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KEY DETERMINANTS FOR HIGH-ALLOYED CAST IRONS FOR MECHANICAL ENGINEERING

H. PACHA-GOŁĘBIOWSKA*
Polytechnic Institute, Jan Komenski University of Applied Sciences, Leszno, POLAND
E-mail: h.pacha.g@gmail.com

W. PIEKARSKA
University of Technology, Faculty of Architekcture, Civil Engineering and Applied Arts
ul. Rolna 43, 40-555, Katowice, POLAND

This work presents the factors determining cast iron, and particularly austenitic high-alloy cast iron as a construction material, which is ranked among the leading casting alloys of iron with carbon, mainly due to its very good service properties, which makes it dedicated as a material for automotive castings, pipe and fitting castings and components resistant to elevated temperatures, corrosion and abrasive wear. Construction materials currently used in industry have increasingly better properties and their potential is depleting quickly. This forces the manufacturers to adjust the requirements and production capabilities of cast iron using the most modern technologies that give the expected beneficial economic and operating effects. The paper quotes the results of research in the field of the offered technologies that give special surface features to machine parts made of cast iron by modernising the parameters of the technological process of obtaining high-alloy austenitic cast iron, i.e., by applying coatings, as well as by appropriate surface treatment, the aim of which is and reinforce the material surface with those properties which are important in a given application.

Key words: alloyed cast iron, wear, machining conditions, alloying additives, coatings, roughness.

1. Introduction

According to various hypotheses relating to the origins of casting, cast iron as a construction material was invented in China in the 5th century BC, and became available in Europe around the 15th century (1454) [1-12]. Some evidence of knowledge on the properties of cast iron, i.e., its resistance to load/stress coupled with lack of tensile strength can be traced to those times. The inventors in those days knew that cast iron was relatively brittle compared to steel, and that it was impossible to use this material for applications where a sharp edge, plasticity and flexibility were required [1].

Initially, cast iron was used to make pots, pagodas and tools. But ever since a method of annealing cast iron to strengthen the surface layer and produce a less brittle surface was developed in ancient China, cast iron found wider application in the world economy at that time [1, 12]. For example, the Ni-Resist austenitic chromium-nickel-copper cast iron was introduced at the beginning of the 20th century and used to construct diesel engine cylinder blocks given its resistance to corrosion [13].

However, “the most important period in the history of mankind.... has always been and always will be the present” [14]. Modern technology poses ever higher demands on the durability and reliability of machines. This presents designers with the daunting task of developing, for example, an increasingly perfected, but yet cheap friction node. The potential contained in the materials used is depleting quickly and therefore it is necessary to use state-of-the-art technologies that produce the expected beneficial economic and operational effects [15, 16].

* To whom correspondence should be addressed

The processing of both high-alloy and alloyed cast iron and other iron-based alloys involves the use of Critical Raw Materials (CRM), a list of which was defined by the European Commission based on economic importance. The review includes, among others, alternative iron-based materials without CRM and with low CRM, such as austempered ductile iron. According to projections by the Organisation for Economic Co-operation (OECD), progressive industrialisation, digitalisation, transition to climate neutrality with the use of metals, minerals and biotic materials in low carbon technologies and products will more than double the demand for critical raw materials (e.g. arsenic, cadmium, strontium, zirconium and hydrogen) from 79 billion tonnes today to 167 billion tonnes in 2060 [65]. It is worth noting the great interest in cast irons developed in recent years with improved properties that are comparable to those of cast or forged steels and even aluminium castings in terms of specific strength. The improvement of cast iron properties is achieved by various additional heat treatments, surface treatments or by adding different particles [64].

On the one hand, these actions make it possible to give machine parts characteristics inherent in certain specific materials. This is done by applying all kinds of coatings, thanks to which cheap materials can exhibit the desired special surface features. This matters when the core of the material has sufficient strength and it is important to improve the surface properties of the element, e.g., hardness, wear resistance, resistance to scuffing, etc.

On the other hand, operational functions of machine parts can be improved by appropriate surface treatment, the purpose of which is to extract and reinforce the surface of the material with those properties that are essential for a given application [17].

However, what is most important for high-alloy cast iron, is obtaining an austenitic structure of castings dependent on the introduction into the alloy of a sufficiently high, total content of elements blocking transformations that may occur during uneven cooling of castings [18].

The structure and properties of castings are determined not only by their chemical composition but also by the parameters of the technological process, such as the cooling rate in the casting mould [18]. Therefore, it seems appropriate to attempt a comprehensive assessment of the determinants/factors predisposing high-alloy cast iron for use in the automotive industry.

2. The influence of alloying additives on the mechanical properties of cast iron

Mainly due to its very good functional properties, high-alloy austenitic cast iron ranks among the leading iron-and-carbon casting alloys [19, 20]. Ductile iron components are often metallurgically optimised to obtain the most homogeneous microstructure possible. This results from the established guidelines for strength confirmation, which are based on the strength parameters published in standards such as [23] including three categories of microstructures and properties depending on the wall thickness [24].

The production of high alloy austenitic cast iron [67] was launched in 1930 by International Nickel Ltd. under the name Ni-Rezist [19]. This cast iron, in its numerous varieties and with special physical properties, has found multiple applications as a material resistant to chemical corrosion, as well as to both high and low temperatures and to gas corrosion [21]. The mechanical properties of cast iron are extremely important as basic indicators for the assessment of the quality of machine and equipment parts subjected to various static or dynamic loads during operation [22].

The structure of such cast iron consists of austenite and graphite, often with eutectic carbide precipitates, and is obtained as a result of a temperature shift of the eutectoid transformation; such shift resulting from the impact of nickel, copper and magnesium [19].

Taking into account research results (Janus, [25]), the author has proved that lowering the nickel content, its partial replacement with manganese and copper, and application of heat treatment such as annealing, produce/generate cast iron with good strength properties. However, this is related to metal matrix structure changing from austenitic to bainitic or martensitic, which causes an increase in the casting hardness, thus worsening their machinability. Even though, as it can be found in relevant literature [26], increasing the strength of Ni-Mn-Cu cast iron by changing the form of the graphite from flake to ball may be difficult due to relatively high copper content, after applying spheroidization [25] to an alloy composed of *3.0-3.3%* C, *1.9-2.2%* Si, *3.0-4.5%* Mn, *7.0-11.0%* Ni, *0.5-3.0%* Cu, *0.l-0.2%* P, max *0.04%* S using Si75T ferrosilicon, the author (Janus, [25]) obtained a basis for determining that carbon, silicon, nickel and copper increase the eutecticity degree of the cast iron, while manganese slightly decreases it. The influence of nickel, manganese and copper is much weaker than that of carbon and silicon. The spheroidization did not result in significant changes in the influence of these elements. Moreover, increasing the content of nickel, manganese or copper causes a decrease in the temperatures of the start and end of the martensitic transformation. Manganese stabilises austenite to the greatest degree, whereas the effect of copper is the weakest. Spheroidization resulted in a change of the graphite form from flake to regular ball graphite. In alloys with increased copper and manganese content, irregular ball graphite also appears (Fig.1a.), and the structure of the metal matrix is austenitic (Fig.1b) [26].

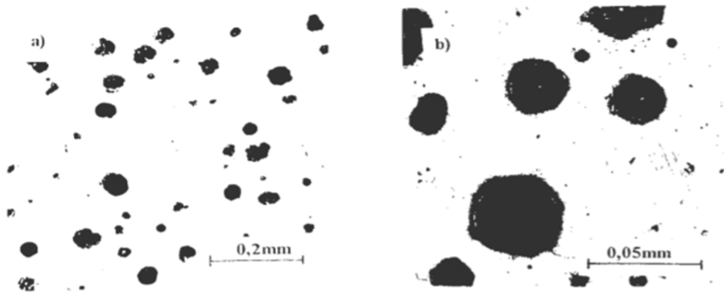

Fig.1. Structure of Ni8Mn4.5Cu3 cast iron; a- graphite, b- austenitic metal matrix [26].

