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TESTING THE TRIBOLOGICAL CHARACTERISTICS OF NODULAR CAST IRON AUSTEMPERED BY A CONVENTIONAL AND AN ISOTHERMAL PROCEDURE

PREIZKUŠANJE TRIBOLOŠKIH LASTNOSTI NODULARNE LITINE, MEDFAZNO KALJENE PO KONVENCIONALNEM IN IZOTERMIČNEM POSTOPKU

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In this paper the heat treatment of ductile iron and the tribological properties of contact pairs (pin and disk) were investigated. Two types of nodular cast iron, EN-GJS-500-7 and EN-GJS-700-2, austempered using an isothermal and a conventional procedure, were tested. The friction-and-wear test was carried using a PIN on DISC Tribometer and the PQ test. The methodology of the classical and nodular cast-iron isothermal austempering and the methodology for the examination are also described. From analysing the results it was concluded that the tribological characteristics depend on the structural characteristic of the nodular cast iron, which are determined by heat treatment. The tested sample, austempered using a classic approach, gives the best performance in terms of friction, but it also showed the worst performance in terms of wear. In the same heat-treatment regime EN-GJS-500-7 is characterized by better tribological characteristics compared to the EN-GJS-700-2. The obtained results can be used for the proper selection of the type and regime of the nodular cast iron's heat treatment, with the aim of improving the exploitation characteristics of the contact pairs.

Keywords: nodular cast iron, heat treatment, friction, wear

Članek obravnava preizkušanje nodularne litine s toplotno obdelavo in tribološke lastnosti kontaktnih parov (klin in disk). Preizkušeni sta bili dve vrsti nodularne litine EN-GJS-500-7 in EN-GJS-700-2, medfazno kaljeni po konvencionalnem in izotermičnem postopku. Preizkus trenja in obrabe je bil izveden s "pin-on-disk" tribometrom in PQ-preizkusom. Prikazana je metodologija izotermnega poboljšanja klasične in nodularne litine ter metodologija preiskave. Analiza rezultatov je pokazala, da so tribološke lastnosti odvisne od značilnosti strukture nodularne litine, ki je določena z vrsto nodularne litine in toplotno obdelavo. Preizkusni vzorec, klasično medfazno kaljen, izkazuje najboljše rezultate glede trenja, hkrati pa največjo obrabo. V istem režimu toplotne obdelave ima EN-GJS-500-7 boljše tribološke lastnosti v primerjavi z EN-GJS-700-2. Dobljeni rezultati se lahko uporabijo pri izbiri primernega režima toplotne obdelave nodularne litine, z namenom izboljšanja lastnosti kontaktnih parov med rabo.

Ključne besede: nodularna litina, toplotna obdelava, trenje, obraba

1 INTRODUCTION

Modern materials used to create the elements of machinery, equipment and vehicles (cars, trucks, tractors, etc.) must possess, in addition to a high hardness, a good toughness and a high fatigue strength, as well as a more satisfactory resistance to friction and wear.[1,2] The first three properties of metallic materials are determined by standard methods. Information about them can be found in the relevant literature and standards, as well as in the technical documentation of the manufacturer of the materials.

The resistance to abrasive wear, as the tribological characteristic of materials, depends not only on their physical and chemical properties, but also on the conditions under which the contact between the elements of the tribomechanical system is achieved, as well as the properties of the other elements in the contact.[3] The measurement of the tribological properties of these two materials is carried out, usually on tribometers that fulfil one of the three possible geometries of contact (touch at a point on the line or on the surface). The paper presents the results achieved for a linear contact.[4,5]

In this paper, using a realized tribomechanical system with a geometric line contact, we examine the basic tribological properties of materials in terms of friction and wear. Part of the results of the tribological characteristics of the two types of nodular cast iron, isothermal and the improved classical procedure, obtained in laboratory conditions and presented in this study, indicate the importance of heat treatment on the resistance to friction and wear.[6–8]

