Microstructure and tribological properties of mottled cast iron with different chemical composition

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ABSTRACT

Purpose: The role of the chemical composition of cast irons for mill rolls in tendencies of diffusionless transformations in the matrix was determined. The investigations of the chemical composition, microstructure and hardness influence on tribological properties of mottled cast iron is presented in the paper.

Design/methodology/approach: The research stand is generally used in the tribological tests, and the counter sample of the material also common in such tests. Bearing steel 100Cr6, of a hardness of 57 HRC, was applied as a counter sample. The tribological tests were performed at a load of 100 N. Samples for tests were taken from seven mill rolls made by various producers. Mottled cast irons had a different chemical composition.

Findings: The role of individual alloying elements in a tendency of the diffusionless transformations in the matrix, hardness, wear resistance and friction coefficient of mottled cast irons used for the mill rolls was estimated. The hardness increase rather increases the wear resistance of the investigated cast irons.

Research limitations/implications: The possibility of designing the chemical composition of mottled cast iron in such a way as to obtain the low tribological wear at retaining, at the same time, the high friction coefficient was found. The relationship between the hardness resulting from the chemical composition and the wear resistance of the investigated mottled cast irons was presented.

Practical implications: The obtained results can be utilised in designing the chemical compositions of the cast iron mill rolls and to obtain materials characterised by the high wear resistance at the assumed friction coefficient.

Originality/value: Surprisingly, the increased chromium content seems to decrease the wear resistance of the investigated cast irons and the wear resistance of the investigated mottled cast irons is rather decreasing when the coefficient of friction increases.

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

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MATERIALS

1. Introduction

Mill rolls are tools operating under very difficult conditions [1-10]. Selection of materials and microstructures of mill rolls, which would meet the requirements for all rolling mills and rolling stands, is not possible in practice. Thus, materials should be selected for the specific rolling stand in the specific rolling mill. E.g. cast iron rolls are used rather for finishing stands at hot rolling.

High requirements demanded from mill rolls, such as: surface hardness, wear resistance and mechanical properties can be satisfied at the definite roll microstructure [11-21]. The demanded microstructure is obtained by the appropriate selection of the material chemical composition, suitable cooling rate and – less often – by the heat treatment. Cast irons used for mill rolls are usually mottled cast irons [15-21]. Cast irons of various graphite and ledeburitic cementite morphology and various matrices are used in the industrial practice. Up to the present there is a lack of complex studies, which would allow to estimate the influence of the chemical composition, microstructure and hardness of cast irons used for the mill rolls on their tribological properties. Unfortunately performing such investigations under conditions ideally the same as industrial ones is not possible because of a very high cost of tools such as mill rolls. Therefore investigations of the chemical composition, microstructure and hardness influence on tribological properties of cast materials on iron matrix should be carried out under laboratory conditions [21-26]. The best for this purpose is the research stand, which is generally used in the tribological tests, and the counter sample of the material also common in such tests. These tests, even when only performed at a room temperature, should provide interesting results, which can constitute the initial data for designing more advanced experiments for the cast iron selection for the mill rolls. The hereby paper undertakes, in detail, the above described research problem.

2. Methodology of investigations

Samples for tests were taken from seven mill rolls made by various producers. Cast irons had of a different chemical composition.

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. Tribological tester T05 (block on ring)

3. Material for tests

The chemical compositions of the tested cast irons, in an order of an increasing chromium content, are listed in Table 1. The investigated cast irons were characterised by the nickel content above 1 % (1.23-3.45%) and a wide content of the remaining alloying elements: Cr: 0.28-1.37%, Si: 0.65-2.19%, Mo: 0.17-0.86%. The addition of magnesium found in two cast irons indicates an application of this element for the graphite spheroidisation. Microstructures of the tested cast irons are presented in Figure 2.

Table 1.
Chemical composition (weight %) of the tested rolls, according to the producers' analysis (nda – no data available)

