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EFFECT OF AUSTEMPERING TEMPERATURE ON THE MICROSTRUCTURE AND RETAINED AUSTENITE OF CAST BAINITIC STEEL USED FOR FROGS IN RAILWAY CROSSOVERS

This work deals with the effect of austempering temperature and time on the microstructure and content of retained austenite of a selected cast steel assigned as a material used for frogs in railway crossovers. Bainitic cast steel was austempered at 400°C, 450°C and 500°C for two selected times (0.5 h, 4.0 h) to study the evolution of the microstructure and retained austenite content. The microstructure was characterized by optical microscopy, X-ray diffraction analyses (XRD), and hardness tests. Phase transformations during and after austempering were determined by dilatometric methods.

The increase in isothermal temperature causes an increase in time to start of bainitic transformation from 0.25 to 1.5 s. However, another increase in temperature to 500°C shifts the incubation time to as much as 11 s. The time after which the transformations have ended at individual temperatures is similar and equal to about 300 s (6 min.). The dilatation effects are directly related to the amount of bainite formation. Based on these we can conclude that the temperature effect in the case of cast steel is inversely proportional to the amount of bainite formed. The largest effect can be distinguished in the case of the sample austempered at 400°C and the smallest at 500°C. Summarizing the dilatometric results, we can conclude that an increase in austempering temperature causes an increase in austenite stability. In other words, the chemical composition lowers (shifts to lower temperatures) the range of bainite transformation. It is possible that at higher austempering temperatures we will receive only stable austenite without any transformation. This is indicated by the hatched area in Figure 4b. This means that the heat treatment of cast steel into bainite is limited on both sides by martensitic transformation and the range of stable austenite. The paper attempts to estimate the content of retained austenite with X-ray diffraction.

Keywords: railway crossover, austempering of bainitic cast steel, heat treatment

1. Introduction

A railway crossover is one of the most important and complex elements of a railway track, not only because of its construction, but also due to its intensive wear. Wrought steels with a pearlitic microstructure (e.g. R260) and a Hadfield cast steel (GX120Mn13) are currently used for frogs [1-7].

The bainitic steels currently used for frogs are mostly low-alloyed. Their heat treatment includes a normalization annealing at 850,950°C followed by a hardening and tempering at 350,650°C [8-11]. As described by Green et al. [12] the wear resistance of bainitic cast steels depends on the temperature of isothermal transformation and tempering conditions, whereas the prior normalizing is indispensable for preparing the material to welding. It is worth noted, that using of currently available CCT diagrams allows obtaining the bainitic microstructure across

the cast frog with a negligible amount of retained austenite [13]. Aglan et al. [14,15] recommend the use of heavily loaded railway crossover tracks made of low carbon steel (<0.03%C) with a bainitic microstructure containing Mo and B.

The influence of isothermal transformation temperature on wear resistance of bainitic cast steel was described in [13,16]. The lower the isothermal transition temperature, the greater the wear resistance [8,17-19]. Hotzman et al. [20] compared their bainitic cast steel (Lo8CrNiMo) with rail steel (R260) in their research. Regardless of the test temperature, bainitic cast steel has better mechanical properties than rail steel. The use of austempering treatment creates fine ferrite laths and inter-lath austenite in the microstructure [21-24]. Such ferrite based microstructure enables ultrahigh strength properties, e.g., 2.5 GPa of compression strength and 2.3 GPa of ultimate tensile strength [25].

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Nevertheless, there is a lack of a compressive study on the effect of austempering treatment on the evolution of microstructure and related mechanical properties in bainitic cast steel designed for the frogs in railway crossovers. Therefore, a filling of this gap has become the main motivation of the presented work.

2. Experimental procedure

A 50 kg bainitic steel ingot, with dimensions of $100 \times 100 \times 5000$ mm, was provided by the Foundry Research Institute in Krakow in the as-cast condition. Its chemical composition is presented in Table 1.

TABLE 1

The chemical composition of the bainitic cast steel (wt. %)

C	Mn	Si	P	S	Cr	Ni	Mo	Ti
0.17	0.57	0.28	0.014	0.013	1.70	2.60	0.46	0.03

The ingot was cut into smaller pieces perpendicular to its longer edge and then the specimens were cut out parallel to the side surface of the ingot. Based on previously described results [13] of our dilatometric analyses, critical temperatures were set as follows: $Ac_{1s} = 690^\circ\text{C}$, $Ac_{1f} = 760^\circ\text{C}$ and $Ac_3 = 850^\circ\text{C}$ and then the normalizing process was designed [6]. Three different temperatures of the austempering treatment (schematically represented in Fig. 1) were applied.

