ENHANCING DUCTILITY OF HOT-WORK TOOL STEEL THROUGH ISOTHERMAL BAINITIC TRANSFORMATION

[1,2]Anže BAJŽELJ, [2]Aleš NAGODE, [2]Tilen BALAŠKO, [1]Barbara ŠETINA BATIČ, [1,2]Jaka BURJA

[1]*Institute of Metals and Technology, Ljubljana, Slovenia, EU, anze.bajzelj@imt.si, barbara.setina@imt.si, jaka.burja@imt.si*

[2]*University of Ljubljana, Faculty of Natural Sciences and Engineering, Department of Materials and Metallurgy, Ljubljana, Slovenia, EU, ales.nagode@ntf.uni-lj.si, tilen.balasko@ntf.uni-lj.si*

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Abstract

Hot-work tool steels are extensively used in industrial applications that require high resistance to mechanical and chemical degradation at elevated temperatures. To meet these requirements, hot-work tool steels must exhibit good mechanical properties, including high tensile strength, hardness, wear resistance, and tempering resistance, as well as high thermal conductivity and ductility. This study investigates the ductility of the hot-work tool steel HTCS-130, which suffers from low ductility due to the presence of stable molybdenum-tungsten carbides (M_6C) on the prior austenite crystal grain boundaries. Increasing austenitisation temperatures or prolonging the dwelling time at temperature can promote intensive migration of grain boundaries, leading to negative effects on the mechanical properties of the steel. To address this issue, isothermal transformation in the bainitic area between 350 and 500 °C was performed. Isothermal transformation at around 350 °C leads to the formation of lower bainite, which has similar hardness to tempered martensite. As the temperature of isothermal transformation increases, the hardness of the material decreases, due to the formation of upper bainite. The hardness analysis was measured using the Vickers method, the impact toughness of the steel samples was measured using a Charpy test with V-notched samples. The microstructure characterization was performed using optical and scanning electron microscopy. The improvement of ductility can be achieved by controlling the isothermal transformation of bainite and adjusting the heat treatment conditions. These findings provide useful insights into the design and optimization of heat treatment processes for hot-work tool steels.

Keywords: Hot-work tool steel, austempering, bainitic transformation, ductility, dilatometry

1. INTRODUCTION

Hot-work tool steels are subjected to mechanical and thermal cyclic loading; therefore, they must possess good mechanical, chemical, and thermal stability. These steels require high strength, hardness, and ductility for hot work applications. Strength and hardness resist high mechanical loads, and high ductility suppresses the formation and propagation of fatigue cracks resulting from mechanical and thermal loads. Typically, these steels are used to manufacture tools for pressure die casting and hot metal forming applications and are used at elevated temperatures, which require the material's thermal stability [1-6].

Ductility of hot-work tool steels is important for ensuring longer tool life. Hot-work tool steels must be ductile both at room temperature and at elevated temperatures, which is ensured by a homogeneous, fine-grained microstructure. In tools, cyclic loading causes local yield strength exceedances, leading to material deformation. Tools with good ductility tend to impede the formation and growth of surface cracks. [1,7-12].

This study investigated the effect of heat treatment on the ductility of a hot-work tool steel of new generation. The investigated hot-work tool steel has increased thermal conductivity, provided fast heat dissipation and consequently reduced the tool's temperature gradient. Unfortunately, the investigated hot-work tool steel does not achieve high impact toughness due to the heterogenous microstructure and presence of undissolved carbides in the microstructure. To improve the impact toughness of the hot-work tool steel, austempering at different isothermal temperatures was applied to the samples. The microstructure of lower bainite is known for better homogeneity in microstructure compared to martensite, and carbides are evenly distributed in the matrix [13-19].

2. MATERIALS AND METHODS

The delivered tool steel was in a spheroidised state with its chemical composition given in **Table 1**. The chemical composition of the steel was determined using optical emission spectroscopy with an ARL 3460 device. The carbon, sulfur, and nitrogen contents were determined using a combustion method with ELTRA CS-800 and ELTRA ON-900. Cylindrical shape specimens with a diameter of Ø4 mm × 10 mm were produced to determine martensite start temperature using a TA DIL805A dilatometer (TA, New Castle, DE, USA). The samples were heated in a vacuum with a heating rate of 10 °C/s to an austenitising temperature of 1080 °C, held at this temperature for 600 s, and then rapidly cooled at a rate of 30 °C/s to the room temperature. Also, using a dilatometer, isothermal transformations of the samples were carried out in an argon atmosphere between 350 and 500 °C. After austenitisation, the samples were cooled at a cooling rate of 30 °C/s to different temperatures of isothermal transformation, they were held at the temperature for 2 hours, followed by rapid cooling to room temperature.