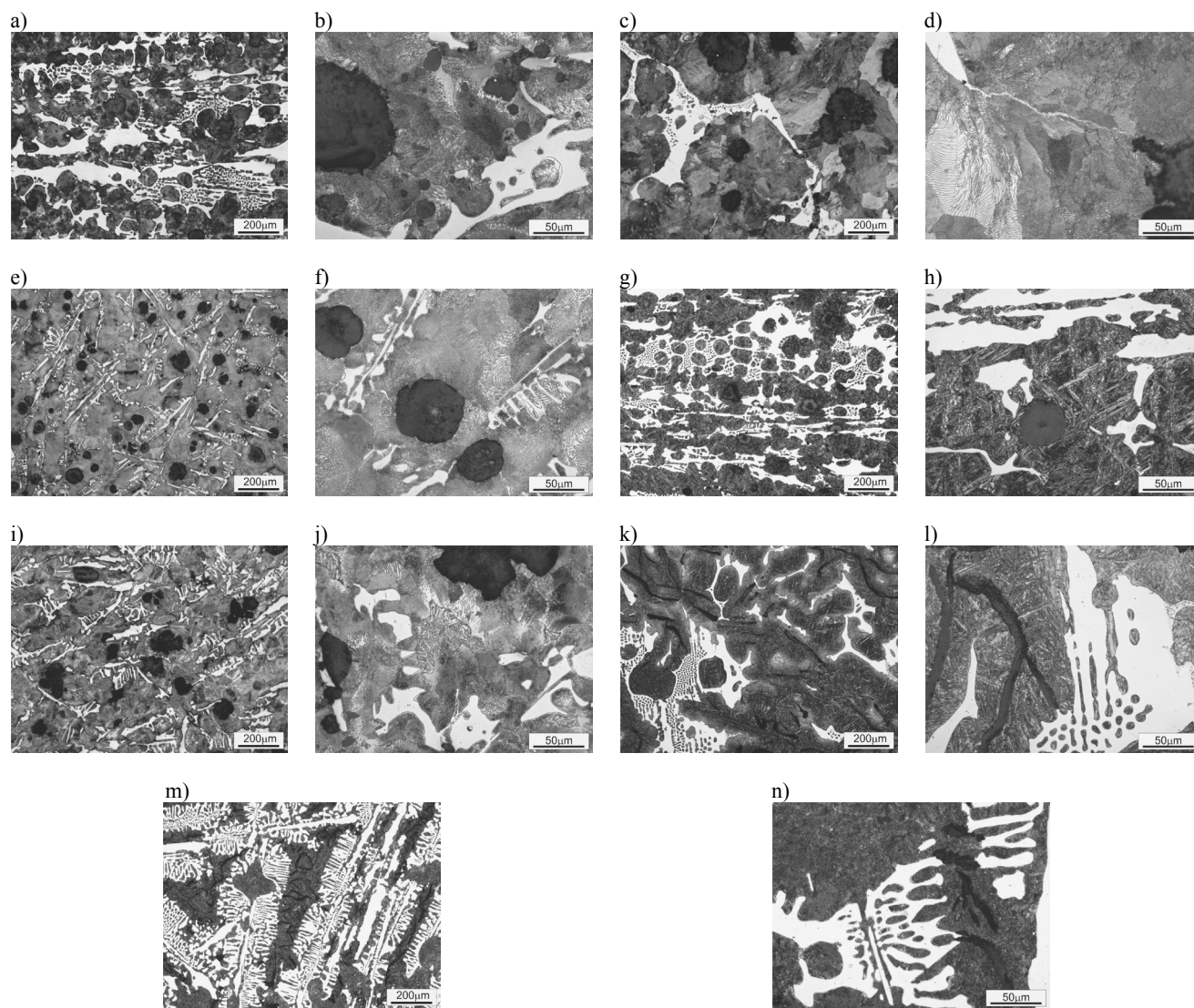| No.	Cast iron	C	Mn	Si	P	S	Cr	Ni	Mo	Mg
1	GJSL 330NiMoCr8-5	3.32	0.72	1.40	0.08	0.01	0.28	2.06	0.52	0.05
2	GJSL 350NiCr6-2	3.46	0.41	1.35	<0.04	<0.01	0.39	1.46	0.17	nda
3	GJSL 300SiNiCr8-6-2	3.04	0.72	2.19	0.10	0.08	0.48	1.32	0.31	0.04
4	GJSL 350NiMoCr12-8-3	3.45	0.65	1.40	nda	nda	0.70	3.07	0.86	nda
5	GJSL 320NiSiCrMo14-8-3	3.22	0.51	2.16	0.06	0.01	0.71	3.45	0.62	nda
6	GJLL 350NiCrMo13-4	3.45	0.53	0.65	nda	nda	1.03	3.23	0.44	nda
7	GJLL 350CrNiMo6-5-3	3.50	0.74	1.22	0.06	0.02	1.37	1.23	0.32	nda

Fig. 2. Microstructures of the investigated cast irons, at the magnification enabling to estimate the morphology of eutectic and graphite precipitates as well as at the magnification allowing to estimate the matrix microstructure: a,b) cast iron GJSL – 330NiMoCr8-5 (No.1), c,d) cast iron GJSL – 350NiCr6-2 (No. 2), e,f) cast iron GJSL – 300SiNiCr8-6-2 (No. 3), g,h) cast iron GJSL – 350NiMoCr12-8-3 (No. 4), i,j) cast iron GJSL – 320NiSiCrMo14-8-3 (No. 5), k,l) cast iron GJLL – 350NiCrMo13-4 (No. 6), m,n) cast iron GJLL – 350CrNiMo6-5-3 (No. 7)

Cast iron No.1 is characterised by a microstructure, which includes the pearlitic matrix with the ledeburitic cementite and spheroidal graphite precipitates. The dendritic character of the austenite crystallisation from liquid is clearly seen. Liquid, which remained in the interdendritic spaces, underwent the eutectic transformation into ledeburite. The dendritic and ledeburitic austenite after exceeding a temperature Ar_1 were transformed into pearlite. As a result of the eutectoidal transformations of the ledeburitic austenite the precipitates of the transformed ledeburite occur in the microstructure. Graphite nucleated on boundaries of the austenitic dendrites and liquid. Graphite in the tested cast iron is of a spheroidal form of two significantly different sizes.

Probably the fine graphite precipitates were formed in the dendritic austenite as a result of decreasing carbon solubility. The most probably on account of this, the hypereutectoid cementite is not seen in cast iron No.1. The described above crystallisation process and the place of taking samples (within columnar crystals) caused, that the distinct banding of ledeburitic cementite precipitates occur in the tested sample.

Similarly, as in the case of cast iron No.1, the microstructure of cast iron No.2 includes the pearlitic matrix with the ledeburitic cementite and spheroidal graphite precipitates. In addition, precipitates of the hypereutectoid cementite in grain boundaries of austenite originated during crystallisation are seen. The ledeburitic

cementite fraction is significantly smaller than in the case of cast iron No.1. The graphite precipitates are larger in cast iron No.2 than in No.1. The pearlitic matrix in cast iron No.2 is characterised by larger interplate distances and larger pearlite grains than the matrix in cast iron No.1. The hypereutectoid cementite precipitated in grain boundaries of austenite originated during crystallisation often 'joins' precipitations of ledeburitic cementite with graphite. The graphitisation has a tendency for occurring from the spheroidal graphite precipitates along boundaries of primary austenite.

The microstructure of cast iron No.3, in a similar fashion as the microstructures of cast irons No.1 and No.2, is characterised by an occurrence of precipitates of the ledeburitic cementite and spheroidal graphite in the pearlitic matrix. It is still not certain whether in primary austenite grain boundaries are precipitates of the hypereutectoid cementite or these are only ferritic microareas. The ledeburitic cementite is not forming any continuous network as it happens in the case of its equivalent in the microstructure of cast iron No.1, and its precipitates are smaller than the ledeburitic cementite in cast iron No.2. The graphite precipitates are smaller than in the case of cast irons No.1 and No.2, while its fraction is comparable to the graphite fraction in cast irons No.1 and No.2. The pearlitic matrix is characterised by smaller interplate distances than in the case of cast iron No.1 and No.2, while the pearlite grains colony seems to be larger than in cast iron No.1, but smaller than in cast iron No.2.

The cast iron No.4 matrix constitutes bainite, not pearlite as in cast irons No.1-No.3, while similarly as in cast irons No.1-No.3 the ledeburitic cementite and spheroidal graphite precipitates occur in these matrices. This bainite constituting the matrix has the morphologic features (in dependence on the observation place) of the upper or lower bainite. The graphite precipitates are of a smaller size than in cast irons No.1-No.3, as well as their fraction seems lower than in the case of cast irons No.1-No.3. The ledeburitic cementite fraction and its morphology can be described as intermediate between the ones in cast irons No.1 and No.3. The cementite precipitates, which can be described as the hypereutectoid cementite, are poorly seen.

