Journal of Achievements in Materials and Manufacturing Engineering

VOLUME 57
ISSUE 1
March
2013

The influence of the heat treatment on the microstructure and tribological properties of mottled cast iron

J. Krawczyk*, J. Pacyna, B. Pawłowski, M. Madej, P. Bała
Faculty of Metals Engineering and Industrial Computer Science,
AGH University of Science and Technology,
Al. Mickiewicza 30, 30-059 Kraków, Poland
* Corresponding e-mail address: jkrawcz@agh.edu.pl

Received 14.01.2013; published in revised form 01.03.2013

Materials

ABSTRACT

Purpose: The objective of this work was to determine the influence of microstructure changes on GJS-HV300(SiNiCr2-3) cast iron tribological properties. Modification of the investigated cast iron microstructure was carried out by the heat treatment.

Design/methodology/approach: The tribological tests were performed on the T05 tester at a load of 100 N. Bearing steel 100Cr6 of a hardness of 57 HRC was applied as a counter sample. The test duration time was 2000 s. During the tribological test the continuous measurements of the friction coefficient were carried out and the friction products were being removed from the counter sample surface. The tribological tests were performed at a room temperature. A stereological analysis of volume fractions of structural components (VV) was performed by means of the point method, with the application of a network deposited on the microstructure photographs. For each variant of the heat treatment 30 depositions of the network were performed. Measurements were done on microphotographs obtained by using an objective of 50 times magnification. The network with 200 measurement points was applied.

Findings: Predicting of wear resistance only on the basis of hardness is unappropriate. The main factor here is the mechanism of wear, which is influenced mainly by the microstructure.

Research limitations/implications: The relationship between the hardness resulting from the microstructure and the wear resistance of the investigated cast iron was presented. This supplements the knowledge concerning the role of the microstructure in the formation of tribological properties of cast iron.

Practical implications: Predicting of the tribological properties of mill rolls.

Originality/value: Heat treatment resulting in decrease of volume fraction of ledeburitic cementite and increase of volume fraction of graphite decreases wear resistance of investigated material.

Keywords: Tool materials; Cast iron; Tribological properties; Microstructure

Reference to this paper should be given in the following way:
J. Krawczyk, J. Pacyna, B. Pawłowski, M. Madej, P. Bała, The influence of the heat treatment on the microstructure and tribological properties of mottled cast iron, Journal of Achievements in Materials and Manufacturing Engineering 57/1 (2013) 15-22.

1. Introduction

Cast iron is a material whose microstructure is still modified in view of the desired properties [1-4]. Examples of mottled cast iron application can be mill rolls [5-11]. Mill rolls are tools operating under very difficult conditions [12-21]. Cast iron rolls due to its fracture toughness and tribological properties are most often used in last rolling stands, where the lowest dynamic loads are present and the most important is surface quality of rolled product [11]. High requirements set for mill rolls applied for hot plastic working of steel incline searching for new materials or modifications of the already used ones. An example of microstructure modification of the mottled cast iron by heat treatment was presented in paper [9]. Elaborated microstructure modification influenced also the mechanical properties of investigated cast iron [10,11]. However, differences in the microstructure of mottled cast iron can also affect the tribological properties [22].

The objective of this work was to determine the influence of microstructure changes on GJS-HV300(SiNiCr2-3) cast iron tribological properties. Modification of the investigated cast iron microstructure was carried out by the heat treatment.

2. Tribological tests methodology

The tribological tests were performed on the T05 tester (Fig. 1) at a load of 100 N. Bearing steel 100Cr6 of a hardness of 57 HRC was applied as a counter sample. The test duration time was 2000 s. During the tribological test the continuous measurements of the friction coefficient were carried out and the friction products were being removed from the counter sample surface. The tribological tests were performed at a room temperature.

Fig. 1. Tribological tester T05 (block on ring)

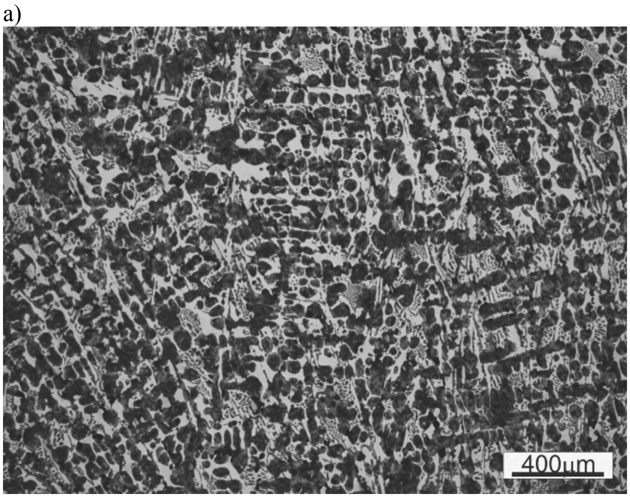
3. Material for tests

Test material constituted a chromium-nickel mottled nodular cast iron GJS-HV300(SiNiCr2-3). Chemical composition of the investigated cast iron is presented in Table 1. The microstructure in as-delivered condition is shown in Fig. 2. The sample hardness was 520 HV.