The use of ductile iron in scientific research has a strong presence, so the paper[9] also considers the microstructures and tribological behaviour of different roller mill specimens, having basically nodular cast iron compositions, produced by conventional static and vertical centrifugal casting methods. Also, in the research work,[10] the initiative was taken to improve the surface hardness as well as the wear resistance of the as-received nodular cast iron using the pack-carburizing technique. The objective of the paper[11] is to evaluate the fatigue life of the nodular cast iron EN-GJS-500-7, which is used for railway brake discs. In the paper[12] the results of the abrasive and adhesive wear resistance of selected grades of nodular cast iron with carbides are presented. The materials of the friction pairs, tested at the stand and subjected to heat treatment and chemical processing in order to attain specific parameters of their surface layers, were studied in the work.[13] The studies conducted enabled a determination of the abrasive wear values for the material samples tested, having entailed the surface-layer parameters and the factors related to the operation of actual structural components used in automotive engineering.

Through a literature review we can see what has already been done in terms of the wear resistance of ductile iron.[14–16] The abrasion wear rates of two-step austempered ductile cast iron (ADI) were investigated.[17] The wear resistance of the ductile cast iron can be improved through a different heat-treatment procedure and surface engineering techniques, each having some limitations and drawbacks.[17,18]

A microstructure of lower bainite consisting of acicular (needle) bainite stable ferrite and carbon-enriched retained austenite, is provided if the isothermal transformation is carried out at low temperatures. The microstructure of the upper bainite, which consists of ferritetile bainite and stable carbon-enriched retained austenite is obtained if the isothermal transformation is carried at a temperature of 390 °C.

With isothermal transformation temperature the distance between the ferrite tile bainite increases while reducing the remaining shares, i.e., the volume fraction of retained austenite was increased.

The impact strength and the fracture toughness can be strongly reduced. The light microscope, however, does not show the difference in the microstructure. Therefore, for a detailed correlation of the mechanical properties depending on the microstructure it is necessary to apply a high-resolution transmission electron microscope (TEM).

For ductile iron of a ferrite base it is strongly recommend to use an isothermal transformation temperature of 350 °C.[19]

The objectives of the research were to prove that for a variety of thermal processing on the same material, a different value for the level of material wear is obtained. In addition, they want to show that the same level of heat treatment applied to different materials, for some sizes that represent the level of friction and wear, are of great importance and influence, whereas for some they are not.

2 EXPERIMENTAL PROCEDURE

2.1 Material

In all the experiments we used a hardened carbon steel (C40E) pin of guaranteed chemical composition and a hardness of 52 HRC. The test program includes two types of nodular cast iron, EN-GJS-500-7 and EN-GJS-700-2, austempered by an isothermal and conventional procedure.[19,20]

The melting of the material was carried out in a network frequency induction furnace pot with an acid coating capacity of 2.5 t in a foundry. After this the desulfurization was carried out in a batch nodulation closed pot using a "sandwich" method with a simultaneous modification at a temperature of 1500 °C. A secondary modification was made before the actual casting. The as-prepared metal was poured into a total 11 Y tube to BS 2789.

All the Y tubes were covered by two tube sections, 25 mm diameter and length 250 mm. Attention was also given to two tubes by tensile tests in the irons JUS C.J2.022 and three tubes with V-notch toughness testing JUS C.A4.004.

The isothermal austenitising was performed in a muffle furnace in a protective atmosphere at 900 °C for 90 min prior to preheating at 520 °C for 60 min. The austempering was carried out in a solar bath (made specifically for this purpose) at a temperature of 390 °C with a hold time of 30 min at a speed of movement for the salts of 0.6 m/s.