The microstructure of cast iron No.5 is characterised by the bainitic-pearlitic matrix with the nodular graphite and ledeburitic cementite precipitates. Bainite occurring in the matrix has the upper bainite morphology. The graphite precipitates are smaller than in cast iron No.2, but larger than in cast iron No.3. The ledeburitic cementite precipitates are larger than in cast iron No.3, but smaller than in No.4. The ledeburitic cementite morphology is similar to its morphology in cast iron No.3.

The microstructure of cast iron No.6 is characterised by the bainitic-martensitic matrix (with the lower bainite) with the flake graphite and ledeburitic cementite precipitates. In addition, a phosphorous eutectic can be seen in the microstructure. The hypereutectoid cementite precipitated along the primary austenite grain boundaries also occurs in the microstructure.

The microstructure of cast iron No.7 is characterised by the very fine pearlite (troostite) matrix with the flake graphite and ledeburitic cementite precipitates. The graphite precipitates have much finer flakes than flakes occurring in cast iron No.6. A large fraction of the ledeburitic cementite precipitates occurs in the microstructure of cast iron No.7, it is the largest of all investigated cast irons and forms a constant network of precipitates.

4. The chemical composition influence on the advancement of diffusion processes in the matrix

A factor, which can be essential due to cast irons functional qualities, is the matrix microstructure. The characteristic feature of the matrix can be the occurrence of structural components indicating the diffusive (pearlite, ferrite), intermediate (upper and lower bainite) and diffusionless transformations (martensite). The range of the microstructure analysis performed in this study allows to differentiate clearly the diffusive transformations (pearlite) occurrence as well as the transformations being at least partially the diffusionless process (bainite, martensite). In order to estimate the influence of alloying elements on the advancement degree of the diffusive processes in the matrix – for each pair of alloying additions – the diagrams showing the range of occurrence the transformations which at least in a part are diffusionless processes were prepared (Figs. 3-12). It should be mentioned that, apart from the chemical composition, a significant influence on the matrix microstructure has the casting process (casting cooling rate) and the eventual heat treatment. Figures 3-12 present pairs of alloying additions.
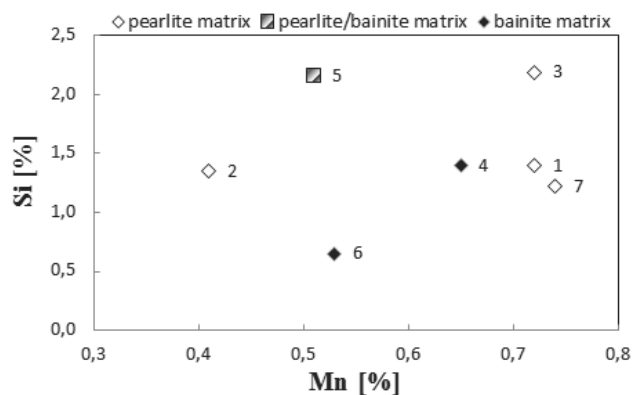
Fig. 3. Manganese and silicon content influence on the advancement degree of the diffusion processes in the matrix
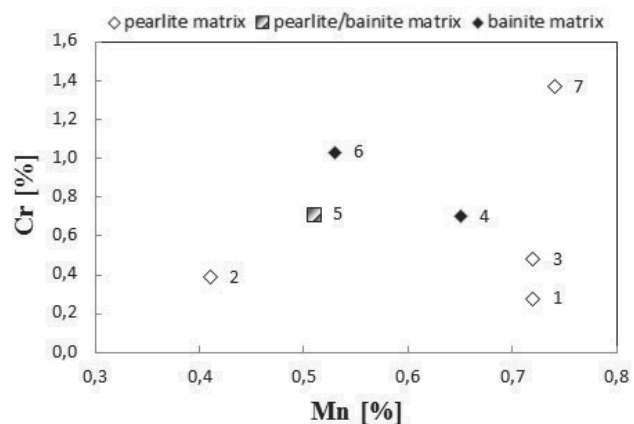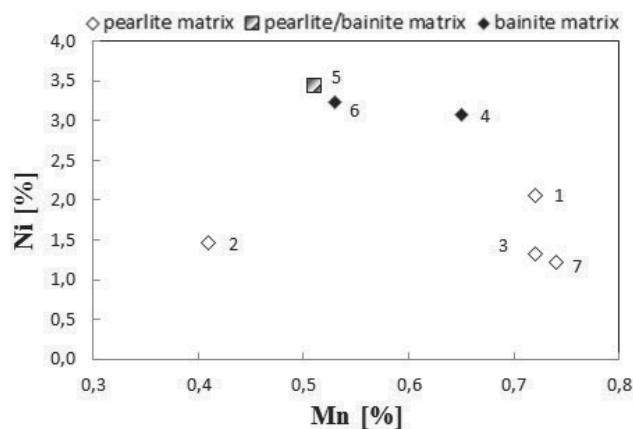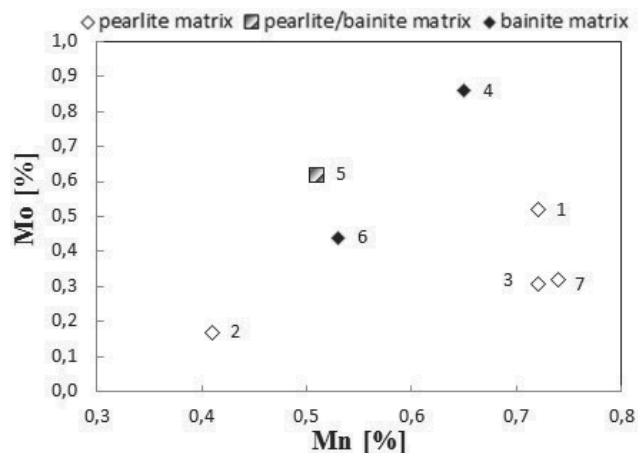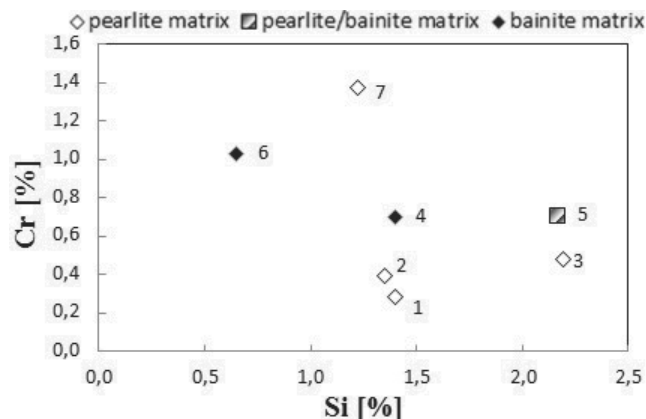
Fig. 4. Manganese and chromium content influence on the advancement degree of the diffusion processes in the matrix

