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SURFACE ROUGHNESS DEPENDING FROM THE CUTTING PARAMETERS OF CGI PARTS DURINGF FINISHING FACE MILLING

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Abstract. *Compacted graphite iron (CGI) is a structural material that has excellent mechanical properties based on the bonding of graphite and iron particles. In the machine-building industry, interest in this material has been growing in recent years. It has attracted particular attention from the automotive industry and has been used as a substitute for grey cast iron due to its improved mechanical properties, such as increased strength and heat resistance. However, due to its high hardness and strength, as well as its complex microstructure, it is difficult to machine. The high pearlite content and the presence of vermicular graphite make it difficult to cut, which can lead to faster tool wear and poorer surface quality. Cast iron surfaces with vermicular graphite often require high quality machining, but due to the brittleness of the material, there is a risk of microcracks and chips forming on the surface, which can negatively affect the quality of the finish. In this study, we obtained the dependences of roughness on cutting parameters and conditions during the finishing face milling of CGI parts surfaces with PVD and CVD coated carbide tools under dry machining conditions and with the addition of coolants using. Based on experimental data, mathematical models of the roughness dependence on cutting parameters and conditions were built. It has been established that PVD-coated tools for face milling of CGI surfaces at high cutting speeds with the addition of cooling provide better surface roughness compared to CVD-coated tools. The best result of surface roughness Ra 0.25 µm was achieved at a cutting speed of 800 m/min, a depth of cut of 0.08 mm and a feed per tooth of 0.1 mm/tooth, using a cooled PVD-coated carbide tool.*

Key words: *Machinability, Compacted graphite iron, Surface roughness, Finishing face milling, Tool material for machining cast iron, Cutting parameters.*

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1. INTRODUCTION

A review of research shows that there is a complex relationship between parameters and cutting conditions. Their impact on surface roughness can be very different due to the tool material, type of coating, cooling conditions and many other factors.

There are many works by foreign scientists who have investigated how cutting conditions and modes affect the surface quality of CGI after face milling. Most of the existing studies focus on roughing and pre-finishing [3–5]. However, finishing face machining is poorly understood, and focuses on the machinability of CGI under dry machining conditions. A small number of works have been devoted to the machining of CGI using coolant. They mainly focused on the impact of cutting parameters (cutting speed, feed rate and depth of cut) and material microstructure, in particular, pearlite content, graphite vermicularity, and non-metallic inclusions, on the surface quality. These factors have a significant impact on the mechanical properties of the material and, as a result, on the machining performance, especially the surface roughness. The most common tool materials for machining the surfaces of CGI parts are coated carbide materials and nitride ceramics [5]. Several researchers have compared the performance of these two types of tool materials for CGI machining in regard to cutting forces, tool wear, and surface quality. Gabaldo et al. [6] analysed the performance of two tool materials (carbide and nitride ceramics) in CGI finishing milling, as well as the wear mechanisms of the cutting tool and its stability at different cutting speeds, and their relationship with surface roughness. It was found that carbide is superior to ceramic in terms of tool life and surface quality in CGI milling. At the same time, these studies are contrary to the research of Niu J., Huang C., Su R. [7], who compared the cutting forces and tool wear of uncoated/coated carbide and cermet tools in CGI milling and found that the best surface quality and wear resistance was with coated cermet tools compared to machining with coated carbide tools for CGI machining. There are a number of studies that have compared the machinability of CGI using carbide tools with different thicknesses of protective CVD and PVD coatings, and found the advantages of CVD coating for roughing and PVD for finishing. However, all of these studies are cross-sectional in nature and do not take into account all the factors involved. The lack of clear recommendations on the optimal cutting parameters to achieve minimum surface roughness in specific conditions can lead to higher production costs, lower product quality, and excessive tool wear. Therefore, the question of specifying and expanding these recommendations is relevant and needs to be addressed.

The purpose of this study is to establish the correlation between the CGI parts surface roughness during finishing face milling and cutting parameters (speed, depth, feed) and cutting conditions (cooling, different tool materials). This will allow us to develop recommendations for choosing the optimal machining modes to ensure minimum surface roughness of CGI parts.

