Journal of Achievements in Materials and Manufacturing Engineering
VOLUME 39
ISSUE 1
March
2010

The microstructure and properties of the bainitic cast steel for scissors crossovers

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Received 04.01.2010; published in revised form 01.03.2010

Materials

ABSTRACT

Purpose: The main purpose of the hereby study was the description of microstructure and properties of the new low-carbon Mn-Cr-Mo-V-Ni bainitic cast steel developed in the AGH Laboratory of Phase Transformations for cast mono-blocks of scissors crossovers. Investigations comprise material in as-cast state and after various variants of normalization as well as normalization and high tempering.

Design/methodology/approach: Analyses of microstructure, strength properties, impact toughness and crack resistance (K_{Ic}) were performed both for material in the as-cast state and after heat treatments. The influence of the initial microstructure on the investigated cast steel hardness – after the normalizing and after the normalizing and tempering – was determined.

Findings: Changes in the microstructure of the cast bainitic scissors crossovers were determined and their properties described.

Research limitations/implications: The investigations were performed in order to estimate a possibility of applying bainitic cast steels for production of scissors crossovers in the form of monolithic blocks.

Practical implications: Application of bainitic cast steels for scissors crossovers in the form of monolithic blocks.

Originality/value: Designing of the chemical composition of the bainitic cast steel (Mn–Cr-Mo-V-Ni) and its heat treatment.

Keywords: Metallic alloys; Bainitic cast steel; Scissors crossovers; Mechanical properties

Reference to this paper should be given in the following way:
J. Pacyna, P. Bała, S. Dobosz, A. Kokosza, S. Kąc, The microstructure and properties of the bainitic cast steel for scissors crossovers, Journal of Achievements in Materials and Manufacturing Engineering 39/1 (2010) 19-26.

1. Introduction

On 23.07.1996 the European Parliament and the Council issued a Decision No 1692/96 to upgrade the trans-European conventional rail network to be equipped for speeds up to 200 km/h with an axle load not less than 230 kN, and in the case of specially built tracks for speeds equal to or higher than 250 km/h. Since that decision there is more interest observed in new materials for rail tracks production including new steels for rail tracks [1-3]. It seems that the highest potential to substitute for the traditional rail tracks with pearlitic microstructure have the low-carbon bainitic steels [4-9]. Rail tracks made of these steels are easy to weld [10] and can obtain very high strength (R_e, R_m) and strain (A, Z) parameters, and are resistant to cracking in dynamic (KV) and static (K_{Ic}) conditions [11].

It is also possible to design their chemical composition making the surface part of the head, on which the wheels roll, subject to self-service [12]. Self-service of head's wheel tread of the rail track consists in that the pits created as a result of operation, micro-cracks and other faults known after their development as squat, head-checking, white layer, corrugated wear etc., are being successively removed by abrasion already during wagon wheels rolling on the tracks. Therefore, such rails do not need any special, periodical grinding in order to remove these defects because the surface is always "like new".

More and more often applications of steels with the bainitic microstructure for production of rails for the heavy-load railway tracks [1,5,13], encourage investigations of the possibility of using such materials for scissors crossovers in the form of cast monolithic blocks. Low-carbon Cr-Mo-V cast steels are applied, among others, as elements of steam turbines [14-16].

The description of the microstructure and properties of the new low-carbon Mn – Cr – Mo – V – Ni bainitic cast steel designed in the Laboratory of Phase Transformations, AGH, for the cast mono-blocks for scissors crossover – was the main aim of the present study. Materials in as-cast state and after the application of various normalizing variants as well as after normalizing and high-temperature tempering were investigated.

2. Material for investigations

All tests were performed on the original low-carbon Mn-Cr-Mo-V-Ni bainitic cast steel designed in the Laboratory of Phase Transformations, AGH. In consideration of patent qualities of this material its chemical composition is not given.

When designing the chemical composition of the investigated cast steel the aspects listed below were taken into account.

1. Sufficient bainitic hardenability;
2. Temperature criterion of the bainitic transformation start;
3. Temperature criterion of the bainitic transformation finish;
4. Influence of alloying elements on the hardness decrease with the tempering temperature;
5. Alloying element cost.

All those rules are compiled and described in reference [13].

