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INFLUENCE OF THE MICROSTRUCTURE ON MACHINING A CENTRAL HOUSING MADE OF PEARLITE GREY CAST IRON

VPLIV MIKROSTRUKTURE NA OBDELOVALNOST CENTRALNEGA OHIŠJA IZ PERLITNE SIVE LITINE

Neva Štrekelj, Milanka Nunić, Iztok Naglič, Boštjan Markoli

Faculty of Natural Sciences and Engineering, University of Ljubljana, Aškerčeva 12, 1000 Ljubljana, Slovenia
neva.strekelj@omm.ntf.uni-lj.si

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This article presents the cause(s) of a relatively increased wear and failure of cutting tools during the final treatment of a central housing made of pearlitic (grey) cast iron with lamellar graphite. Castings with a proper (designated as 'good') and an inadequate (designated as 'bad') microstructures were investigated. Chemical analyses showed a higher concentration of carbide-forming elements in the bad casting, particularly at the edges. Vickers hardness was also measured and the results indicated a higher hardness of bad castings. A microstructural analysis showed that the good casting had the targeted microstructure of the pearlitic matrix and the type A graphite with the size of 4–6. In addition to the narrow, initially austenitic zone that extended only by about 200 µm into the bad casting, steadite was observed, which adversely affected the properties. Moreover, the shape of the graphite and its distribution were uneven, which was also reflected in a low machinability of the bad casting. The inner regions of the castings included graphite of a suitable shape and size, while the edges showed that the solidification of the alloy started by following a stable system with a solidification of the primary austenite and continued according to a metastable one. In the bad casting this area occurred just below the surface, while in the good casting it stretched into the interior. In the bad casting the type B graphite was mainly developed. The influence of the quality of the cutting tools was not investigated.

Keywords: microstructure, grey cast iron, machining

Namen članka je bil ugotoviti vzrok relativno povečane obrabe in lomljenja nožev pri obdelavi centralnega ohišja iz perlitne sive litine z lamelnim grafitom. Analiza je bila opravljena na ulitku s primerno (označen kot 'dober' ulitek) in neprimerno (označen kot 'slab' ulitek) mikrostrukturo. Preverjena je bila kemijska analiza. Rezultati so pokazali višjo koncentracijo karbidotvornih elementov v slabem ulitku, zlasti na robovih. Izmerjena je bila mikrotrdota po Vickersu, pri čemer so nastopile težave zajemanja grafita v posamezen vtisek, vendar pa se je izkazalo, da je slabši ulitek trši od dobrega. Analiza mikrostrukture je pokazala, da ima dober ulitek predpisano mikrostrukturo iz perlitne osnove in grafita tipa A, velikosti 4–6. V slabem ulitku je poleg ozke izhodne avstenitne cone, ki se razteza v notranjost le približno 200 µm, opažena še prisotnost steadita, ki neugodno vpliva na lastnosti sive litine. Poleg tega je oblika grafita in njegova porazdelitev neenakomerna, kar se tudi izraža kot slabša obdelovalnost ulitka. V notranjosti ulitkov sta bili velikost in oblika grafita primerni, medtem ko je bilo na robovih opaziti, da se je strjevanje zlitine začelo po stabilnem sistemu z izločanjem primarnega avstenita, nadaljevalo pa po metastabilnem. Pri slabem ulitku je to območje segalo tik pod površino, pri dobrem pa bolj v notranjost. V slabem ulitku se je grafit razvijal večinoma z obliko B. V okviru raziskav vpliv kvalitete rezilnega orodja ni bil obravnavan.

Ključne besede: mikrostruktura, siva litina, končna strojna obdelava

1 INTRODUCTION

A central housing is a casting made of grey cast iron with lamellar graphite in the pearlitic matrix. It is the essential supporting component for a turbocharger, which is under heavy loads so the accuracy and quality of the final machining are essential. The final mechanical machining was carried out using common practice in casting from two different foundries.