Summary of the main material. In modern machine building and metalworking, the requirements for surface quality of machined parts are constantly increasing. Finishing face milling is one of the ways to ensure high quality machining, in particular, minimum surface roughness (Ra). It ensures high performance, improves mechanical properties and increases the quality of the finished product. This is especially important for parts that operate in challenging environments or require high precision and reliability. CGI has high strength and stiffness, which can make it difficult to achieve a high quality surface [2]. Finishing milling can achieve low roughness, which is essential to ensure high quality parts. In addition, CGI has an increased tendency to develop residual stresses due to its complex microstructure [3]. Finishing milling helps to reduce these stresses, which increases the durability and reliability of the parts. However, milling vermicular graphite cast iron is challenging due to its mechanical properties, such as high strength and abrasiveness, which have a negative impact on tools during machining. The difficulty of machining them also lies in the significant heat generation in the cutting zone and rapid wear of the cutting tool. When machining cast irons, cutting tools experience high force and temperature loads, which are constantly changing during machining, leading to adhesive, abrasive, diffusion wear, structural changes and other wear mechanisms and deterioration of the machined surface quality.

Manufacturers of tool materials for milling cast iron CGI suggest using carbide materials with PVD and CVD wear-resistant coatings They suggest machining at low cutting speeds, up to 250 m/min. Sandvik Coromant's recommended cutting conditions for milling K-group cast irons, which include CGI, are shown in Table 1.

Table 1

Cutting parameters recommended by Sandvik Coromant for milling cast iron of group K [8].

WC carbide with PVD coating	WC carbide with CVD coating
fz: 0.1–0.42 mm/tooth Vc: 120–190 m/min	fz: 0.1–0.42 mm/tooth Vc: 155–240 m/min

However, CGI processing under such conditions does not allow obtaining a surface roughness like after finishing. Therefore, there is a need to search for cutting parameters that would provide CGI surface roughness like after finishing. To improve the quality of the machined surface, tool material manufacturers suggest machining cast iron with coolant. This is primarily due to the fact that during dry machining, the temperature in the cutting zone is much higher, especially during high-speed machining, which causes greater tool wear. Coolants help cool the tool and workpiece, reducing the risk of machined surface defects and tool failure [9]. In addition, coolant machining typically results in better surface quality due to reduced thermal deformation and better lubrication during milling. However, the use of cutting fluids (coolants) increases production costs and has a negative impact on the environment, which is encouraging scientists and researchers to look for alternative methods. One of these approaches is dry machining and machining with minimal quantities of lubricant (MQL) [10]. These methods minimise or completely cancel the use of coolants, reducing environmental pollution, increasing maintenance costs, and improving safety for operators. Much research has been devoted to the machinability of CGI in dry machining [3–7]. They have mostly focused on the effect of cutting parameters (cutting speed, feed rate, and depth of cut) and microstructure (pearlite content, vermicularity, non-metallic inclusions) on cutting force, temperature, and tool life in dry machining of CGI. Sadik [11] studied the machinability of CGI during dry milling using CVD-coated carbide tools of different thicknesses (4, 6, and 9 μm) and uncoated ceramic tools at cutting speeds (150 and 300 m/min) and feed rates (0.1 and 0.3 mm/tooth). The author found that the ceramic tools had better performance only at cutting speeds above 300 m/min in combination with low feed rates and depth of cut. Gabaldo et al. [6] analysed the performance of two tool materials (carbide and PVD coated nitride ceramics) in high-speed CGI milling (850 m/min) and found that the coated carbide was superior to the coated ceramic in terms of tool life and surface finish in CGI milling. In recent years, the minimum quantity of lubricant (MQL) technique has been introduced for machining hard-to-machine materials, but mainly for such materials as Ti-6Al-4V titanium, 316L stainless steel, and AISI 4140 steel [10]. MQL can significantly minimise the friction between cutting tools and workpieces, which helps to reduce tool wear and improve machining quality. However, the use of MQL in the process of machining compact graphite iron (CGI) is still an incompletely researched area. There are only a few works, including the study by Da Silva et al. [12], which evaluated the machinability of vermicular graphite cast iron by face milling under dry machining conditions and with the addition of a minimum amount of coolant, investigating the dependence of Ra from cutting parameters, coating type, and cutting conditions. As can be seen in Fig. 1, the geometry of the cutting tool has the greatest influence on the machined surface roughness Ra, which indicates the importance of rational selection of tool parameters. The next most influential factors are cutting speed (Vc) and tool material. Tool coating and machining conditions (dry or lubricated) also have a significant, but somewhat lesser, impact. The tooth feed (f) has the least influence.