Table 1 Chemical composition of analysed hot-work tool steel in wt%

C	Si	Mn	S	Ni	Mo	W	N
0.32	0.04	0.02	0.0009	0.03	3.2	1.7	0.001

In order to determine the impact toughness, isothermal bainitic transformation of larger pieces was carried out, austenitisation of the samples was carried out in an electric furnace, followed by rapid cooling in a preheated salt bath, where the samples were held for 2 h between 350 and 500 °C. The isothermal transformation was followed by rapid cooling of the samples to room temperature. After the heat treatment, standard V-notch specimens with dimensions of 55 mm x 10 mm x 10 mm were machined for the Charpy impact test. Charpy impact measurements were performed at room temperature with a 300 J pendulum.

Samples for metallographic analysis were ground, polished, and etched with Nital. Microstructure was analysed with an optical microscope Zeiss Axio Imager (Z2m, Carl Zeiss AG, Oberkochen, Germany), and a scanning electron microscope Zeiss CrossBeam 550 (Carl Zeiss AG, Oberkochen, Germany). Vickers hardness (HV10 and HV0.025) was measured on metallographic specimens using an Instron Tukon 2100B (Wilson Instruments, Norwood, MA, USA).

3. RESULTS AND DISCUSSION

Figure 1a shows initial state of the analysed material, spherodised microstructure of hot-work tool steel sample. **Figure 1b** shows microstructure of hot-work tool steel sample after austenitisation at 1080 °C following quenching to room temperature. The martensite start (M_S) temperature was determined as 405 °C by analysing the dilatometric curve.

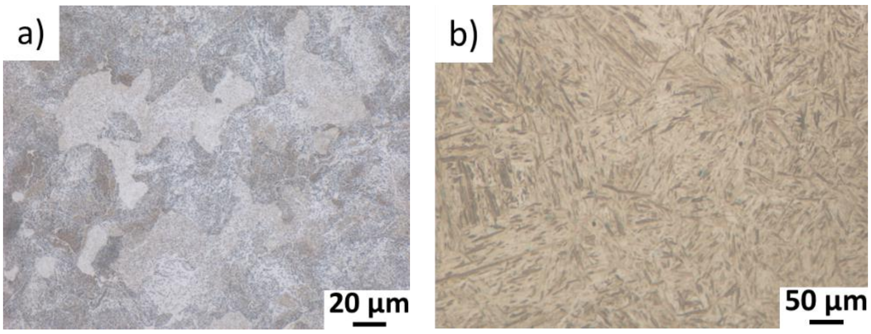

Figure 1 a) Microstructure of received hot-work tool steel in spherodised state, b) quenched sample of analysed hot-work tool steel

Figure 2 shows dilatometric curves of the absolute change in length of the samples held at temperatures of isothermal transformation. The isothermal transformations were also carried out in a salt bath heated between 350 and 500 °C, with a holding time of 2 hours, followed by rapid cooling to room temperature. The left part of the figure shows the initial stage of temperature holding, where most of the isothermal transformation occurred, while the right part of the figure shows the change in length of the samples in the final minutes of isothermal holding and during cooling to room temperature. During cooling of the sample to 350 °C, there was a slight deviation in the dilatation curve, indicating martensitic transformation during cooling to the isothermal temperature, while there was no deviation in the other samples. The presence of martensite before isothermal holding accelerates the nucleation of bainite and shortens the incubation time of bainitic transformation [20,21]. With an increase in the temperature of isothermal transformation, the incubation time for the onset of bainitic transformation increases, indicating slower nucleation of bainite. With increasing temperature, the kinetics of isothermal transformation decreases, due to the greater stability of austenite at higher temperatures. For the sample held at 350 °C, isothermal transformation is completed after approximately 15 seconds, for the sample held at 400 °C, transformation is completed after 50 seconds, for the sample held at 450 °C, it takes 65 seconds, while for the sample held at 500 °C, the transformation takes the entire time. After cooling to room temperature, there is still a deviation in the dilatation curve for the sample held at 500 °C, indicating martensitic transformation.