The grey cast iron with lamellar graphite is an iron-based alloy with certain amounts of carbon and silicon.[1] It can also contain manganese, phosphorus and sulphur. The toughness and tensile strength of such a material are usually lower because of the graphite lamellae intersecting the metallic matrix, which may also cause a notch effect. Mechanical properties depend heavily on the quantity, size, shape and distribution of the graphite particles.[2–4] The notch effect is more pronounced if these are larger and vice versa.

Moreover, alloying elements can affect the machinability of grey cast iron with lamellar graphite, as grey cast iron with fine lamellae (which is due to the additions of modifying alloying elements) is very hard and has high strength[3]. In practice it is found that the greatest difficulty in the final machining of grey cast iron is the presence of the so-called hard spots.

Therefore, a comparison of the two castings of the central housing from two different foundries was performed in order to establish the effect of the microstructure on machinability. The reasons for the poor machinability of the castings can also be the cutting tools themselves, but this was not studied in this investigation.

The castings supplied by the first foundry were made with the Croning cast procedure, while in the second case the castings were cast into a bentonite-clay-mixture mould.

For a reliable identification of the constitution of grey cast-iron castings and revealing the cause(s) for the poor machinability, it is important to calculate the values of certain indicators of microstructural features. In our case we calculated the following ones: the graphitization factor (k), the amount of eutectic graphite (AEG), the degree of saturation (S_C) and the carbon equivalent (CE). For calculation purposes the data on chemical compositions were used as supplied by the foundries.

1.1 Calculation of the graphitization factor k (degree of graphitization)

In addition to the slow cooling rates, the cast iron should have a chemical composition ensuring a sufficiently high tendency to form graphite or a tendency towards graphitization. This criterion is met if the graphitization factor k is properly adjusted in relation to the cooling rate or wall thickness of the castings as expressed in the equation (1)[5,6]:

$$k = \frac{4}{3}\,\mathrm{Si}\left(1 - \frac{5}{3\mathrm{C} + \mathrm{Si}}\right) \tag{1}$$

1.2 Calculation of the amount of eutectic graphite (AEG)

$$\mathrm{AEG} = \mathrm{C}_{\mathrm{total}} - 2{,}0 + 0{,}1(\mathrm{Si} + \mathrm{P}) \tag{2}$$

The amount of eutectic graphite (equation (2)[6]) greatly influences the properties of grey cast iron (in addition to the state of the matrix – ferrite and pearlite or pearlite only[7]). Because of its physicochemical properties graphite has a strong, favourable influence in terms of tribology, namely, it reduces the friction and acts as a lubricant for the cutting tools.

1.3 Calculation of the degree of saturation (S_C)

The influence of individual elements on a eutectic composition is expressed with the degree of saturation, which is given as follows (Pfannenschmidt[8]):

$$S_C = \frac{\mathrm{C}}{4{,}23 - 0{,}312\mathrm{Si} - 0{,}330\mathrm{P} + 0{,}066\mathrm{Mn}} \tag{3}$$

1.4 Calculation of the carbon equivalent (CE)

Since grey cast iron contains the chemical elements that promote a formation of graphite instead of cementite, influencing the amount of carbon developed in the form of graphite, it is essential to use an equivalent amount of carbon in a Fe-C system according to the equation (4)[5]:

$$CE = \%\ \mathrm{C} + 0{,}30\ \%\ \mathrm{Si} + 0{,}33\ \%\ \mathrm{P} \tag{4}$$

2 EXPERIMENTAL WORK

In order to identify the cause(s) for the problems arising during the final machining of the castings (the good and the bad one), the following methods were used:

- Light optical microscopy (LOM);
- Chemical analyses via a mass spectroscopy – the results obtained from the foundries were verified;
- Microhardness measurements via Vickers hardness and
- Size, type and distribution of the graphite determination.