The change of graphite form from flake to ball caused R_m to more than double. Cast iron containing *8.0%* Ni, *4.5%* Mn and *2.5%* Cu exhibits the greatest strength. In alloys with the best mechanical properties, the R_m strength is *420-450 MPa* at elongation A_5 *8.5-10.0%* and hardness *220-240 HB*.

Table 1. Chemical composition of the obtained ductile iron [27].

Cast number	Content								
	C	Si	Mn	P	S	Mg	Ni	Cr	V
1	*3,5*	*2,7*	*0,3*	*0,05*	*0,006*	*0,08*	*9,7*	-	-
2	*2,8*	*2,3*	*4,0*	*0,04*	*0,015*	*0,08*	*23,0*	-	-
3	*3,0*	*2,3*	*4,1*	*0,04*	*0,010*	*0,05*	*24,2*	*1,2*	-
4	*3,0*	*2,1*	*3,5*	*0,03*	*0,009*	*0,08*	*24,0*	-	*0,63*
5	*2,4*	*3,0*	*4,0*	*0,05*	*0,010*	*0,08*	*25,0*	-	*0,65*

Table 2. Description of the graphite precipitates and matrix of the ductile iron tested [27].

Cast number	Graphite form	Matrix
1	Gf9 – Gw *90/60%* Gf8 – Gw *90/40%*	martensite + austenite
2 3 4 5	Gf9 – Gw *90/40%* Gf8 – Gw *90/60%*	austenite +eutectic and secondary carbides

Despite the development of several factors, determining the structure and properties of austenitic ductile cast iron, the author [27] pointed to the need to determine and present the optimum chemical composition of cast iron, selection of metal batch charge composition and an appropriate technological process for the production of cast iron. The original cast iron, with the following chemical composition: C=*2.8-3.4%*, Si=*2.3-3.0%*, Mn=approx.*4.0%*, P=approx.*0.4%*, S=approx.*0.015%*. Ni=*10.0-25%*, Cr=*1.0-1.2%*, V=*0.5-0.8%*, was tested. FeNiMg17 master alloy was used for spheroidization, and then Si75 ferrosilicon was used for the modification procedure [27]. In four out of five melts (Tables 1, 2 [27]) samples of austenitic matrix ductile iron were obtained (Fig.2) [27].

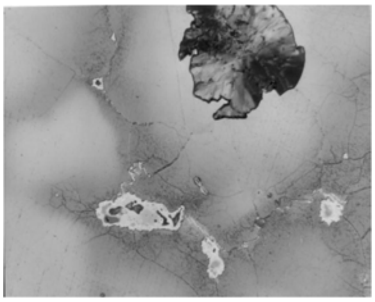

Fig.2. Microstructure of ductile iron from melt No. 2 (Tab.1). austenite + carbide phase + graphite. Grav. Ni15Fe, pow. [27].

The conducted research (Tabor and Rączka, [27]) shows that in order to ensure high quality of austenitic matrix ductile cast iron, the chemical composition of the initial cast iron before spheroidization should fit the ranges: *3.0-3.5%* C, *1.8-2.0%* Si, *3.5-4.0%* Mn, *0.04%* P, *0.02%* S, *20-24%* Ni, using a magnesium-nickel master alloy containing *17%* Mg in the amount of *1.8-2.0%* in relation to the weight of the metal, thus ensuring that the magnesium content in the cast iron be within the range of *0.03-0.05%* Mg. Additionally, the casting temperature of the cast iron and the mould type significantly influence the formation of the correct cast iron structure. As evidenced by research, the casting temperature should be maintained within the range of $1380-1400^{\circ}C$, while the mould material should ensure free solidification and cooling of castings; and what proves beneficial to optimise mechanical properties is the homogenisation of castings.

Another researcher Jura and Jura [28] stresses the influence of elements and the degree of graphite spheroidization in cast iron on its mechanical properties. Manganese influenced the Rm strength of cast iron to the largest degree. This element has a decisive influence on the structure of cast iron. Low manganese content favours the formation of a ferritic structure, whereas its high content favours the formation of a perlitic structure. The impact of phosphorus is marginal, mainly due to its low content. The degree of graphite spheroidization influences R_m strength significantly. The elongation of ductile cast iron is significantly influenced by manganese (Mn), phosphorus (P) and the relative, volumetric proportion of very fine graphite precipitates. The greater the amount of graphite, the lower the A_5 elongation. The author [28] has also proved that the addition of manganese greatly increases the hardness of cast iron, which promotes the formation of a perlitic structure. Phosphorus, which forms a solution and strengthens the cast iron matrix, has a similar effect. Silicon promotes graphitization and thus increases the amount of ferrite in cast iron. Moreover, results obtained by another author [19] indicate a significant effect of the chemical composition of cast iron on the tensile strength of cast iron (at *1.5-2%* wt. Si content) depending on temperature from R_m value of ca. *400 MPa* at ambient temperature to ca. *630 MPa* in $-270^{\circ}C$.

Alp *et al.* [29] demonstrated the strong influence of the microstructural state, i.e., shape and distribution of graphite, on the mechanical and physical properties of graphite cast iron. He found that the cooling rate greatly influences the size and distribution of graphite crystals. According to the author, during cast iron solidification, as the temperature is lowered, the eutectic solidification in the interdendritic fluid begins, the eutectic being Fe-Fe3C or Fe-graphite. Depending on their composition, structure, continuity and fineness, the proeutectic dendrites strengthen the cast iron. The properties of dendrites are significantly influenced by the transformation in the solid-state, which in turn depends on the composition of the austenite and the cooling rate. The formation of perlite, which increases the strength of alloyed cast irons, is in turn fostered by a fast cooling rate, alloying elements such as Mn, Ni, Cr and trace elements such as Cu, Sn, Sb, As. Fig.3 presents the influence of perlite on mechanical properties in spheroidal graphite irons.

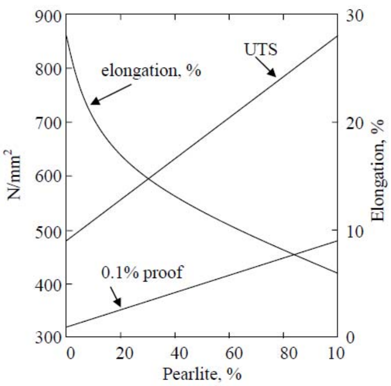

Fig.3. Effect of pearlite fraction on mechanical properties in spheroidal graphite irons [30].

Heat treatment, such as austempering in the case of ductile irons or isothermal heat treatment to produce a bainitic matrix, can result in extremely high cast iron strength combined with good elongation [21]. Alp *et al.* [29] has shown that in various cast irons the mechanical properties are more dependent on the microstructure than on the chemical composition. For example, coarse-flake graphite cast irons exhibit lower tensile strength than fine-flake graphite cast irons. In alloyed cast irons, changing the matrix from a ferritic to a perlitic increases strength but reduces ductility. More intensely intertwined and less sharp ferrite needles were found to reduce the stress concentration effect [31].