Their basic characteristics are listed in **Table 1**.[19] We present the chemical composition, the conventional austempering regimes, the isothermal austempering and the hardness of the tested parts.[21]

Figure 1 shows the metallographic structure of the nodular cast iron used in the test. It is important to mention that the EN-GJS-500-7 is ferrite-pearlite structure

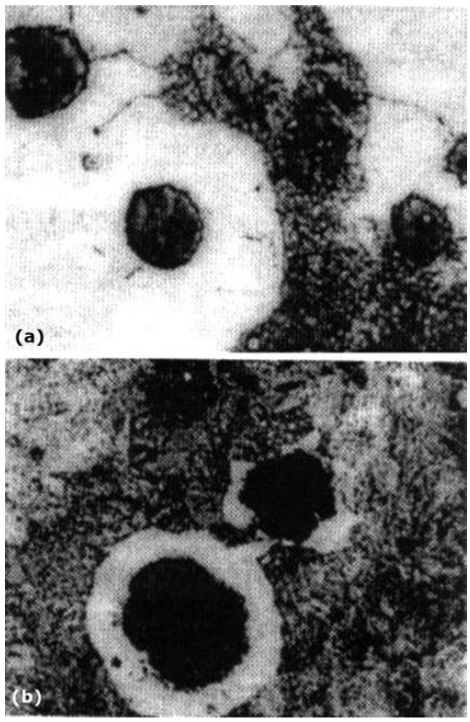

Figure 1: Microstructures of: a) EN-GJS-500-7 and b) EN-GJS-700-2
Slika 1: Mikrostruktura: a) EN-GJS-500-7, b) EN-GJS-700-2

Table 1: The chemical composition and heat-treatment regimes of nodular cast iron EN-GJS-500-7 and EN-GJS-700-2
Tabela 1: Kemijska sestava in režimi toplotne obdelave nodularne litine EN-GJS-500-7 in EN-GJS-700-2

Material of Disk	Heat Treatment			Hardness HB	Legend		Structure	
	T_a/°C	T_p/°C / t/min						
EN-GJS-500-7	900	390/30		355	EN-GJS-500-7-30		ferrite-pearlite	
		520/60		302	EN-GJS-500-7-k			
EN-GJS-700-2		520/60		320	EN-GJS-700-2-k		mostly pearlitic	
		390/30		365	EN-GJS-700-2-30			
	Chemical composition, w/%							
	C	Si	Mn	Mg	P	S	Cu	Ni
EN-GJS-500-7	3.85	2.9	0.076	0.035	0.02	0.004		1.5
EN-GJS-700-2	3.76	2.35	0.51		0.02	0.004	1.48	1.5

based (50 % ferrite and 50 % pearlite and more than 90 % of graphite-type-K size 3) and the EN-GJS-700-2 is predominantly pearlitic-structure based. During the structural test of the nodular cast iron the etching was performed with 2 % HNO_3 and increased 500-times. **Figure 1** shows that the black parts have a pearlitic structure, and the white parts are a softer ferrite structure. In the middle are the visible graphite nodules surrounded by a highly visible ferrite structure.[4]

Figure 2 shows the austempered ductile iron microstructure. The mechanical properties depend on the structure of the material. One pearlitic ductile cast iron has, before the isothermal treatment, an improved microstructure consisting of pearlite, and in it are the graphite nodules. After the isothermal improvement the material microstructure consists of bainite and retained austenite. The amount of retained austenite is relatively high (aged between 20 % and 40 %). The austenite contributes to the high toughness and the ductility of the austempered ductile iron.

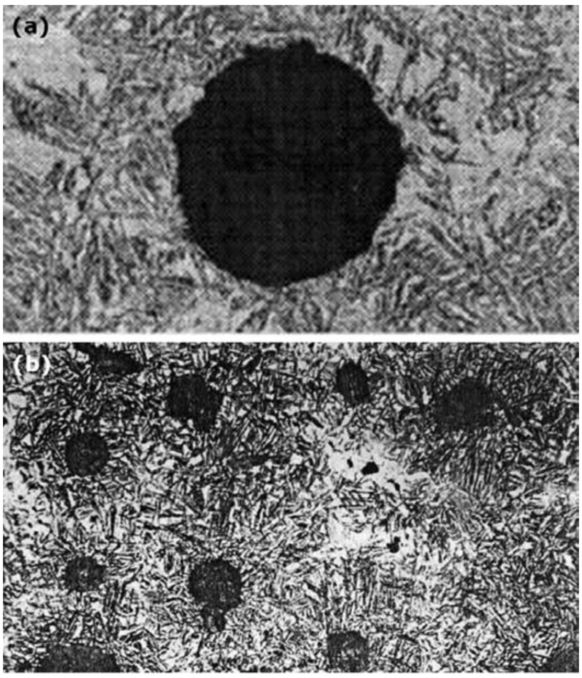

Figure 2: Microstructure of austempered ductile iron: a) EN-GJS-500-7 and b) EN-GJS-700-2
Slika 2: Mikrostruktura izotermno poboljšane nodularne litine: a) EN-GJS-500-7, b) EN-GJS-700-2