According to the given geometry and the final machining process, critical points on the castings were selected and samples were cut out using a water-cooled circular saw (**Figure 1**). The specimens were metallographically prepared and were suitable for determining the shape, size, type and distribution of the graphite without etching. Furthermore, the samples were etched (2 % nital), so that the constitution of the matrix was revealed along with the presence of the other microstructural constituents. The samples prepared in this way were suitable for the microhardness measurements and an investigation using LOM.

The microhardness measurements using the Vickers method were carried out on one good and two bad castings, using a Shimadzu microhardness tester. The used loads were of 100 g with the loading times of 10 s.

The method of LOM using a ZEISS Axio Imager. A1m microscope gave an insight into the size, shape and distribution of the microstructural components.

The procedure for determining the shape, size and type of graphite followed the EN ISO 945: 1994 instructions.[9]

Figure 1: Samples of the: a) good casting and b) bad casting
Slika 1: Vzorci: a) dobrega ulitka in b) slabega ulitka

3 RESULTS AND DISCUSSION

3.1 Calculations

For a reliable identification of the constitution of grey cast-iron castings and determination of the cause(s) for a difficult machining of a product, the values of certain indicators of microstructural features had to be assessed.

In both cases the graphitization factor was greater than 1, i.e., 1.713 and 1.528, which confirmed that the cast iron in our case was grey cast iron. In the good casting the graphitization factor was slightly higher than in the bad one. The values suggested that lamellar graphite should be one of the constituents of a microstructure. It was obvious that the bad casting had a smaller amount of eutectic graphite (1.566) than the good one (1.712), which, of course, caused poorer machinability of the bad casting. The values of the degree of saturation for both castings clearly indicated that microstructural differences in both castings were to be expected. In both castings the alloy was hypoeutectic, since the S_c was less than one in both cases (0.970 and 0.920). When the undercooling of the melt is taken into account (common in the foundry operations) the solidification starts with primary crystallization of both graphite and austenite. With a lower value of the S_C the amount of austenite in the microstructure was higher, thus, when the cooling was fast a higher quantity of pearlite was obtained, which increased the wear of the cutting tools. The values of the carbon equivalent were 4.165 in the good casting and 3.980 in the bad casting indicating that the bad casting is more hypoeutectic than the good one. These calculations alone do not provide sufficient grounds for predicting the casting behaviour during the final machining. Therefore, the measurements of microhardness, chemical analyses and a microstructural characterization of the castings were necessary.

3.2 Microhardness

Microhardness measurements for one good and two bad castings were performed. **Figure 2** shows the points of the microhardness measurements on individual castings. Points 1–6 (**Figure 2a**) on the good casting represent the edges where the process of the machining was carried out. Points 7 and 8 were in the inner region of the good casting. It should be noted that the imprints of the microhardness measurements very often included graphite. This is not in accordance with the principles of reliable hardness measurements, therefore the results are somewhat compromised. But for the evaluation of the casting machinability the hardness of the whole casting is important and, thus, the results clearly indicated why the machining of a bad casting was more difficult and the cutting-tool wear greater.

The microhardness on the edges of the good casting (points 1–5, **Figure 2a**) was 160–260 HV, while for the bad casting (bad 1) it was higher, as high as 350 HV (point 7, **Figure 2b**). Similar values were obtained with the microhardness measurements for the other bad casting (not in **Figure 2**), where the microhardness of the matrix was ≈335 HV. The results of the hardness measurements are graphically presented in **Figure 3**.

Apparently the highest microhardness was on the edges of all the castings, but for the bad castings the values were significantly higher. The difference between the maximum hardness of the bad and the good casting was almost 100 HV, which clearly indicated a higher probability of an increased wear of the cutting tools.

For the clarification of the reasons for the increased tool wear the microhardness measurements were not sufficient. Therefore, the data on the chemical compositions of the castings from the foundries were reviewed.

