

The effect of cast steel chemical composition on its microstructure and tribological properties in mill rolls

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Materials

ABSTRACT

Purpose: The influence of the chemical composition on a microstructure and tribological properties (wear and friction coefficient) of cast steels used for the mill rolls is presented in the paper. The role of the chemical composition in a tendency of the graphite formation was determined.

Design/methodology/approach: Samples for investigations were taken from seven mill rolls originated from various producers. Cast steels, from which rolls were produced, were of various chemical compositions. Tribological tests were performed at a load of 100 N. Bearing steel 100Cr6, of a hardness of 57HRC, was applied as a counter sample.

Findings: The role of individual alloying elements in a tendency of the graphite formation was estimated. The influence of the chemical composition on the hardness, wear resistance and friction coefficient of cast steels used for the mill rolls was estimated. The relationship between a hardness and wear resistance was presented.

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

Practical implications: The obtained results can be utilised in designing the chemical compositions of the cast steel mill rolls.

Originality/value: For the first time the complex assessment of the chemical composition influence on the tribological properties of high-carbon steels of a variable microstructure was successfully achieved.

Keywords: Tool materials; Cast steel; Tribological properties; Chemical composition

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1. Introduction

Analysis of a steel products production indicates that the highest fraction (on account of a weight) constitutes rolled products. Therefore, from the economic point of view, designing

and selection of materials for mill rolls is very important. The selection of materials must take into account working conditions of these tools [1-10]. High variety of rolled materials, a range of rolling temperatures, as well as a range of loads (in dependence of a shape and cross-section reduction) cause, that currently several alloys on iron matrix are used for rolls production. A material

selection complexity is even larger when one takes into consideration the applied presently modifications of their working surfaces e.g. by chromium plating of external layers or rolls jacketing (on the cheaper material core the jacket of a more expensive material of better tribological properties, is placed by means of the thermo-shrinkage method). However, obtaining the optimal tribological properties of the mill rolls is mainly achieved by the proper chemical composition and the heat treatment of their structure. The research team, which member is the author of this paper, has been carrying out - for many years already - numerous investigations on designing the chemical compositions and heat treatments and their influence on properties of new, original alloys - on the iron matrix - for the mill rolls [11-19]. The valuable supplements of these investigations are tribological tests of materials applied for the mill rolls. Those tests are performed on samples taken from the commissioned mill rolls.

One of the material groups, which are used for producing the mill rolls are cast steels [14-19]. This results from the possibility of including in them large volume fractions of carbides as well as their low production costs (as compared e.g. with forged steel rolls). Cast steel rolls are usually operating in hot mills. However, before difficult and costly tribological tests in high temperatures, these materials should be investigated under conditions of much cheaper tests of low-temperature tribological tests.

Thus, the low-temperature tribological investigations for seven cast steels, used for the mill rolls, are the subject of this paper.

2. Methodology of investigations

Samples were taken from seven mill rolls made by various producers. Cast steels were of different chemical compositions.

The metallographic examinations were performed by the light microscope. Polished sections were etched in 2% HNO₃ solution in C₂H₅OH. The hardness measurements were done using the Vickers method.

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 coefficient of friction were carried out and the friction products were being removed from the counter sample surface. The tribological tests were performed at a room temperature.

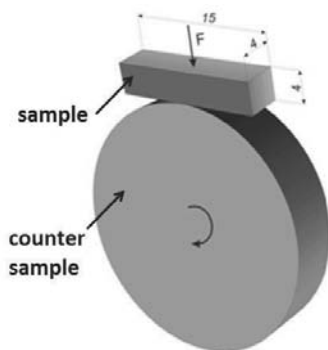


Fig. 1. The schematic presentation of the tribological system

3. Material for tests

Chemical compositions of the investigated cast steels are listed in Table 1. They are arranged in a sequence of the decreased carbon content. The investigated cast steels were characterised by a weight percentage of a carbon content: 1.22-2.10%; manganese: 0.50-1.10%; silicon: 0.51-1.30%; chromium: 0.83-1.30%; nickel: 0.30-1.81%; molybdenum: 0.10-0.42%. All those cast steels can be classified into the adamite cast steel group. These cast steels have a high carbon content, above 1%; a chromium content app. 1% and they have nickel and molybdenum additions. Silicon content, in case of some investigated cast steels, is above 1% in consideration of its influence on casting properties and/or as a graphitisation component. The graphitisation can be also obtained by a nickel addition. In such cases the investigated cast steel should be described as graphitised. Additions of chromium and molybdenum are aimed to ensure the proper fraction of secondary carbides (in case of a higher carbon content, also ledeburitic).

Table 1.

Chemical composition (wg. %) of the investigated cast steels

No.	cast steel	C	Mn	Si	Cr	Ni	Mo
1	200CrNi4-4	2.10	0.50	0.70	1.20	1.20	0.20
2	200SiCrNi4-4	2.00	0.70	1.12	0.84	0.51	0.33
3	200CrSiMn4-4	2.00	1.10	1.20	1.20	0.30	0.10
4	200NiSiCr8-4-4	1.99	0.80	1.30	1.24	1.81	0.35
5	200CrNiMo4-3-3	1.83	0.64	0.56	1.30	0.47	0.33
6	150SiCrNi4-4-3	1.34	0.65	1.12	0.83	0.60	0.19
7	120CrNiMo4-3-3	1.22	0.73	0.51	0.99	0.47	0.42

Microstructures of the investigated cast steels are seen in Fig. 2. Cast steel No. 1 is characterised by a microstructure, in the composition of which the pearlitic matrix with the hypereutectoid cementite precipitates, transformed ledeburite and graphite is present. Graphite occurs in a spheroidal form. Such graphite precipitated on the austenite dendrite boundaries during the crystallisation process. The remaining liquid underwent the eutectic transition into ledeburite. After the eutectoid transition the transformed ledeburite was obtained. To this end the transformed ledeburite precipitates occur in between the austenite grains originated during the crystallisation (dendrites).