Irons that were improved during a low-temperature isothermal transformation have a structure of lower bainite and about 400 HB hardness (HRC about 43), and are suitable for first gear and applications that must be resistant to high pressures.

Irons that were improved at higher temperatures of isothermal transformation have an upper bainite structure and a hardness from 260 HB to 350 HB (HRC 27 to 38), and have a particularly high ductility, impact strength and fatigue strength.

Figure 3 shows a diagram of the classical austempering procedure of nodular cast iron.[14] The process of austempering conventional materials was achieved by heating up to a temperature of 900 °C, where it is held for about 90 min and then by rapid cooling (water or air) to room temperature. After this it is heated to a temperature of 520 °C and is then cooled to room temperature.

Figure 4 shows a diagram of the discs' isothermal austempering, made of an EN-GJS-500-7 ferrite-pearlite base and an EN-GJS-700-2 made of a very pearlite base. The austempering is done by heating the disks to a tem-

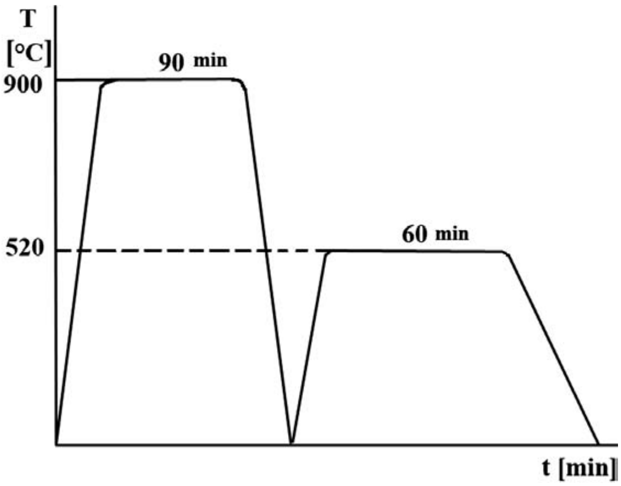

Figure 3: Diagram of conventional discs' austempering
Slika 3: Diagram klasičnega poboljšanja ploščic

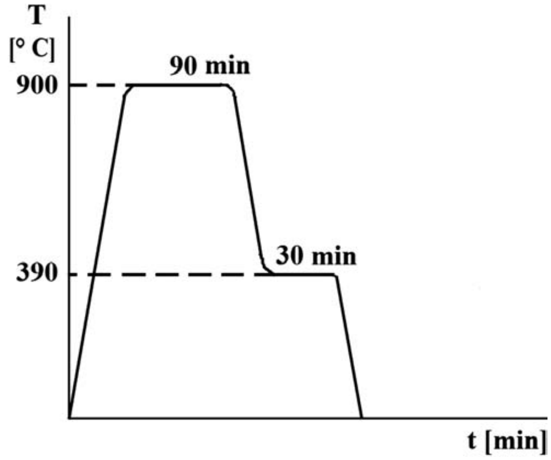

Figure 4: Diagram isothermal discs' austempering
Slika 4: Diagram izotermičnega poboljšanja ploščic

perature of 900 °C, at which it is held for about 90 min, and then fast cooled to a temperature of 390 °C.

The discs of EN-GJS-500-7 and EN-GJS-700-2 were kept for 90 min and 30 min at the temperature of 390 °C. In this way we get a bainite structure (upper or lower bainite) that enables improved toughness, and in this case the wear resistance (abrasion of discs).