The system Mn-Si (Fig. 3) indicates, that neither manganese nor silicon have an influence on the diffusionless transformations (matrix hardenability).

It results from the Mn-Cr system (Fig. 4), that manganese does not show a distinct influence on the advancement of the diffusive transformations in the investigated cast irons matrices, while chromium shows a weak influence (indicating that it favours the diffusionless processes – increasing the matrix hardenability). A weak influence of chromium can be caused by the fact, that it is mainly present in carbides not in the matrix.

The system Mn-Ni (Fig. 5) indicates, that manganese does have an influence on the diffusive transformations in the matrix (probably due to its large solubility in the cementite), while nickel has a distinct influence on such transformations (it increases the matrix hardenability).

Fig. 5. Manganese and nickel content influence on the advancement degree of the diffusion processes in the matrix

It results from the system Mn-Mo (Fig. 6), that molybdenum favours diffusionless processes in the matrix (increases its hardenability), while manganese seems to limit the molybdenum activity in this range.

Fig. 6. Manganese and molybdenum content influence on the advancement degree of the diffusion processes in the matrix

It results from the system Si-Cr (Fig. 7), that chromium indicates a weak tendency to favour diffusionless processes of phase transformations in the matrix, while silicon does not indicate any influence in this range.

Fig. 7. Silicon and chromium content influence on the advancement degree of the diffusion processes in the matrix

The successive system, Si-Ni (Fig. 8) indicates, that nickel significantly favours the diffusionless transformations in the matrix (increases hardenability), while silicon weakly limits the nickel activity in this range.

It results from the system Si-Mo (Fig. 9), that molybdenum favours the diffusionless transformations in the matrix of the investigated cast irons, without a distinct influence of silicon on such molybdenum activity.
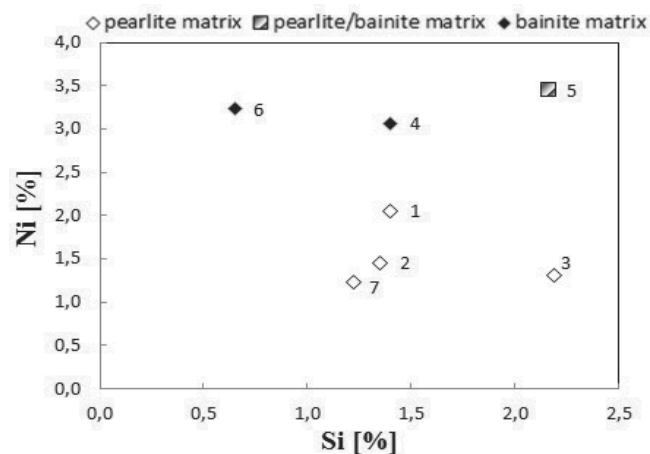

Fig. 8. Silicon and nickel content influence on the advancement degree of the diffusion processes in the matrix

It results from the system Cr-Ni (Fig. 10), that nickel favours the diffusionless processes in the investigated cast irons matrices (increases the matrix hardenability) without any distinct influence of chromium on such nickel influence.
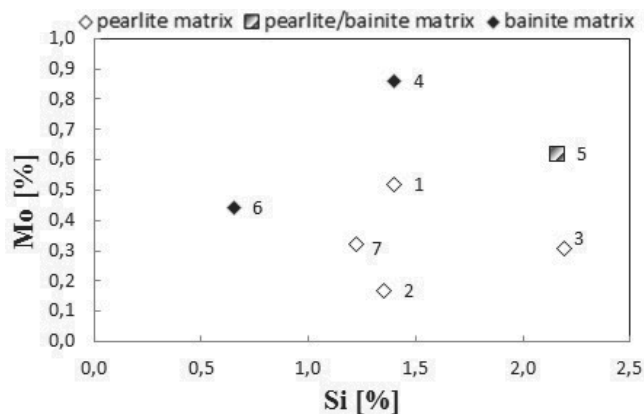
Fig. 9. Silicon and molybdenum content influence on the advancement degree of the diffusion processes in the matrix
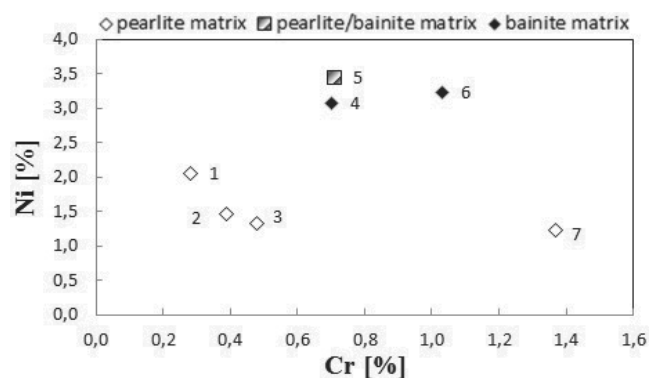

Fig. 10. Chromium and nickel content influence on the advancement degree of the diffusion processes in the matrix

It results from the system Cr-Mo (Fig. 11), that molybdenum seems to favour the diffusionless processes in the investigated cast iron matrices (increases the matrix hardenability), while chromium does not interfere with this molybdenum activity.
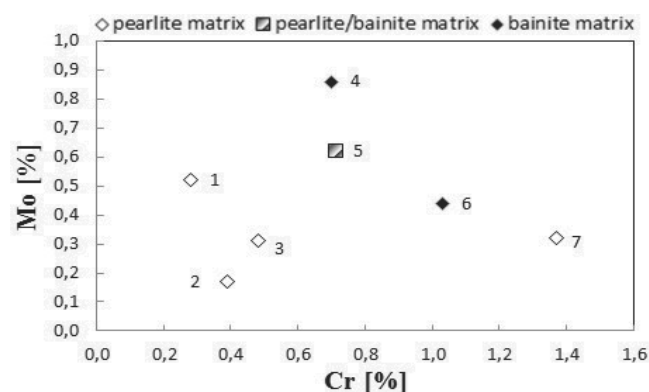