Three austempering temperatures after cooling from an austenitization were selected: 400°C , 450°C and 500°C . The first temperature was in the M_s temperature range, however, the isothermal treatment should stop this transformation and favor the bainitic transformation. The next two temperatures higher than M_s should allow obtaining a large amount of bainite. Samples from the austenitizing temperature were cooled to isothermal stops at a rate of 100°C/s . After the austempering, the samples were cooled at a rate of 1°C/s . Such slow cooling should be sufficient to register any transformation during cooling.

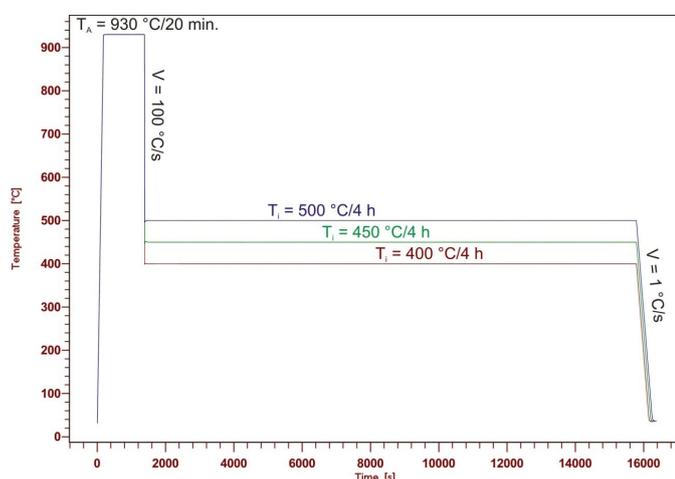


Fig. 1. Schematic representation of the austempering treatment

Dilatometric investigations were performed using the high-resolution dilatometer Linseis L78 RITA (Rapid Intensive Thermal Analysis) equipped with an induction heater. Experiments were performed in a high purity helium atmosphere. For temperature measurements K (NiCr/Ni) type thermocouples were used. The samples used for the study had dimensions $\phi 3 \times 10$ mm. A microstructure evaluation was performed using Leica DMLM light microscope (LM). The volume fraction of retained austenite was measured by X-ray diffraction (XRD) technique by using PANanalytical AERIS diffractometer ($\text{CuK}\alpha 1$ radiation ($\lambda = 1.54178 \text{ \AA}$) was applied. The hardness of heat treated specimens were measured using the Vickers pyramid indenter and a load of 98.1 N (10 kG).

3. Results and discussion

Figure 2 shows the results of heating the bainitic cast steel at a rate of 0.08°C/s . This figure shows the change in sample length ΔL (dilatometric curve) over time and the corresponding change in thermal expansion coefficient α . On the dilatometric curve, we can identify three very characteristic temperature ranges. The first range up to the temperature of austenite formation corresponds to a change in which the initial state of the sample affects. A strong positive effect is probably associated with the transformation of retained austenite in the temperature range $250\text{--}400^\circ\text{C}$. This effect is overlapped with smaller negative associated with the cementite precipitation. This indicates that the bainitic cast steel in the initial state was partially hardened. The second range corresponds to the formation of austenite. The dominant effect is visible and very clear. The beginning is set at 670°C and the end at 860°C . The last third observed range occurs in the austenitic matrix range. We can distinguish an intensely negative effect above 940°C , which is caused by the dissolution of carbides and grain growth. Based on these tests, it can be concluded that 930°C is the optimal austenitizing temperature.