The hypereutectoid cementite occurs in three forms. The first form of the hypereutectoid cementite is the cementite, which precipitated during cooling, in the austenitic range, on primary austenite grain boundaries. It 'builds on' to the ledeburitic cementite forming together with it (in some places) continuous precipitates in the primary austenite grain boundaries. The second cementite form constitutes the cementite precipitated in the Widmannstätten system. It has a form of characteristic aciculars growing into the primary austenite grains. The third form of the hypereutectoid cementite is the cementite of a form close to the spheroidal one, which precipitated in the prior austenite grain boundary formed as the re-austenitisation result.

Cast steel No. 2 is - in a similar fashion as cast steel No. 1 - characterised by a microstructure containing the pearlitic matrix with precipitates of graphite, transformed ledeburite and hypereutectoid cementite. Graphite, similarly as in cast steel

No. 1, is of a spheroidal form, however its precipitates are larger. A prior austenite grain is in the case of cast steel No. 2 much larger than in No. 1.

The ledeburitic cementite together with the built on hypereutectoid cementite (along primary austenite grain boundaries) forms a continuous network. The hypereutectoid cementite precipitated in the Widmannstätten system is weakly shaped. This cementite reprecipitated inside the austenite grains, originated during the crystallisation, is characterised by an uneven distribution in the matrix (there are zones of its large concentration - near the primary austenite grain boundaries and other zones practically without it - interiors of the large primary austenite grains). This probably results from the lack of the carbon concentration equalisation in the whole volume of the large austenite grain after the crystallisation and during the heat treatment. This hypereutectoid cementite is characterised by precipitates of the same size as the hypereutectoid cementite from cast steel No. 1, but is not forming precipitates which would mark the secondary network in the austenite grain boundaries obtained during the re-austenitisation. Such network can be only seen in zones adjacent to the primary austenite grain boundaries.

The pearlitic matrix, in case of cast steel No. 2 is characterised by significantly larger grains and interlamellar distances as compared with cast steel No. 1. Cast steel No.3 is characterised, in the similar fashion just as cast steels No. 1 and 2, by the microstructure containing the pearlitic matrix with spheroidal precipitates of graphite, transformed ledeburite and hypereutectoid cementite. The graphite precipitates are smaller than the ones in cast steel No. 1 and especially No. 2. However, this is still the spheroidal graphite. The ledeburitic cementite together with built on the primary grain boundaries the hypereutectoid cementite forms continuous precipitates in grain boundaries - to a lesser degree than in cast steel No.1 and especially No.2. The reason for such situation is the applied heat treatment, which caused fragmentations of precipitates. The hypereutectoid cementite precipitates in the Widmannstätten system are shaped worse than in cast steel No. 1, but better than in cast steel No.2. The hypereutectoid cementite precipitated in the secondary austenite grain boundaries has morphology similar to the hypereutectoid cementite, as in the case of cast steel No.1 (leading to the formation of the network of the secondary carbide precipitates in the austenite grain, obtained during the re-austenitisation, boundaries). This austenite grain sizes are larger than in the case of cast steel No.2. Interlamellar distances in the pearlite are intermediate between distances in cast steels No. 1 and 2.

Cast steel No. 4, likewise the previous ones, is characterised by the microstructure having the pearlitic matrix with graphite, transformed ledeburite and hypereutectoid cementite precipitates. In addition a large amount of phosphorous eutectic was observed. The graphite form significantly differs from the previously analysed cast steels. Apart from the very fine spheroidal graphite precipitates also large precipitates - of a morphology resembling the so-called crab graphite are observed. Ledeburitic cementite and primary cementite built on in the prior austenite grain boundaries form only locally continuous network. This effect of the formation a continuous network in grain boundaries can be estimated as more intensive than in the case of cast steel No. 3, however weaker than in case of cast steels No. 1 and 2. The size

of the austenite grain originated during the crystallisation is in cast steel No. 4 larger than in cast steels No. 1 and 3, but significantly smaller than in cast steel No. 2. As it was mentioned above, numerous phosphorous eutectics occur in the cast steel No. 4 microstructure.

The hypereutectoid cementite precipitates are very poorly developed in the Widmannstätten system (in practice they do not occur). The hypereutectoid cementite precipitates - inside the primary austenite grain - indicate a tendency (but not so intensive as in case of cast steel No. 3) of the secondary network formation in grain boundaries of the austenite grains obtained during the re-austenitisation. The grain size of this austenite is similar to the austenite grain size occurring in the microstructure of cast steel No. 3. The interlamellar distance in pearlite seems to be not much larger, than the one observed in the cast steel No.3 microstructure.

Cast steel No. 5 is characterised, in an identical fashion as the previously described cast steels, by the pearlitic matrix with transformed ledeburite and hypereutectoid cementite precipitates, while there is practically a lack of any graphite precipitates. The distinct phosphorous eutectic was not observed. Transformed ledeburite together with the hypereutectoid cementite built in along the primary austenite boundary, form a continuous network on long segments. The grain size of the austenite originated during the crystallisation, surrounded by this carbide network seems to be even larger than the one observed in cast steel No. 2. A quite large fraction of the hypereutectoid cementite precipitates in the Widmannstätten system exists in the microstructure. The tendency of forming such hypereutectoid cementite morphology is the highest among the investigated cast steels. The hypereutectoid cementite precipitates on boundaries of the austenite grains obtained during the re-austenitisation indicate a tendency to form the continuous network. The austenite grain size, characterised by the mentioned above network of precipitates is only larger than in cast steel No. 1. The pearlitic matrix is characterised by a small interlamellar distance comparable with the one in cast steel No. 1.

Cast steel No. 6 is characterised with the microstructure of the pearlitic matrix with not numerous graphite precipitates as well as with the hypereutectoid cementite precipitates. A significantly smaller carbon content, than in the previously investigated cast steels causes the lack of the transformed ledeburite in its microstructure. The hypereutectoid cementite is not present in the Widmannstätten system. Graphite occurs in small amount, in small precipitates of a variable morphology, resembling spheroidal graphite. The hypereutectoid cementite indicates a tendency for precipitating in grain boundaries. The grain size of the austenite obtained during the re-austenitisation characterised by these precipitates is similar (not much larger) to the grain size of such austenite observed in the microstructure of cast steel No.5. The interlamellar distance in the pearlitic matrix is significantly smaller than the one in cast steel No. 2 and seems not much larger from the one occurring in cast steel No. 4.