Fig. 11. Chromium and molybdenum content influence on the advancement degree of the diffusion processes in the matrix

The system Ni-Mo (Fig. 12) indicates, that nickel favours the diffusionless transformations in the investigated cast irons matrices (increases their hardenability), while the influence of molybdenum on such nickel activity is difficult for any estimation within the analysed chemical compositions of cast irons.
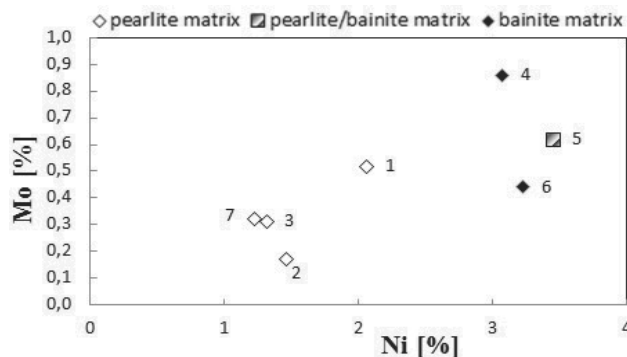
Fig. 12. Nickel and molybdenum content influence on the advancement degree of the diffusion processes in the matrix

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

The influence of the chemical composition on the investigated cast irons hardness depends on the role of the alloying elements in forming the microstructure. The hardness dependence on the carbon and main alloying elements content, is presented in Figures 13-18. Since carbon should be treated as 'a building material' of the carbide phase and graphite, its influence on the hardness will depend on the alloying elements, which will decide on the carbides and graphite fractions. Therefore differences in the carbon content applied in the investigated cast irons have no essential influence on the hardness, as can be seen in Fig.13.
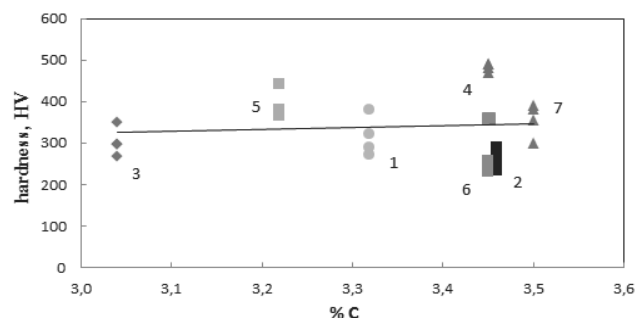

Fig. 13. Influence of the carbon content on the hardness of the investigated cast irons

Manganese, regardless of its good solubility in the carbide phase, has the influence on the hardness (Fig. 14), which increases with the manganese content increase. The most probably it results from the manganese influence on the matrix hardenability as well as from its role as the element favouring the pearlitic structure disintegration and influencing the ferrite solid solution strengthening.
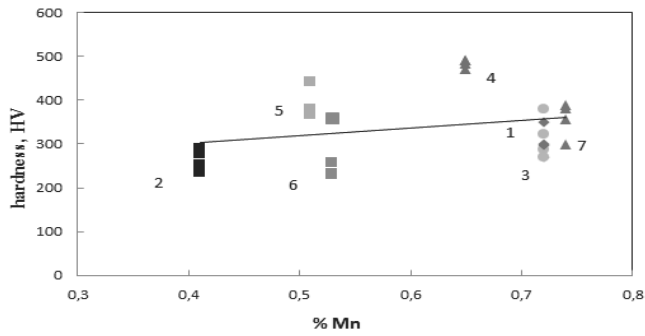
Fig. 14. Influence of the manganese content on the hardness of the investigated cast irons

Silicon also seems to favour the hardness increase (Fig. 15). This effect is seen regardless of the known (found) silicon activity as the graphitising element. Silicon as not the carbide forming element remains soluble in ferrite increasing its hardness by the solid solution strengthening.
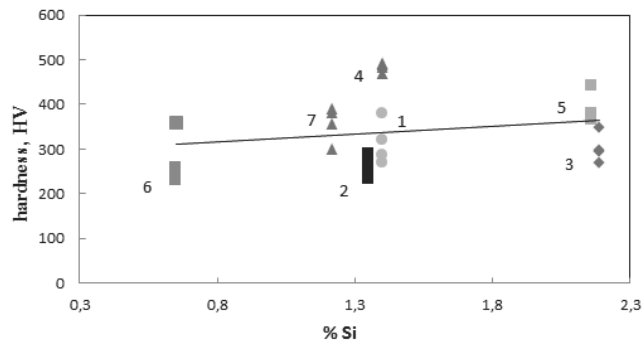

Fig. 15. Silicon content influence on the hardness of the tested cast irons

Chromium demonstrates similar to silicon and manganese tendency for the hardness increase (Fig. 16). However, the stronger chromium influence on the hardness increase should be expected due to its carbide forming ability (favouring chills formation).
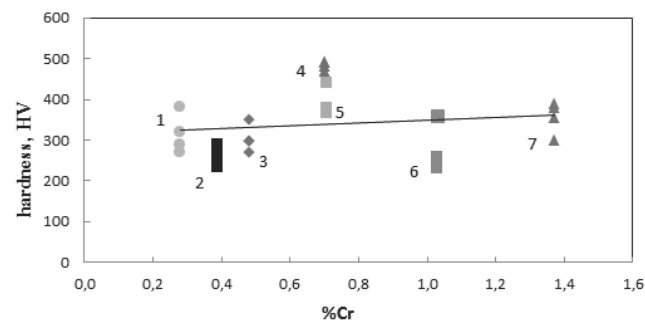