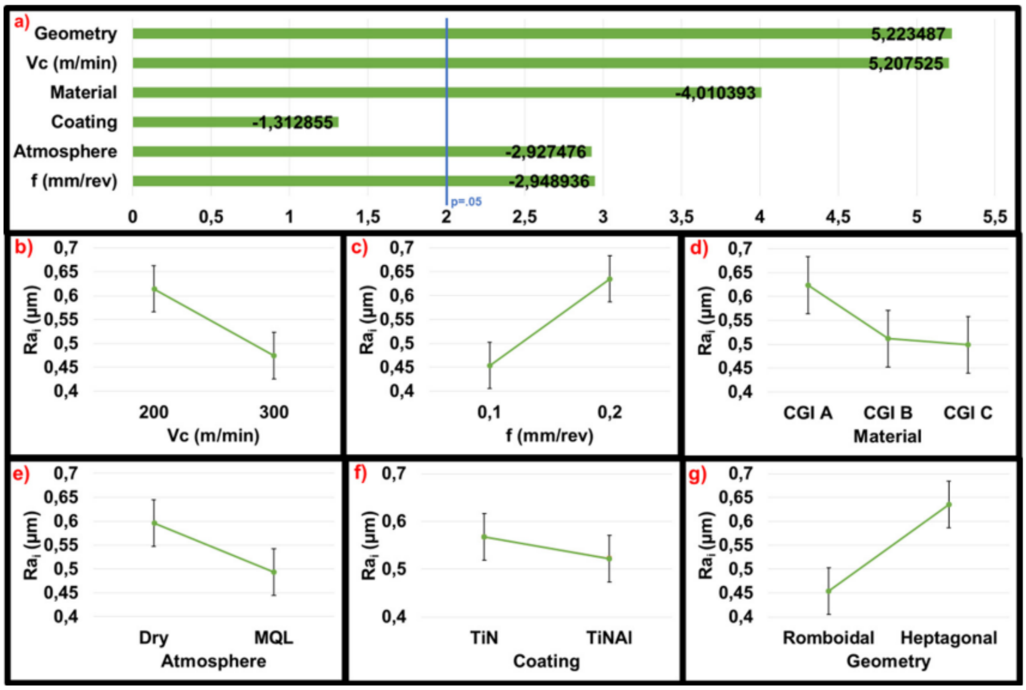


Figure 1. Influence of the input parameters on the roughness of the first machined tool path in the tests. (a) Pareto diagram; (b) influence of the cutting speed; (c) Influence of feed rate; (d) Influence of machined material; (e) Influence of the lubricant condition; (f) influence of the coating; (g) Influence of tool geometry [12]

Similar studies conducted by Tu et al. [13], demonstrate a significant effect of using supercritical CO_2 MQL ($ScCO_2$-MQL) in improving surface quality and reducing cutting forces during CGI machining. The effect of different cutting conditions on the surface roughness Ra during face milling of different CGI was investigated. Three variables were considered: cutting speed, feed per tooth, depth of cut, and different machining conditions: dry machining, use of CO_2 ($ScCO_2$) and its combination with MQL (minimum amount of lubricant). It was found that with an increase in cutting speed, a decrease in Ra surface roughness was observed for all materials (FGI, CGI, NGI). The use of $ScCO_2$ and especially $ScCO_2$+MQL provided significantly better results than dry machining. Fig. 2 shows that the lowest Ra values were achieved using $ScCO_2$+MQL at the highest cutting speed (300 m/min). With increasing feed rate, Ra increases for all three materials. Increasing the depth of cut leads to a little increase in Ra, but this effect is smaller compared to the feed per tooth.