Cast steel No. 7 is characterised with the microstructure of the pearlitic matrix with precipitates of the hypereutectoid cementite, however neither the transformed ledeburite nor graphite precipitates are present (the most probably due to the least carbon content). The hypereutectoid cementite precipitates have various morphology inside the austenite grains originated during the

crystallisation and in the vicinity of their boundaries. This austenite grain size can be described as not much smaller as compared with cast steel No. 2. The hypereutectoid cementite in the vicinity of the austenite boundaries precipitates to a small degree, revealing by its morphology the re-austenitised austenite grain size. The grain size obtained during the re-austenitisation can be estimated, as similar to the one observed in cast steel No. 1. Morphology of the hypereutectoid cementite precipitates changes in the direction of the austenite interior. This cementite starts to show more tendencies to form the network of precipitates in grain

boundaries of the austenite grains obtained during the re-austenitization. In the middle part of the primary austenite grain the hypereutectoid cementite exhibits already very high tendency to precipitate in grain boundaries of the re-austenitised grains and to form the continuous network of precipitates. This austenite grain size inside the austenite grain originated during the crystallisation can be estimated as only a little bit smaller than in cast steel No. 2. The interlamellar distance in the pearlitic matrix in cast steel No. 7 is estimated as the smallest out of the investigated cast steels.

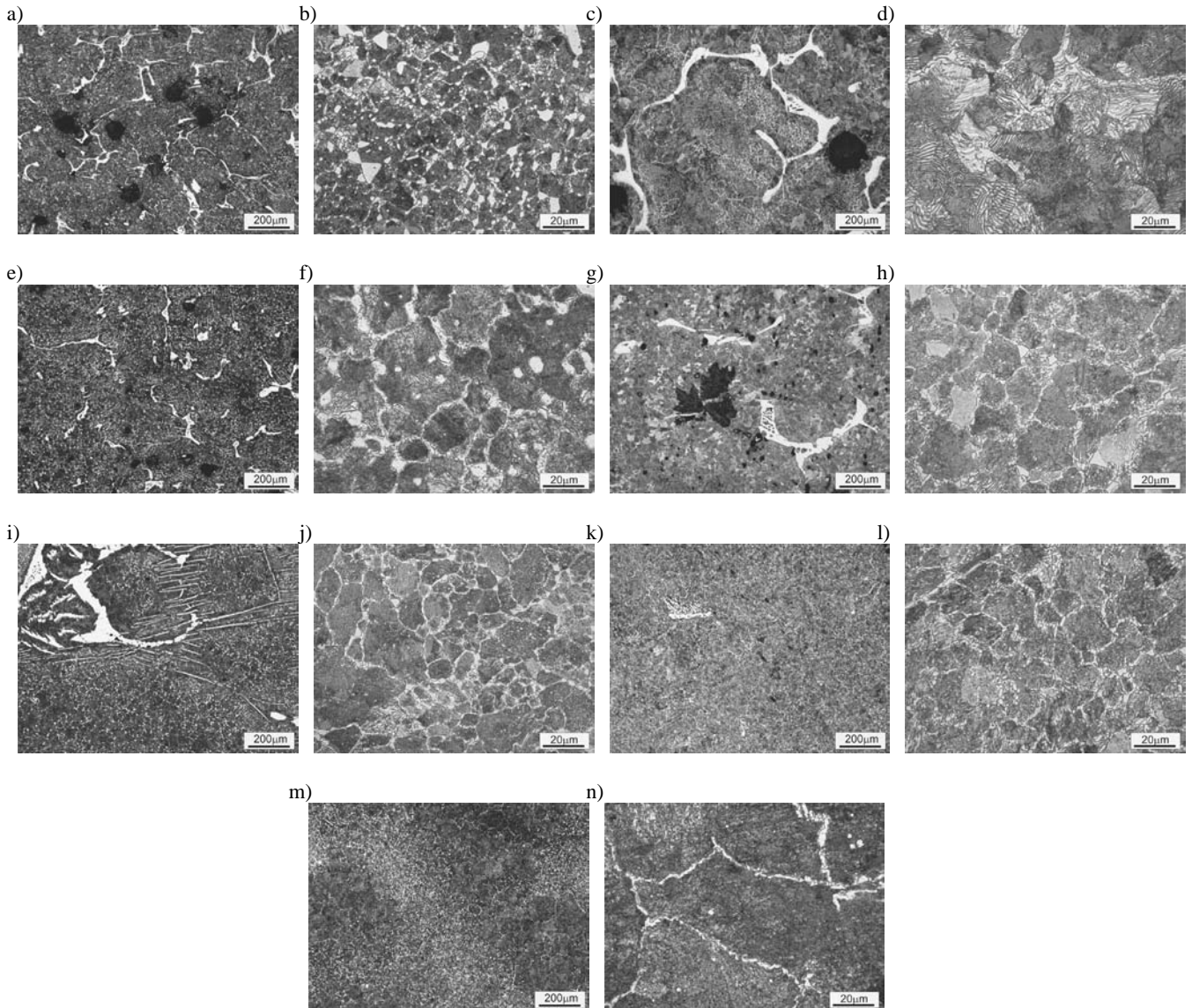


Fig. 2. Microstructures of the tested cast steels, at the magnification allowing the estimation of the prior austenite grain size, morphology of eutectic precipitates, graphite morphology and at the magnification allowing the estimation of the matrix microstructure in the middle part of the prior austenite primary grain: a,b) cast steel 200CrNi4-4 (No. 1), c,d) cast steel 200SiCrNi4-4 (No. 2), e,f) cast steel 200CrSiMn4-4 (No. 3), g,h) cast steel 200NiSiCr8-4-4 (No. 4), i,j) cast steel 200CrNiMo4-3-3 (No. 5), k,l) cast steel 150SiCrNi4-4-3 (No. 6), m,n) cast steel 120CrNiMo4-3-3 (No. 7)

4. Chemical composition influence on the graphite formation

A factor, which can be important for functional properties of the rolls, is the graphite presence or absence in their microstructure. In order to estimate the influence of alloying elements on the graphite formation in cast steels, utilised for the metallurgical rolls, the diagrams describing - for each pair of alloying elements - zones of the graphite occurrence in the cast steel microstructure are developed (Figs. 3-17). These Figures present pairs of alloying elements. The influence of carbon and successive alloying elements on the graphitising process of cast steel is presented in Figures 3-7.