Fig. 16. Chromium content influence on the hardness of the tested cast irons

Nickel also seems to favour the hardness increase of the investigated cast irons, regardless of its graphitising influence (Fig. 17). In a similar fashion as in the case of silicon, nickel also can favour the hardness increase by the solid solution strengthening, as well as – contrary to silicon – the matrix hardenability increase.
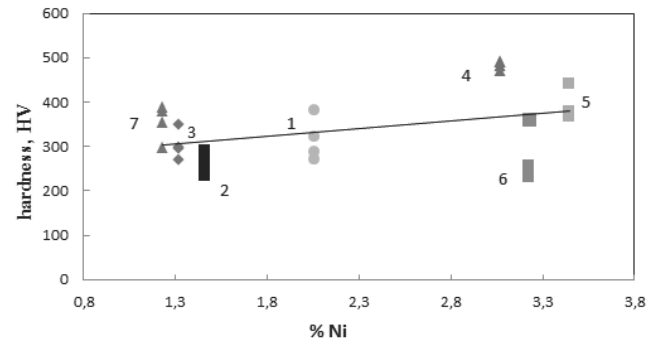

Fig. 17. Nickel content influence on the hardness of the tested cast irons

The highest influence on the hardness increase seems to have molybdenum (Fig. 18). This is the carbide forming element (influences chills of the cast iron microstructure), and the one, which has the highest influence on the hardenability.
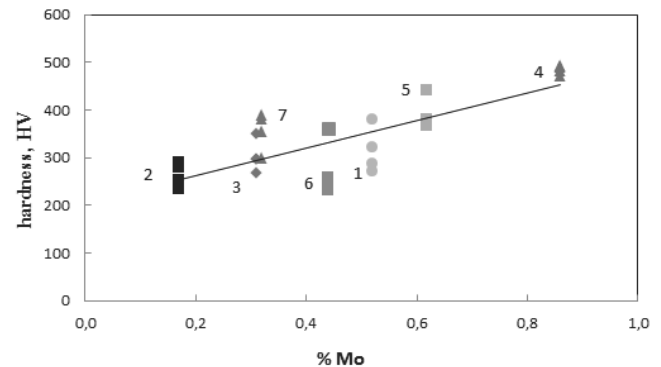

Fig. 18. Molybdenum content influence on the hardness of the tested cast irons

6. Chemical composition influence on the friction coefficient

Since there is the dependence between the chemical composition and microstructure and in between the microstructure and friction coefficient, the dependence between the chemical composition of the investigated cast irons and the friction coefficient should be expected. The results of this analysis are presented in Figures 19-23.

It can be observed that the manganese content in the analysed cast irons group does not influence the friction coefficient of mottled cast irons (Fig. 19).
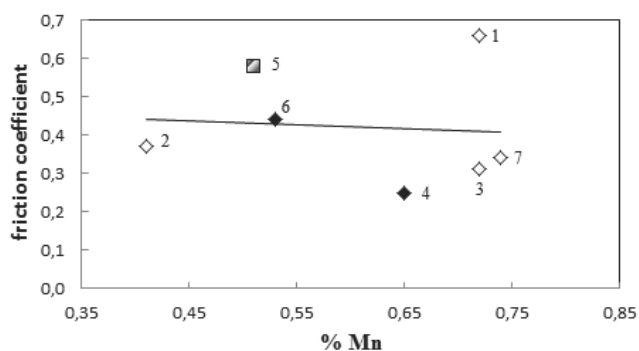
Fig. 19. Manganese content influence on the average friction coefficient during the tribological test

Similarly as in the case of manganese also the silicon content does not demonstrate any explicit influence on the friction coefficient of the tested cast irons (Fig. 20).

However, the increased chromium content seems to decrease the friction coefficient (Fig. 21). This can be explained by the chromium influence on the cast iron chilling degree (increased content of the carbide forming chromium should increase the ledeburitic cementite fraction), it means by the decrease of the friction coefficient with the ledeburitic cementite content increase.
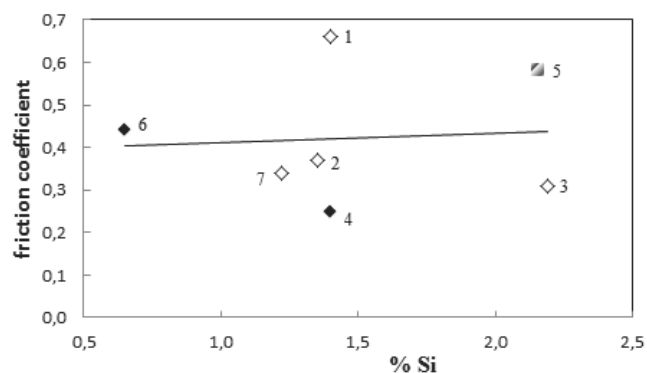

Fig. 20. Silicon content influence on the average friction coefficient during the tribological test
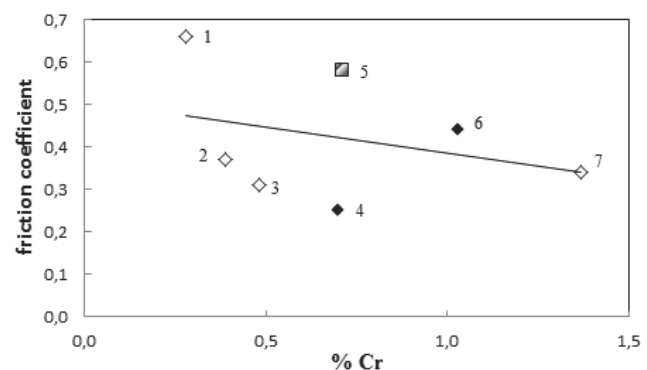

Fig. 21. Chromium content influence on the average friction coefficient during the tribological test

The nickel content increase increases the friction coefficient in the tested cast irons group, despite the fact that nickel is the graphitising element and decreasing the advancement of diffusive transformations in the matrix (increasing the matrix hardenability) – Fig. 22. To this end the observed influence of the nickel content on the friction coefficient increase can be the result of its influence as the element increasing the ferrite solid solution strengthening and its influence on the graphite precipitates morphology (the larger graphite precipitates the larger friction coefficient).
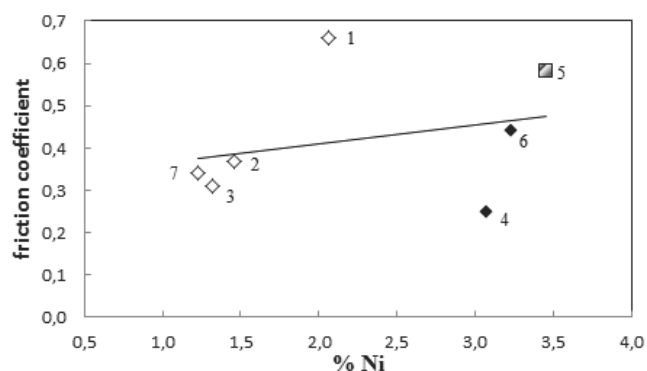