According to Studnicki *et al.* [32], the chemical composition affects the hardness of cast iron both by influencing the type and hardness of the matrix and by affecting the proportion, form, size and type of the other components of the alloy structure. With an increase in the silicon content in the cast iron, the value of the modulus of elasticity initially decreases as a result of an increase in the gratification capacity of the cast iron (in the range up to *3%* wt. Si), and then, with a further increase in the silicon content (silicon reduces the solubility of carbon in the matrix), this value increases with particularly high values of the modulus of elasticity being obtained for medium-silicon cast iron (ca. *5%* wt. Si) cast in vacuum.

Alloying additives cause an increase in ferrite hardness (Fig.4.) as a result of the deformation of its crystal lattice [19].

As can be seen from Fig.4, silicon greatly influences the impact strength of ferrite, especially with its contents exceeding *0.6%* wt.However, once silicon content exceeds *2%* wt, no significant effect on the impact strength of cast iron was found [22]. The introduction of *1%* by weight of chromium into the cast iron increases the impact strength, but a higher content of this element significantly reduces this strength [34].

In turn, the hardness of cast iron grows with an increase in the content of carbide-forming elements that form durable carbides (Cr, Mn, V). As silicon content rises, cast iron hardness decreases initially, until a ferritic matrix is created in the cast iron (approx. *3%* wt. Si). With a further increase in silicon content, the hardness gradually increases, reaching a hardness of *300-460 HB* in high-silicon cast iron [22].

The overall quality of ductile iron is characterised by the amount of ferrite and pearlite, which is classically controlled by the addition of alloys with Mn and Cu. Other elements that stabilise ferrite/perlite can contribute to the eutectoid transformation, such as increased Si content in cast iron strengthened in solid solution according to the standard [23]. Furthermore, the surface properties of the casting can be influenced by specially regulated contact conditions between the alloy and the moulding material. These include locally applied additives and the influence of flow and cooling conditions on the solidification kinetics of the surface layer. As reported [24], in addition to strengthening and tempering in solid solution, the main approach to controlling the mechanical properties of ductile iron is to use the amount of perlite and ferrite in the metallic matrix Looking at typical ductile iron grades, the effect of strengthening the strength of the perlite for static loads is obvious [66].

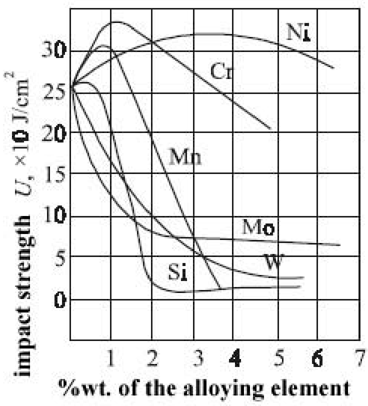

Fig.4. Influence of alloying elements content on the impact strength of ferrite [33].

According to Ripplinger *et al.* [24], in the case of ductile iron it is known that the failure occurs due to local plastic deformations in the areas surrounding the graphite nodules Once a critical level is reached, these deformations result in the formation of interfacial cracks. Increasing loads lead to a circumferential growth of these interfacial cracks until the entire nodule is detached from the matrix. The resulting voids act as initiation sites for microcracks growing into the matrix perpendicular to the nodules. Using the same macroscopic global strain for different grades of ductile iron, higher local plastic strain was observed in ferrite surrounding graphite nodules compared to perlite. Further results lead to the assumption that the initiation of microcracks in ductile iron is stress-controlled. It can therefore be seen that the ductile ferrite phase causes the initiation and growth of microcracks at lower global strains or stresses. Comparable to the behaviour under static loads, the fatigue strength of ductile cast iron increases with the concentration of perlite.

3. Analysis of the influence of coatings on the wear of austenitic spheroidal cast iron components

Modern technology poses ever higher demands on the durability and reliability of machines. In a machine, friction nodes are the construction elements which determinie the quality of the entire machine. Action can be taken to make it possible to give machine parts characteristics inherent in certain specific materials. This is done by applying all kinds of coatings, thanks to which cheap materials can exhibit the desired special surface features. This matters when the core of the material has sufficient strength, and it is important to improve the surface properties of the element [27]. Due to their resistance to abrasive wear, erosion and corrosion, the coatings are used in very diverse operating conditions of structural components.

As it follows from available research [35], chromium carbide Cr3C2-NiCr based coatings applied by plasma spraying directly on ductile iron substrates, both without and after melting processing, show a compact structure without cracks and good adhesion to the substrate. This is indicative of favourable conditions for the application process, ensuring adequate adhesion of the coating to the substrate. Plasma-sprayed coatings without remelting are characterised by the presence of flattened grains, typical for the plasma application process. Additionally, they feature relatively high surface roughness.

Furthermore, it can be noted that the remelting of coatings produced by plasma spraying causes the disappearance of pores and other structural defects, which consequently increases the adhesion of the coating to the substrate.

The value of the R_a roughness parameter for the coated substrate was *13.55* µ*m*, while the remelted coating exhibits a much lower surface roughness of only *1.73* µ*m* (Fig.5). The low roughness value is a very favourable feature for machine elements exposed to erosive wear during operation.

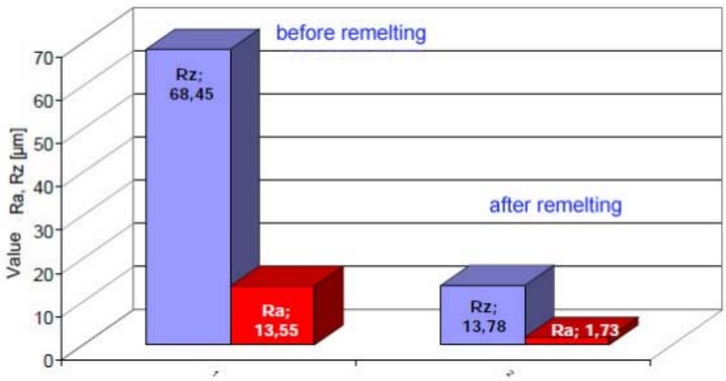

Fig.5. Roughness parameters: R_a (the arithmetic average of the roughness profile deviation from the mean line), R_z (roughness height) [35].

On the other hand, the microhardness of the coatings, both without and after coating remelting, is at a similar level of about *1000* µ*HV* (Fig.6.). Compared to the microhardness of the substrate, the microhardness of the coating increased 3 times. At the substrate-coating boundary, the microhardness values are lower than at a considerable distance from this boundary. The variation in microhardness values in the coating is related to the occurrence of a structure typical of remelting, i.e., microdendritic structure [35].

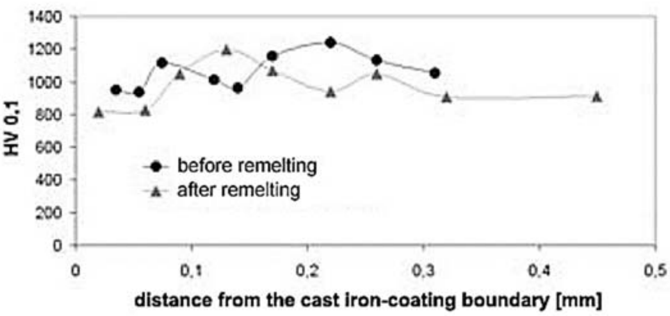

Fig.6. Microhardness of Cr3Cr2-NiCr coating applied by plasma spraying [35].

The research illustrated in Tchórz *et al.* [35])shows that the application of coating remelting based on plasma-sprayed Cr3C2-NiCr carbide results in good adhesion to ductile cast iron, a significant reduction in the coating surface roughness, and an increase in its durability under cyclic load changes. When compared to coatings without remelting, the hardness of plasma-sprayed and remelted coatings are similar; in both cases there is a significant increase in coating hardness compared to the substrate. Remelting the coating material, in turn, causes favourable changes in the morphological structure of the coating such as reduction of porosity in the coating, micro- and macro-structural defects, homogenisation of chemical composition and disappearance of structural layering, as well as strong structural fragmentation. Therefore, a claim that chromium plasma-sprayed carbide-based remelted coatings may provide effective protection for ductile iron castings operating in conditions of high dustiness and cyclic loads may be justified [35].