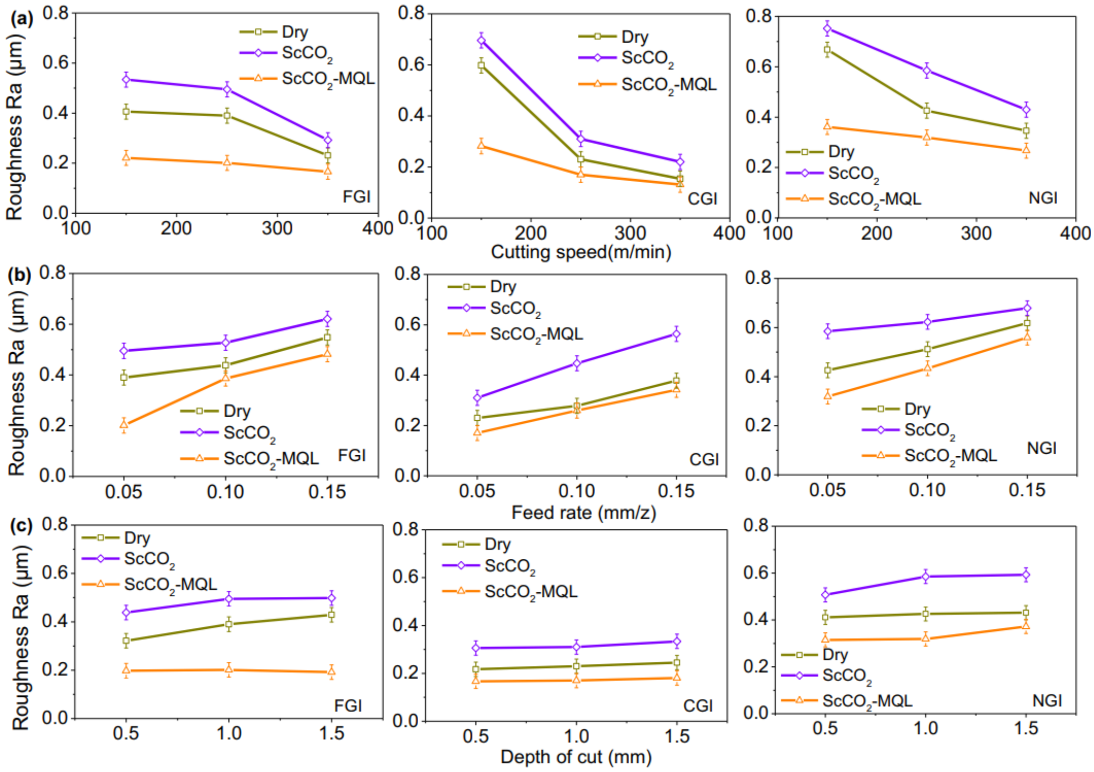


Figure 2. Evolution of machined surface roughness Ra of FGI, CGI, and NGI depend on the (a) cutting speed vc, (b) feed rate fz, and (c) depth of cut ap under dry, ScCO2, and ScCO2-MQL condition [13]

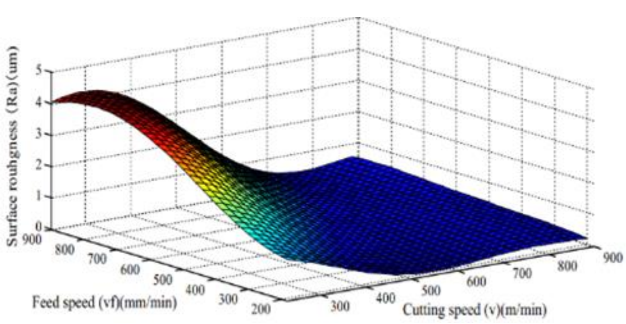


Figure 3. Effect of cutting speed and feedspeed on Ra

Lu, Zhang, Yuan and the others studied the relationship between machining parameters and surface roughness Ra of CGI parts during milling [14]. Fig. 3 shows 3D graphs based on their prediction model built using experimental data, which shows the relationship between machining parameters and Ra. According to them, the depth of cut does not have a significant impact on the Ra roughness value. Meanwhile, feed rate and depth of cut do, and the roughness decreases with increasing cutting speed and decreasing feed rate.