Fig. 22. Nickel content influence on the average friction coefficient during the tribological test

The molybdenum content in the investigated cast irons has no significant influence on the friction coefficient (Fig. 23). However, analysing the molybdenum content change to app. 0.5% can be noticed, that it rather increases the friction coefficient, while the increase of its content from 0.5% to app. 0.9% favours decreasing the coefficient of friction.
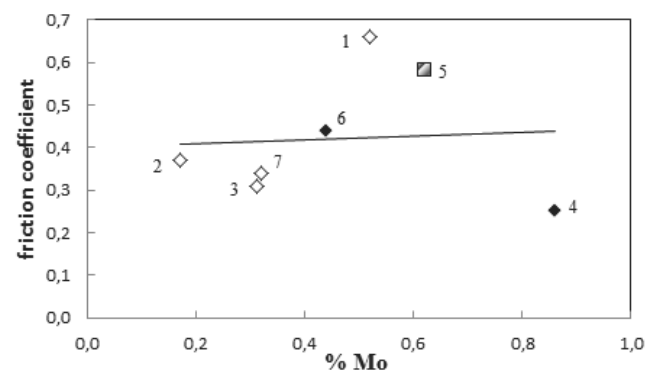

Fig. 23. Molybdenum content influence on the average friction coefficient during the tribological test

7. Hardness influence on the friction coefficient

The microstructure complexity, the occurrence of several structural components in the investigated mottled cast irons are

the reasons, that the relationship between the hardness and friction coefficient is not a simple one (Fig. 24). However a certain tendency, that the hardness increase is rather a factor decreasing the friction coefficient is observed.
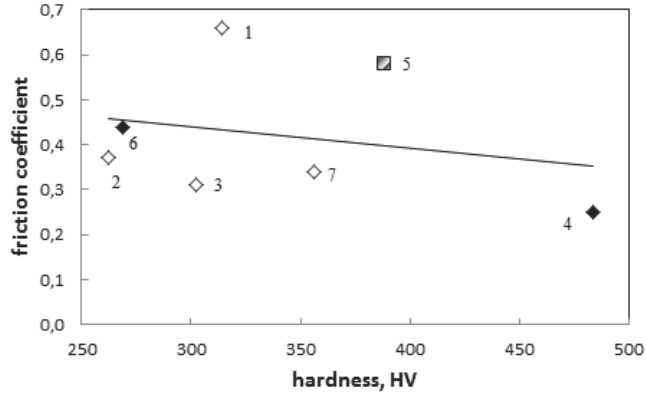

Fig. 24. Hardness influence on the average friction coefficient of the investigated cast irons

8. Chemical composition influence on the wear value

Since the chemical composition was one of the main factors influencing the microstructure of the investigated cast irons and simultaneously it can have a significant influence on properties of phases being included in the microstructure (especially properties of ferrite), it was decided to analyse the chemical composition influence on the tribological wear of cast irons (Figs. 25-29).

The manganese content change seems not to have any essential influence on the wear resistance of the investigated cast irons (Fig. 25).
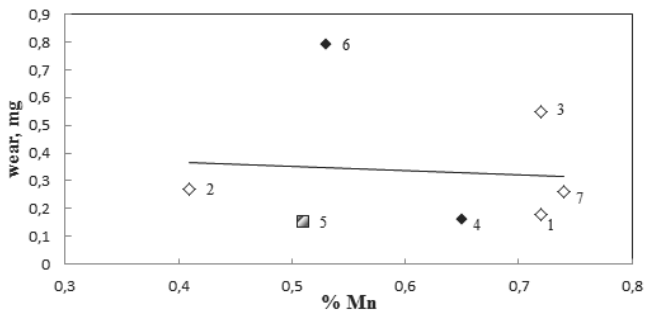

Fig. 25. Manganese content influence on the tribological wear of the investigated cast irons

The silicon content increase seems to increase the wear resistance of the investigated cast irons (Fig. 26). The most probably it is the result of the ferrite solid solution strengthening by silicon.
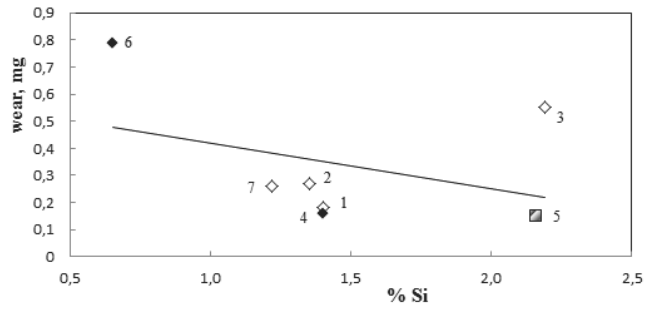

Fig. 26. Silicon content influence on the tribological wear of the investigated cast irons

The increased chromium content slightly decreases the wear resistance of the investigated cast irons (Fig. 27). This result is rather surprising, since chromium as a carbon forming element (forming chills) should rather increase the wear resistance, by the increased ledeburitic cementite fraction in the microstructure.
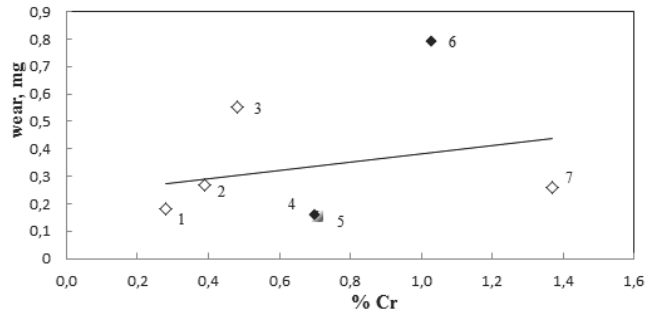

Fig. 27. Chromium content influence on the tribological wear of the investigated cast irons