Table 1.
Chemical composition (weight %) of the investigated GJS-HV300(SiNiCr2-3) cast iron

C	Mn	Si	P	S	Cr	Ni	Mo
3.2	0.52	2.24	0.07	0.012	0.53	3.49	0.56
Mg	Cu	Al	Ti	V	As	Nb	Fe
0.047	0.20	0.008	0.014	0.020	0.002	0.024	bal.

a)



b)

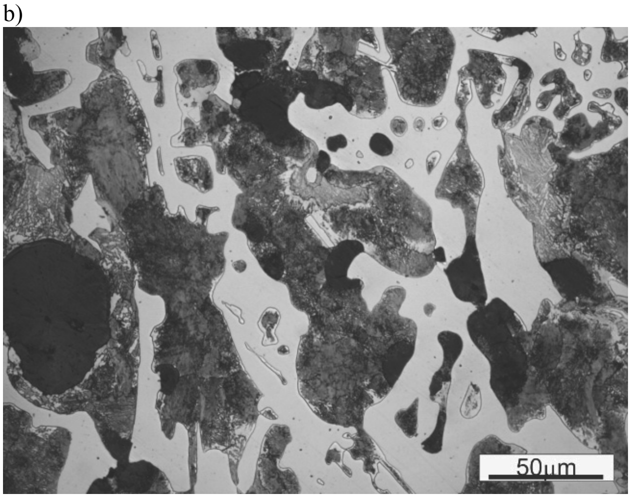


Fig. 2. Microstructure of GJS-HV300(SiNiCr2-3) cast iron in as-cast condition: a) Picture allowing to assess the dendritic structure, b) Picture allowing to assess the matrix microstructure. Etched with 2% nital

One may see that, it is mottled cast iron with pearlite-bainitic matrix (with upper bainite). It is characterized by high content of ledeburitic cementite (with adjoined hypereutectoid cementite), which creates a continuous net. A stereological analysis of volume fractions of structural components (V_V) was performed by means of the point method, with the application of a network deposited on the microstructure photographs. For each variant of the heat treatment 30 depositions of the network were performed. Measurements were done on microphotographs obtained by using an objective of 50 times magnification. The network with 200 measurement points was applied. Stereological analysis revealed that the microstructure of as-delivered specimens consist of the 47.8% pearlite, 2.6% ferrite, 8.2% upper bainite, 38.6% ledeburitic cementite and 2.9% graphite (volume fraction).

Test material was sampled from cast roll delivered by the manufacturer. The samples were collected in a way that allowed collecting them from the places where the conditions of crystallization would be possibly the same (Fig. 3).

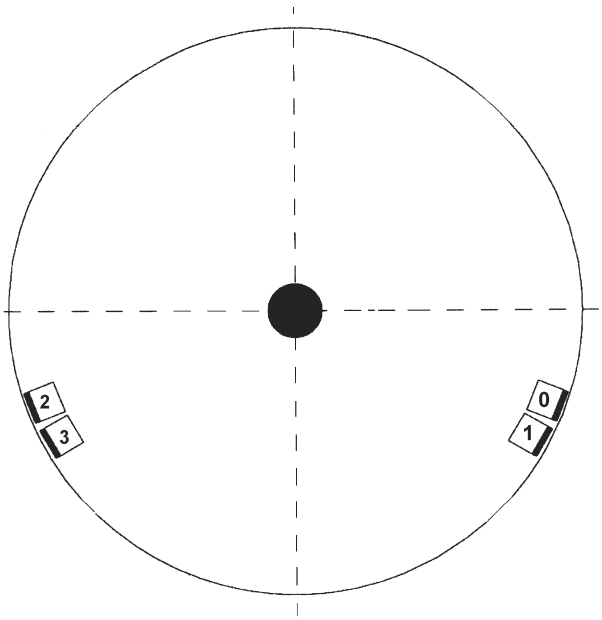


Fig. 3. The scheme of the sampled methodology of the investigated GJS-HV300(SiNiCr2-3) cast iron from cast roll delivered by the manufacturer

4. Heat treatment

Variant I of the heat treatment (Fig. 4) was characterised by cooling (45°C/h) within the range of austenite occurrence (to a temperature of 700°C). Further cooling was performed in such a way as to ensure the pearlitic matrix formation (18°C/h).

Variant II of the heat treatment (Fig. 5) was characterised by cooling (45°C/h) within the range of austenite occurrence (to a temperature of 700°C). Further cooling was performed in such a way as to ensure the bainitic matrix formation (216°C/h).