Analysis of C and Mn influence (Fig. 3) indicates that an increased concentration of manganese does not influence the cast steel graphitisation, while an increased concentration of carbon favours this graphitisation.

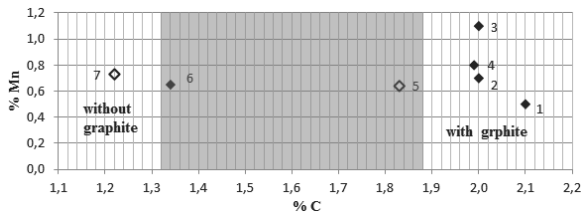


Fig. 3. Carbon and manganese contents influence on the graphite formation in the investigated cast steels (transient zone is marked in grey)

When analysing the influence of C and Si (Fig. 4) it can be noticed, that increasing their content favours the cast steel graphitisation.

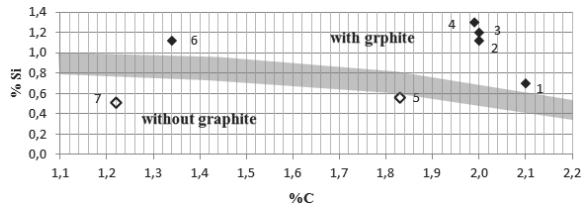


Fig. 4. Carbon and silicon contents influence on the graphite formation in the investigated cast steels (transient zone is marked in grey)

When analysing the influence of C and Cr (Fig. 5) it can be noticed, that increasing the C content favours the graphitisation, while the increased Cr content limits the graphitisation process.

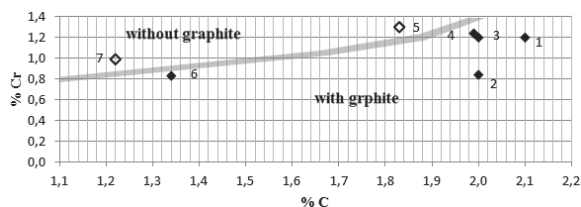


Fig. 5. Carbon and chromium contents influence on the graphite formation in the investigated cast steels (transient zone is marked in grey)

When analysing the influence of C and Ni (Fig. 6) it can be noticed, that increasing their content favours the graphitisation process.

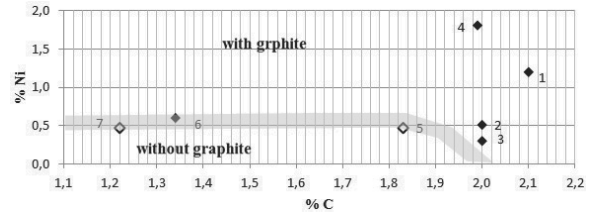


Fig. 6. Carbon and nickel contents influence on the graphite formation in the investigated cast steels (transient zone is marked in grey)

When analysing the influence of C and Mo (Fig. 7) it is seen, that the increased carbon content favours the graphitisation, while the increased molybdenum content blocks the graphitisation.

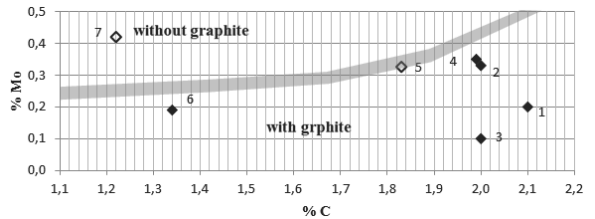


Fig. 7. Carbon and molybdenum contents influence on the graphite formation in the investigated cast steels (transient zone is marked in grey)

Concluding, it can be stated that the increased carbon content favours the graphitisation, regardless of the content of other alloying elements. It means, that none of the alloying elements - occurring in the investigated cast steels - changes the carbon presence influence, which always favours the graphitisation process.

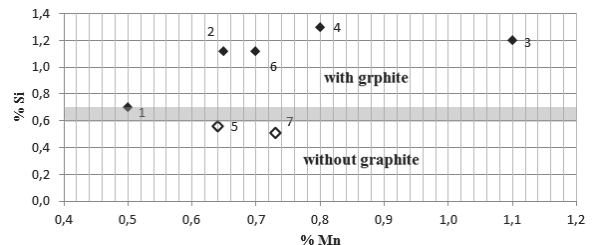


Fig. 8. Manganese and silicon contents influence on the graphite formation in the investigated cast steels (transient zone is marked in grey)

When analysing the influence of Mn and Si (Fig. 8) it is seen that manganese does not influence the graphitisation process, while silicon favours this process.

From the analysis of the influence of Mn and Cr (Fig. 9) it results, that chromium should hamper the graphitisation process and manganese - in a certain range of its content (0.55-0.75%) supports such influence.

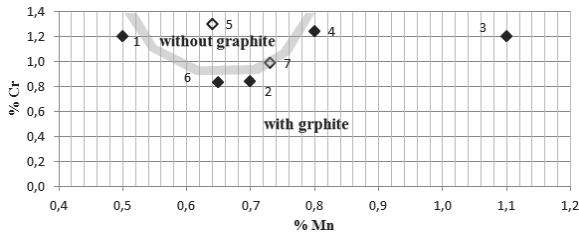


Fig. 9. Manganese and chromium contents influence on the graphite formation in the investigated cast steels (transient zone is marked in grey)

The analysis of the influence of Mn and Ni (Fig. 10) indicates, that nickel favours the graphitisation process simultaneously causing that manganese starts - to a small degree - to facilitate the graphitisation process.

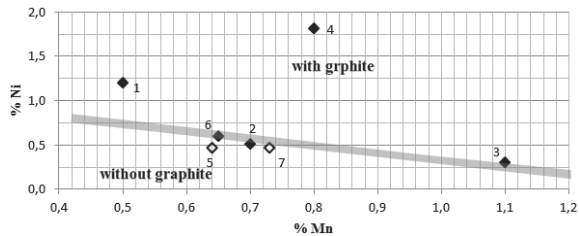


Fig. 10. Manganese and nickel contents influence on the graphite formation in the investigated cast steels (transient zone is marked in grey)

The analysis of the influence of the consecutive pair: Mn and Mo (Fig. 11) indicate that molybdenum blocks the graphitisation process, however simultaneously causes that manganese - in its presence - favours the graphitisation process.