In turn Granat [22] demonstrates the possibility of producing Fe-C-Cr-Si layers on cast iron of the EN-GJL-200 grade, resistant to abrasion, corrosion and oxidation, which in the foundry production process were characterised by a tendency to form a network of microcracks and increased brittleness. For research purposes, the author used two alloys with the following chemical compositions: *2.27%* wt. C, *18.61%* wt. Cr and *10.36%* wt. Si (determination *360*) and *3.83%* wt. C, *25.84%* wt. Cr and *10.48%* wt. Si (determination *560*) The conducted tests have shown that it is possible to produce thick alloyed layers by spraying *200* μ*m* thick coatings in a single passage, the layers adhere well to the substrate, while the hardness of the obtained alloy layers is *542 HV 0.5* for the 360 alloy and is about *10%* lower than for the cast material [36]. For the 560 alloy, the hardness is *543 HV 0.5* and practically does not differ from that of the cast alloy. The hardness of the cast iron substrate was *194 HBW 2.5/187.5*. The surface roughness of the sprayed coatings, determined by the arithmetic mean deviation of the profile from the mean R_a line, and the R_z profile height were, for the 360 alloy, respectively: R_a from *7.46* to *9.53* μ*m* and R_z from *37.12* to *58.24* μ*m*, and for the 560 alloy: R_a from *6.73* to *8.09* μ*m* and R_z from *38.29* to *49.53* μ*m*. This roughly corresponds to the values reported in the literature for coarsely ground surfaces ($R_a = 2.5 - 10\mu m$, $R_z = 10 - 40\mu m$) [22].

In research where Fe- C- Cr- Si alloys were used to produce alloy layers on cast iron castings using plasma transferred arc, the author [22] used a cast iron EN-GJL-200 substrate with a hardness of *175 HBW 2.5/187.5*, as well as ground material obtained in the casting process with the following chemical composition: *2.13%* wt. C, *19.65%* wt. Cr and *6.28%* wt. Si (determination 340) and *3.84%* wt., C, *30.42%* wt. Cr and *3.46%* wt. Si (determination 530). A single-layer, well-spread padding weld was obtained, without defects for both the 340 and the 530 alloys. The hardness of monolayered welding pads was *630 HV 30* for the 340 alloy with a cast alloy hardness of *590 HV 30*, and for the 530 alloy the hardness of the welding pad was *710 HV 30* with a cast material value of *625 HV 30*. The microstructure of the welding pads does not exhibit any defects (such as cracks or blisters) and is typical of Fe- C- Cr alloys. Based on the results of the study, the author concluded that it was possible to produce Fe- C- Cr - Si alloy layers on iron castings by spraying or plasma-spraying methods. Such layers may be applied in the regeneration of damaged or worn machine parts or as special protective layers produced in places exposed to the destructive influence of adverse factors [22].

In the case of structural elements used in the automotive industry, especially in the construction of combustion engines, the application of additional layers is key in improving tribological properties of mating surfaces under mixed friction conditions, and materials from which the layers are made have properties that differ significantly from those of the native material and thus positively modify the phenomena occurring in mixed friction conditions is played by Babiak [37]. In his work, the author presents the layers currently used on the load-bearing surface of a combustion engine piston, which contains graphite dissolved in a polyamide-imide resin, applied by screen-printing and cured at high temperature. The commonly used coating called Grafal 255, which contains about *35%* of graphite additive and no additives acting as friction modifiers, can serve as an example. Figure 7 presents the effect of applying a coating containing graphite on the value of average pressure of friction loss [38].

New types of coatings contain molybdenum disulphide (EvoGlide type) and other friction-modifying chemical compounds [38]. Research results presented in the thesis by Kotnarowski [39] confirm the possibility of getting very favourable effects also by using molybdenum disulphide. The influence of the type of layer covering the load-bearing surface of the piston on the wear of mating surfaces and friction losses has been the subject of intensive research [38, 40,41]. Research results obtained in these studies unequivocally confirm the positive role of standard coatings in reducing the possibility of piston seizure in the cylinder and reducing the wear of the cylinder surface under normal engine operating conditions.

Tribological tests carried out outside the engine have additionally shown the possibility to significantly reduce the friction force by coating the aluminium alloy with the coatings under analysis. Under real engine operating conditions, the total friction loss depends primarily on the fluid friction, and that is why the application of coatings does not translate into major benefits in terms of friction reduction. These relationships are presented as graphs in Fig.8. [38].

According to Babiak, [37], works on the application of carbon-containing coatings in various friction nodes of a piston combustion engine are intense. The DLC (diamond-like carbon) coating, recently introduced into mass production of engines, containing amorphous carbon can serve as an example, and it has so far been successfully used in many non-engine applications. Thus, we can cite Babiak, [37] who says that the DLC coating is used in various variants on the cam mating surface of valve followers and pins and piston rings [42-44]. DLC coating of the GOE 245 type has been developed to coat the sliding surface of the rings and it is characterised by high resistance to adhesive wear and capacity to initiate favourable tribochemical reactions. Another version of this coating, designated GOE 247, consists of multiple layers with a layer containing amorphous hydrogen-bonded carbon on the outside. Such coatings contribute to a significant, even *20%* reduction in ring friction loss [42].

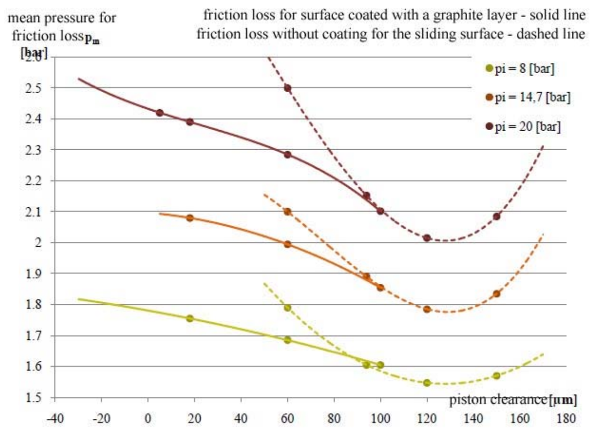

Fig.7. Dependence of the mean pressure of the engine friction loss on the piston clearance and bearing surface coverage; the results were obtained for different engine loads at a rotational speed of *4000 rpm*, for a coolant temperature of $90^{\circ}C$ [38].

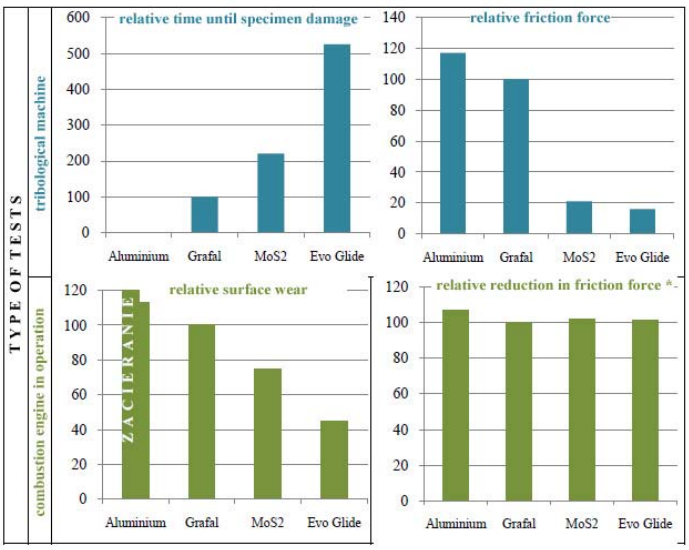

Fig.8. Effect of coatings on piston bearing surface on friction under tribological test bench and engine conditions; applies to an engine without accessories [38].