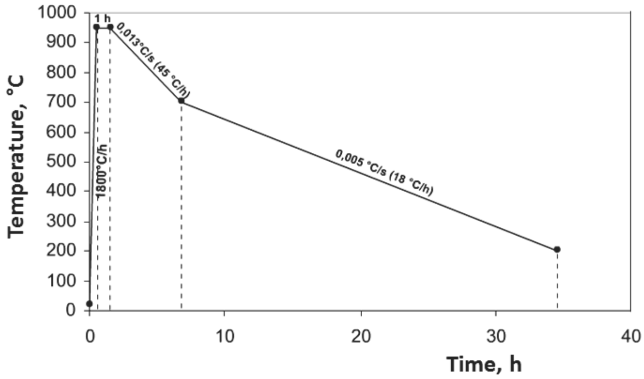


Fig. 4. The diagram of variant I of heat treatment

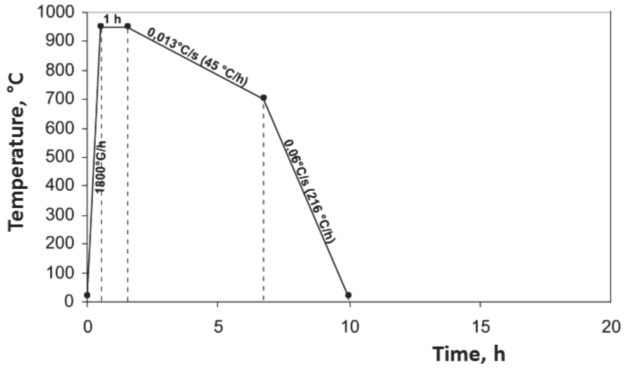


Fig. 5. The diagram of variant II of heat treatment

5. Microstructure after heat treatment

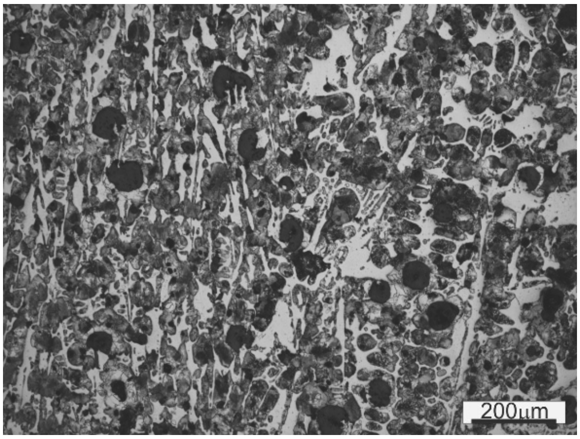
The applied heat treatment caused significant changes in the matrices of the investigated cast iron. Microstructures after these two variants are presented in Figs. 6 and 7.

The heat treatment, regardless of the variant applied, caused the significantly visible fragmentation of ledeburitic cementite precipitates and the decrease of its fraction in the cast iron volume (from 39±4% in as-cast condition to 25±3% in the case of the I^{st} variant of the heat treatment and to 25±4% in the case of the II^{nd} variant of the heat treatment). An increase of dimensions of graphite precipitations and their fraction in the cast iron volume after the heat treatment can also be noticed (from 3±2% in as-cast condition to 6±2% in the case of the I^{st} variant of the heat treatment and to 5±2% in the case of the II^{nd} variant).

This indicates that during the heat treatment of cast irons containing graphite a part of carbon will always diffuse from ledeburitic cementite and the matrix into graphite and in result this matrix will be depleted of carbon and the fraction of ledeburitic cementite will be reduced. However, it can be assumed that after both variants of the heat treatment the same amount of transformed ledeburite and similar amount of graphite are formed, since the cooling rate in the austenite range was the same, which means that the diffusion process should be advanced in a similar way.

The applied cooling rates in the eutectoid transformation range allowed to obtain the expected structure in the matrix. In the case of the Ist variant of the heat treatment the matrix majority constitutes pearlite (73%) and the remaining parts are ferrite (26%) and spheroidite (1%). In the case of the IInd variant of the heat treatment the matrix majority constitutes upper bainite (75%) and the remaining part is lower bainite (25%).

a)



b)

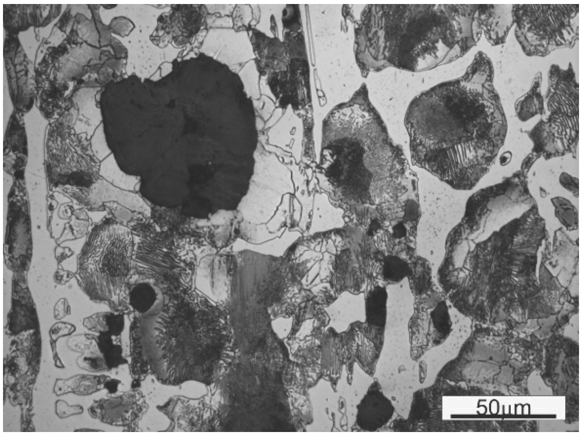


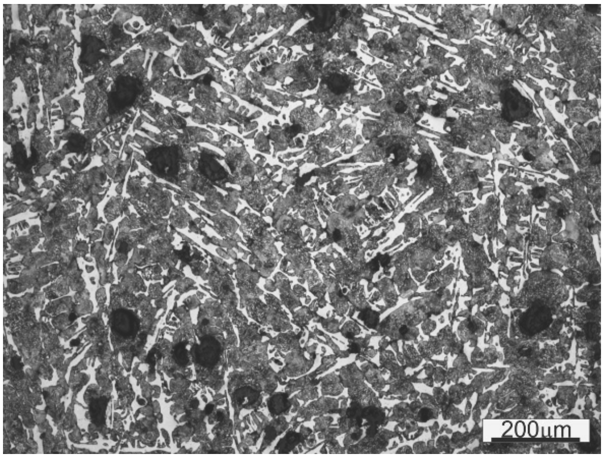
Fig. 6. Microstructure of GJS-HV300(SiNiCr2-3) cast iron after the Ist variant of the heat treatment: a) Picture allowing to assess the dendritic structure, b) Picture allowing to assess the matrix microstructure. Etched with 2% nital