3.3 Chemical composition of the castings

The results of the microchemical analyses of the good and bad castings were compared considering the foundry data and are summarized in **Table 1**. Chemical analyses revealed small differences between the bad and the good castings in the contents of carbon, silicon and

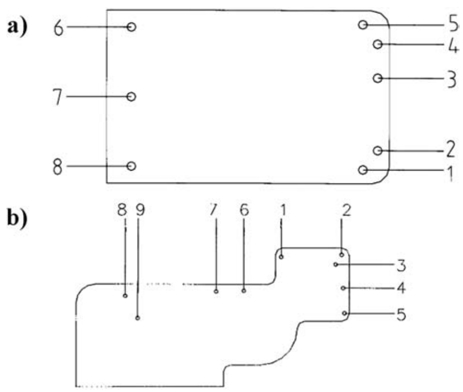

Figure 2: Areas of microhardness measurements: a) good casting, b) bad casting

Slika 2: Področja meritev mikrotrdote: a) dobrega ulitka, b) slabega ulitka

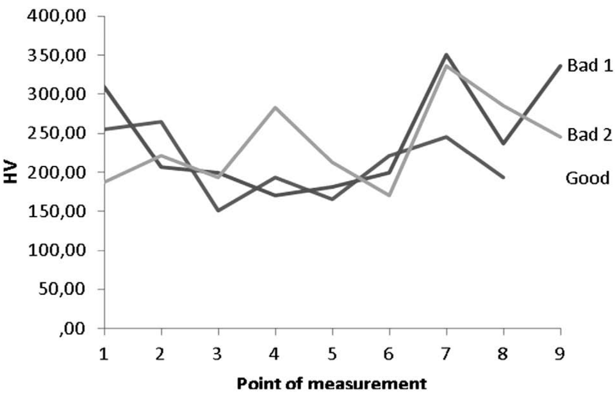

Figure 3: Microhardness measurements where the points of measurements correspond to the numbers in **Figure 2** for the two bad and one good casting

Slika 3: Mesta meritev mikrotrdote, ki odgovarjajo številkam na **sliki 2** v dveh slabih in enem dobrem ulitku manganese (**Table 1**). The good casting had higher amounts of carbon and silicon, while the content of manganese (as well as chrome, sulphur and phosphorus) was lower. This explained, to a great extent, the difference in the machining between the good and the bad castings.

Table 1: Results of the microchemical analyses carried out in the foundries in mass fractions (*w*/%)

Tabela 1: Rezultati mikrokemijskih analiz iz livarn v masnih deležih (*w*/%)

Element	Good casting (*w*/%)	Bad casting (*w*/%)
C	3.49	3.36
Si	2.13	1.96
Mn	0.51	0.79
Cr	0.06	0.07
P	0.45	0.11
S	0.05	0.06

Lower contents of silicon and carbon with increased levels of manganese meant a higher propensity to white solidification (in the bad casting) and, thus, a higher amount of pearlite. Chromium can also contribute to this by stabilizing and forming carbides, thus increasing the casting hardness. Furthermore, phosphorus formed hard microstructural constituents, for example Fe_3P, which appeared within the ternary eutectic (α_{Fe}+Fe_3C+Fe_3P) called steadite. Ultimately, the casting parameters and casting geometry can influence the homogeneity of a microstructure.

3.4 Metallographic analysis

In this part of the investigation the form and the distribution of the graphite was analysed first.

Based on the images of the good casting (**Figures 4a, b**) graphite was mainly of form A and size 4–6 and its skeleton showed a better contiguity than the one in the bad casting (**Figures 5a, b**). In the bad casting the graphite skeleton was frequently interrupted by austenitic areas, which were also more extensive. This caused a larger dynamic load for the cutting tools because of a great number of the transitions from the areas with a better machinability into the areas with a poorer machinability.

