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Investigation of Plastic Properties of Hotvar Hot-work Tool Steel During Martensitic Transformation

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This article presents the investigation of transformation plasticity (especially high permanent plasticity) of Uddeholm Hotvar hot-work tool steel (C = 0.55 %, Cr = 2.60 %, Mo = 2.30 %, V = 0.90 %, Si = 1.0 %, Mn = 0.80 %) that has high wear resistance and resistance to thermal fatigue. The steel is used for manufacturing of hot working tools, i. e., dies, punches and other deforming parts. The tests were performed during martensitic transformation of steel. For the investigation of steel transformation plasticity the specimens were austenized at 1050 °C, 1070 °C and 1090 °C and air quenched. The load that was generated 100 MPa bending stress ($\leq$ 10 %×($R_{P0.2}$) of material at the temperature of the test) was applied on specimens got out from the heating furnace and placed in the bending device. The start of bending was at 550 °C – 530 °C temperature. Plastic deflection was observed through all cooling process till room temperature and was measured with 0.01 mm accuracy. It was determined that bending of specimen in the temperature range of ~220 °C to ~30 °C gave the deflection 5 – 7 times higher than after bending in 550 °C – 30 °C temperature range. The magnitude of deflection is related with austenitic-martensitic transformation and with phenomenon of transformation plasticity, as well.

Keywords: martensite transformation, Hotvar steel, microstructure, plasticity, deflection.

1. INTRODUCTION

The accuracy in size of hot-work dies is a very important question in manufacturing of forgings. The hot-work die can be affected by various stresses originating during the long-term exploitation of tool and the precise measurement of die can be lost. The stresses mentioned are:

- residual stresses after mechanical or heat treatment;
- microstructural stresses caused by constituents volume mismatch in microstructure;
- stress relaxation under the heat effect, especially when transformation plasticity proceeds;
- thermal stresses related with different ratios of thermal expansion of martensite, austenite and other constituents.

The regimes of quenching and tempering used for tools, simple or complex geometry of dies also could be mentioned, e. g. parts with high length-to-diameter ratio have a tendency to quenching distortion. Such distorted parts could be easily straightened out by tension, bending or other methods performing during transformation plasticity effect. Therefore the research of properties of each steel grade during thermal operations is very important.

The variation in plasticity of different sorts of steel during martensitic transformation and following tempering can be multiform [1 – 3].

The transformation plasticity of steel can be qualitatively assessed by comparing the plastic deflection of equal-sized specimens tested at certain transformations. Computed modulus E_{tp} of transformation plasticity can present quantitative analysis of this effect [3]. Steel has the highest plasticity when it undergoes martensitic transformation; i. e. plasticity of the quenched specimen is greater from several to dozen times comparing to the one obtained after tempering. The value of plasticity of quenched steel is affected by carbon content. Also, the plasticity of steel is under the influence of the temperature of quenching and tempering, the content of alloying elements, etc.

In some cases, steel products and hot-work die components are heated treated under the transformation plasticity effect for ensuring their accuracy in measurement. Unfortunately the results often are not satisfied because of instability of required dimensions. The most common mistakes are too high temperatures for air quenching start that causes slight thermal stress, especially when cooling is asymmetrical. Also, the load force used for correction of geometric shape can be applied too early or too late in the point of martensitic transformation. Loss of transformation plasticity or self-deformation occurs because of varying of the intensity of ongoing martensitic transformation. The specimens may bend themselves even as they are not externally loaded or affected by thermal stresses [1, 4]. In order to make efficient use of the effect of transformation plasticity of precise steel production technology it is necessary to know the kinetics of transformation plasticity of each steel grade and its heat treatment peculiarities.

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This work presents the investigation of transformation plasticity during martensitic transformation of the Swedish company Uddeholm hot-work tool steel Hotvar alloyed with chromium, molybdenum and vanadium, used in hot-deformation dies, mould fabrication, etc.