3. Investigation methods and heat treatments

Investigations began from the analysis of microstructures and properties of the material in the as-cast state (Figs. 1 and 2). Then, by means of the dilatometer DT1000, the critical temperature were determined. They are as follows: Ac_{1s}=725 °C, Ac_{1f}=820 °C, Ac_3=875 °C. It was assumed that the optimal normalizing temperature will be: Ac_3 + 55°C= 930 °C.

a)
b)
c)

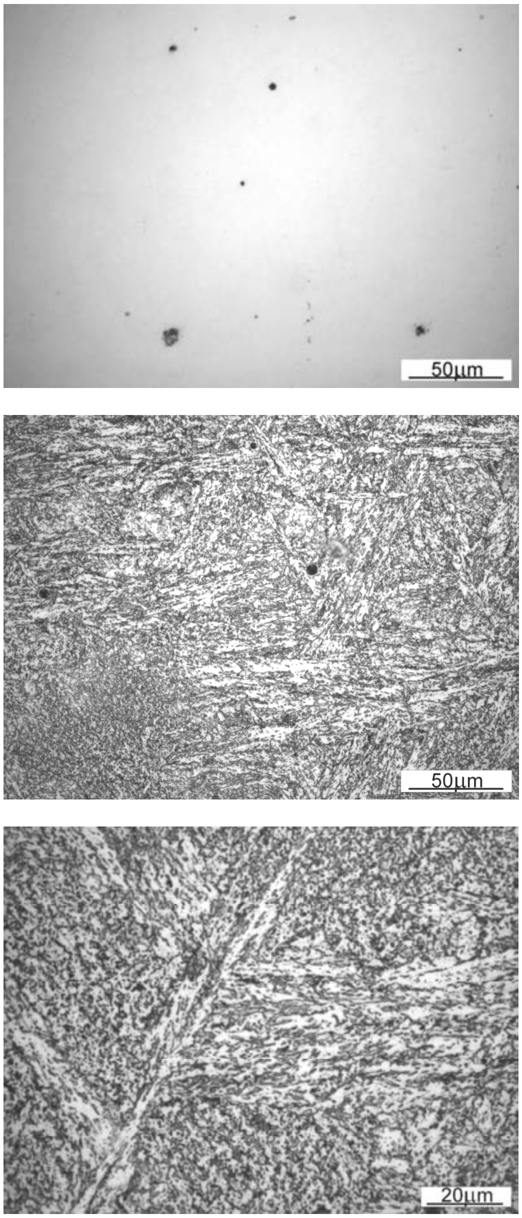

Fig. 1. Microstructure of the investigated cast steel in the as-cast state: a) unetched polished section; b,c) polished section etched with 2% nital

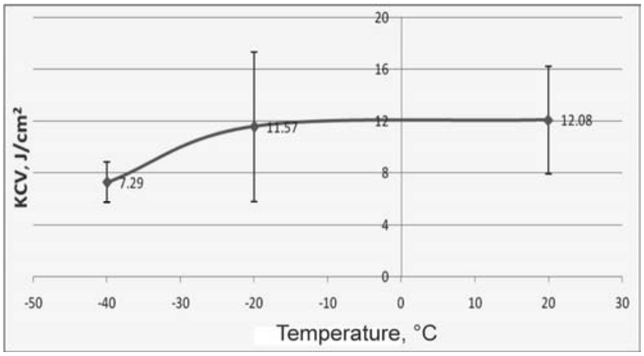

Fig. 2. Influence of a temperature on impact toughness of the investigated cast steel in as-cast state

The analysis of microstructure, strength properties and crack resistance by means of the stress intensity factor K_{Ic} (at temperature: +20 °C, –20 °C) was performed. Impact toughness (at temperature: +20 °C, –20 °C, –40 °C, samples with V notch) of material in as-cast state and after the heat treatment – was measured.

The analysis of the initial microstructure of the investigated cast steel on its hardness after normalizing followed by tempering, was carried on. The normalizing annealing variants performed are graphically presented in Figure 3.

Variant I – normalizing for 0.5 hour at a temperature of 930 °C followed by air cooling;

Variant II – normalizing, performed twice, for 0.5 hour at a temperature of 930°C followed by air cooling;

Variant III – normalizing for 0.5 hour at a temperature of 930°C, cooling to a temperature of 650 °C with a rate of 48 °C/h, holding in this temperature for 10 hours, cooling to a temperature of 250 °C with a rate of 20 °C/h, and then air cooling to a room temperature;

Variant IV – normalizing for 0.5 hour at a temperature of 930 °C, cooling to a temperature of 650 °C with a rate of 48 °C/h, holding in this temperature for 10 hours, cooling to a temperature of 250 °C with a rate of 20 °C/h air cooling to a room temperature, normalizing for 0.5 hour at a temperature of 930 °C, air cooling to a room temperature (7 °/s).

Samples, prepared in such a way, were tempered at temperature: 500 °C, 550 °C, 600 °C and 650 °C, and then their hardness was measured by the Vickers method.

The microstructure of the investigated steels were examined by the light microscope Axiovert 200 MAT

The fracture surfaces were observed using the Hitachi 3500N type SEM analyzing microscope.