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Carbon nanotubes (CNT) are modern materials, belonging to the group of nanomaterials, and subject of research on their application to the piston load-bearing surface. Selected features of carbon nanotubes, which may play an important role in application on the piston load-bearing surface, as well as the results of research on friction losses in pistons covered with a CNT layer, have been presented in Kałużny [45]. These results are promising, but at the same time, they indicate the need for further research, especially on increasing the durability of CNT-ad ded layers [37].

In his work Kaźmierczak [46] presented the results of research on the influence of an antiwear titanium nitride (TiN) coating applied on piston rings, which is known for many industrial applications [47, 48]. In Polish literature on the topic, they are called hard coatings, whereas in foreign literature the term ceramic coatings can be found [49-51].

An antiwear titanium nitride coating can be obtained on the working surface of a piston ring using various surface engineering technologies. They include plasma-spraying [52], electron, laser, implantation, fluorescence technologies, CVD (Chemical Vapour Deposition) and PVD (Physical Vapour Deposition) methods. Kaźmierczak [46] presented the results of research on a titanium nitride coating deposited using the PAPVD arc-vacuum method (physical plasma-assisted deposition of coatings from the gaseous phase) on a piston ring where it proved to be the most favourable process allowing for its constitution on the piston ring working surface. It is worth presenting the results for friction coefficient values that Kaźmierczak [46] demonstrated for a cast-iron ring mating in synthetic oil with a specimen with titanium nitride coating (Fig.9). The measurements were taken along the friction path of *27000 m*, and after this, the measured friction coefficient values changed from *0.023* to *0.067*. The author shows that the value of the friction coefficient obtained by analysing the regression function after covering a friction path of *27000 m* is equal to *0.044*, whereas after covering *13500 m* it is equal to *0.067*.

Figure 10 shows the courses of the friction coefficient values for a nitride-coated ring mating in synthetic oil with a titanium nitride-coated specimen. Measurements were taken along a friction path of *27000 m*, where the measured values of the friction coefficient changed from *0.004* to *0.018*. The value of the friction coefficient obtained from the regression function after covering a friction distance of *27000 m* is equal to *0.015*, whereas after a distance of *13500 m* is equal to *0.031*.

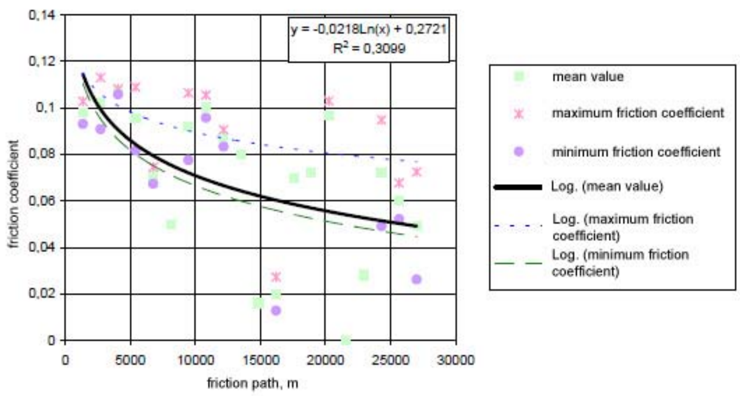

Fig.9. The friction coefficient as a function of path for the cast iron ring (W1P) sliding against the TiN-coated specimen lubricated with synthetic oil [46].

A clear tendency can be seen in the presented results , that is a significantly lower value of the friction coefficient for a nitride-coated ring with a titanium nitride-coated specimen compared to a cast iron ring with a titanium nitride-coated specimen. The values of this coefficient are lower both for mating in mineral oil and synthetic oil. Another feature to be notices is that the value of the friction coefficient is lower for mating in mineral oil than in synthetic oil [46].

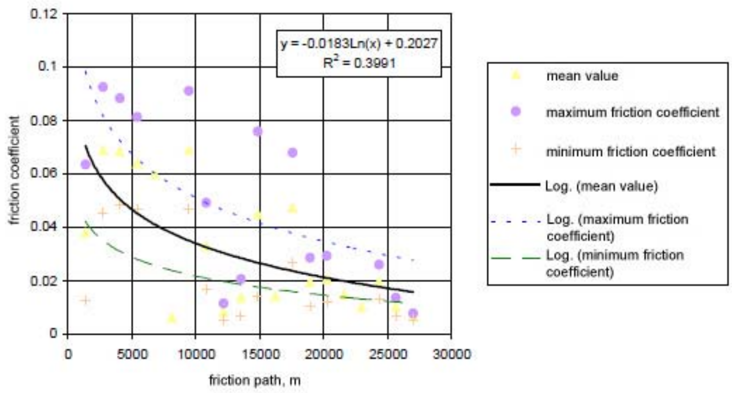

Fig.10. The friction coefficient as a function of path for nitrite-covered cast iron sliding against the TiN-coated specimen lubricated with synthetic oil [46].

As Kaźmierczak [46] claims, despite higher friction factor values being found for both material combinations in synthetic oil in comparison to mineral oil, significantly lower values of total wear were found during operation in synthetic oil. This confirms that future use of synthetic oil as a lubricant for the ring seal in question would be advisable, which is a practical guideline in terms of the operation of combustion engine components.

WC-Co+Cr high velocity oxy-fuel thermal spray (HVOF) coatings are increasingly being used to increase the wear resistance of various structural components operating in different industrial environments. HVOF, or High-Velocity Oxy-Fuel, is an ever-evolving surface modification technology leading to increased resistance to erosion and corrosion resistance, and thus increasing the service life of key parts of machinery and equipment [68]. This technology allows to significantly increase the durability and reliability of machine parts, reduce production costs and save materials and energy. In particular, carbide coatings formed by thermal spraying techniques have attracted the interest of researchers due to their high wear resistance, resistance to high-temperature corrosion, and meeting the most stringent conditions for demanding power applications [69].

Due to the relatively low process temperature and the relatively short time for the powder to occupy the charge in the gas stream, adverse phenomena associated with changes in the phase composition of coatings, such as decomposition of carbides and oxidation of metallic and carbide materials, are reduced. This makes it possible to produce carbide coatings with special properties such as high hardness, high abrasion and erosion resistance, resistance to high-temperature corrosion, good thermal conductivity and lower porosity, as well as higher adhesion to the substrate compared to coatings generated using conventional plasma spraying [70-72]. These coatings are characterized by a compact structure with a small number of visible pores, no cracks and good adhesion to the substrate (the boundary between the substrate and the coating is continuous), which indicates favorable conditions of the spraying process to ensure proper adhesion of the coating to the substrate [68], their average microhardness is *2523HV0.1* ± *30* and the value of the roughness parameter $R_a = 5.36 \pm 0.6 \mu m$.

4. Analysis of the effect on the wear of austenitic ductile cast iron parts by burnishing and machining

Ductile cast iron has very good strength and ductility properties. Additionally, it can be easily formed using casting techniques. As a result, it is widely used in mass production, for example in the automotive industry. It is used to make crankshafts, camshafts, connecting rods, steering parts, gears and many other components. Poor machinability is among the main disadvantages of this material [53]. The condition and properties of the thin surface layer of the elements are of primary importance for mechanical wear as they influence the nature of the forming secondary structures and the development of material's adaptive-structural ability in the operation process [54]. It is worth noting that, as presented by Paszeczko and Kindrachuk [54], the mechanical and chemical processes of formation of secondary structures on the friction surface depend on the external mechanical actions, the type of materials of friction pairs and the chemical composition of the environment in which the material is placed. The adaptive-structural capacity of materials emerges as a result of friction. These are regularities changing the structure and properties of surface layers in an energetically favourable direction, which means that the initial surface layer structure of abrasive materials is changed into a stable form, more favourable in terms of energy for given stress conditions.