2. EXPERIMENTAL DETAILS

The chemical composition of investigated steel is listed in Table 1.

Table 1. Chemical composition of Uddeholm Hotvar, %

C	Si	Mn	Cr	Mo	V	Fe
0.55	1.00	0.80	2.60	2.30	0.90	Bal.

The investigated steel rods were used for manufacturing of the specimens of rectangular cross-section and measurement dimensions of $100 \times 8 \times 6$ mm^3. The specimens were austenized for air quenching at 1050 °C, 1070 °C and 1090 °C temperatures in the protective gas of $N_2 + CO + CO_2$. For the investigation of transformation plasticity, the austenized specimen was placed in the special testing device [2] and air quenched. At the set temperature the specimen was loaded by bending load generated bending stress of 100 MPa and did not exceed 10 % of steel yield strength $R_{p0.2}$ at the certain temperature (yield strength of Hotvar is $R_{p0.2}$ = 1110 MPa, at T = 550 °C [5]). Then, the plastic deflection of specimen was measured with accuracy of 0.01 mm until the temperature of specimen reached room temperature. The ranges of bending temperatures were:

- from 550 °C to room temperature (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;
- from 180 °C – 160 °C to RT;
- from 550 °C to 180 °C – 160 °C temperature following by free-load cooling to RT.

During the second temperature-bending regime, the specimen was started bending when the martensite transformations had been already passed for several minutes. During the third regime the specimen was bent from the start of its air quenching, but was unloaded not waiting the end of martensite transformation. These different regimes allowed us to determine different plastic deflection of transformation plasticity and to observe the effect of autodeformation as well.

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

The microstructure of the specimens was investigated by monitoring with the laser analyser LMA Carl Zeiss using a video camera YCH15. Heat or thermo-mechanically treated specimens were ground, polished, and etched in 3 % Nital solution for optical analysis.

The content of retained austenite was determined by ballistic device BU-2.

The temperature of specimen during heat treatment was measured by welded chromel-alumel thermocouple of 0.3 mm wire diameter.

3. RESULTS AND DISCUSSION

The analysis of quenched cross-cuts microstructure, measurements of hardness HRC and retained austenite quantity showed that after heat treatment the structure was formed of lath martensite and retained austenite mixture with dispersive carbides of iron, chromium, molybdenum and vanadium (Fig. 1). The martensite can be identified as grey brindle zones located in bright austenite matrix with the primary grain boundaries. The carbides are very small and can be seen as miniature black spots.

The steel contained vanadium has a very fine microstructure: grains are several micrometers in size, i. e. about the size of ASTM 9 [6]. Significant differences between the microstructure of the cross-cuts from different quenching temperatures were not observed.

The cross-cuts of quenched specimens showed high hardness: 63 – 66 HRC irrespective of the austenizing temperature. Large hardness values are also related with the presence of dispersive carbides.

It was determined that the content of retained austenite in quenched steel was 12 %, 14 % and 26 %, when austenizing temperatures were 1050 °C, 1070 °C and 1090 °C, respectively.