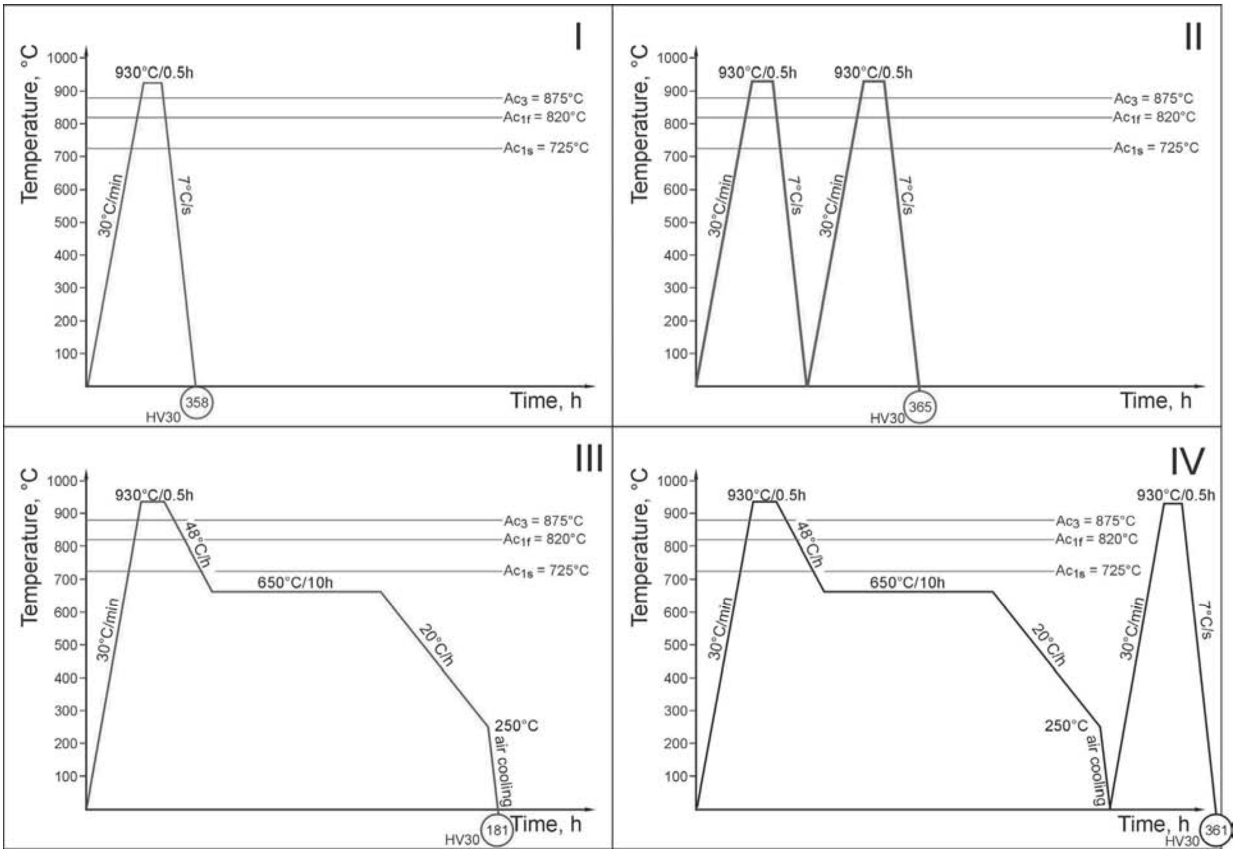

Fig. 3. Schemes of normalizing annealing and the obtained hardness (HV30) of the investigated cast steel of the initial hardness (in the as-cast state) 336 HV30

4. Obtained results and their discussion

The most important mechanical properties of the investigated cast steel in as-cast state are listed in Table 1. Samples were taken from the surface layer of an ingot of a mass of app. 30 kg. As can be seen (Table 1), at a hardness of 336 HV30, (which according to PN–93/H-04357 corresponds to 320HBW), the new cast steel – even directly after casting - is characterised by a high yield strength $R_{p0,2}$ = 745 MPa and a high tensile strength R_m = 1084 MPa at an elongation: A_5 = 7.6%.

Photographs of the unetched metallographic polished sections of the investigated cast steeal in the as-cast state are shown in Figure 1a. Clusters of non-metallic inclusions and pores revealed there are known – from the EDS analysis – to be manganese sulphides. The microstructure of the investigated cast steel, revealed by etching with 2% nital shown in Figures 1b and 1c, indicates that this is the typical bainitic cast steel. Morphologic features of the bainitic laths exhibited in microphotographs – at the largest magnification – indicate that the upper bainite prevails in the ingot microstructure. This observation means, that a small carbon content in the tested alloy had a dominating influence on the start temperature bainitic transformation beginning (B_s). The presence of Mn and Mo did not manage to eliminate the upper bainite, known as having a very low crack resistance. Therefore it can be, already now, expected that scissors crossovers produced from this cast steel will need to undergo the normalizing annealing with an accelerated cooling. Eventually this normalization should be supplemented by a high-temperature tempering, in order to obtain coagulation of carbides precipitated on boundaries of the bainitic ferrite laths.