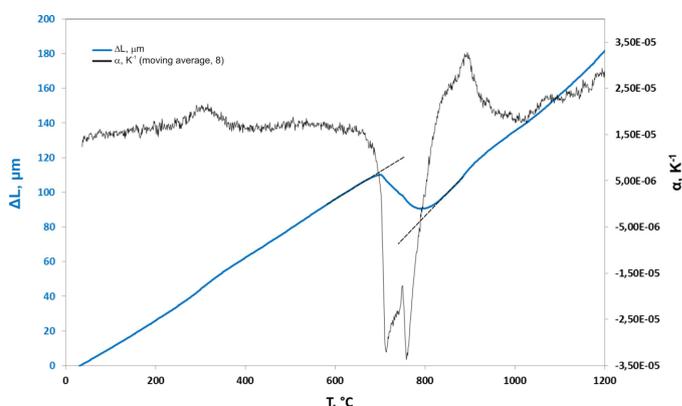


Fig. 2. Dilatometric curve with the corresponding curve of thermal expansion coefficient for the tested cast steel, recorded during heating with a 0.08°C/s rate

Investigated cast steel has a good hardenability, which shows a CCT diagram [13]. Another part of the study was to

demonstrate and confirm whether cooling rate of 100°C/sec will be sufficient not to get other transformations than martensitic. This was verified by dilatometric tests, performed from the austenitizing temperature 930°C. At the curve it can be distinguished only one dominant effect associated with the martensitic transformation. The Ms temperature is equal 405°C [Fig. 3].

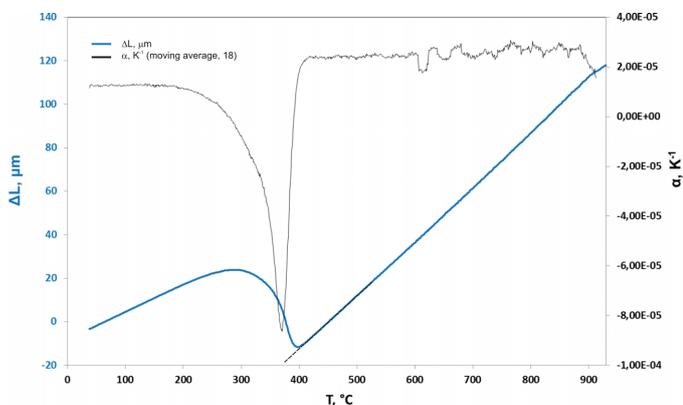


Fig. 3. Dilatometric curve with the corresponding curve of thermal expansion coefficient changes for the tested cast steel recorded during cooling from the austenitizing temperature at a rate 100°C/s

Figure 4 shows the only a part of dilatometric investigations of austempering test for a range of isothermal holding. Based on these results it can be concluded that temperature has a significant impact on the progress of bainitic transformation (like in the most cases). The temperature increase causes an increase incubation time of the start of the bainite transformation from 0.25 to 1.5 s. However, another increase in temperature to 500°C shifts the incubation time to as much as 11 s. The time after which the transformations have ended is similar and amounts to approx. 300 s (6 min.). The dilatation effects are directly related to the amount of bainite formation. Based on these we can conclude that in the case of cast steel the temperature effect is inversely proportional to the amount of formed bainite. The largest effect can be distinguished in the case of the sample austempered at 400°C and the smallest at 500°C. Summarizing the dilatometric results, we can conclude that an increase in austempering temperature causes an increase in austenite stability. In other words, the chemical composition lowers (shifts to lower temperatures) the range of bainite transformation. It is possible that at higher austempering temperatures we will receive only stable austenite without any transformation. This is indicated by the upper blue hatched area in Figure 4b. This means that the heat treatment of cast steel into bainite is limited on both sides by martensitic transformation and the range of stable austenite. It means that the chemical composition of cast steel caused a decrease in the bainitic transformation range and only the upper half of the characteristic “C” phase transformation range is observed (the other half approximated by gray hatches). Exceeding the 1.500 s (25 min.) in the case of 400°C and 450°C temperatures a decrease in the sample length can be observed. However in the case of a 500°C sample an increase occurs. Most likely this is a consequence of the same processes. Isothermal holding in each

case allows for diffusion processes in particular of carbon (e.g. carbon diffuses from supersaturated bainite ferrite to austenite) and partial coagulation of carbides. It means that in the case of tested cast steel at selected temperatures and also set of times the transformations did not come to an end. This is confirmed by the cooling dilatograms after isothermal holding Figure 5.