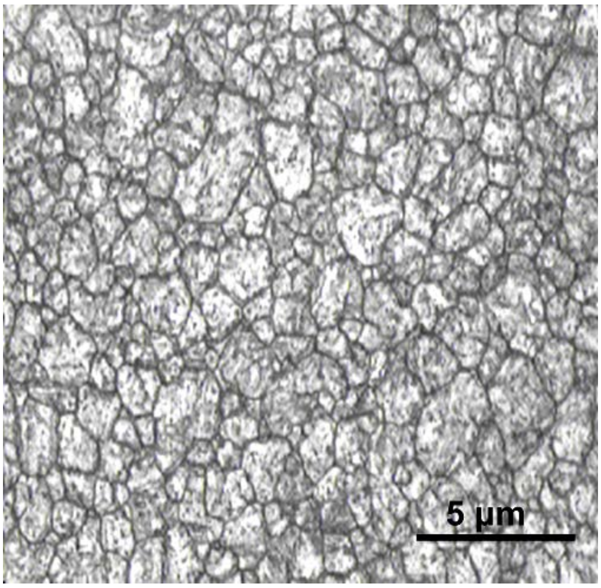

Fig. 1. Microstructure of Hotvar steel after air quenching from 1090 °C

At the moment of starting bending of air quenching specimen, the one is able to resist bending force as its yield strength is rather greater than bending stresses. The manufacturer indicates [5] that martensitic transformation start temperature of Hotvar hot-work tool steel is about 220 °C. The intense bending of specimens began when temperature of the specimen had reached the mentioned one (Fig. 2). When stresses σ = 100 MPa, the specimens bent 1.30 mm, 1.39 mm and 1.52 mm during loading through all martensitic transformation. The higher temperatures were applied to the specimens the greater deformations were obtained: when austenizing temperature was 1070 °C and 1090 °C, the plastic deflection was reached greater of 8 % and 15 % comparing to the one obtained after quenching from 1050 °C (Fig. 2).

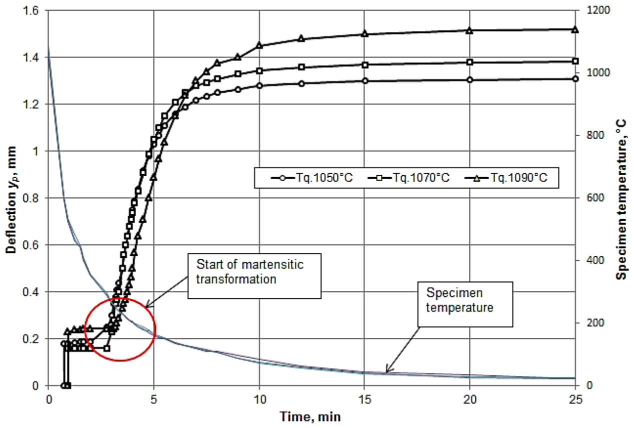

Fig. 2. Plastic deformation of specimens' air quenched from different austenizing temperatures

Deformation rate depends directly on the temperature of austenizing because at higher temperatures austenite has more dissolved carbides, and solid solution obtained more saturated with carbon and alloying elements. The principle role plays carbon dissolved in the austenite lattice.

Martensitic transformation is non-diffusional process, so when it proceeds, all carbon dissolved in face-centred-cubic (FCC) austenite lattice remains in the new phase – martensitic lattice saturated with carbon. It is known, that at room temperature α-iron may contain just up to 0.006 % carbon, as austenite may reach even 2.14 % [7]. During $\gamma \rightarrow \alpha$, the FCC lattice of austenite transforms to body-centred-cubic (BCC) martensite lattice. Carbon atoms may occupy the sites of austenite lattice parallel to [100], [010] and [001] crystallographic directions. The transformation $\gamma \rightarrow \alpha$ is non-diffusional, therefore, during changes of FCC austenite lattice to BCC martensite lattice, carbon atoms remain inserted in martensite lattice only in [001] direction (and at the centres of planes parallel to (001)) thereby stretching the parameter *c* of tetragonal lattice [7].

So increasing temperature of austenizing, more and more carbides are dissolved in austenite. As austenite becomes more rich in carbon atoms, the more of them intervene in [001] crystallographic directions. Increased carbon content weakens the binds between the neighbouring iron atoms and, therefore the specimens reach higher plastic deflections during bending. In this case the stress effect on transformation plasticity of steel is just an instrumental way to show the transformation plasticity phenomenon as its conditioning was always a constant value.