This stability of form ensures that energy losses resulting from friction are minimized and the work needed to wear down a given volume of surface layer material is maximized. As a result, the external friction process stabilizes, and the system finds dynamic equilibrium and self-regulation. If the dynamic equilibrium is violated, the system transitions to another level, and in critical conditions, pathological wear processes and damage of friction node elements occur.

Restructuring is performed by changing the mechanical, physical and chemical properties of surface layers and them transitioning to a thin-film state, highly transparent and resistant to both physical and chemical agents. The phenomenon of material structural adaptability at friction is associated with the occurrence of elastic-plastic deformation, structural-thermal activation and temporary passivation, which lead to the formation of secondary structures.

This set of interrelated processes causing structural adaptability of materials ensures a stable dynamic state of resistance to wear combined with antifriction properties only if the system is in dynamic equilibrium, the process finds self-regulation, and energy relationships are met [54]:

$$\int_V \frac{\Delta E(V)}{A} dV = \min \;, \tag{4.1}$$

$$\frac{A}{I} = \max \tag{4.2}$$

where: ΔE – change in absorbed energy; A – work performed by friction forces; V – volume; I – wear.

Dynamic equilibrium and self-regulation are characterized by the fact that all processes related to the phenomenon of structural adaptability stabilize over time.

Together with the development of technology, increasingly higher requirements are posed for the performance of both machines and their parts, especially their reliability, accuracy and durability. Resistance to wear is among the main features of the technological quality of machine parts and it is most often determined by the properties of their surface layer (SL). The relevant SL properties of machine parts are most often achieved in mechanical treatment processes, often preceded by heat or thermal and chemical treatment. The wear resistance of mating machine parts is significantly affected by the roughness of their surfaces and SL hardness [55].

Of the many known finish treatment methods, burnishing is the one that makes it possible to obtain SL with favourable functional properties. In (Kalisz *et al.* [55]), the authors presented the results of tests of orthogonal and perpendicular burnishing (in relation to the direction of milling preceding the burnishing). Based on these tests, in line with test conditions established and presented in [55], the dependences of the R_a surface roughness parameter and the KR_a coefficient of roughness reduction on the F_N burnishing force and the f_{wn} transverse feed for the material tested were given. The KR_a coefficient of roughness reduction was determined by calculating the ratio of mean deviation of the profile from the middle line (value before burnishing) ($R_a{}'$) and the R_a value after burnishing. Figures 11 and 12 present a comparison of the mean values of the R_a parameter for different rolling and sliding burnishing directions, with the assumed significance level $\alpha = 0.05$. In turn, the dependence of the R_a and KR_a dependent variables on the F_N and f_{wn} independent variables is graphically represented by the contour plots shown in Fig.13-14.

Having analyzed the performed tests, the authors [55], concluded that the study of the burnishing strategy orthogonal and perpendicular to the direction of milling preceding the burnishing showed that, out of the many known finish treatment methods, burnishing is the one that makes it possible to obtain SL with favourable functional properties.

Moreover, comparing the test results obtained for orthogonal rolling and sliding burnishing, the researchers concluded that rolling burnishing yields lower R_a values and higher KR_a values [55].

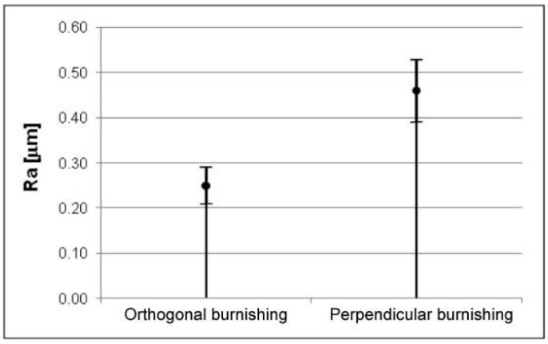

Fig.11. Comparison of average values of R_a roughness parameter for different sliding burnishing directions with a force $F_N = 60 N$ and transverse feed $f_{wn} = 0.01 mm$; level of significance $\alpha = 0.05$ [55].

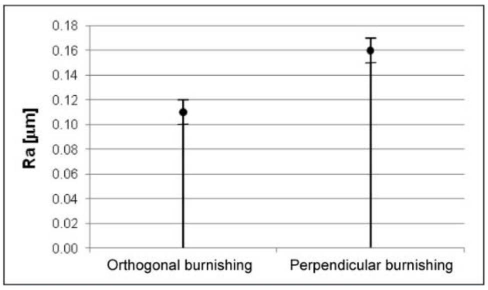

Fig.12. Comparison of average values of roughness parameter R_a for different directions rolling burnishing directions with a force $F_N = 130 N$ and transverse feed $f_{wn} = 0.04 mm$; level of significance $\alpha = 0.05$ [55].

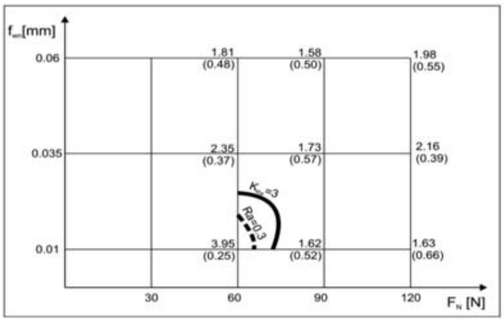

Fig.13. Dependence of the KR_a coefficient of roughness reduction and the R_a surface roughness on the F_N force and f_{wn} transverse feed after orthogonal sliding [55].

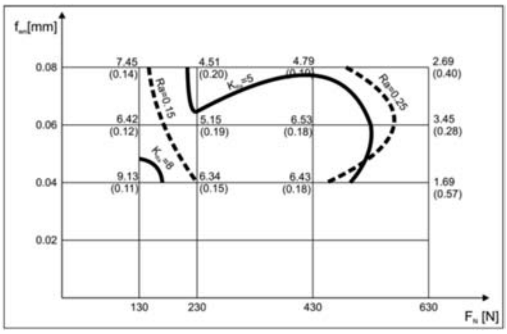

Fig.14. Dependence of the KR_a roughness reduction factor and the R_a surface roughness parameter on F_N force and f_{wn} transverse feed after orthogonal rolling burnishing [55].

At present, machining of superalloys is becoming more and more important. Construction materials currently used in the industry exhibit increasingly better properties, in particular increased mechanical strength, increased hardness, increased abrasion and corrosion resistance. Heat resistance and high temperature creep resistance are also becoming another key elements. Greater demand for components with increased mechanical properties leads to their manufacturers adjusting production capacities in their machining [56].

In [57], the author presented the results of research on the machinability of ductile cast iron in relation to the condition of the surface layer after such treatment. From the machine designer's point of view, ductile cast iron covers a wide range of mechanical properties listed in the PN - EN 1563 standard: from high-strength and low ductility cast iron with bainitic or martensitic matrix through perlitic (Fig.15a), perlitic-ferritic (Fig.15b) and ferritic matrix (Fig.15c) exhibiting high ductility and considerable strength [58].