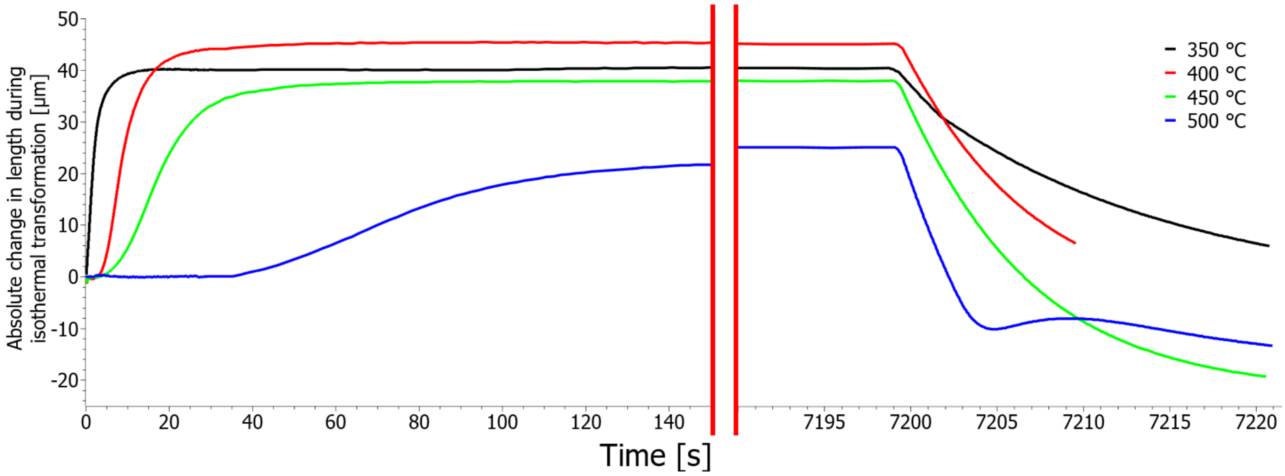

Figure 2 Absolute change in length during isothermal transformation

Figures 3 a-d show etched microstructures of samples held at transformation temperatures between 350 and 500 °C, with labelled phases and corresponding measured microhardness values (HV0.025). Results of hardness measurements (HV10) are given in the top edges of the figures. Microhardness values are significantly higher than those measured with greater loads, which is consistent with literature data [22]. The sample held at a temperature of 350 °C contains both bainite and martensite. The difference in microhardness between the bainite and tempered martensite is minimal. In the samples held at temperatures of 400 and 450 °C, bainite was formed. As the temperature of the isothermal transformation increases, the hardness decreases due to more intense diffusion of elements (especially carbon), at the boundaries of bainitic ferrite the formation of carbides is more intense which soften the matrix. Samples held at transformation temperatures of 350, 400, and 450 °C are predominantly bainitic, such microstructure represents good potential for higher ductility of the material. In the sample held at 500 °C, after cooling to room temperature, a martensitic transformation of stabilised austenite occurred, which is also evident from the microstructure images and hardness measurements. The resulting martensite is untempered, which is reflected in higher microhardness values. Stabilised austenite was also present between the bainite grains, and martensitic transformation occurred during cooling, resulting in higher microhardness values of bainitic grains compared to the bainite in other samples.