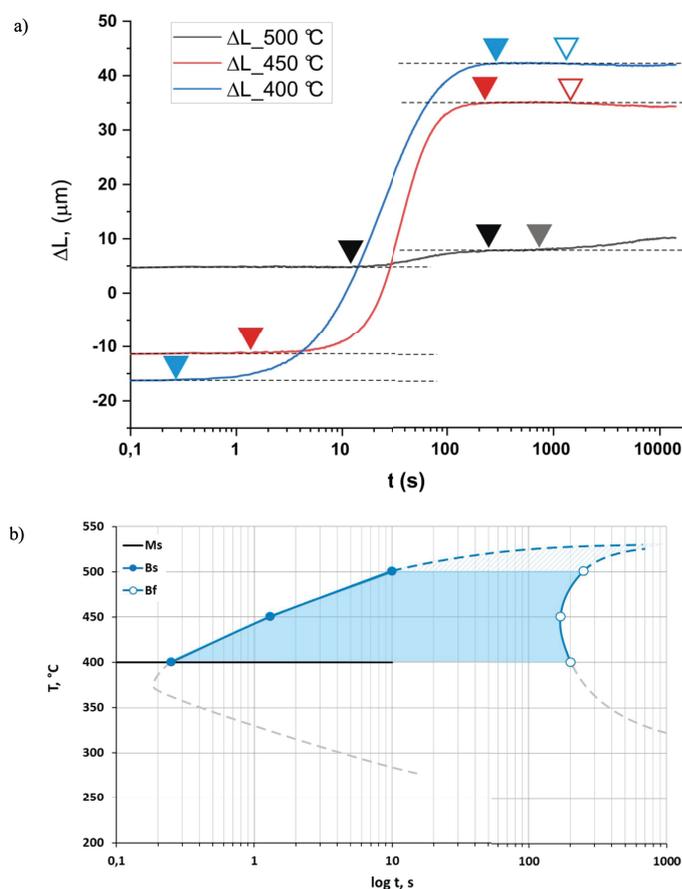


Fig. 4. a) dilatometric curve with the corresponding curve of dilatometric effect for the tested cast steel for isothermal holding, b) part of the TTT diagram based on the results from Figure 4a

Figure 5 shows the cooling curves after isothermal holding from three selected temperatures. Additionally for better comparison of the samples, changes in the thermal expansion coefficient are presented Figure 6. On each of the curve we can distinguish a dilatation effect related to the phase transformation. The strength of the effects are closely related to how much of austenite transformed during isothermal holding. The biggest effect was observed for the sample that was held at a temperature of 500°C and the lowest almost invisible to the samples, hold at 400°C. Comparing the obtained Ms temperatures for individual samples with the Ms temperature determined in Figure 3, it can be seen that for samples withstand at 500°C it increased by 30°C. For the sample cooled after holding at 450°C it decreased by 40°C and for the last one it decreased by 130°C. The decrease in Ms temperatures is probably associated with the diffusion of carbon from bainite to austenite or the pushing of carbon through the emerging phase transformation boundary. The increase in the first case, can be due to either segregation of the chemical

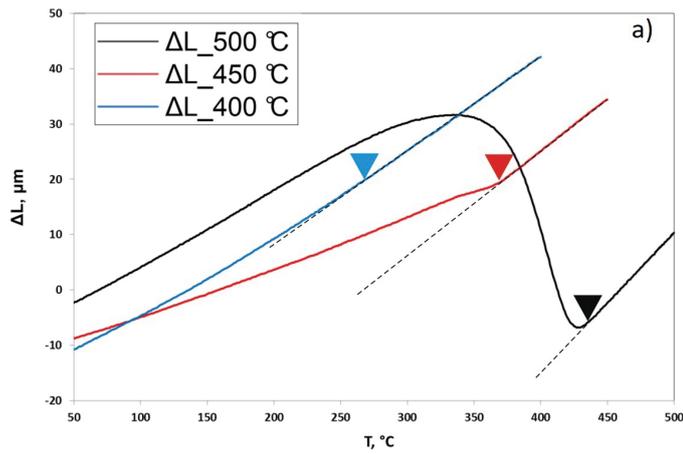


Fig. 5. Dilatometric curves of cooling with 1°C/s rate after isothermal holding at given temperatures