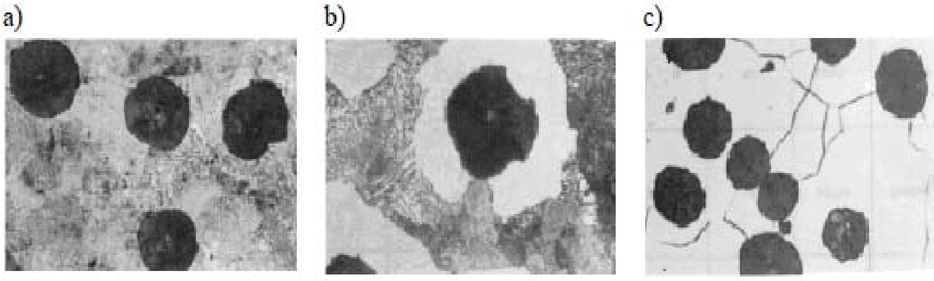

Fig.15. Ductile iron with varied matrices: a) perlitic, b) perlitic-ferritic, c) ferritic [59].

It is worth noting that thanks to its strength and mechanical properties, ductile cast iron finds extensive applications in various industries. This cast iron can successfully replace cast steel as well as steel forgings. It is used in machine construction industry - in machine tool bodies, crankshafts, engine cylinders, piston rings, agricultural machinery components and fittings [60]. Table 4 illustrates the trend in cast iron application in the automotive industry and typical tools dedicated to machining particular cast irons. Please note that tool ceramics have found wide application in the automotive industry, as they are ideally suited for making cast iron components such as brake discs, brake drums and flywheels [61].

For machining the above-mentioned materials, it is recommended to use tool materials with longer tool life, such as multilayer-coated sintered carbides, nitride ceramics and superhard materials made of regular boron nitride CBN. The use of silicon nitride facilitates high-speed machining not achievable with carbide cutting plates [57].

For machining cast iron with CBN blades, Kiszka [57] confirmed longer blade life, as well as better surface quality (R_a), compared to carbide-based blades. The application of a coating to the cutting blades, which contribute to improving the quality of the obtained surface, was also very significant. Samples of EN-

GJS-500-7 cast iron were turned with tools made of uncoated nitride ceramics (CN), coated nitride ceramics (CC) and CBN in test conditions presented in [57].

Table 4. Application of cast iron in the automotive industry [62].

Cast iron grade	**Trend**	**Typical components**	**Typical cutting Edge Materials**
Grey (EN-GJL)	↘	Cylinder blocks, heads, Frames, brace disks	Carbides coated with Al_2O_3, nitrie ceramics, Si_3N_4, CBN
Vernicular (EN-GJV)	↗	Cylinder blocks for Diesel Engines, connector and Fixing elements	As per requirements for the machining proces
Spheroidal (EN-GJS)	↗	Crankshafts, camshafts, toothed wheels, bodies, housings	Multi-layer coated carbides whit the MT-CVD and PVD methodes (TiCN-Al_2O_3-TiN), (TiCN- Al_2O_3-TiN/TiCN),cermetals, mixed ceramics, CBN

As can be seen in Fig.16, as the machining speed increases, a decrease in the value of the R_z parameter is observed, and thus a decrease in the values of the individual R_p and R_v components. The value of the R_z parameter varied from about 10.5 µm to about 6 µm depending on the applied machining speed and material grade of the cutting tool blade [57]. Based on Fig. 16, the researchers observed that an increase in feed rate is accompanied by an increase in the value of the R_z parameter from about *4 µm* to about *12 µm*. As seen in Fig.17, $R_v > R_z$. The lowest values of the R_z parameter were obtained when machining with a CBN blade in the analysed feed range [57].

Damage in machines and equipment begins in the surface layer of matin elements [50], which is influenced by the condition of their contact areas. Wear of machine parts is the wear of the surface layer and it entails changes in weight, geometric surface structure or shape. For these reasons, it is necessary to produce such a surface layer of machine parts so as to ensure their optimum service life. Heterogeneity of the surface layer of machine parts may result from structural changes in the material caused by external loads. Therefore, it is necessary to give the surface layer properties that would make them resist the destructive effect of the operating conditions, such as friction, chemical agents in the environment, load etc. (Podrzucki, [19]).

It is worth citing the results of (Feldshtein and Pacha-Gołębiowska [63]) who, among other things, presented the results of research on the properties of the surface layer of elements made of GJS2131 cast iron using blades made of CBN boron nitride, K10 sintered carbide and GC coated ceramics and CC nitrogen ceramics in the presented testing conditions.

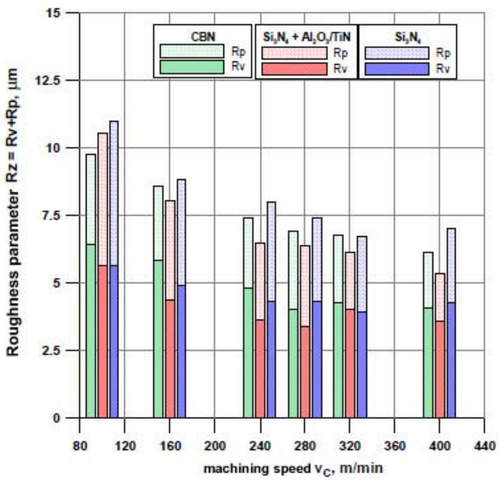

Fig.16. Effect of cutting speed on R_z surface roughness $\left(v_c = 100 \div 400\, m/min,\ f = 0.12\, mm/rev,\ a_p = 0.8\, mm\right)$ [57].

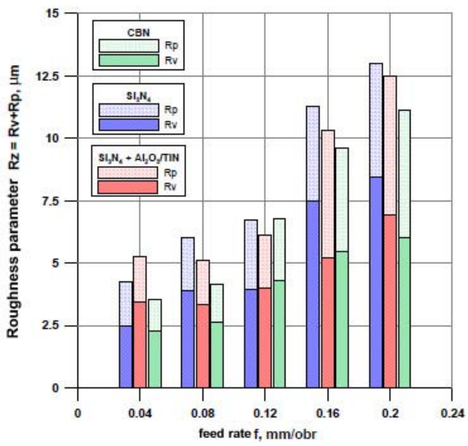

Fig.17. Influence of feed rate on R_z roughness parameter $\left(v_c = 320\, m/min, f = 0.04 \div 0.2\, mm/rev,\ a_p = 0.8\, mm\right)$ [57].

Figure 18 presents the changes in R_a roughness values for different blade materials for the specified feed ranges. The best surface properties, such as the lowest values of the R_a parameter and smooth surfaces without irregular cavities, were obtained after turning with CBN plates in the feed range $f = 0.10 \div 0.20\, mm/rev$. The highest (3 times higher when compared to CBN) values of the R_a parameter were obtained after turning with sintered carbide K10 plates [63]. Figure 18 presents the influence of machining speed on the value of the R_a parameter and smooth surfaces without irregular cavities, which were obtained after turning with CBN plates in the feed range $f = 0.04 \div 0.2\, mm/rev$. The highest (3 times higher when compared to CBN) values of the R_a parameter were obtained after turning with sintered carbide K10 plates [63]. Figure 19 present the influence of machining speed on the R_a parameter when turning with blades made of varied materials.