Nickel seems not to have influence on the abrasion resistance of the investigated cast irons (Fig. 28). However, when only cast irons of the pearlitic matrix are analysed then the increased nickel content increases their wear resistance.
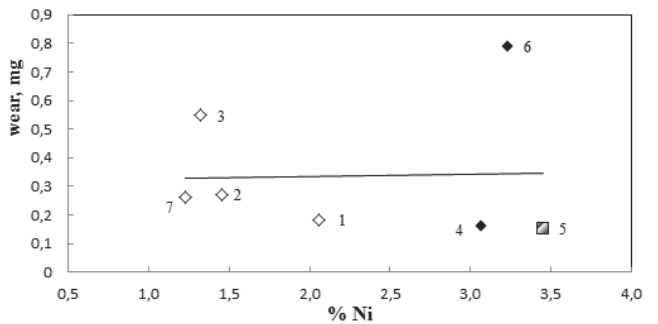

Fig. 28. Nickel content influence on the tribological wear of the investigated cast irons

The increased molybdenum content significantly increases the wear resistance (Fig. 29).
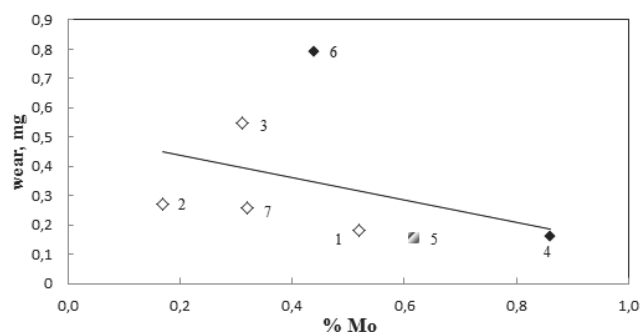
Fig. 29. Molybdenum content influence on the tribological wear of the investigated cast irons

9. Hardness influence on the wear value

Since the basic parameter, which is the most often taken into account, by the users of the mill rolls, at forecasting the wear resistance is their hardness, it was decided to compile information on the hardness influence on the wear resistance of the investigated cast irons (Fig. 30). It can be seen that the minimum hardness considered the required one to assure the good wear resistance (300 HV) is the hardness within which both very high and very low wear of the investigated cast irons can occur. In this case other factors must be decisive e.g. a wear mechanism depending on the microstructure. However, increasing the hardness to app. 500 HV seems to decrease the influence of the remaining factors on the wear resistance. In addition, it can be observed that the hardness increase rather increases the tribological wear.
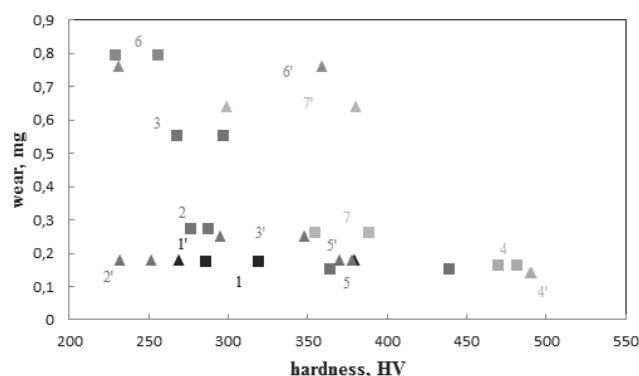

Fig. 30. Hardness influence on the wear of the investigated cast irons

10. Friction coefficient influence on the wear value

The optimisation of the tribological properties of the mill rolls requires designing of materials – for their production – in such a way that they would be characterised with a good wear resistance at given conditions and the appropriately selected friction coef-

ficient. Too low friction coefficient can hinder gripping the strip by the rolls, while too high can cause sticking the strip to the rolls. The dependence of the average friction coefficient and the wear of the investigated cast irons is presented in Figure 31. The tendency of increasing the wear resistance with the friction coefficient increase can be noticed, which seems to be the inverse dependence than the generally accepted for materials more microstructurally homogeneous than mottled cast irons. This indicates the significant influence of the microstructure on the wear mechanism of these materials. Simultaneously, it creates the possibility of such way of designing cast irons for the mill rolls as to obtain materials characterised by the high wear resistance at the assumed friction coefficient.
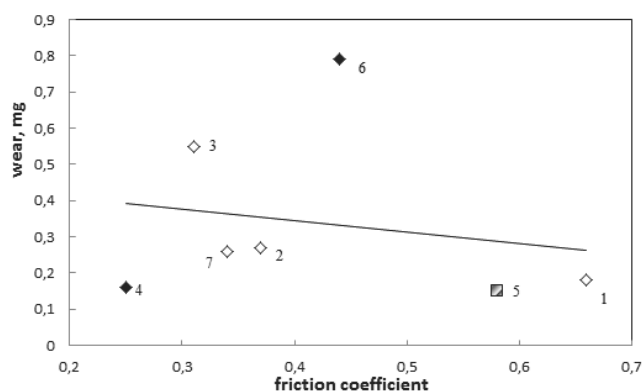

Fig. 31. Dependence between the average friction coefficient and the wear of the investigated cast irons

11. Summary and conclusions

Investigations carried out in the hereby study allow to formulate main conclusions in the scope of the chemical composition influence on the microstructure, hardness and tribological properties of the investigated cast irons:
1. Manganese and silicon does not indicate any significant influence on diffusionless transformations in the investigated cast irons.
2. Nickel clearly increases the matrix hardenability.
3. Molybdenum increases the matrix hardenability, while manganese seems to limit such molybdenum activity.
4. Chromium favours diffusionless transformations in the matrix.
5. The highest influence on the hardness increase of the investigated cast irons has the molybdenum content increase.
6. Increasing the chromium content seems to decrease the friction coefficient of the investigated cast irons.
7. Increasing the nickel content seems to increase the friction coefficient of the investigated cast irons.
8. The friction coefficient value seems to decrease with the hardness increase.
9. The silicon content increase increases the tribological wear resistance of the investigated cast irons.
10. Surprisingly, the increased chromium content seems to decrease the wear resistance of the investigated cast irons.

11. The increase of the molybdenum content increases the wear resistance of the investigated cast irons.
12. The hardness increase rather increases the wear resistance of the investigated cast irons.
13. Surprisingly, the wear resistance of the investigated cast irons is rather decreasing when the coefficient of friction increases.

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