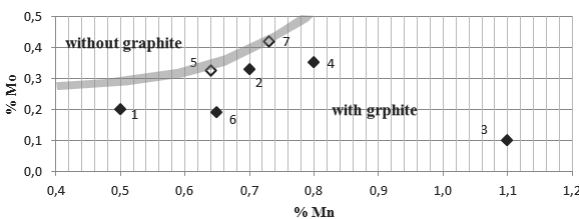


Fig. 11. Manganese and molybdenum contents influence on the graphite formation in the investigated cast steels (transient zone is marked in grey)

Summarising, it seems that manganese - when being present together with molybdenum and nickel - favours the graphitisation process. However, in the presence of the remaining alloying elements manganese has no influence on the graphitisation process.

The analysis of the influence of Si and Cr (Fig. 12) indicates, that chromium limits the gratification process, while silicon favours this process.

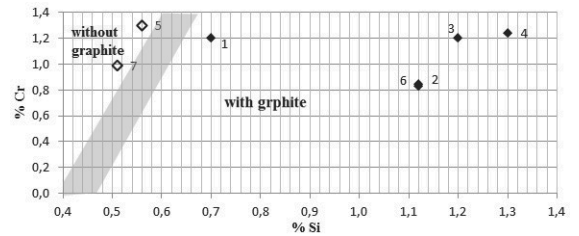


Fig. 12. Silicon and chromium contents influence on the graphite formation in the investigated cast steels (transient zone is marked in grey)

The analysis of the influence of Si and Ni (Fig. 13) indicates, that nickel as well as silicon favours the graphitisation process.

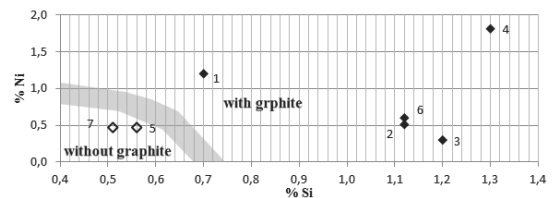


Fig. 13. Silicon and nickel contents influence on the graphite formation in the investigated cast steels (transient zone is marked in grey)

The analysis the Si and Mo content presented in Fig. 14 indicates, that Si favours the graphitisation process, while molybdenum blocks this process.

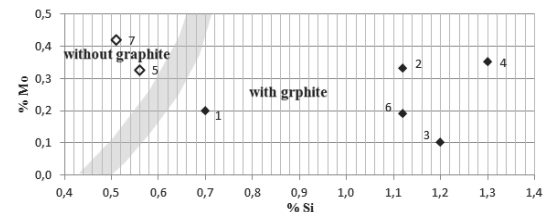


Fig. 14. Silicon and molybdenum contents influence on the graphite formation in the investigated cast steels (transient zone is marked in grey)

Summarising, it can be stated that silicon favours the graphitisation process regardless of the remaining elements.

The analysis of the influence of Cr and Ni (Fig. 15) indicates, that nickel favours the graphitisation process simultaneously limiting the chromium influence.

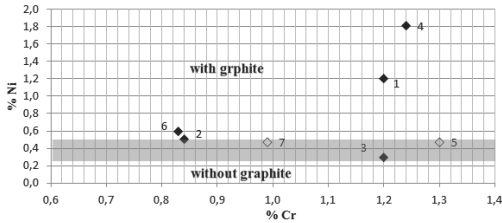


Fig. 15. Chromium and nickel contents influence on the graphite formation in the investigated cast steels (transient zone is marked in grey)

It results from the analysis of the Cr and Mo influence (Fig. 16), that these both elements hamper the cast steel graphitisation.

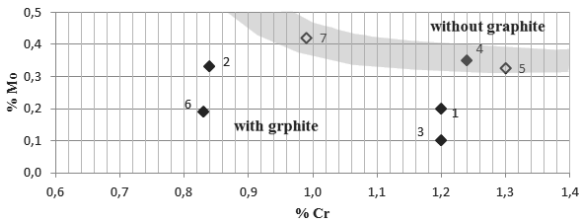


Fig. 16. Chromium and molybdenum contents influence on the graphite formation in the investigated cast steels (transient zone is marked in grey)

Concluding, it can be stated, that chromium hampers the graphitisation process. However such chromium influence can be blocked by nickel.

Analysing the influence of Ni and Mo (Fig. 17) one can say, that nickel favours the graphitisation process, while molybdenum hampers such process.

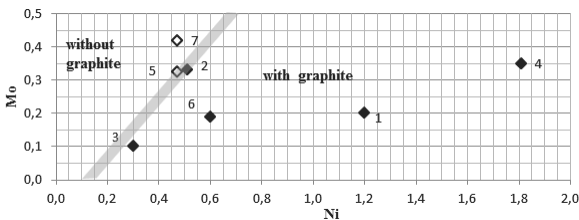


Fig. 17. Nickel and molybdenum contents influence on the graphite formation in the investigated cast steels (transient zone is marked in grey)

Concluding, it can be stated that molybdenum, regardless of the remaining alloying elements, exhibits an inclination to hamper the graphitisation process.

5. Chemical composition influence on the hardness of the investigated cast steels

The contents of the alloying elements and carbon, apart from shaping the microstructure (which influences its hardness), can also influence the strength properties, including the hardness e.g. by a solid solution strengthening. In order to determine a general influence of carbon and alloying elements on the hardness the diagrams presented in Figures 18-23 were developed.

It can be observed that the carbon content increase causes the hardness increase - within the range of the investigated cast steels chemical compositions (Fig. 18). The most probably it is mainly caused by the carbide phase fraction increase.

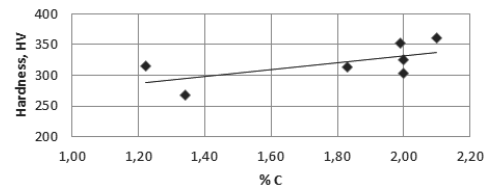


Fig. 18. Carbon content influence on the investigated cast steels hardness

Manganese does not exhibit any distinct influence on the investigated cast steels hardness (Fig. 19). This can be due to a significant manganese solubility in the cementite (it should be mentioned here that the cementite fraction in the microstructure of the cast steels used for the metallurgical rolls is large).