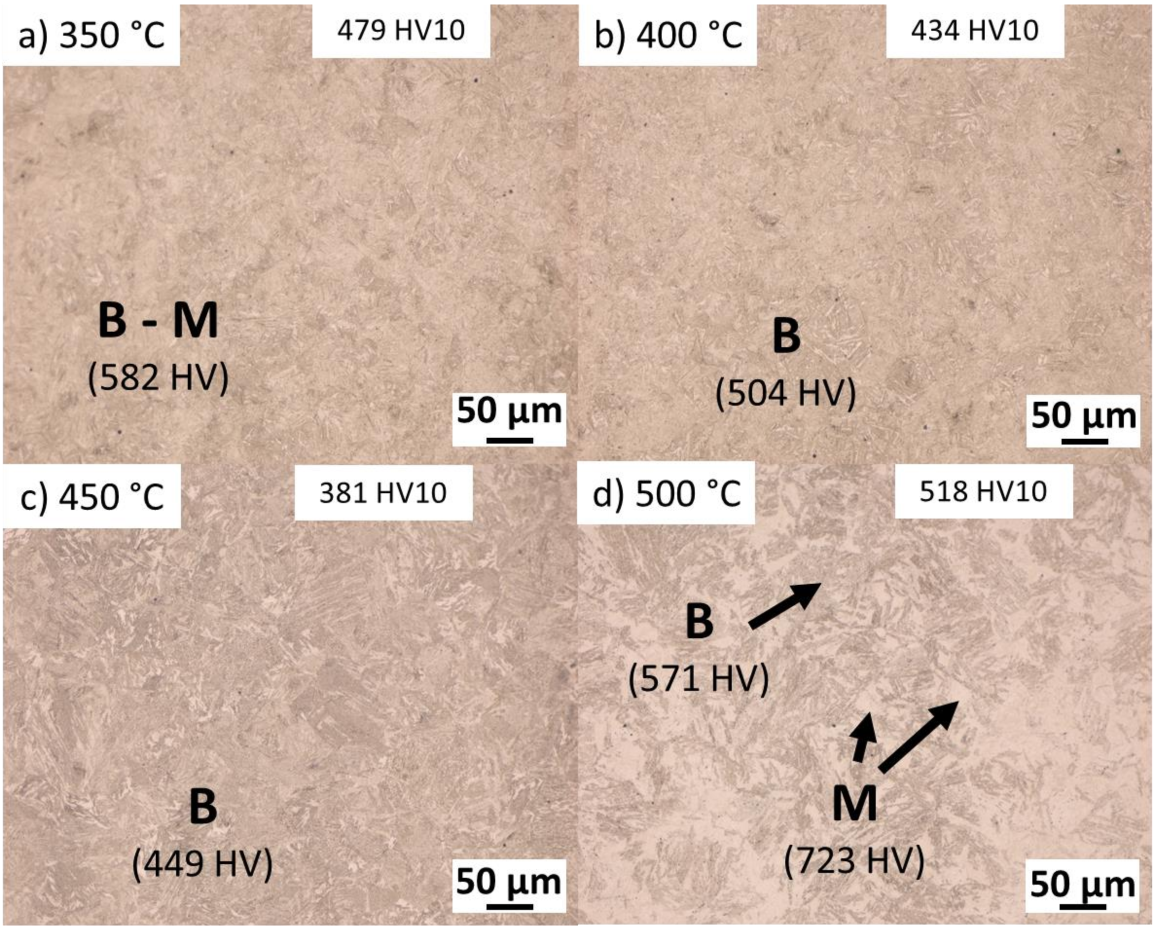

Figure 3 Optical microscopy of the samples held 2 hours at the isothermal transformation temperatures a) 350 °C, b) 400 °C, 450 °C and d) 500 °C

Table 2 shows the average values of the impact toughness of samples held at different temperatures of isothermal transformation. The impact toughness of samples after conventional heat treatment (CHT) was 4.5 J, where these samples were quenched from a temperature of 1080 °C, followed by triple tempering to a hardness of 47 HRC [23]. Samples after isothermal transformation have a slightly higher impact toughness. The sample held at the transformation temperature of 500 °C achieves the lowest average impact toughness due to the presence of untempered martensite, which was formed from stabilised austenite during cooling to room temperature. Samples held at temperatures of 400 °C and 450 °C have an average impact toughness of 8.5 J, where the higher toughness is a result of the absence of martensite in the microstructure. Despite having a fully bainitic structure, the toughness is low, indicating the formation of a combination of upper and lower bainite. The sample held at the transformation temperature of 350 °C has a microstructure of tempered martensite and lower bainite and an average impact toughness of 17.5 J. Below the M_S temperature, a more tough, lower bainite is formed beside the martensite. With an increase in the temperature of isothermal transformation, the proportion of lower bainite decreases, and a greater amount of upper bainite is formed, which has poorer ductility.

Table 2 Average impact toughness of analysed samples

Temperature of isothermal transformation [°C]	350	400	450	500	CHT*
Average impact toughness [J]	17.5	8.5	8.5	5.0	4.5

CHT * data from [23].