The constitution of the castings after the etching was determined also by using LOM. An image of the edge of the good casting (**Figure 6a**) showed a ferrite-graphite area, which had extended into the casting interior, where the matrix was slowly becoming pearlitic. It was obvious that the solidification of the casting was conducted separately with the primary solidification of the austenite on the edge of the casting and eutectic crystallization of the graphitic eutectic. Then the consecutive evolution of the microstructure followed the constitution of the Fe-Fe_3C system and the microstructure of the casting

a)
b)

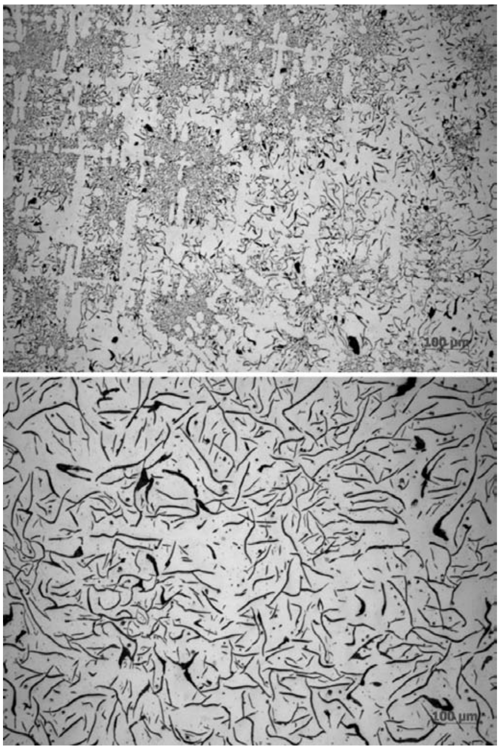

Figure 4: LOM images of the distribution and shape of graphite A, 4–6 in size, in the good casting

Slika 4: Posnetka porazdelitve in oblike grafita A, velikosti 4–6 v dobrem ulitku

a)
b)

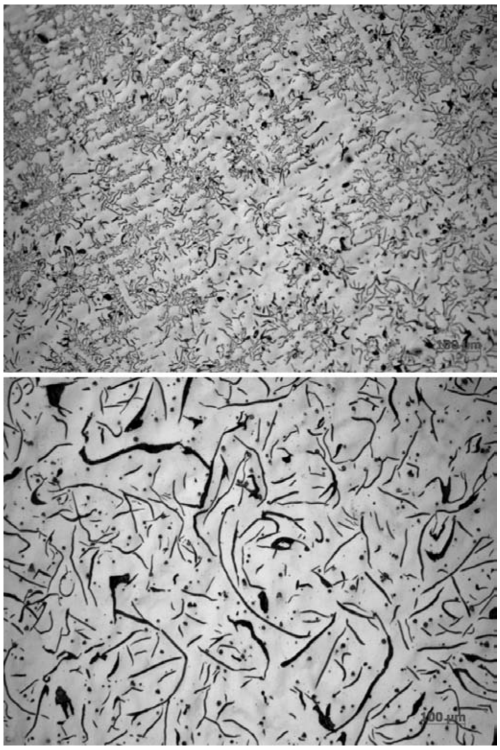

Figure 5: LOM images of the distribution and shape of graphite, showing larger graphite lamellae and a poorer contiguity of the graphite skeleton in the bad casting

Slika 5: Posnetka porazdelitve in oblike grafita, ki kažeta večje grafitne lamele in slabšo kontiguiteto grafitnega skeleta v slabem ulitku