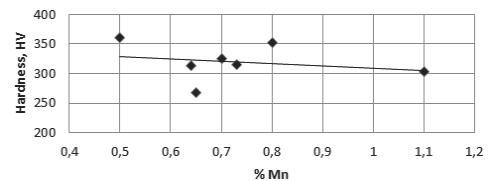


Fig. 19. Manganese content influence on the investigated cast steels hardness

Also silicon seems not to demonstrate any significant influence on the hardness of the investigated cast steels (Fig. 20). This can be caused by the fact, that the solid solution strengthening of ferrite by silicon should increase the hardness but silicon simultaneously favours the graphitisation causing the hardness decrease. Of course, favouring the graphitisation only by silicon would not be sufficient (at its content applied in the

investigated cast steels) however it should be remembered that, apart from silicon, there is a significant addition of nickel, which also favours the graphitisation process (see Fig. 13).

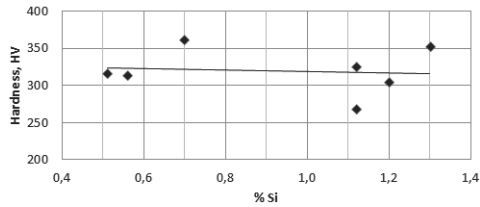


Fig. 20. Manganese content influence on the investigated cast steels hardness

The chromium addition increases the hardness, the most probably on account of its carbide forming ability (Fig. 21).

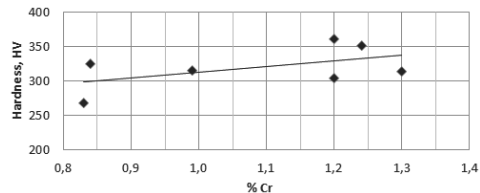


Fig. 21. Chromium content influence on the investigated cast steels hardness

Nickel increases the hardness of the investigated cast steels (Fig. 22). Thus, it can be inferred that the influence of nickel by the ferrite solid solution strengthening is stronger in the investigated cast steels than its graphitising ability (in respect of its influence on the hardness).

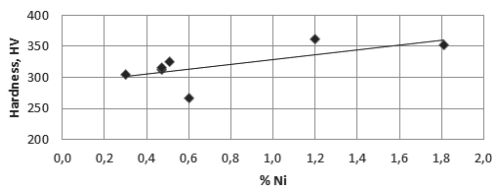


Fig. 22. Nickel content influence on the investigated cast steels hardness

Molybdenum, in the applied range, seems to have a tendency to increase the investigated cast steels hardness (Fig. 23).

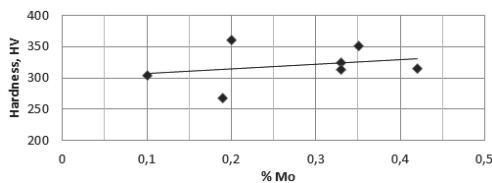


Fig. 23. Molybdenum content influence on the investigated cast steels hardness

6. Influence of the chemical composition on the investigated cast steels wear

In order to supply information, essential for designing the chemical composition of cast steels, the lists determining the dependency in between the carbon and alloying elements content and the wear resistance of the investigated cast steels - were prepared (Fig. 24-29).

When analysing the diagram presented in Figure 24 it can be stated, that an increase of the carbon content to app. 2% should increase the wear resistance of cast steels. In a similar fashion as carbon, but less distinctly, influences the wear resistance an increase of the manganese content to above 1% (Fig. 25).

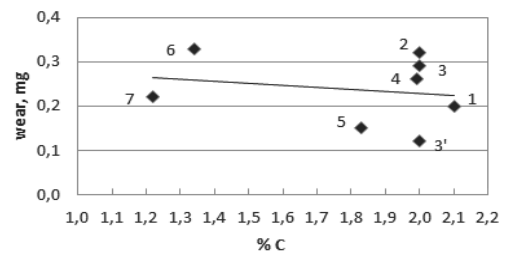


Fig. 24. Influence of the carbon content on the wear resistance of the investigated cast steels

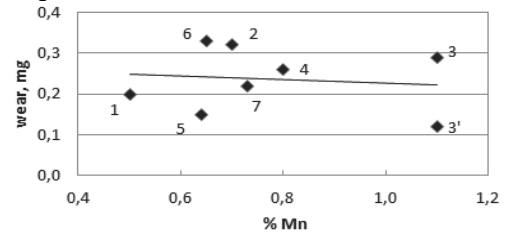


Fig. 25. Influence of the manganese content on the wear resistance of the investigated cast steels

However, an increase of the silicon content to above 1% seems to decrease the wear resistance (Fig. 26). Such silicon influence is probably related to its graphitising preference.

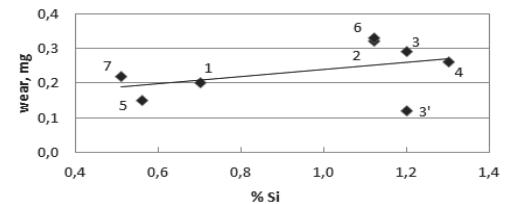


Fig. 26. Influence of the silicon content on the wear resistance of the investigated cast steels

Chromium is the most effective in increasing the wear resistance (Fig. 27).

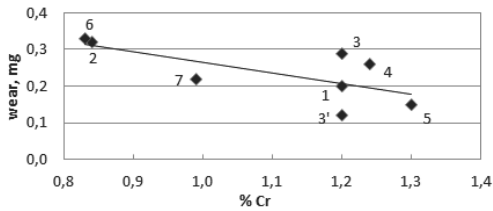


Fig. 27. Influence of the chromium content on the wear resistance of the investigated cast steels

An increase of the nickel content - in accordance with the diagram in Figure 28 - will rather decrease the cast steel wear resistance. A likewise weak influence on the wear increase can have a small increase of the molybdenum content (Fig. 29). However, this dependence is very weak and can be the result of other factors not necessarily the molybdenum content (it can be just a random result).