6. Tribological tests

Tribological wear mechanisms of tested samples were determined by metallographic observation. Results of metallographic examinations of the surface layer of the samples after tribological tests are presented in Figs. 8-10. As it is shown, the ledeburitic cementite particles as well as graphite precipitations are present on the surface of tribologically tested specimens.

For as-delivered specimens fragmentation of ledeburitic cementite particles occurred, but no chipping phenomenon was observed. Fragmented cementite particles acted as cutting tool for the counter sample than as abradant for tested mottled cast iron. For as-delivered cast iron the dominant wear mechanism is microcutting and ploughing through counter sample carbides. The Ist variant of the heat treatment significantly alter the wear mechanism of investigated mottled cast iron. Not only the fragmentation of ledeburitic cementite particles occurs but also chipping of cementite was observed causing abrasive wear of tested specimen. The Ist variant of the heat treatment decreased volume fraction of ledeburitic cementite and reduced the thickness of its continuous grain boundary net which facilitate chipping phenomenon. Matrix softening (sample hardness 350 HV) and increase of volume fraction of graphite precipitation (compared to as-delivery condition) also promote the chipping of the ledeburitic cementite particles. Low matrix hardness should facilitate the microcutting and ploughing through chipped cementite particles, however, soft matrix acts as reservoir for these particles and consequently decreases wear intensity.

a)



b)

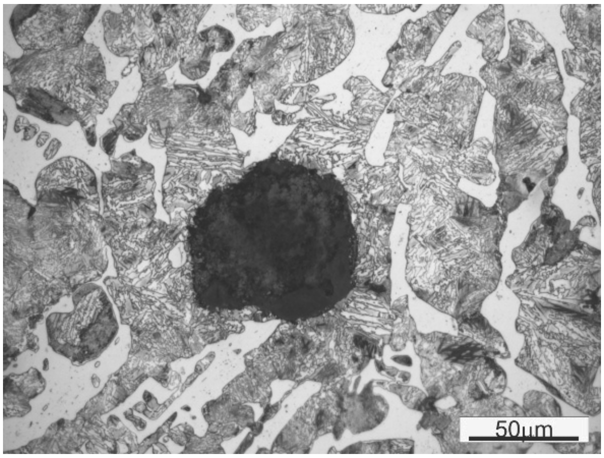


Fig. 7. Microstructure of GJS-HV300(SiNiCr2-3) cast iron after the IIst variant of the heat treatment: a) Picture allowing to assess the dendritic structure, b) Picture allowing to assess the matrix microstructure. Etched with 2% nital