Rui Su, Chuanzhen Huang [15] and other studied changes of cutting performance under different workpiece removal volume during normal speed and high speed milling of compacted graphite iron. They found that at higher cutting speeds, the amount of material removed has less influence on the roughness than at lower cutting speeds. Figure 4 illustrates the surface roughness measurements (Ra) during the milling of CGI using carbide tools with CVD coatings. It compares the surface quality at different material removal volumes (Q) and cutting speeds (V). The results show that the lower cutting speed of 134 m/min leads to higher surface roughness after removing a larger material volume. In contrast, the higher cutting speed of 800 m/min produces lower roughness values, indicating a better surface finish. The surface roughness is less influenced by material removal when milling CGI at higher speeds.

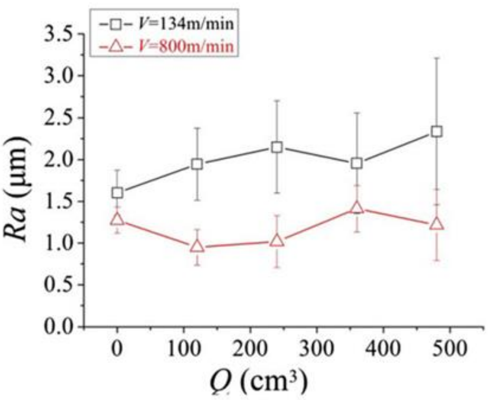
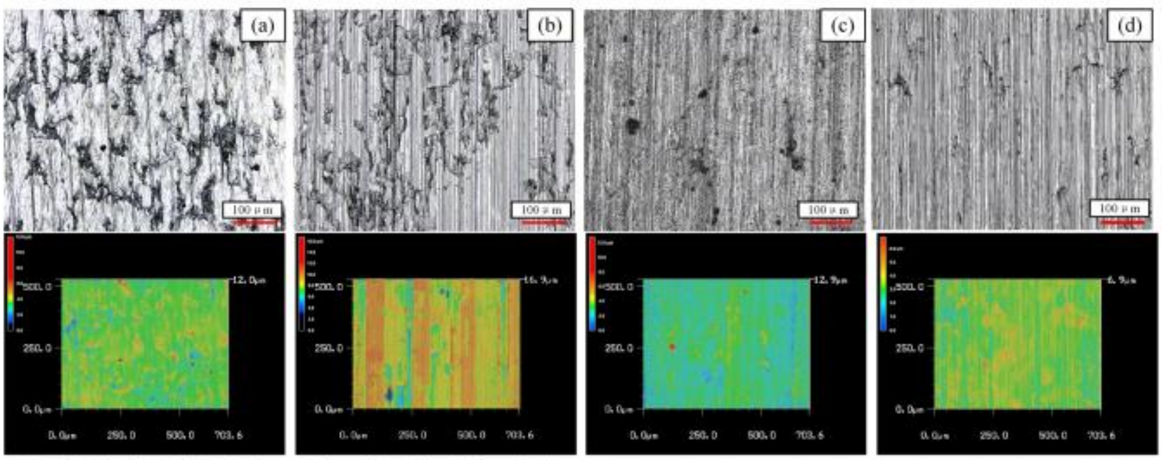


Figure 4. Dependence of roughness and removed material

Therefore, higher cutting speeds are more favorable for achieving a finer surface finish when using CVD-coated carbide tools in the milling of CGI.