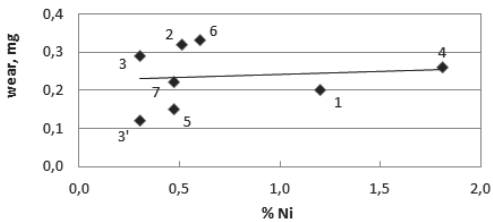


Fig. 28. Influence of the nickel content on the wear resistance of the investigated cast steels

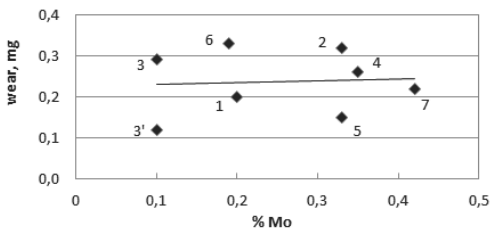


Fig. 29. Influence of the molybdenum content on the wear resistance of the investigated cast steels

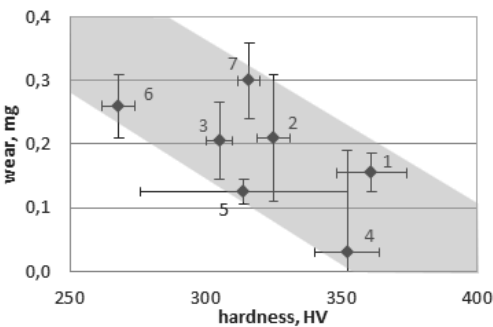


Fig. 30. Influence of the hardness on the wear resistance of the investigated cast steels

7. Influence of the hardness on the wear resistance of the investigated cast steels

When analysing the hardness influence on the wear resistance of the investigated cast steels (Fig. 30) one can observe that the increased hardness increases the wear resistance.

8. Influence of the chemical composition on the friction coefficient of the investigated cast steels

Since the microstructure, and due to that the properties of the investigated cast steels depend in large measure on their chemical composition, and - in addition - alloying elements can influence the ferrite properties via e.g. its solid solution strengthening, it was decided to analyse the influence of the alloying elements content on the friction coefficient.

The carbon content increase resulting in the carbide phases or graphite content increase seems to support the decreasing stability of the tribological wear process, which causes the friction coefficient scatter in case of the higher carbon content (Fig. 31). The similar influence on the friction coefficient change has an increase of the manganese content (Fig. 32). However, in case of manganese a weak tendency to decrease the friction coefficient can be noticed, probably due to manganese refining the pearlitic structure.

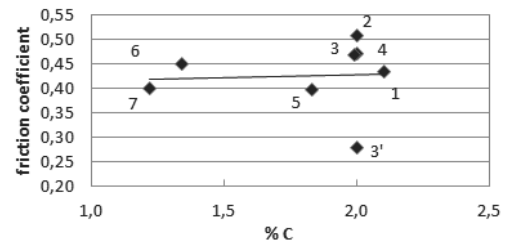


Fig. 31. Carbon content influence on the average friction coefficient of the investigated cast steels

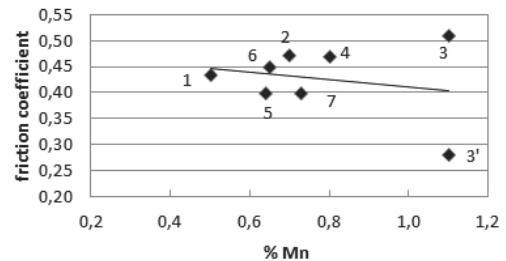


Fig. 32. Manganese content influence on the average friction coefficient of the investigated cast steels

The silicon content increase favours the friction coefficient increase (Fig. 33). It can be the result of silicon acting as the graphitising element as well as the element causing the solid solution strengthening of ferrite.

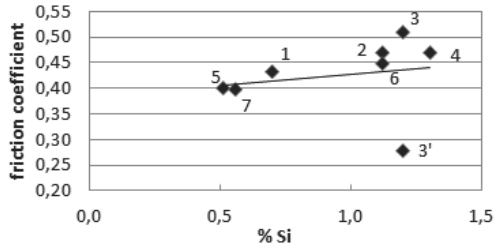


Fig. 33. Silicon content influence on the average friction coefficient of the investigated cast steels

The chromium content increase seems to decrease the friction coefficient (Fig. 34). The most probably it results from the increased fraction of carbide phases with chromium additions.

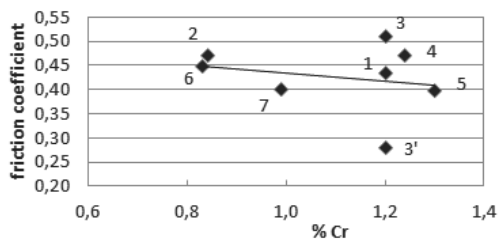


Fig. 34. Chromium content influence on the average friction coefficient of the investigated cast steels

The nickel content increase in the investigated cast steels appears to have a similar influence on the friction coefficient as the silicon content increase (Fig. 35). It can be suspected that increasing of the friction coefficient with the nickel content increase is caused by the same mechanisms as in the case of silicon.

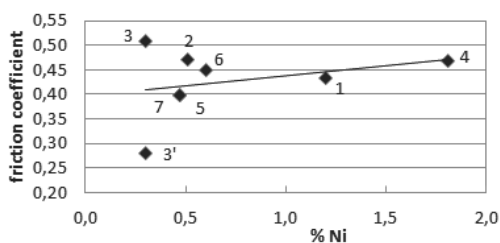


Fig. 35. Nickel content influence on the average friction coefficient of the investigated cast steels

It is very difficult to determine the influence of the molybdenum content increase - in the range of its applicability in the investigated cast steels - on the friction coefficient (Fig. 36).

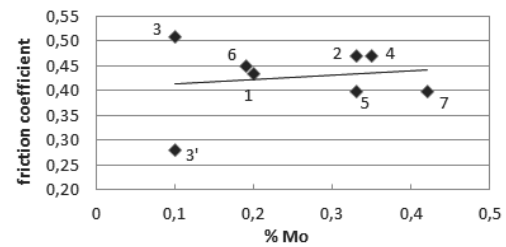


Fig. 36. Molybdenum content influence on the average friction coefficient of the investigated cast steels

9. Influence of the hardness on the friction coefficient of the investigated cast steels

The hardness influence on the friction coefficient is presented in Figure 37. It is seen that the increased hardness of the investigated cast steels causes the friction coefficient decrease.