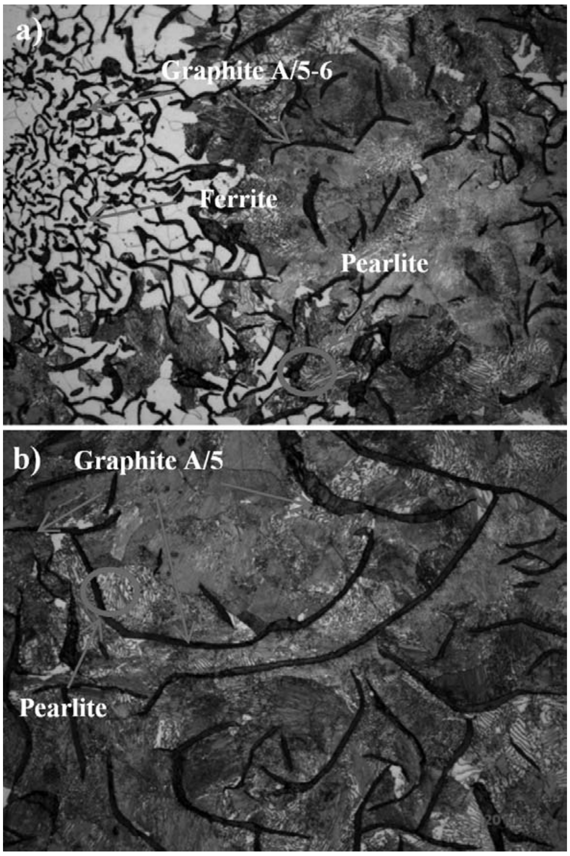

Figure 6: LOM images of the good casting: a) on the edge, showing a ferrite-graphite area and b) in the centre, showing fine lamellar pearlite and graphite lamellae

Slika 6: Posnetka mikrostrukture dobrega ulitka: a) na robu, ki kaže feritno-grafitno območje, in b) v sredini, ki kaže lamelarni perlit in lamele grafita

interior consisted of fine lamellar pearlite, interrupted by graphite lamellae (A5) (**Figure 6b**).

Furthermore, the ferrite-graphite zone situated mostly on the edge of the casting extended into the casting interior to a depth of ≈1200–1500 µm. This was exactly the depth to which the cutting tools reached during the final machining. According to the hardness measurements of the matrix on the edge of the casting and the presence of the graphite skeleton, it is clear that the good casting exhibited a better machinability and caused a lower wear of the cutting tools.

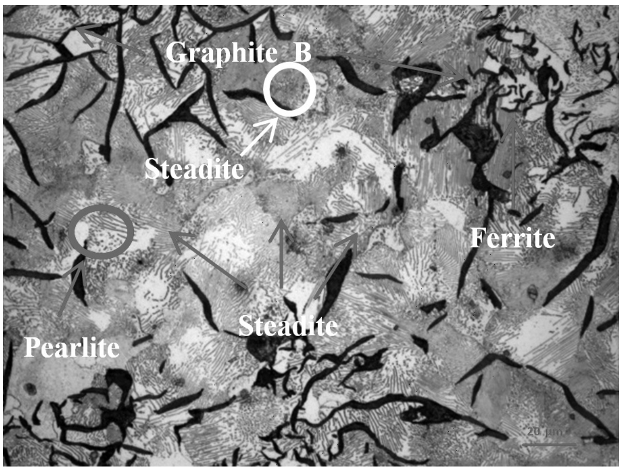

Figure 7: LOM image of the bad-casting edge, showing the pearlite matrix, graphite A-B, 4-5 in size, and steadite

Slika 7: Posnetek mikrostrukture roba slabega ulitka, ki kaže perlitno osnovo, grafit A-B, velikosti 4–5, in steadit