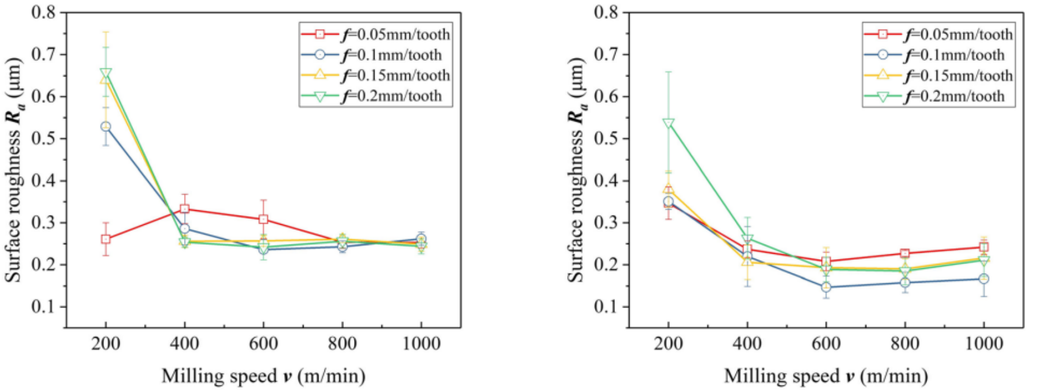
Their next research was focused on the surface integrity of compacted graphitized cast iron milled with cemented carbide coated PVD and ceramic tools. In this study, they investigated the effect on roughness of different cutting parameters (speeds varying from 200 m/min to 1000 m/min and feeds varying from 0.05 mm to 0.2 mm). The surfaces of cast iron with vermicular graphite (CGI) after face milling at the lowest and highest cutting speeds and feeds per tooth are shown in Fig. 5. At a cutting speed of 200 m/min and a feed rate of 0.05 mm/tooth, a significant surface roughness with deep scratches and irregularities is observed, indicating a poor machining quality at these parameters. At a cutting speed of 200 m/min and a feed rate of 0.2 mm/tooth, the surface appears slightly smoother, but still with noticeable defects. The high cutting speed of 1000 m/min significantly improves the surface quality. The best result was achieved in combination with a feed rate of 0.2 mm. Visually, the surface has a smoother appearance with fewer defects, indicating that increasing the cutting speed has a positive effect on the quality of the finish. However, the result was worse with a lower feed rate.



(a) v=200m/min, f=0.05mm/tooth (b) v=200m/min, f=02mm/tooth (c) v=1000m/min, f=0.05mm/tooth (d) v=1000m/min, f=0.2mm/tooth

Figure 5. CGI image of the surface after face milling at low 200 m/min and high 1000 m/min cutting speeds [16]

They also showed the relationship between surface roughness and milling speed when machining CGI, with different feeds per tooth. The figure 6 shows their result. There says, that as the milling speed increases from 200 to 400 m/min, the surface roughness decreases significantly. Milling speeds between 400 and 600 m/min provide the lowest surface roughness for all feeds, indicating the optimum operating range for achieving smoother surfaces during CGI milling. When the speed reaches 800 m/min, the feed rate has no effect on the roughness value for carbide tool, and becames higher for ceramic tool. Ceramic tool provides better quality. There showed that these two kinds of tool materials could meet the quality requirements of the machined surface of high-speed milling CGI, and ceramic tool was more suitable for the high-speed finish milling of CGI than cemented carbide tool to obtain smaller surface roughness and better machining quality. Face milling can achieve a better machined surface quality in the speed range of 400~800 m/min.



(a) Surface roughness of CGI milled by cemented carbide tool (b) Surface roughness of CGI milled by ceramic tool

Figure 6. The machined surface roughness of CGI with carbide and ceramic tool.[16]

Thus, the combination of high cutting speeds with feed rates up to 0.2 mm/tooth and shallow depth of cut can ensure improved surface quality and minimal surface roughness of partially aligned graphite (CGI) after finishing end milling. In order to study these relationships in more detail, we decided to conduct laboratory studies aimed at determining the effect of cutting parameters on the surface roughness of CGI.

2. EXPERIMENTAL METHODS

The research was conducted using PVD and CVD coated carbide tools under two different conditions: with and without cooling. The machining was carried out on a DMU 80 eVo CNC machine with a Sandvik Coromant R200-051Q22-12H face milling cutter with round inserts. Roughness measurements were performed using a Keyence VR series profilometer and a stylus profilometer. Material of the workpieces used in the experiment GJV450. The workpieces were made with the following dimensions: 110 mm long, 45 mm wide and 70 mm high. Only one cutting insert was mounted on the milling cutter. The purpose of the study was to determine the dependencies between these parameters and the roughness of the obtained surfaces to find the best tool material and cutting conditions. For this purpose, we conducted experiments using a face milling cutter at the following parameters:

- Cutting speed: 200 m/min, 400 m/min, 800 m/min
- Depth of cut: 0.08 mm and 0.15 mm
- Feed rate per tooth: 0.1 mm/tooth and 0.15 mm/tooth.

3. RESULTS AND DISCUSSION

Based on the experimental data obtained, we plotted the dependence graphs and developed regression equations that allow us to predict the surface roughness under different processing conditions. The best was obtained in case using PVD coated carbide tool with coolant.