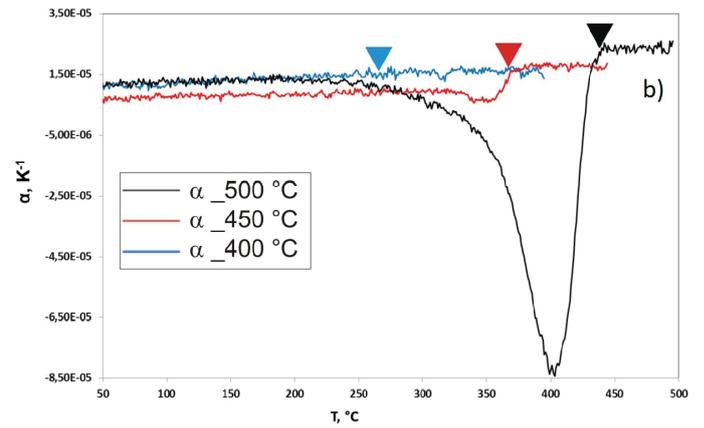


Fig. 6. Thermal expansion coefficient changes curves after isothermal holding

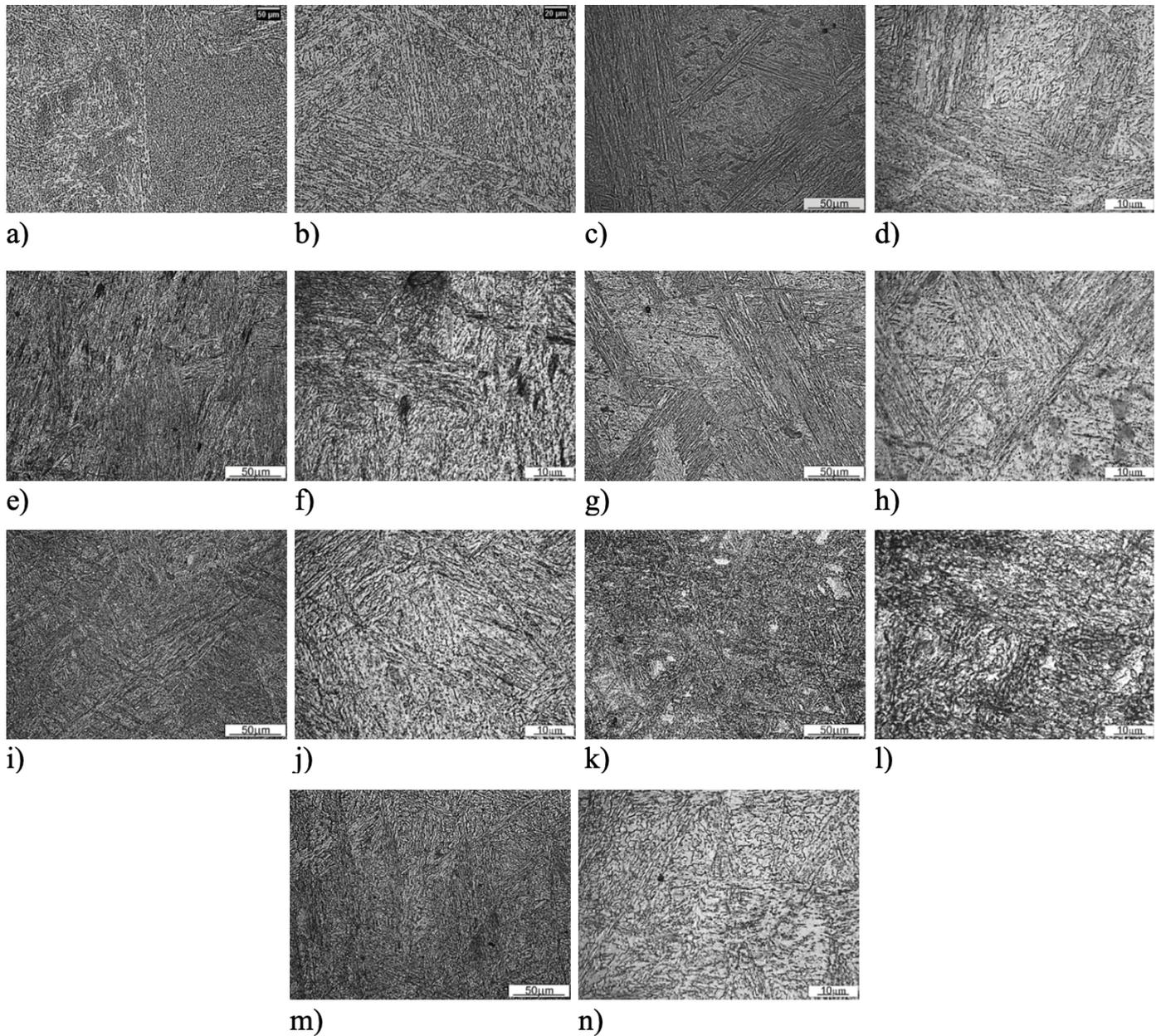


Fig. 7. Light microscopy images showing the microstructure of the bainitic cast steel after austempering: a,b) as cast condition; c,d) 400°C/0,5h; e,f) 400°C/4,0h; g,h) 450°C/0,5h; i,j) 450°C/4,0h; k,l) 500°C/0,5h; m,n) 500°C/4,0h