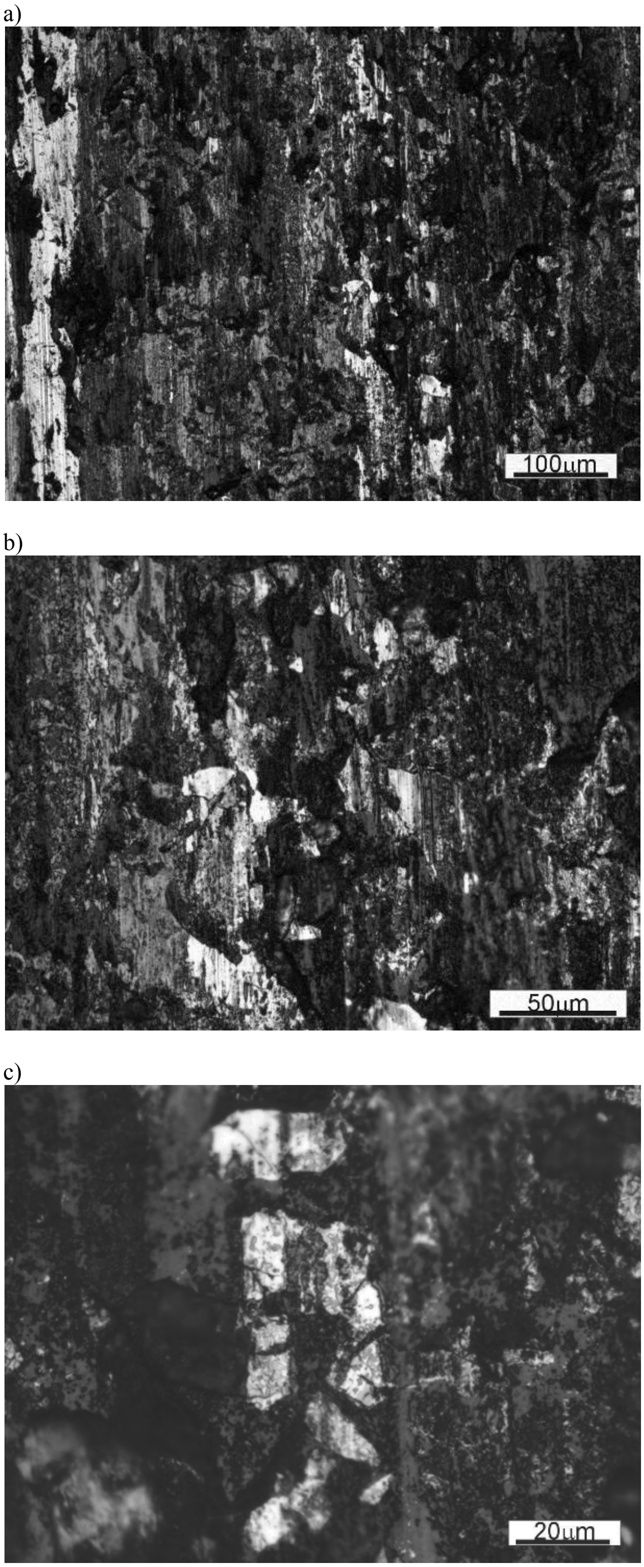


Fig. 8. Wear scars for investigated cast iron for sample in as-delivery state

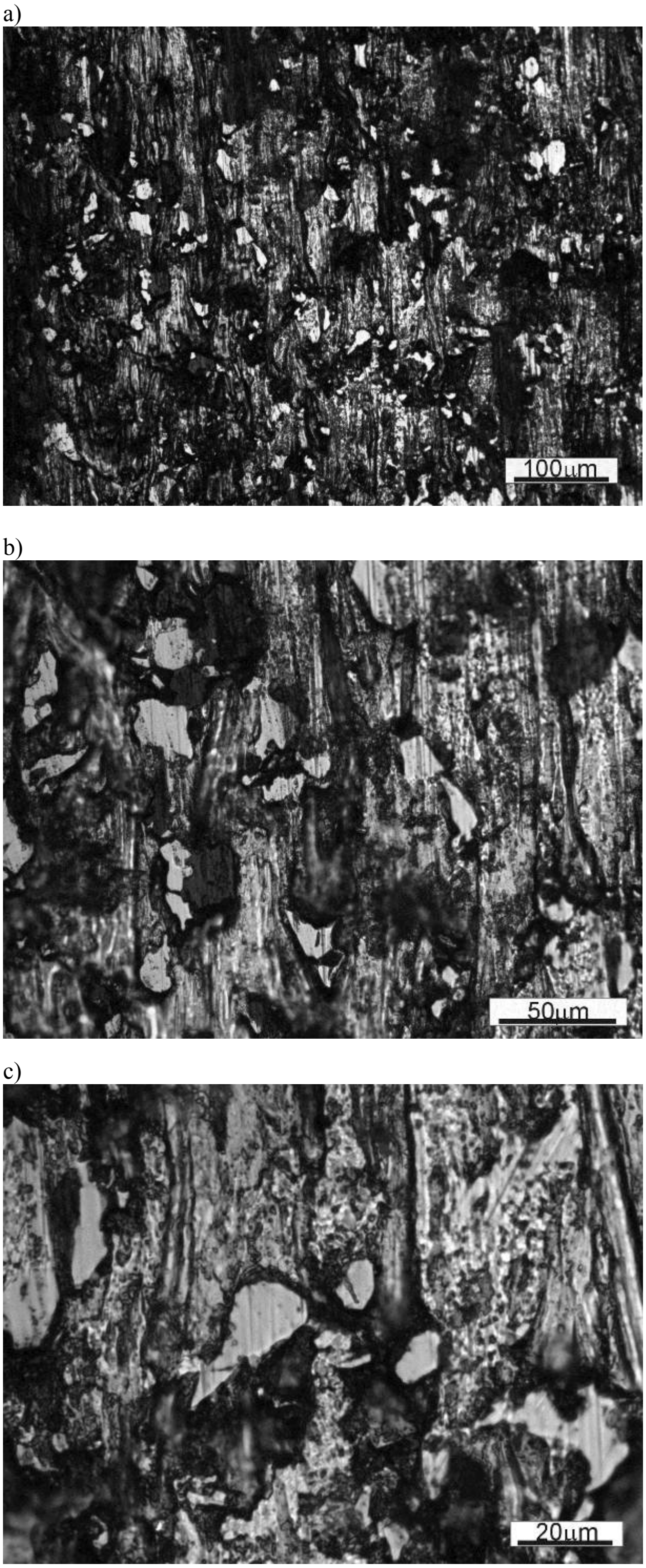


Fig. 9. Wear scars for investigated cast iron for sample after Ist variant of the heat treatment

a)