Figure 4 shows SEM fracture surface of the samples held at the isothermal transformation temperatures 350 and 500 °C. Fractures in all samples are mostly brittle, with small islands of voids indicating a ductile fracture. As the temperature of isothermal transformation decreases, the proportion of ductile fracture increases and the size of the fracture facets decreases. As the temperature of isothermal transformation increases, more upper bainite is formed and consequently the fracture becomes more brittle. There are no traces of undissolved carbides or other defects on the fracture surfaces that could cause crack initiation.

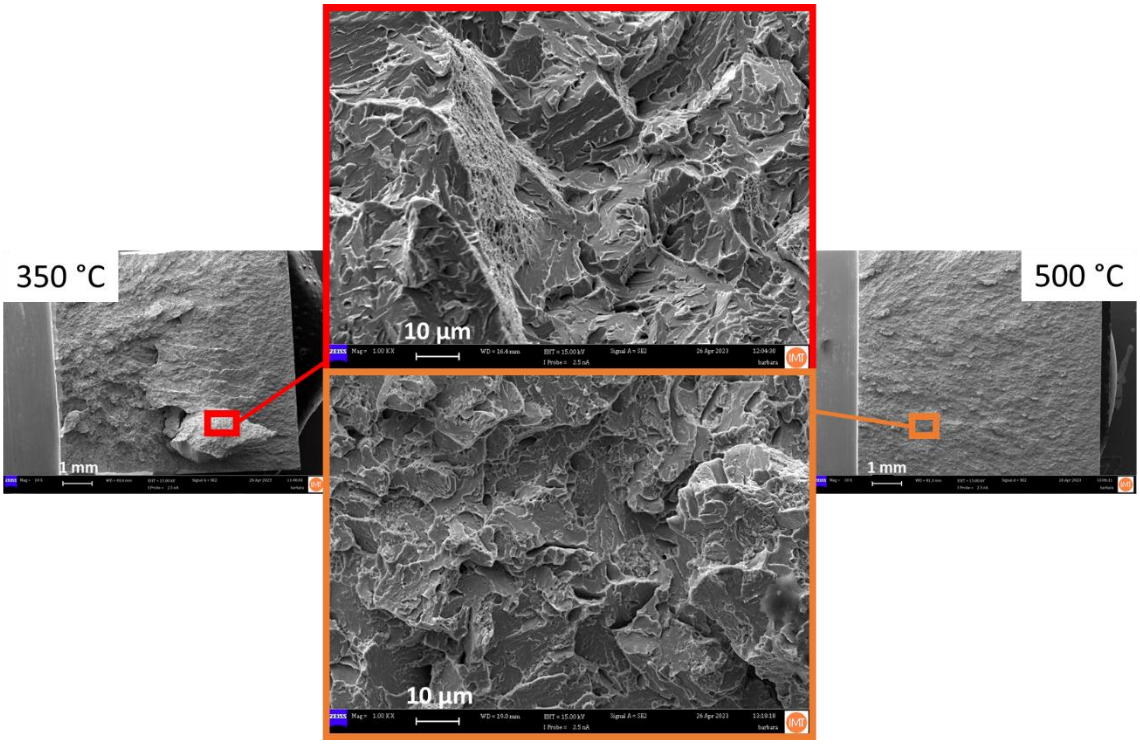

Figure 4 Scanning electron microscopy of the fracture surface of the samples held at the isothermal transformation temperatures 350 °C and 500 °C

4. CONCLUSION

The work focused on improving the ductility of a new generation hot-work tool steel. Based on the results, the following findings can be summarized:

- Predominantly bainitic microstructure is formed at isothermal transformation temperatures between 350 and 450 °C. At isothermal transformation temperature of 350 °C, a martensitic-bainitic microstructure is formed. With increasing transformation temperature, a larger proportion of upper bainite is present in the microstructure, which is reflected in lower hardness values of the samples.
- Isothermal transformation at 500 °C proceeds slowly, and in addition to bainite, stabilised austenite is also present in the microstructure, which transforms into martensite upon cooling to room temperature.
- The impact toughness of samples with a bainitic microstructure exhibits higher values compared to the microstructure of tempered martensite. With decreasing temperature of isothermal transformation, the proportion of ductile fracture increases.

Austempering represents a solution for improving the ductility of the investigated hot-work tool steel. In further analysis, it would be advisable to examine the austempering around isothermal temperature 350 °C, where a higher amount of lower bainite is formed in the microstructure.

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