The influence of a temperature on KCV impact toughness of the investigated cast steel in as-cast state is graphically presented in Figure 2. Impact toughness starts to decrease from -20 °C.

The character of fractures of the toughness samples in as-cast state tested in a temperature of +20 °C - are shown in Figure 4. As can be seen, fractures are brittle and cleavable, while voids and non-metallic intrusions existing in easy cracking paths seem to act as traps for the cracks propagation.

Analogical fracture investigations were performed for testing temperature of -20°C (Fig. 5) and -40°C (Fig. 6). As could be expected, fractures at such low temperature are of a cleavable trans-crystalline character and to a lower and lower degree the typical casting defects (pores, micro-shrinkages and non-metallic inclusions) can be found on their surfaces. This can indicate that cracking at such low temperature is accompanied by a small zone of plastic deformation.

Data given in Table 1 indicate that the crack resistance of the investigated cast steel in the as-cast state was estimated by means of the stress intensity factor K_{Ic}. It is worth mentioning, that the average value (from 3 samples) was at a room temperature: K_{Ic} = 55.9 MPa·m$^{1/2}$, while at a temperature of -20°C: K_{Ic} = 47.2 – 54.4 MPa·m$^{1/2}$. Material for rails of the R350LAHT grade is required to have factor K_{Ic} of a minimum value 29 MPa·m$^{1/2}$ at room temperature. In case of the investigated bainitic cast steel the stress intensity factor at room temperature was nearly twice as high as the required one, although this cast steel was in the as-cast state (without any plastic working).

The consecutive stage of investigating this new bainitic steel was estimation of the microstructure achieved due to the normalizing procedures. Bainitic character of the new material was the reason that its air cooling – from the range of homogeneous austenite to room temperature - allows for its subsequent rehardening into bainite. Therefore four variants of the normalizing annealing were developed and their schematic presentation is given in Figure 3.

Table 1.
Mechanical properties of the new bainitic cast steel for scissors crossovers

HV30	$R_{p0,2}$ MPa	R_m MPa	A %	Z %	$KV_{+20°C}$ J	$KV_{-20°C}$ J	$KV_{-40°C}$ J	$K_{Ic+20°C}$ MPa·m$^{1/2}$	$K_{Ic\ -20°C}$ MPa·m$^{1/2}$
336	745	1084	7.6	10.3	12.8	11.6	7.3	55.9	47.2-54.4

a) b)

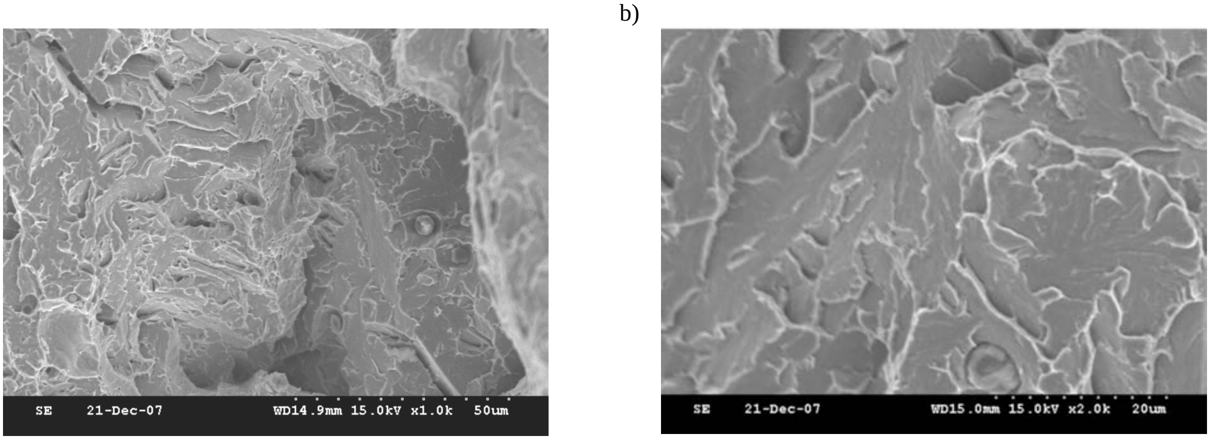

Fig. 4. Fractures of toughness samples (testing temperature +20°C) of the investigated cast steel in the as-cast state

a) b)