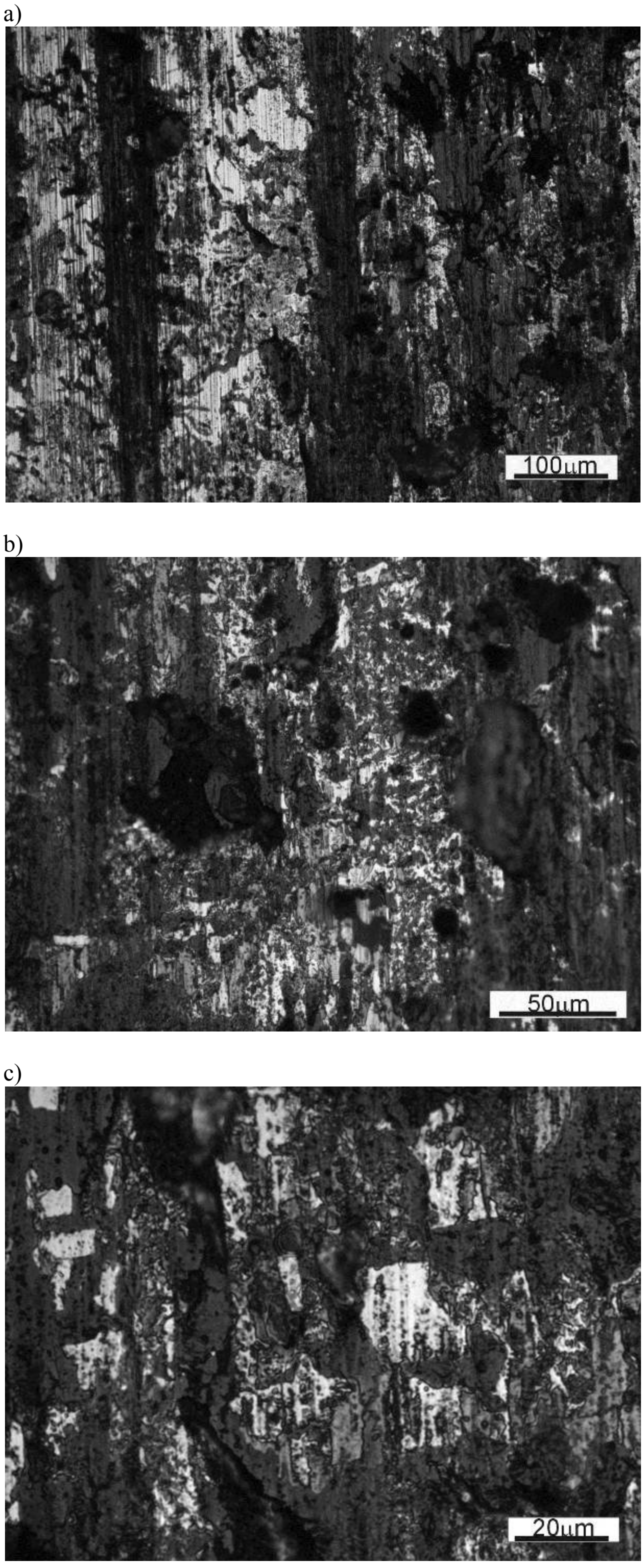


Fig. 10. Wear scars for investigated cast iron for sample after IInd variant of the heat treatment

In case of the IInd variant of the heat treatment, hard bainitic matrix (sample hardness 450 HV) decreases the chipping of the ledeburitic cementite particles on the surface of the tribologically tested specimen (compared to the Ist variant of the heat treatment). This reduces the abrasive role of the cementite particles but increases microcutting of counter sample. Microcutting of counter sample is in this case less intensive than in as-delivery state of investigated cast iron because of lower volume fraction of ledeburitic cementite after the IInd variant of the heat treatment. However, hard bainitic matrix could not act as reservoir for cementite particles chipped from the microstructure as well as counter-sample carbides.

For sample after the IInd variant of the heat treatment the dominant wear mechanism is microcutting.

7. Weight wear investigation

Weight wear of investigated mottled cast iron is defined as weight difference for specimen before and after the tribological test. For as-delivery specimen weight wear was equal -0.95 mg (i.e. there has been weight wear increase rather than weight decrease). For specimen after the Ist variant of the heat treatment mean weight wear loss was 0.37 mg and for the specimen after the IInd variant of the heat treatment mean weight wear loss was 1.29 mg.

Weight wear increase observed for as-delivery specimen was due to the absence of ledeburitic cementite chipping and microcutting wear mechanism which caused deposition of cutted counter sample material on the surface of investigated specimen. The graphite precipitation could play role of the most convenient places for such deposition process. In case of the Ist variant of the heat treatment lower weight wear, comparing to the IInd variant of the heat treatment, was due to the absorption by soft and plastic matrix of the chipped ledeburitic cementite particles. As a result of this, the number of hard particles on the surface increases during tribological test. Such a phenomenon does not occur for specimen treated according to the IInd variant of the heat treatment. In this case hard, bainitic matrix could not absorb the chipped ledeburitic cementite particles which cause greater weight wear.

8. Friction coefficient characteristics

Changes of the friction coefficient values of the investigated material, recorded continuously during the tribological test, are shown in Figs. 11-13. For the as-delivery specimen the mean value of the friction coefficient was 0.615, the same value was measured for the specimen after the Ist variant of the heat treatment. Similar mean value of the friction coefficient, equal 0.617 was established for the specimen after the IInd variant of the heat treatment.