The regression equation for the dependence of surface roughness of cast iron with vermicular graphite after milling with a PVD-coated carbide with cooling is as follows:

$$Ra=0.4492-0.0003\cdot V+0.18\cdot t+0.2276\cdot fz$$

In all equations obtained by us, the cutting speed has a negative effect, which improves the roughness as it increases. The positive effect of the depth of cut in all cases indicates that increasing the depth of cut increases the surface roughness.The feed rate has the greatest influence on surface roughness, especially in the case of coolant. Increasing the feed rate significantly degrades the surface quality, especially with coolant CVD coatings. The use of cooling improves roughness for all types of coatings, especially for PVD coatings, where its effectiveness is more noticeable.

Based on the data obtained during the experiment to determine the surface roughness of cast iron with nodular graphite (CGI) under different cutting parameters and conditions, a graph of the surface roughness (Ra) versus different cutting parameters was constructed. The experiment took into account the use of different types of PVD and CVD coated tools, both with and without cooling.

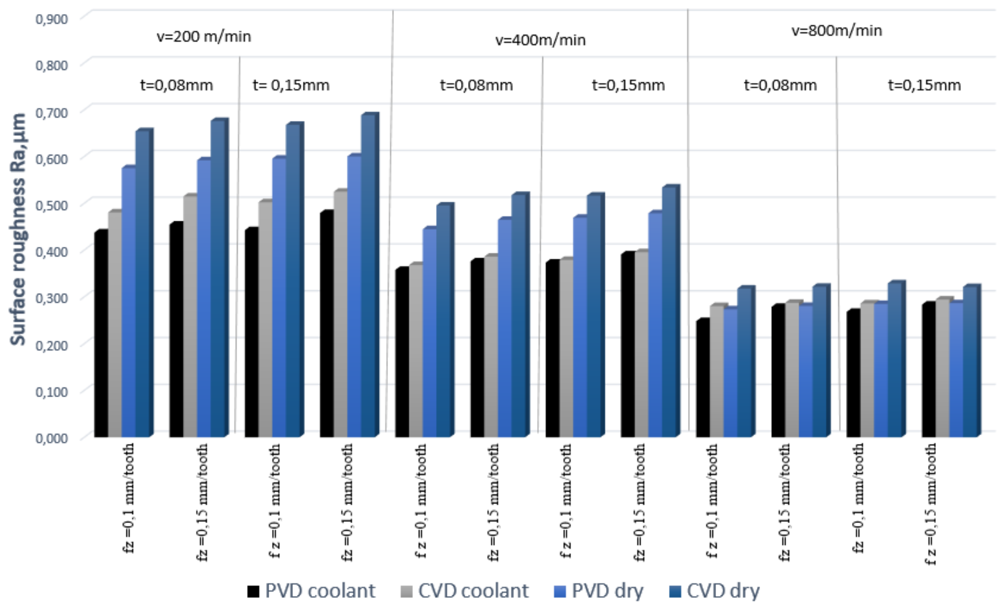


Figure 7. Dependence of various parameters and cutting conditions on surface roughness (Ra) when using different types of tools (PVD and CVD) with and without cooling

The following dependencies were obtained as a result of the study:

- At a speed of 200 m/min, the highest surface roughness was obtained for all combinations of parameters and cutting conditions. In particular, a roughness of Ra = 0.68 µm was obtained at the highest depth of cut and feed rate for the CVD-coated carbide material without cooling. This is due to the fact that lower cutting speeds can lead to higher levels of vibration and increased material deformation during machining, which negatively affects the surface quality. At 400 m/min, a lower roughness value was obtained, indicating that the machining quality was improved at medium cutting speeds. At this speed, vibrations become less intense and the material cut becomes more stable, which reduces roughness. The lowest level of roughness Ra = 0.25 µm is observed at a cutting speed of 800 m/min. Moreover, this value was obtained at the lowest depth of cut and feed rate with a PVD-coated carbide tool using coolant. This can be explained by the fact that the high speed combined with the use of coolant results in less heat build-up and more uniform cutting, which contributes to a smoother surface.