composition (often in the case of castings) or a decrease in the concentration of alloying elements in the remaining austenite. This is very likely because it was held at highest temperature where diffusion of alloying elements is easy. At this temperature, alloy carbides probably precipitated on grain boundaries. Important results in these tests are changes in the thermal expansion coefficient. Comparing the results for the samples, it can be stated that in the initial cooling stage before the transformation, the sample withstands at 500°C had the highest factor. Which proves a large amount of initial retained austenite, but unfortunately unstable, which transforms intensively at lower temperatures. The sample austempered at 450°C has the middle coefficient before transformation. It is important in this case that after the transformation the lowest value of the coefficient was obtained. However, for the 500°C and 400°C samples, the coefficients are slightly higher. Based on this, it can be assumed that in these two samples we should obtain a certain amount of retained austenite.

Due to a non-uniform intensity of chemical etching, a local segregation sites formed upon the crystallization may be observed in the microstructure (Fig. 7a,b). Regardless of the temperature of the austempering the microstructure has bainitic-martensitic nature. With shorter times of holding the martensitic morphology, it is visible. This can be seen clearly for temperatures 400°C and 450°C. For durability of 0.5h, typically martensitic morphology prevails in the microstructure. The prolonged holding time due to the incubation time of the bainitic transformation will allow obtaining a bainitic microstructure (Fig. 7c-j). The carbide phase is clearly finer when using lower austempering temperatures (visible at Fig. 7c, d from Fig. 7m,n). Increasing the temperature to 500°C allowed obtaining only

bainite microstructure (Fig. 7k-n) with characteristically thicker needles and a larger amount of carbide phase.

The hardness test results correlate with the results of dilatometric tests. At 400°C, the material is austempering below the Ms line, which indicates an increase in hardness. The temperature higher than 450°C and 500°C allows for only a bainitic microstructure which decreases the hardness (Fig. 8).

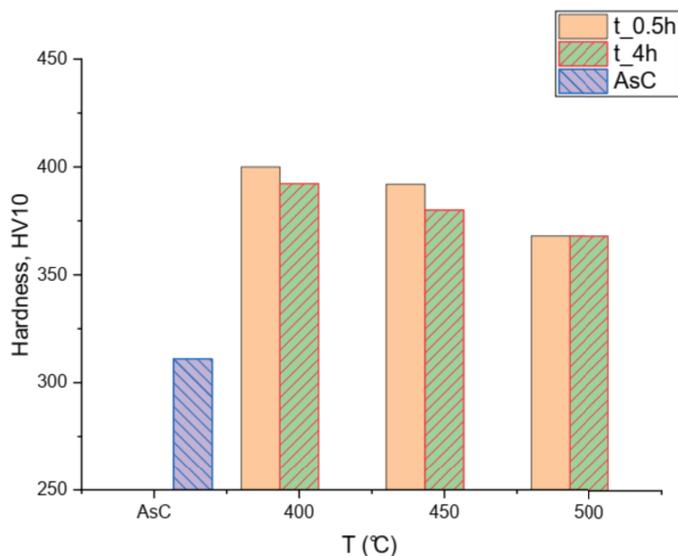


Fig. 8. The hardness results for bainitic cast steel after austempering and in AsC

Phase analysis has shown that the dominant steel component is ferrite with a small proportion of austenite (Fig. 9). Due to