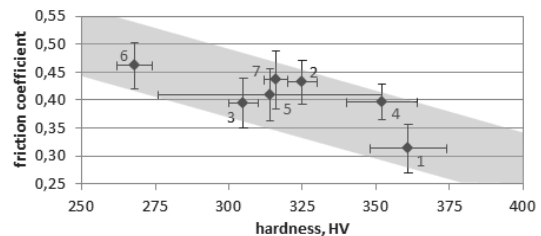


Fig. 37. Hardness influence on the friction coefficient of the investigated cast steels

10. Relationship between the friction coefficient and wearing of the investigated cast steels

Designing mill rolls should take into account their wear resistance (on account of their working time) as well as the friction coefficient (on account of facilitating gripping the strip by the rolls). Thus, striving should be directed towards limiting the wear and increasing the friction coefficient (however, this increase should not be too high since it can cause the strip sticking to the rolls).

The schematic presentation of the relationship between the friction coefficient and the wear resistance is seen in Figure 38. It can be noticed that together with the friction coefficient increase the wear degree also increases. It is difficult to design cast steel characterised simultaneously by the high wear resistance and high friction coefficient.

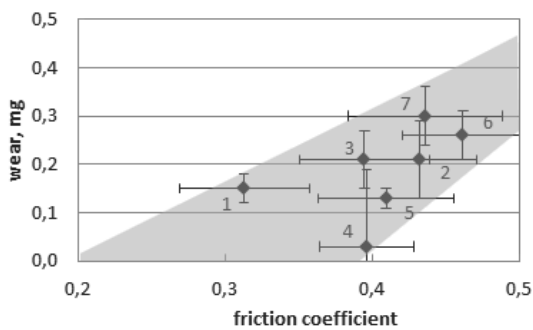


Fig. 38. Relationship between the friction coefficient and wear resistance of the investigated cast steels

11. Conclusions

Investigations of the tribological properties of cast steels used for the production of metallurgical rolls carried out in the presented here work must be considered in two scientific domains. At first the chemical composition influence on the microstructure and hardness should be investigated and only then the chemical composition influence on the tribological properties of the investigated cast steels.

The analysis of the obtained results in the range of the influence of the chemical composition on the microstructure and hardness of the investigated cast steels allows formulating the written below conclusions.

- Analysing the influence of carbon and alloying elements on the graphitisation process of the investigated cast steels it can be stated that:
 - The increased carbon content favours the graphitisation;
 - Manganese, even when the molybdenum content was increased to 0.42%, but at the presence of silicon up to 1.20%, seems not to influence the graphitisation process;
 - Chromium hinders the graphitisation process, however the addition of nickel can block such chromium activity;
 - Nickel favours the graphitisation process;
 - Molybdenum hinders the graphitisation process.
- The increased carbon content favours the increase of the ledeburite-transformed fraction in the microstructure of the investigated cast steels. However, in the content range of the applied alloying elements, their distinct influence on the ledeburite presence in the microstructure of the investigated cast steels was not found.
- Increasing of the silicon content seems to increase the interlamellar distance in the pearlitic matrix of the investigated cast steels.
- Increasing of the carbon content increases the hardness of the investigated cast steels.
- Increasing of the chromium, nickel and molybdenum content negligibly increases the hardness of the investigated cast steels.

The analysis of the influence of the chemical composition, microstructure and hardness on the tribological properties of cast

steels used for the metallurgical rolls allows to formulate several conclusions:

- Increasing of the manganese and chromium content seems to decrease the average friction coefficient, while increasing of the silicon, nickel and molybdenum content seems to increase the average friction coefficient of the investigated cast steels.
- The increased hardness favours decreasing of the friction coefficient.
- Increasing of the carbon, manganese and chromium content seems to increase the wear resistance, while increasing of the silicon and nickel content seems to decrease the wear resistance of the investigated cast steels.
- The increased hardness of the investigated cast steels increases their wear resistance under conditions of the performed test.
- When the friction coefficient increases the wear resistance of the investigated cast steels decreases.

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References

- 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.
- M. Knapinski, The numerical analysis of roll deflection during plate rolling, *Journal of Materials Processing Technology* 175 (2006) 257-265.
- 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.
- 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.
- D.-F. Chang, Thermal stresses in work rolls during the rolling of metal strip, *Journal of Materials Processing Technology* 94 (1999) 45-51.
- F.J. Belzunce, A. Ziadi, C. Rodriguez, Structural integrity of hot strip mill rolling rolls, *Engineering Failure Analysis* 11 (2004) 789-797.
- S.X. Zhou, An integrated model for hot rolling of steel strips, *Journal of Materials Processing Technology* 134 (2003) 338-351.
- 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.
- R. Cola's, J. Ramirez, I. Sandoval, J.C. Morales, L.A. Leduc, Damage in hot rolling work rolls, *Wear* 230 (1999) 56-60.
- Ž. Domazet, F. Lukša, M. Šušnjar, Failure analysis of rolls with grooves, *Engineering Failure Analysis* 14 (2007) 1166-1174.

- [11] J. Krawczyk, J. Pacyna, Effect of the cooling rate on the mottled cast iron microstructure designed for the mill rolls, *Metallurgy and Foundry Engineering of Science and Technology* 35 (2009) 101-110.
- [12] 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.
- [13] 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.
- [14] 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.
- [15] 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*, ed. C.C. Sih, Th.B. Kermanidis, Patras, 2004, 203-207.
- [16] J. Krawczyk, E. Rożniata, J. Pacyna, The influence of hypereutectoid cementite morphology upon fracture toughness of chromium-nickel-molybdenum cast steel of ledeburite class, *Journal of Materials Processing Technology* 162-163 (2005) 336-341.
- [17] E. Rożniata, J. Pacyna, Hypereutectoid cementite morphology and mechanical properties of Cr-Ni-Mo cast steel, *Journal of Achievements in Materials and Manufacturing Engineering* 17 (2006) 145-148.
- [18] E. Rożniata, J. Pacyna, Effect of annealing on mechanical properties of ledeburitic cast steel, *Journal of Achievements in Materials and Manufacturing Engineering* 20 (2007) 187-190.
- [19] J. Pacyna, E. Rożniata, Effect of annealing on structure and properties of ledeburitic cast steel, *Journal of Achievements in Materials and Manufacturing Engineering* 24 (2007) 84-90.