2.2 Method

Figure 5 provides a schematic view of the contact pair (pin and disk) and an image using the Tribometer TPD-93 where the coefficient of friction is measured for the inline contact.[5] With this equipment it is possible to measure the friction force, the normal force, the coefficient of friction, the acoustic emission temperature of the oil and the contact temperature. The characteristics of the tribometer are: normal load 1–500 N, sliding speed 0.1–5 m/s, the motor power A is 1.5 kW, the motor power B is 0.37 kW, and the overall dimensions are 1 200 mm × 600 mm × 1 300 mm.

By measuring the normal and friction forces at different levels of load and sliding speed v = 1.3 m/s, the friction coefficients for a given combination of contact pairs are determined. In the given range of load F_n = 1–3 N the differences in friction coefficients are less than 5 %, so the comparison is the heat-treated nodular cast iron EN-GJS-500-7 and EN-GJS-700-2 derived for the adopted level of load F_n = 2 N. This force was set on the tribometer.

To determine the *PQ* index we used the *PQ* 2000 Particle quantifier shown in **Figure 6**. According to the procedure methodology the value of the *PQ* index is directly proportional to the quantity of the wear products (greater than 5–10 μm) that are contained in the oil used for lubrication of the contact zone, during the disk sliding along the pin. For this purpose the used oil was Polar INA 55-K.

The *PQ* index is the average value obtained from several measurements. The average measurements of the

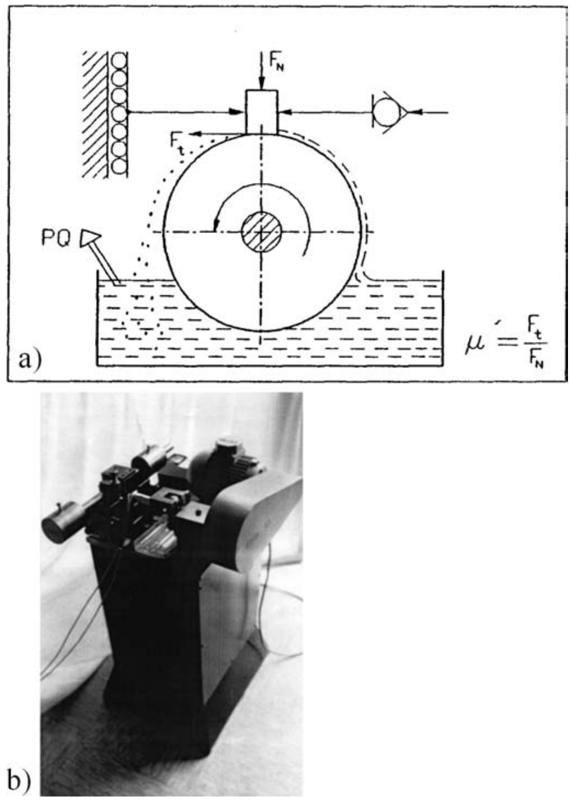

Figure 5: a) Schematic view of the contact pair (pin and disk) and b) image of Tribometer TPD-93
Slika 5: a) Shematski prikaz kontakta para (pin in disk) in b) tribometer TPD-93

PQ index for a sample of oil containing products in the research conducted was 10. In most cases the measurement error did not exceed 10 %.

The duration of the contact in the experimental operations was about 30 min. The friction force was measured at the beginning and at the end of the actual contact (t_p = 1 min, t_k = 29 min). There was a line contact