The amplitude of the friction coefficient changes during the tribological test is the smallest in the case of specimen after the IInd variant of the heat treatment (Fig. 13). The nature of changes in the friction coefficient values during the tribological tests indicate that the friction process has been stabilized immediately (less than 100 s) after the start of the test. This is most likely related to the relatively large amount of ledeburitic cementite and hard bainitic matrix present in the microstructure of the sample after the IInd variant of the heat treatment. In the case of the other analyzed microstructures (as-delivery and after the Ist variant of the heat treatment) friction process stabilization occurs at a similar time of the test, but the wear mechanisms change with duration of the test which result in destabilization of tribological conditions which increase the amplitude of the friction coefficient. For the specimen after the Ist variant of the heat treatment it should be explained by the intensification of the ledeburitic cementite chipping process. In the case of as-delivery specimen that is most likely related to the "exposing" (during the tribological test) of the ledeburitic cementite precipitates and microcutting of the counter sample. The above mentioned instability of tribological conditions for the as-delivery specimen begins at about 1000 seconds the time duration of the test, in the case of the specimen after the Ist variant of the heat treatment at about 800 s. Large amplitude changes in the friction coefficient (especially after 800 s duration of the test) in the case of specimen after the Ist variant of the heat treatment should be explained by the start of the intensive chipping process of the ledeburitic cementite particles which act as an abradant during the tribological contact.

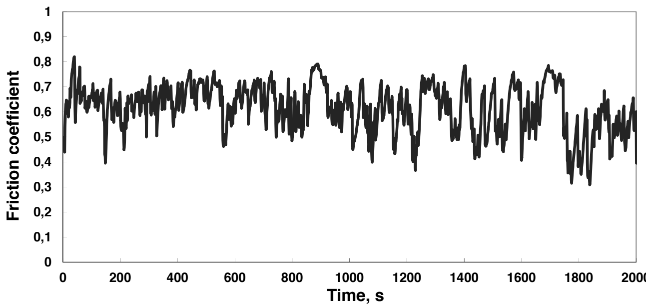


Fig. 11. Relationship between friction coefficient and time for as-delivery specimen

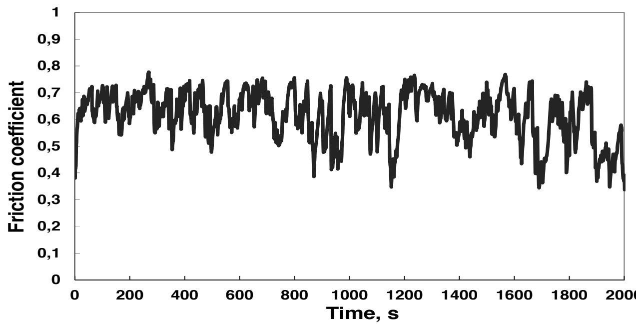


Fig. 12. Relationship between friction coefficient and time for specimen after the Ist variant of the heat treatment

The lowest value of friction coefficient, up to the 800 s of the time duration of the test, was observed for specimen after the IInd variant of the heat treatment. It can be explained by the influence of the hard bainitic matrix of relatively large amount of ledeburitic cementite, which blocks cementite chipping.

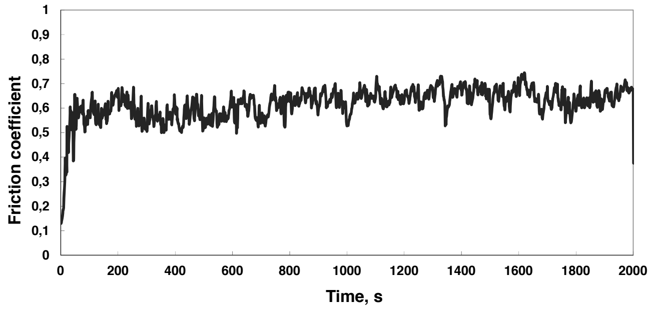


Fig. 13. Relationship between friction coefficient and time for specimen after the IInd variant of the heat treatment

Similar changes of the friction coefficient values for the as-delivery specimen and for the specimen after the Ist variant of the heat treatment are probably related to the fact that for both specimens there is no significant change in wear mechanism during the tribological test. It can therefore be assumed that in spite of various wear mechanisms the as-delivery specimen as well as the specimen after the Ist variant of the heat treatment have a similar effect on the friction coefficient.

Presented descriptions of changes in the wear mechanisms caused by differences in the microstructure of investigated specimens help explain a similar average friction coefficient values for the as-delivery specimen, specimen after the Ist and IInd variant of the heat treatment.

9. Summary and conclusions

Research performed in this work allowed us to formulate the following conclusions:

1. The heat treatment of investigated mottled cast iron can change its tribological properties.
2. Heat treatment resulting in decrease of volume fraction of ledeburitic cementite and increase of volume fraction of graphite decreases wear resistance of investigated material.
3. Large amount of ledeburitic cementite promote microcutting process of the counter sample.
4. The change in hardness from about 350 to 450 HV as a result of matrix change from pearlitic to bainitic does not increase the wear resistance but even slight decline was observed. Therefore, predicting of wear resistance only on the basis of hardness is inappropriate. The main factor here is the mechanism of wear, which is influenced mainly by the microstructure.