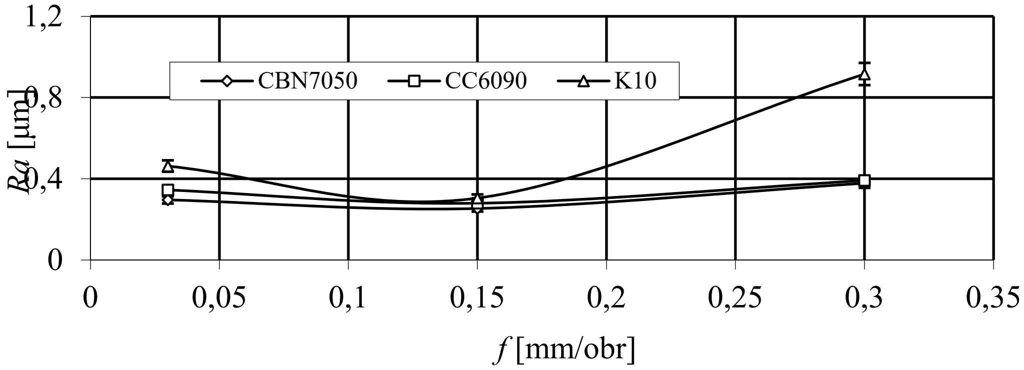

Fig.18. R_a roughness parameters depending on the *f* feed rate, obtained after turningplates made of various materials, cast iron GJS2131 [63].

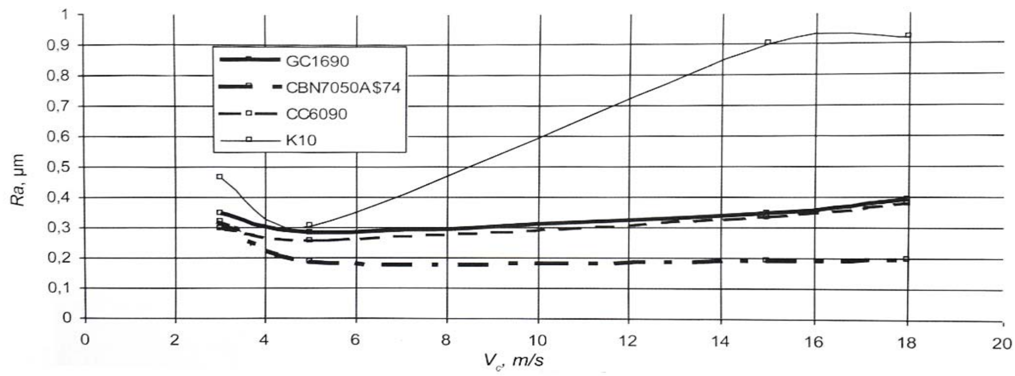

Fig.19. Roughness parameters R_a vs. cutting speed V_c, obtained after turning with inserts made of different materials, cast iron GJS2131 [63].

Based on their research, the authors concluded that the lowest values of the turned surface roughness, at constant cutting speed, were obtained when CBN inserts were used, while the highest values of the R_a parameter, almost twice as high, were obtained for the K10 insert.

5. Conclusion

What is decisive in the manufacturing process of machine parts made of austenitic cast iron, including Ni-Mn-Cu cast iron, is the course of their solidification in the casting mould. This is the stage of the technological process on which basically all the most important casting characteristics depend. In the analysed cast iron, the course of the casting solidification process mainly depends on carbon and silicon. The influence of nickel, manganese and copper is less significant. However, due to the relatively high total content of these elements, this effect is statistically significant [18].

To ensure high quality of austenitic matrix ductile cast iron, the chemical composition of the initial cast iron before spheroidization should fit the ranges: *3.0-3.5%* C, *1.8-2.0%* Si, *3.5-4.0%* Mn, *0.04%* P, *0.02%* S, *20-24%* Ni, using a magnesium-nickel master alloy containing *17%* Mg in an amount of *1.8-2.0%* in relation to the weight of the metal, thus ensuring that the magnesium content in the cast iron be within the range of *0.03-0.05* Mg%. Moreover, the casting temperature of the cast iron and the mould type have a significant influence on the formation of the correct cast iron structure. Research shows that the casting temperature should be maintained within the range of $1380-1400^{\circ}C$, while the mould material should ensure free solidification and cooling of castings. Additionally, the homogenisation of castings proves beneficial in optimizing mechanical properties [27].

Many different coatings for cast iron surfaces are used in a variety of technological processes. Chromium carbide Cr3C2-NiCr based coatings applied by plasma spraying directly on ductile iron substrates, both without and after melting processing, show a compact structure without cracks and good adhesion to the substrate. This indicates favourable conditions for the application process, ensuring adequate adhesion of the coating to the substrate. Furthermore, it can be noted that the remelting of coatings produced by plasma spraying causes the disappearance of pores and other structural defects, which consequently increases the adhesion of the coating to the substrate [35].

The use of a layer that contains graphite dissolved in a polyamide-imide resin gives excellent results in terms of reducing friction and wear on the piston load-bearing surface in a combustion engine. The layer is applied by screen printing and cured at high temperature. The commonly used coating called Grafal 255, which contains about *35%* of graphite additive and no additives acting as friction modifiers, can serve as an example [38]. New types of coatings contain molybdenum disulphide (EvoGlide type) and other friction-modifying chemical compounds [38]. These research results unequivocally confirm the positive role of standard coatings in reducing the possibility of piston seizure in the cylinder and reducing the wear of the cylinder surface under normal engine operating conditions.

DLC coating of the GOE 245 type has been developed for coating the sliding surface of the rings and it is characterised by high resistance to adhesive wear and capacity to initiate favourable tribochemical reactions. Another version of this coating, designated GOE 247, consists of multiple layers with a layer containing amorphous hydrogen-bonded carbon on the outside, which also contributes to a significant reduction in friction loss on the rings, reaching even *20%* [42].

Through the use of various surface engineering technologies such as plasma spraying [52], electron, laser, implantation, glow deposition, CVD (Chemical Vapour Deposition) and PVD (Physical Vapour Deposition) methods, titanium nitride coatings are increasingly widely used, which give the surface of an element very good antiwear properties. A clear trend towards a significantly lower value of the friction coefficient is visible [46].

On the other hand, WC-Co+Cr composite coatings, produced by the HVOF method on ductile iron substrates, are characterised by good resistance to erosive wear. The composite coating (WC-Co + Cr) has better (by almost *22%*) abrasion resistance in abrasive suspension than ductile cast iron. The surface morphology after abrasion resistance tests in abrasive suspension indicates that the wear mechanism is related to the formation of craters, lips, microcracks in the cobalt-chromium matrix and cracks in the pore area and the carbide-matrix interface area. Adhesive and abrasive wear is determined on the worn surface [68].

Resistance to wear is among the main features of the technological quality of machine parts and it is most often determined by the properties of their surface layer (SL). Of the many known finish treatment methods, burnishing is the one that makes it possible to obtain SL with favourable functional properties. In particular, rolling burnishing helps obtain lower values of the Ra parameter.

Machining to form the SL of cast iron components, especially with CBN (cubic boron nitride) blades, also yields a better surface quality (Ra) compared to carbide-based blades. As machining speed increases, the value of the Rz parameter decreases. Its lowest values were obtained when machining with a CBN blade in the analysed feed range [57]. Thus, it is necessary to produce such a surface layer of machine parts so as to ensure their optimum service life [50].

Nomenclature

A – work of friction forces

a_p – depth of cut

CRM – Critical Raw Materials

FN – burnishing force

ΔE – change of absorbed energy

f – feed rate

f_{wn} – drilling feed rate in sequential milling

HV – Vickers microhardness

HBW – Brinell hardness determined using a hard alloy ball

HVOF – High-Velocity Oxy-Fuel

I – wear

Kr_a – roughness reduction factor

OECD – Organisation for Economic Coopetation

R_a – arithmetic mean deviation of profile from the mean line

R_m – tensile strength

R_p – height of the highest elevation of the roughness profile

R_z – height of the roughness according to ten points of the profile

R_v – height of the lowest indentation of the roughness profile

U – impact resistance

V – volume

v_c – cutting speed

α – significance level

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