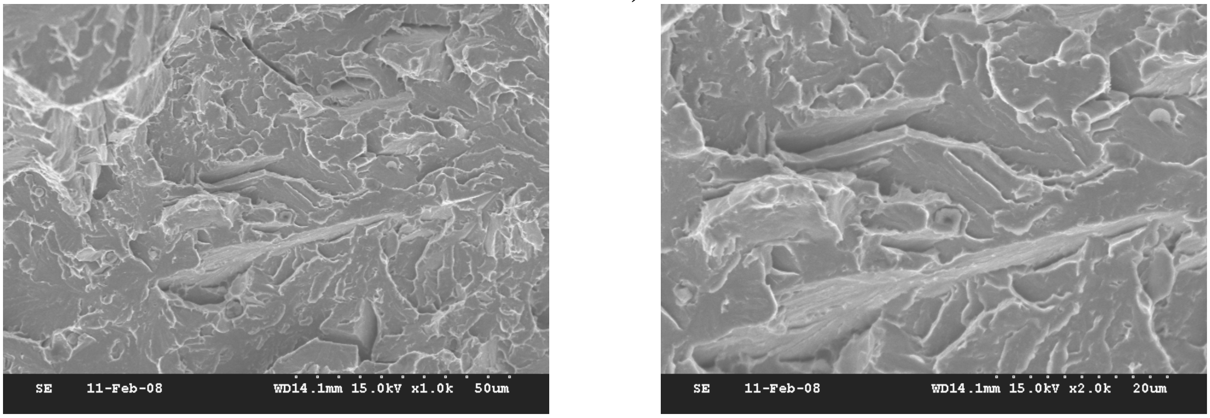

Fig. 5. Fractures of toughness samples (testing temperature -20°C) of the investigated cast steel in the as-cast state

a) b)

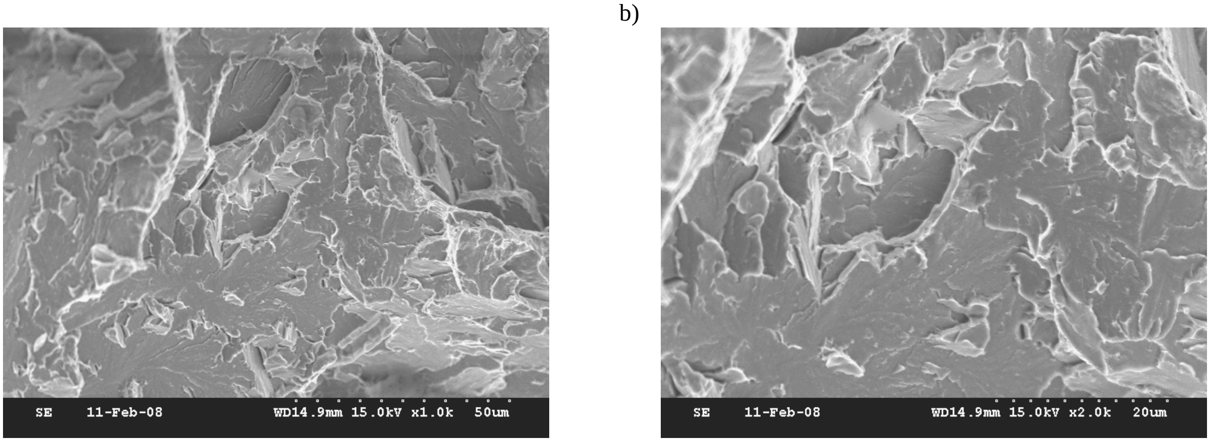

Fig. 6. Fractures of toughness samples (tested at a temperature of -40°C) of the investigated cast steel in the as-cast state

The first variant (marked “I”) consisted of heating into the homogeneous austenite range (with a rate of 30°C/min) and short holding followed by air cooling (with an average rate of approximately 7°C/s). The second variant (“II”) consisted of normalizing performed twice, in order to test the influence of the repeated procedure on the microstructure and hardness of this new material. Variant III consisted of heating to 930°C followed by a slow cooling (48°C/hour) to 650°C, holding in this temperature for 10 hours and next a very slow cooling with a rate of 20°C/hour to a temperature of 250°C and then in a quiet air to room temperature. During the isothermal holding at 650°C austenite should transform itself into ferrite and eventually into pearlite. This is a microstructure close to the equilibrium state, which can be considered as the appropriate initial microstructure for reheating to 930°C (homogeneous austenite) to perform the proper grain normalizing, which means its formation from ferrite and pearlite and not from the unbalanced bainitic microstructure (compare variants I and II). This last variant of the heat treatment consisting of an additional heating of the ferritic-pearlitic microstructure followed by cooling in a quiet air is marked „IV” in Figure 3.