The described theory should be based under the additional experiments as there is no undivided opinion about the relationship between parameters ratio *c*/*a* of tetragonal martensite lattice and carbon content in austenite and following martensite. Some researchers present the results of studies when the ratio *c*/*a* becomes larger than one only when the carbon content in austenite exceeds 0.6 % [8, 9]. The Hotvar steel contains total amount of carbon of just 0.55 %, moreover, the part of carbon is combined with carbides of chromium, molybdenum and vanadium, so the carbon content remained in austenite is rather lower than the mention 0.6 % limit. Hence, no matter how high austenizing temperature is, we could not reach the required carbon content for $c/a > 1$. As a result, the distance between adjacent iron atoms in martensite lattice in [001] crystallographic direction should not increase with rising austenizing temperature, so the same binds between atoms should occur. Hence, ductility should not increase, too.

One can find other scientific works which the opposite results. For example, Kremnev indicated that quenching from various temperatures of high speed steel that contains 0.30 %, 0.42 % and 0.43 % of carbon in martensite, the ratio *c*/*a* of martensite lattice parameters was obtained greater than one – 1.014 – 1.019 [10]. In this case, the interpretation of the increasing of steel plastic deflection dependent on austenizing temperature would be in a correct way. Of course, influence of alloying elements on transformation plasticity needs to be checked as it was also mentioned by Kremnev.

At the air quenching of specimens after heating at austenizing temperature martensitic transformation did not begin immediately, but after 3 – 4 minutes when the specimen was withdrawn from the furnace, i. e. when the temperature dropped to 220 °C – 250 °C. This was clearly seen when the specimens were started bending immediately after heating (Fig. 2). When the specimen was started bending already during the originated martensite transformation, i. e. at 4th or 5th minute of cooling, they immediately began bending (Fig. 3). However, the deflections were got almost 30 % – 40 % lower than in the first case (see total deflection at Fig. 2). As the later the specimen was loaded, the more the loss of plasticity was obtained, because towards the end of the transformation, the nuclear binds became stronger.

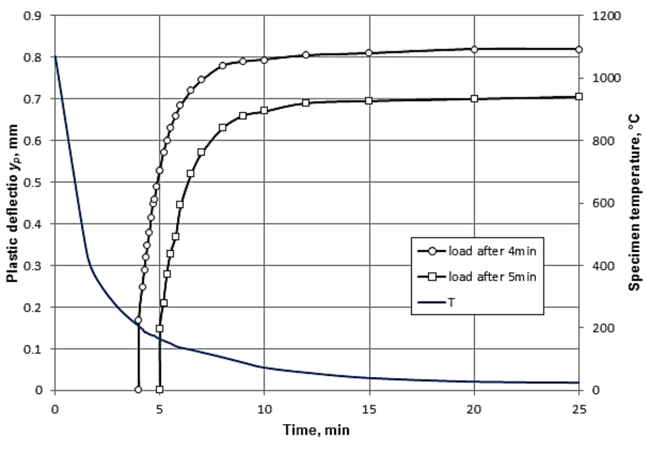

Fig. 3. Plastic deformation of specimens after bending that began at 4th and 5th minutes of cooling. Austenizing temperature 1070 °C

An interesting phenomenon has been observed, when steel specimens were unloaded at the beginning of the air quenching, i. e. at 4th or 5th minutes of the test, and the monitoring of deflection of specimen was continued. It was noted that curved and unloaded specimens successfully bent in the same direction as they were bent just in a lesser intensity (Fig. 4). In this case the external stress has a direct impact on transformation plasticity passing as bending load generated compression and tension stresses in specimen at the same moment. Compression stimulates