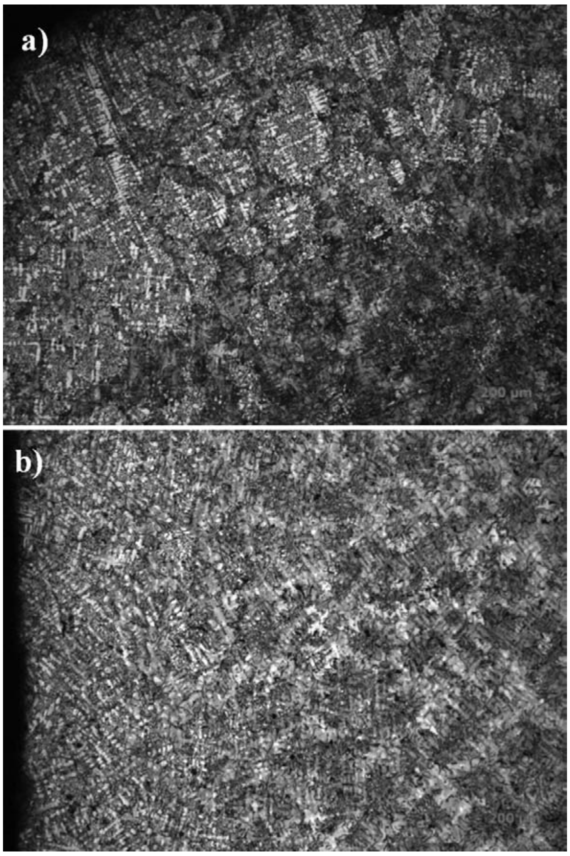

Figure 8: LOM images of: a) the good-casting edge, where the ferrite zone was ≈1200–1500 µm thick and b) the bad-casting edge, where the ferrite zone was only ≈200 µm thick

Slika 8: Posnetka mikrostrukture: a) roba dobrega ulitka, feritno območje sega ≈1200–1500 µm globoko v vzorec in b) roba slabega ulitka, feritno območje sega le ≈200 µm globoko v vzorec

Metallographic analyses of the bad casting showed a pearlite matrix and graphite (A–B and 4–5), but also the presence of steadite (**Figure 7**). In addition to steadite, the form of the graphite was less favourable in terms of the final machinability. The graphite skeleton also has a lower contiguity.

When comparing the depths of the ferrite zones in the good (**Figure 8a**) and bad castings (**Figure 8b**), it was obvious that the latter had a less profound ferrite zone. The depth of this area was only ≈200 µm in the case of the bad casting, while in the good one it was ≈1200–1500 µm. Thus, during the final machining of the bad casting, the cutting tool quickly reached the hard pearlite matrix, which also contained extremely hard and brittle particles of steadite. Because of the coarser and more unevenly distributed graphite in the casting, the wear of the cutting tools was even higher.

4 CONCLUSIONS

In this article the possible causes for a poorer final machinability of grey cast-iron castings with lamellar graphite are discussed and the potential reasons for the increased wear and failures of the cutting tools were presented. The conclusions can be summarized as follows:

- Established calculations confirmed that the investigated material was hypoeutectic grey cast iron with lamellar graphite. The calculations were not absolutely accurate and provided only the information about which type of grey cast iron was most likely to be formed.
- The hardness of grey cast iron with lamellar graphite was measured via Vickers microhardness, because it enables the measurements of the hardness of individual microconstituents and the matrix. The hardness of bad castings was higher than that of the good casting.
- Chemical analyses showed higher contents of manganese and phosphorus in the bad casting and higher silicon levels in the good casting.
- The casting edges of the polished samples showed a dendritic morphology, which was a result of the solidification sequence with primary austenite. Then it transformed into ferrite and graphite and/or into pearlite. In the casting interior we identified the size and shape A of graphite. In the bad casting a larger quantity of type-B graphite with fine lamellar graphite and uneven distribution of graphite was observed.
- The depths of the transformed primary austenite in the bad and good castings were compared and clearly the depth in the good casting was greater.
- Microstructural analyses showed a presence of graphite, pearlite and, on the edges of the casting, also the undercooled D graphite and ferrite. The bad casting also contained a significant amount of steadite, which was one of the main reasons for the difficult final machining of the central housing.
- The main reason for a poor machinability and greater wear of the cutting tools lies in the constitution of the microstructure. The nucleation of austenitic primary crystals and of the graphite from the eutectic is not optimal or it is even harmful. It is obvious that the transformed primary austenitic particles are relatively large. Undercooled forms of graphite were also observed.
- The influence of the cutting-tool quality should be taken into account when the final and definitive reason for the breakage and wear of cutting knives is determined.

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