a = b \neq c$ [18]. The carbide determined in the structure of our researched steel has dissolved iron, i. e. some chromium atoms are changed by the ones of iron. This special carbide may contain about 30 % – 50 % iron atoms instead of chromium ones [19].

According to the data base PDF2 [13], carbide M_7C_3 may have not only hexagonal lattice, but also orthorhombic structure, as this type of carbide is often detected in heat resistant steel [20]. XRD analysis showed



a

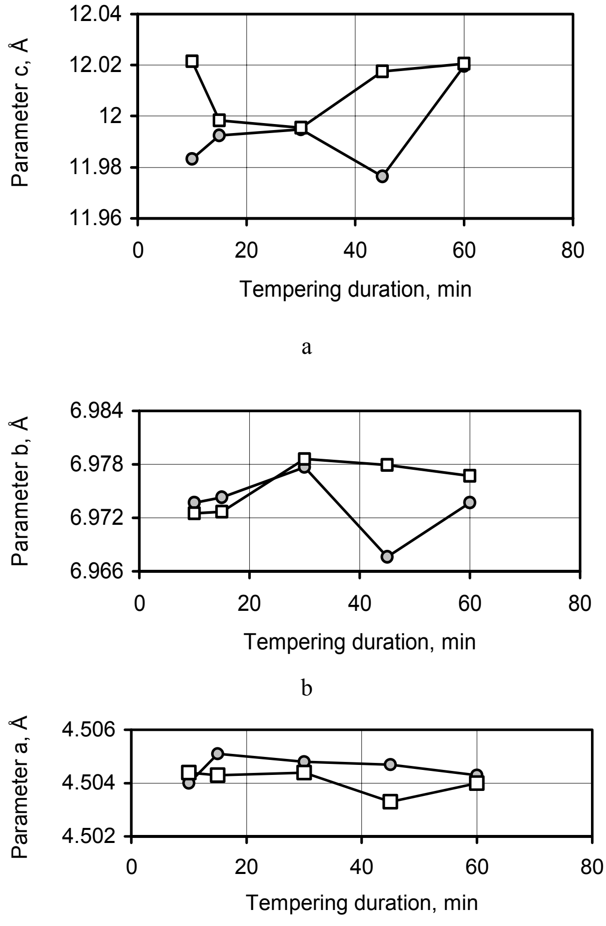
b

c

d

e

Fig. 4. Carbides X–ray diffraction patterns of X12Ф1 steel specimen compressed and stretched surfaces tempered at 520 °C for various duration: a – 10 min; b – 15 min; c – 30 min; d – 45 min; e – 60 min



a

b

c

Fig. 5. Influence of tempering duration and compression and tensile stress on lattice parameters of M_7C_3: ○ – compressed surface; ☐ – stretched surface

that dominant carbide in our researched steel has orthorhombic structure $a \neq b \neq c$.

Fig. 5 shows that the parameter *a* of carbide has the minimal effect of stresses, heating duration and temperature. The values of parameter *c* of carbide have biggest differences between compressed and stretched layers. The relation between iron and chromium contents in the carbide M_7C_3 may vary in wide range, but in this work it was not determined. Since this process is diffusive, so, it depends on duration, temperature and may be different sign of stresses. This relation may be indicated and evaluated in the following works.

CONCLUSIONS

The influence of stresses and various duration of heating at the tempering temperature on the structure of steel X12Ф1 specimens were determined. It was obtained:

- The fragmentation of retained austenite in the compressed and stretched parts begins at different time. The straightening of specimen at the interval of ~ (5 – 45) minutes of heating caused by different intensity of volume decrease of saturated solid solution in compressed and stretched layers could prove this assumption.
- During tempering at the certain conditions, the precipitation of carbon and chromium from martensite proceeds all heating time (until the maximal duration of 1 hour). This is proved by the continuous decrease of tetragonality degree of martensite lattice. This process is faster in the compressed layers of specimen.
- Compression and tensile stresses affect insignificantly the formation of carbide particles. More comprehensive investigation of carbide M_7C_3 under the effect of duration, temperature and stresses requires the following experiments.

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