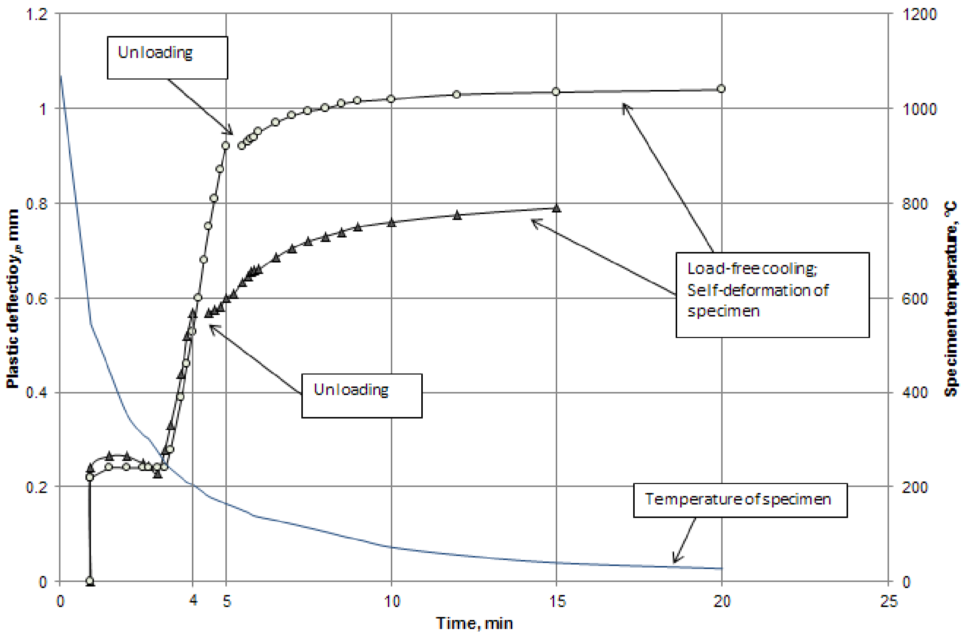

Fig. 4. The phenomenon of autodeformation of Hotvar steel after unloading of specimens bent and air quenched from 1070 °C

austenite transformation while tension blocks it [3].

The influence of tension and compression stresses that were generated inside the specimens is different on the martensitic transformation start temperature M_s and its intensity. This phenomenon is related to anisotropy of volume changes that creates self-deformation of steel parts, so called, autodeformation, even in that way, when the value of external stresses is $\sigma = 0$ [4].

The autodeformation of bent, unloaded at the certain moment and turned for following load-free cooling specimens has reached about 28 % and 12 % of plastic deflection when specimen was unloaded at 4 min or 5 min of total cooling time, respectively.

Altogether, martensitic transformation is very sensitive to stress, thus, deforming the initial structure – austenite, the martensitic transformation may occur at higher temperatures than M_s [1]. In addition, it was found that at the quenching of steel, the transformations (decomposition of austenite and self-tempering of martensite) proceeds at different stages in stretched and compressed sides [3]. Therefore, it must be assumed that the tensile and compressive stresses differently work on quenching and tempering transformations. As the bent and unloaded specimens curved further at the cooling process, therefore, the stretched volume of specimens was increased. It was determined that the specific volume of austenite is the smallest, and the one of martensite is the largest [1, 7].

Obviously, that martensitic transformation was inhibited in stretched volume of specimen, so, unloading was following by increasing of volume as the result of intensive formation of new martensite crystals. Decomposition of austenite into martensite inside the compressed part of specimen have been started before, so its proceeding has been stopped. When transformation performs at different intensities, the volumetric changes can make the specimen to bend to one side or the other. The value of deflection alteration has shown the quantitative differences in transformations.

4. CONCLUSIONS

1. The transformation plasticity of Hotvar hot-work tool steel specimens increases from 8 % to 15 % when austenizing temperature rises from 1050 °C to 1090 °C, respectively. It is quite possible that interstitial carbon atoms positioned in [001] crystallographic direction have the main influence on reducing the atomic binds.
2. It was determined that the loss of transformation plasticity is about 30 % – 40 % when the bending was started at temperatures lower than M_s.
3. The specimens were self-bending in the same direction as they were bent when the load was removed at the temperatures below M_s. It allows assumption that the stretched side of specimen had less martensite comparing to the compressed one at the moment of unloading.

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