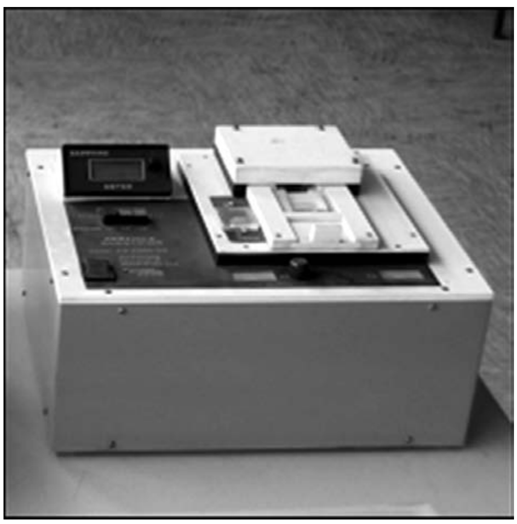

Figure 6: PQ 2000 Particle quantifier
Slika 6: Kvantifikator delcev PQ 2000

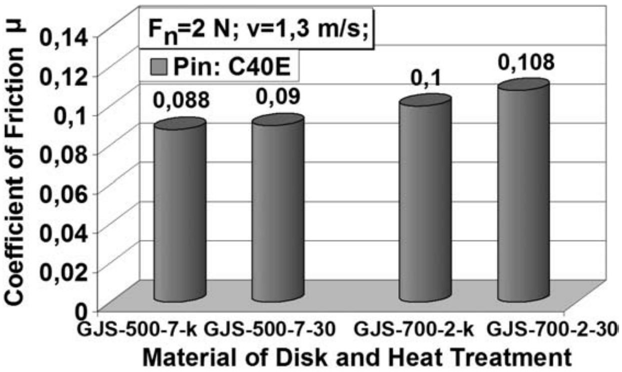

Figure 7: Histogram of the obtained friction coefficients for the tested materials
Slika 7: Histogram prikazuje dobljene koeficiente trenja preizkušanih materialov

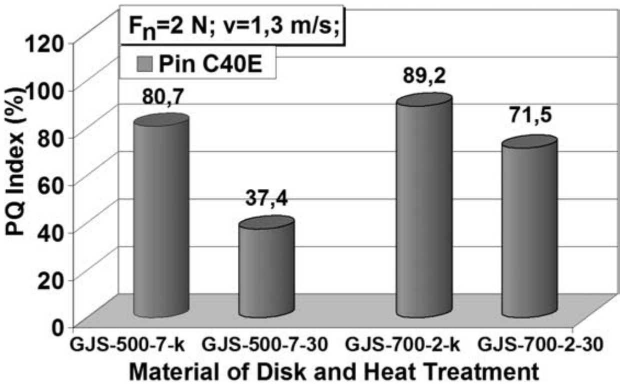

Figure 8: Histogram values of PQ index
Slika 8: Histogram prikazuje dobljene vrednosti PQ-indeksov

between the pin and the disc. The measurement of the *PQ* indices in a sample of oil in which there are wear products was performed 3 times on 10 samples.

The *PQ* index was determined based on the quantity of wear products per mg of oil produced during the sliding of one element of the tribomechanical system over the other for t = 30 min. The different values of the *PQ* index indicate the amount of wear product for the samples in contact in the lubricant are a direct consequence of the greater or lesser intensity of the wear of the contact pair. The test covered above thermally austempered discs of nodular cast iron EN-GJS-500-7 and EN-GJS-700-2. The wear of the pins for 30 min was carried out under the same contact conditions and based on samples of oil particle quantifiers over the levels of the *PQ* indices.

3 RESULTS AND DISCUSSION

3.1 Experimental results

3.1.1 According to the experimental results

In order to determine the influence of the heat-treatment type on the tribological properties of ductile iron, on two types of ductile iron EN-GJS-500-7 and EN-GJS-700-2, the test of the friction and wear according to a pre-defined methodology of experimental research was conducted. **Figure 7** shows the histogram displaying values of the friction coefficients at the line of contact for the disc and pin, obtained from the derived values of forces, recorded by the measuring instrumentation. The histogram shows that the heat treatment of the ductile iron EN-GJS-500-7 has a small (approximately 2 %), practically negligible, impact on the value of the friction coefficient. Simultaneously, the EN-GJS-700-2 ductile iron isothermally improved by about 8 % higher coefficient of friction than the same nodular cast iron improved using the classical procedure. On the other hand, the coefficient of friction in a ductile iron EN-GJS-700-2 increased by 15–20 % more than the values that were obtained for ductile iron EN-GJS-500-7.