Hardness results (HV30) are placed at the end of lines illustrating cooling and heating procedures of samples after the relevant heat treatment. As can be seen, independently of the number of normalizing procedures and the ways of their realization, the sample hardness are nearly equal contained in the range 358-365 HV30. A low hardness of 181 HV30 was obtained only for variant „III” consisting of a slow cooling. This indicates that in case of a decision of normalizing annealing of scissors crossovers produced from this new cast steel one heating procedure into the homogeneous austenite range (approximately 930°C), followed by cooling either in a open air or by means of the artificial blow, is sufficient. This artificial blow should enable obtaining a sufficiently higher hardness than the required 340 HBW and it would be only when tempering was applied after cooling.

Photographs of the investigated cast steel microstructures, after four variants of annealing are placed in Figures 7 to 10. As can be seen, in comparison to as-cast state (Fig. 1), the microstructure is significantly comminuted and the brightly etched network formed mainly along prior austenite grain boundaries is the most probably the bainitic area enriched in carbon.

a) b)

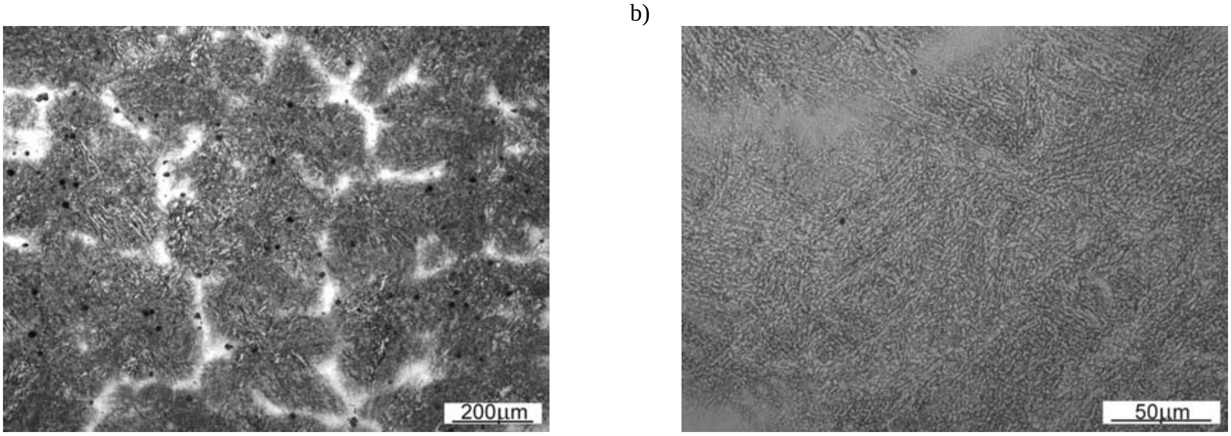

Fig. 7. Microstructures of the investigated cast steel after the application of variant I of normalizing annealing. a) segregations in grain boundaries; b) bainitic microstructure in one grain area

a) b)

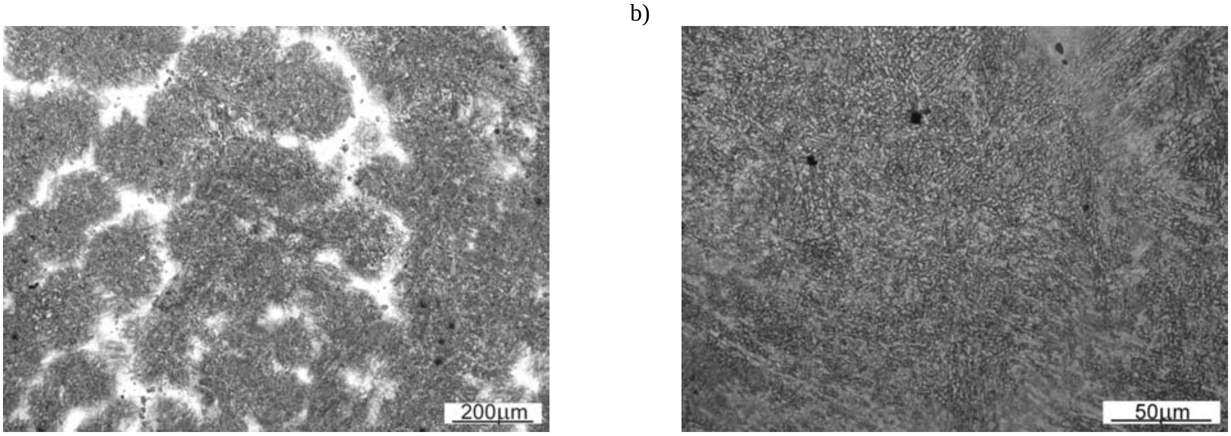

Fig. 8. Microstructures of the investigated cast steel after the application of variant II of normalizing annealing. a) segregations in grain boundaries; b) bainitic microstructure in one grain area

a) b)