- In all cases, a lower depth of cut (0.08 mm) resulted in a lower surface roughness compared to a higher depth (0.15 mm). This can be explained by the fact that a lower depth of cut reduces the cutting force and therefore reduces the deformation of the material and tool, which improves the quality of the machined surface. The higher depth of cut (0.15 mm) slightly increased the roughness in all cases. This can be explained by the fact that a larger depth of cut generates more friction and heat, which can lead to micro deformation of the material and increase roughness.
- A lower feed per tooth (0.1 mm/tooth) resulted in a better surface finish, as each tool pass left less pronounced marks on the surface at a lower feed. Increasing the feed rate per tooth (0.15 mm/tooth) resulted in an increase in roughness. This may be due to the fact that at higher feeds, the tool leaves deeper marks on the machined surface, which increases the roughness.
- The PVD-coated tools generally showed better roughness results. This can be attributed to the fact that PVD coatings have less friction and better resistance to wear, resulting in a better finish. However, cooling further improves the results as it reduces the heating of the tool and the workpiece, which reduces the risk of microcracks and deformation. CVD-coated tools performed slightly worse than PVD tools. This may be due to the characteristics of the CVD coating, which is thicker and can cause some additional tool deformation at high cutting speeds and high feeds.
- All results where cooling was used showed a lower surface roughness. Cooling helps to reduce friction and temperature in the cutting zone, resulting in a more stable machining process and reduced roughness. In machining without cooling, there was an increase in roughness, which is associated with increased temperature and possible deformation of both the tool and the material being machined.

4. CONCLUSIONS

The best result of a surface roughness of Ra 0.25 μm was achieved at high cutting speeds (800 m/min), lower depths of cut (0.08 mm) and lower feeds per tooth (0.1 mm/tooth), with the use of cooling and PVD-coated tools. The PVD-coated tools generally showed better machining quality compared to CVD-coated tools and can be recommended for achieving better surface quality.

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УДК 621.914

ЗАЛЕЖНОСТІ ШОРСТКОСТІ ВІД РЕЖИМІВ ТА УМОВ РІЗАННЯ ПРИ ФІНІШНОМУ ТОРЦЕВОМУ ФРЕЗЕРУВАННІ ДЕТАЛЕЙ З ЧВГ

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Резюме. *Проаналізовано залежність шорсткості від режимів та умов різання при торцевому фрезеруванні поверхонь деталей з чавуну з вермикулярним графітом (ЧВГ), конструкційним матеріалом, який має відмінні механічні властивості, що ґрунтуються на зв'язку частинок графіту та заліза. У машинобудуванні протягом останіх років почав зростати інтерес до цього матеріалу. Особливо велику увагу він привернув з боку автомобільної промисловості й почав використовуватися як замінник сірого чавуну завдяки своїм поліпшеним механічним властивостям, таким, як підвищена міцність і термостійкість. Однак через високу твердість і міцність, а також складну мікроструктуру він важко піддається механічній обробці. Високий вміст перліту та наявність вермикулярного графіту ускладнює процеси різання, що призводить до швидшого зношення інструменту й отримання поверхні гіршої якості. Поверхні з чавуну з вермикулярним графітом часто вимагають високоякісної обробки, але через крихкість матеріалу існує ризик утворення мікротріщин та відколів на поверхні, що може негативно вплинути на якість фінішної обробки. Отримано залежності шорсткості від параметрів та умов різання при фінішному торцевому фрезеруванні поверхонь деталей з ЧВГ твердосплавними інструментами з покриттям PVD і CVD в умовах сухої обробки і з додаванням охолоджувальних рідин. На основі експериментальних даних побудовано математичні моделі залежностей шорсткості від параметрів та умов різання. Встановлено, що інструменти з PVD покриттям при фінішному торцевому фрезеруванні поверхонь ЧВГ на високих швидкостях різання з додаванням охолодження забезпечують кращу шорсткість поверхні у порівнянні з інструментами з CVD покриттям. Найкращий результат шорсткості поверхні Ra 0,25 мкм досягнуто при швидкості різання 800 м/хв, глибині різання 0,08 мм і подачі на зуб 0,1 мм/зуб при використанні охолодження інструментом з твердосплавного матеріалу з PVD покриттям.*

Ключові слова: *оброблюваність, чавун з вермикулярним графітом, шорсткість поверхні, фінішне торцеве фрезерування, інструментальні матеріали для обробки чавунів, параметри різання.*

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