Figure 8 shows a histogram of the *PQ* index values for the observed contact pairs (pin and disk), the load level of 2 N and the slip velocity v = 1.3 m/s. The histogram displays the values of the *PQ* index, different than the coefficient of friction, which shows that the treatment regimens have a very large impact on the aspects of wear. In both nodular irons the *PQ* index is higher for iron improved by the classical procedure, especially for EN-GJS-500-7 (approx. 115 %). On the other hand, the ductile iron EN-GJS-500-7, improved the isothermal and classic approach, has a significantly lower *PQ* index for iron EN-GJS-700-2 (approx. 10–90 %).

Figure 9 shows a comparative review of the tribological characteristics of the tested discs, in terms of friction and wear, i.e., by the indicators $P_t = \mu_r/\mu_x$ and $P_h = PQ_r/PQ_x$. Here, μ_r and PQ_r are the values of the friction coefficient and the wear index of the reference contact pairs (it was a material austempered using the classical procedure), whereas μ_x and PQ_x are the values of the investigated contact pair. In doing so, for the reference a contact couple with the lowest coefficient of friction and wear is chosen, which receives the same indicator value for the maximum of 100 %.

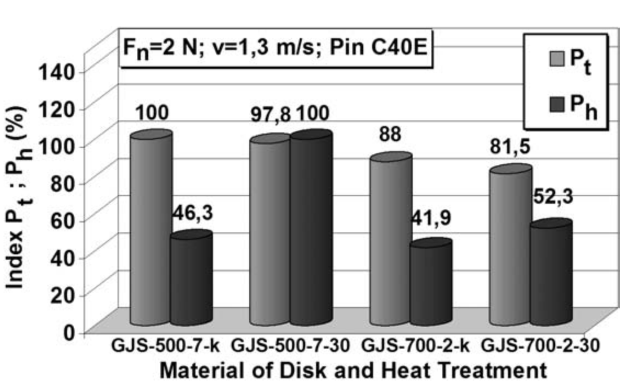

Figure 9: Histogram P_t, P_h index of the tested materials with different heat treatments
Slika 9: Histogram P_t, P_h-indeksov preizkušenih materialov z različno toplotno obdelavo

3.2 Discussion

By analysing the results obtained, it can be concluded that ductile iron, austempered using the classic approach, has different tribological properties in terms of friction and wear.[6,7,14–17] The tribological characteristics significantly depend on the type of nodular cast iron, and the heat treatment.

By comparing the tribological characteristics of the tribomechanical system elements, made of some kind of ductile iron, some coefficients of friction lead to the conclusion that the thermal treatment has no practical impact. Differences in the tribological characteristics of the same elements, however, are very large if the tribological characteristics are determined by the size of their wear, which occurs after a specified duration of the contact.

The difference in the coefficients of friction is slightly higher when comparing the two studied materials. The coefficient of friction of the ductile iron EN-GJS-700-2 is slightly larger than the coefficient of friction of the material EN-GJS-500-7.

The *PQ* index is higher in the material EN-GJS-700-2. Both classical materials' heat-treated *PQ* index is greater than the isothermally processed material. Based on this we can conclude that the higher wear is in the conventionally heat-treated material. The isothermal heat treatment helps to reduce the wear of these materials

The indicator of the friction coefficient between the investigated disks P_t is higher for the classical heat-treated material. Also, the indicator P_t is significantly lower for the material EN-GJS-700-2, which suggests that the friction is less for this material. The values of the parameters P_h are higher for the materials EN-GJS-500-7, whether it is a classic procedure or isothermally processed. It is confirmed that the materials that are isothermally processed have less contact wear than the classically heat-treated materials.

4 CONCLUSIONS

The tested sample, a disc made of EN-GJS-500-7 austempered using the classic approach, gives the best performance in terms of friction, but it also showed the worst in terms of wear. The disc made of a hardened EN-GJS-500-7 and isothermally austempered has excellent features from the point of view of friction and wear. In the same heat-treatment regime EN-GJS-500-7 is characterized by better tribological characteristics than the EN-GJS-700-2.

The laboratory studies of the improved tribological properties of nodular cast iron can be used during the selection of materials and heat treatment in order to reduce the friction and wear in the contact pairs' exploitation conditions. Further research is planned to follow the tribological properties of selected materials in specific industrial conditions.

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