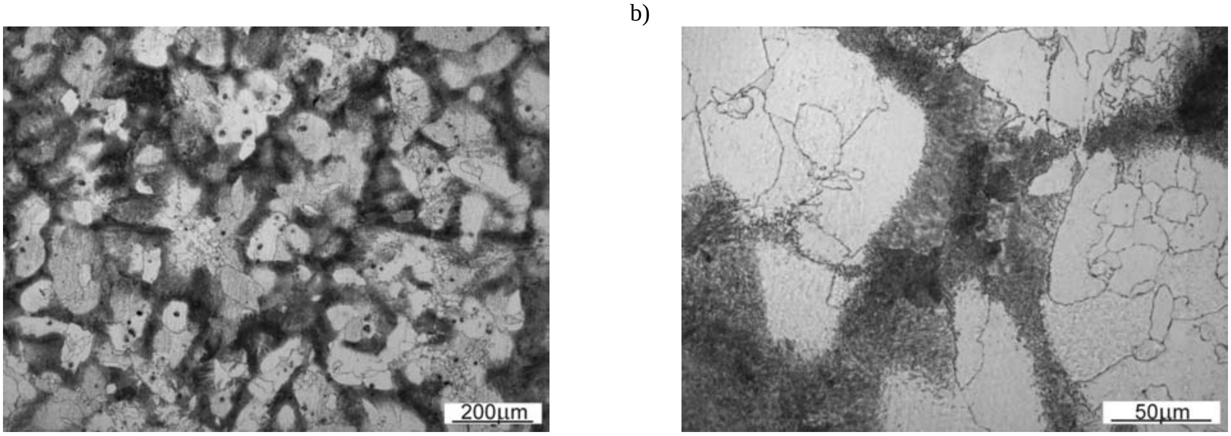

Fig. 9. Microstructures of the investigated cast steel after the application of variant III of normalizing annealing. a) ferrite and perlite microstructure; b) morphology of ferrite and perlite

a) b)

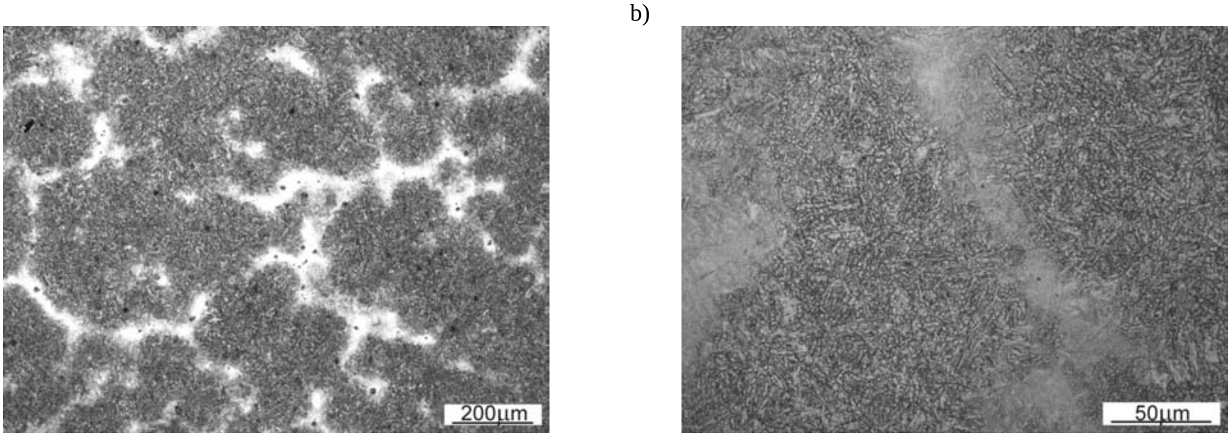

Fig. 10. Microstructures of the investigated cast steel after the application of variant IV of normalizing annealing. a) segregations in grain boundaries; b) bainitic microstructure

a) b)