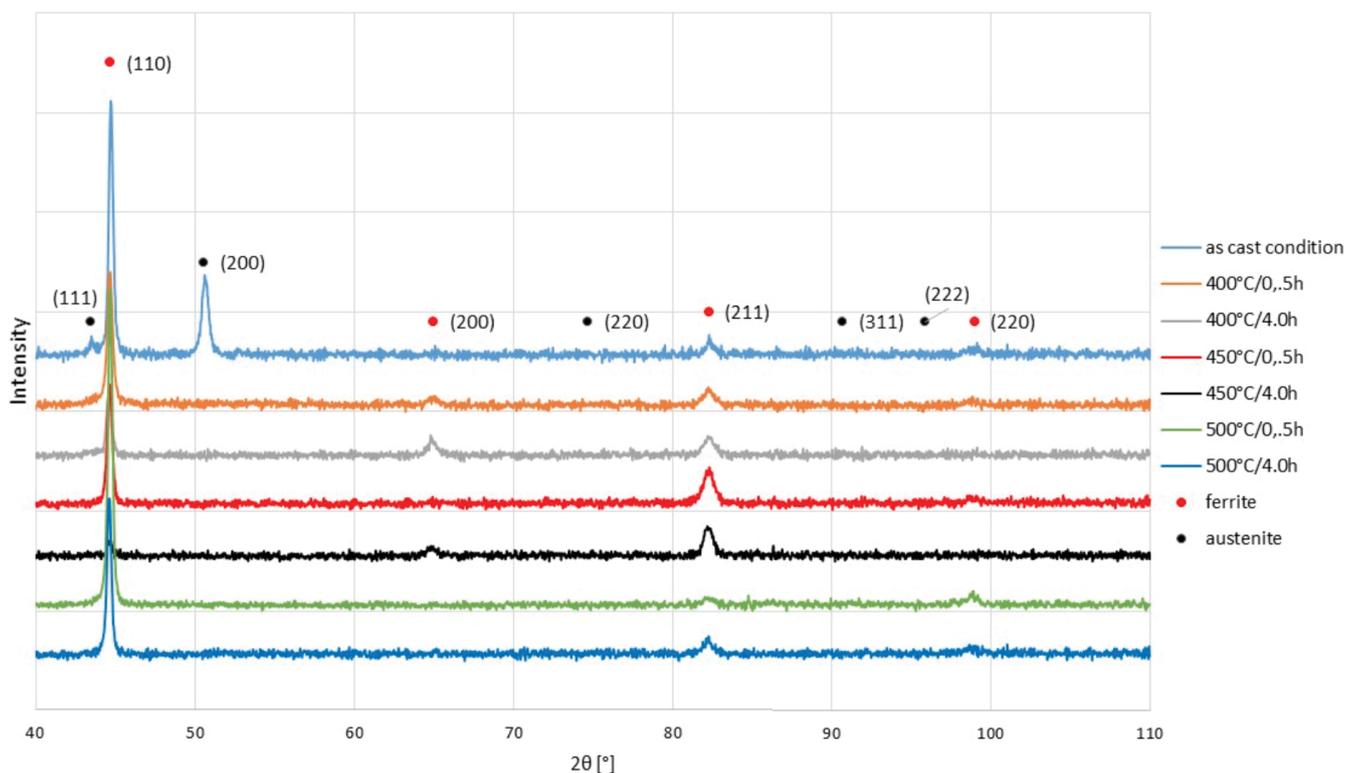


Fig. 9. The results of XRD for bainitic cast steel

the strong texture, it is not possible to determine the individual contribution from phases using the method of direct comparison of diffraction line intensities. In the material isotropic ratio of 111 to 200 austenite diffraction line should be, while in the analyzed sample it is 0.1. It shows strongly favoured orientation of 200 austenite. A similar situation has placed in for sample after austempering 450°C/4.0 h. In this case, ferrite shows strong texture as evidenced by the very poor line 110 relative to line 200. In other cases, the share of austenite is small on detection limit of the method, this is confirmed by the very low intensity of austenite line 111 and no line 200 except textured sample.

4. Conclusions

1. Summarizing the dilatometric results, we can conclude that an increase in austempering temperature causes an increase in austenite stability. The chemical composition lowers (shifts to lower temperatures) the range of bainite transformation.
2. With shorter times to holding martensitic morphology, it is visible, indicating that the start of bainite transformation has been shifted to longer times. Comparing the dilatation effects that are directly related to the amount of bainite formed, we can conclude that the temperature effect is inversely proportional to the amount of bainite formed.
3. The prolonged holding time due to the incubation time of the bainitic transformation will allow obtaining a bainitic microstructure. The carbide phase is clearly finer when using lower austempering temperatures.
4. In this case, ferrite shows strong texture as evidenced by the very poor line 110 relative to line 200. In other cases, the share of austenite is small on detection limit of the method, this is confirmed by the very low intensity of austenite line 111 and no line 200 except textured sample.

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