Acknowledgements

The authors would like to thank Mr Piotr Krzysiak for his help in the realisation of the presented here investigations.

References

[1] R.A. Gonzaga, P. Martínez Landa, A. Perez, P. Villanueva, Mechanical properties dependency of the pearlite content of ductile irons, Journal of Achievements in Materials and Manufacturing Engineering 33 (2009) 150-158.

[2] J. Piaskowski, J. Tybulczyk, A. Kowalski, Ductile iron - the greatest achievement in foundry materials of the laterst fifty years, Proceedings of the 8th Scientific International Conference Achievements in Mechanical and Materials Engineering, Gliwice-Rydzyna-Pawlowice-Rokosowa, 1999, 473-476.

[3] A. Pytel, K. Sekowski, Microstructure and mechanical properties of vermicular low-alloy cast iron, Proceedings of the 7th Scientific International Conference Achievements in Mechanical and Materials Engineering, Gliwice-Zakopane, 1998, 435-438 (in Polish).

[4] S. Pietrowski, T. Szymczak, Effect of silicon concentration in bath on the structure and thickness of grey cast iron coating after alphinising, Archives of Materials Science and Engineering 28 (2007) 437-440.

[5] J. Krawczyk, J. Pacyna, Effect of tool microstructure on the white layer formation, Journal of Achievements in Materials and Manufacturing Engineering 17 (2006) 93-96.

[6] J. Krawczyk, J. Pacyna, A. Kokosza, Fracture toughness of cast materials for mill rolls, Proceedings of the 6th International Conference for Mesomechanics: Multiscaling in Applied Science and Emerging Technology: Fundamentals and Applications in Mesomechanics, Patras, 2004, 203-207.

[7] J. Krawczyk, Effect of the microstructure on tribological phenomena occurring on the surface of a mill roll made of SA5T cast iron (GJSL-HV600-GJSL-330NiMoCr12-8-3), Archives of Foundry Engineering 8 (2008) 170-174.

[8] J. Pacyna, J. Krawczyk, The influence of heat treatment on transformed ledeburite morphology in hypoeutectic alloys, Proceedings of the 10th Jubilee International Science Conference Achievements in Mechanical and Materials Engineering, Gliwice-Kraków-Zakopane, 9-13, 2001, 429-434 (in Polish).

[9] J. Krawczyk, J. Pacyna, Effect of the cooling rate on the mottled cast iron microstructure designed for the mill rolls, Metallurgy and Foundry Engineering 35 (2009) 101-110.

[10] J. Krawczyk, J. Pacyna, Influence of a matrix on properties of mottled cast iron applied for mill rolls, Archives of Foundry Engineering 10 (2010) 45-50.

[11] J. Krawczyk, J. Pacyna, The influence of microstructure of mottled cast iron for mill rolls on its properties, 18th International Conference on Metallurgy and Materials Metal 2009, Hradec nad Moravici, 2009, 100–106.

[12] Z.Y. Jiang, H.T. Zhu, A.K. Tieu, Mechanics of roll edge contact in cold rolling of thin strip, International Journal of Mechanical Sciences 48 (2006) 697-706.

[13] M. Knapiński, The numerical analysis of roll deflection during plate rolling, Journal of Materials Processing Technology 175 (2006) 257-265.

[14] H. Li, Z. Jiang, K.A. Tieu, W. Sunb, Analysis of premature failure of work rolls in a cold strip plant, Wear 263 (2007) 1442-1446.

[15] A. Saboonchi, M. Abbaspour, Analysis of premature failure of work rolls in a cold strip plant, Journal of Materials Processing Technology 148 (2004) 35-49.

[16] D.F. Chang, Thermal stresses in work rolls during the rolling of metal strip, Journal of Materials Processing Technology 94 (1999) 45-51.

[17] F.J. Belzunce, A. Ziadi, C. Rodriguez, Structural integrity of hot strip mill rolling rolls, Engineering Failure Analysis 11 (2004) 789-797.

[18] S.X. Zhou, An integrated model for hot rolling of steel strips, Journal of Materials Processing Technology 134 (2003) 338-351.

[19] R.D. Mercado-Solis, J. Talamantes-Silva, J.H. Beynon, M.A.L. Hernandez-Rodriguez, Modelling surface thermal damage to hot mill rolls, Wear 263 (2007) 1560-1567.

[20] R. Cola´s, J. Ramírez, I. Sandoval, J.C. Morales, L.A. Leduc, Damage in hot rolling work rolls, Wear 230 (1999) 56-60.

[21] Ž. Domazet, F. Lukša, M. Šušnjar, Failure analysis of rolls with grooves, Engineering Failure Analysis 14 (2007) 1166-1174.

[22] J. Krawczyk, Microstructure and tribological properties of mottled cast iron with different chemical composition, Archives of Materials Science and Engineering 51 (2011) 5-15.