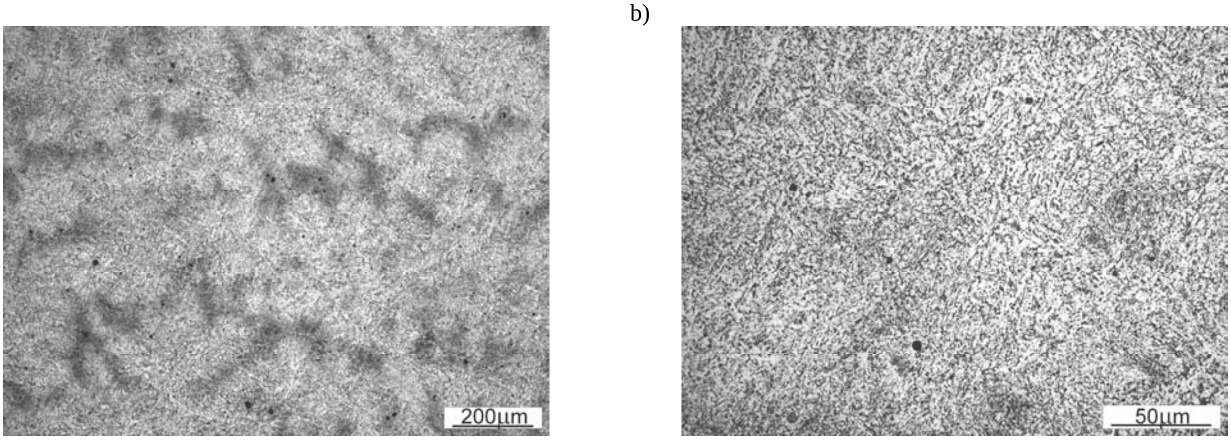

Fig. 11. Microstructures of the investigated cast steel after the applied heat treatment (normalizing + high tempering)

In order to estimate the influence of a tempering temperature after the applied four variants of normalizing the hardness values are listed in Table 2. Tempering was performed at temperature of 500, 550, 600 and 650°C for 2 hours. The hardness of the investigated cast steel was high - up to a temperature of 600°C – with an exception of variant „III" (with 10 hours of isothermal annealing at 650°C).

Table 2.
Hardness HV30 after the normalizing procedures (shown in Fig. 3) and additional tempering

	After normalizing	Tempering temperature, °C			
		500	550	600	650
I	358	346	358	347	281
II	365	356	358	356	284
III	181	176	186	182	172
IV	361	358	358	350	287

As can be noticed, variants I, II and IV provided similar hardness values to the ones in the as-cast state. Since complicated heating cycles did not drastically change the hardness values, it seems that the single heating up to a normalizing temperature is sufficient for this material.

Based on the investigation results presented above the technology of the heat treatment allowing the optimal improvement of impact toughness, was developed. Normalizing for the investigated cast steel means quenching it to the bainitic steel + high tempering. Several important mechanical properties of the new cast steel after the heat treatment are listed in Table 3. It can be seen that after the heat treatment the hardness decreases to 256 HV30, which is the value similar to the one corresponding to pearlitic rail steels [5,13].

Figure 11 presents photographs of microstructures after such heat treatment. This microstructure is resembling a spheroidite of very fine carbides. Cast steel after the heat treatment has very good plastic and mechanical properties as well as a sufficient hardness. The obtained results encourage the authors to undertake exploitation tests of the investigated cast steel.

Table 3.
Mechanical properties of new bainitic cast steel for scissors crossovers after the heat treatment

HV30	$R_{p0,2}$ MPa	R_m MPa	A %	Z %	$KV_{+20°C}$ J	$KV_{-20°C}$ J	$KV_{-40°C}$ J	$K_{Ic+20°C}$ $MPa·m^{1/2}$	$K_{Ic -20°C}$ $MPa·m^{1/2}$
256	666	777	18.1	62.3	78.0	43.4	15.2	80-90	79-92

5. Conclusions

Based on the performed investigations the following conclusions can be drawn:

- Scissors crossovers cast from the new bainitic cast steel should exhibit homogeneous bainitic microstructure on the whole cross-section. However, at a small content of C, Mn and Mo it was not possible to eliminate the upper bainite – known for its small crack resistance - from the investigated cast steel microstructure.
- The investigated Mn-Cr-Mo-V cast steel in as-cast state shows moderate impact toughness, KCV (12.08 J/cm^2). Its fractures are cleavable and brittle while voids and non-metallic inclusions present on a crack path seem to act as traps for propagating cracks. Despite a low impact toughness, in this state, only a temperature of -40°C causes a further decrease of this property.
- Regardless of the initial microstructure for normalizing, the investigated cast steel is characterised by a similar hardness level, and there is only a slight hardness decrease with a tempering temperature after normalizing. A significant decrease is caused by tempering at high temperature (650°C).
- In the case of the investigated bainitic cast steel the stress intensity factor in as-cast state (without any plastic working) at a room temperature is nearly twice as high than the one required for rolled rail material of the R350LAHT grade (factor K_{Ic} must be equal at least 29 $MPa·m^{1/2}$).
- The new cast steel after the specially designed heat treatment has very good plastic and mechanical properties and a specially sufficient hardness. Its microstructure is resembling spheroidite of very fine carbides. The obtained results encourage the authors to perform exploitation tests of the investigated cast steel.

Acknowledgements

This work was financed within the frames of the Research – Development Project No R07 007 02.

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