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ANALYSIS OF CHIP COMPRESSION RATIO IN TURNING OF POLYOXYMETHYLENE COPOLYMER

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Abstract: *The turning process is influenced by a synergy of various parameters that affect the machining mechanisms and the resulting process efficiency. Among these factors, the evaluation of chip morphology is of paramount importance and can often be quantified by the chip compression ratio. This key figure serves as a quantitative measure of the overall plastic deformation and provides information about the energy expended during cutting and the friction behavior at the interface between the chip and the cutting tool. This research is specifically concerned with modeling and analyzing the chip compression ratio during dry turning of polyoxymethylene copolymer (POM-C) using a polycrystalline diamond (PCD) tool. The experimental setup comprised a face-centered, central compound test in which three main parameters — depth of cut, feed rate and cutting speed - were adjusted to each other. After conducting the turning experiments and collecting the measurement data, a second-order mathematical model was formulated to establish the relationship between the turning parameters and the chip compression ratio. Statistical analysis of the results revealed notable main effects of depth of cut and feed rate, a quadratic effect of depth of cut and an interaction effect between feed rate and cutting speed, all of which have a significant effect on the change in chip compression ratio.*

Key words: turning, chip compression ratio, POM-C, PCD, modelling.

Faktor sabijanja strugotine pri struganju industrijske plastike. *Na proces struganja utiču sinergijski efekti brojnih parametara koji na kraju definišu mehanizme obrade i rezultirajuće performanse procesa. Morfologija strugotine je od suštinskog značaja za procenu obradljivosti i može se kvantifikovati kao factor sabijanja strugotine. Ovaj parametar se može koristiti kao kvantitativna mera ukupne plastične deformacije, ima tendenciju da ukaže na količinu energije potrošene tokom procesa rezanja, kao I na ponašanje trenja u tačkama interakcije strugotine i reznog alata. Ova studija se fokusira na modeliranje i analizu faktora sabijanja strugotine pri suvom uzdužnom struganju polioksimetilen kopolimera (POM-C) korišćenjem polikristalnog dijamantskog (PCD) alata. U tom cilju, eksperiment je realizovan korišćenjem centralnog kompozitnog dizajna pri čemu su varirana tri glavna parametra (dubina rezanja, pomak i brzina rezanja). Nakon realizacije eksperimenta i prikupljanja podataka merenja, razvijen je matematički model drugog reda za određivanje faktora sabijanja strugotine. Rezultati statističke analize ukazuju na izražene glavne efekte dubine rezanja i pomaka, kvadratnog efekta dubine reza i interakcijskog efekta pomaka i brzine rezanja utiču na promenu vrednosti faktora sabijanja strugotine.*

Ključne reči: *struganje, faktor sabijanja strugotine, industrijska plastika, modelovanje*

1. INTRODUCTION

Turning stands out as the primary method for crafting circular components of diverse forms [1]. The process of turning is intricate, relying on various parameters whose collective impact determines the efficiency of the process, considering both the physical execution and the intricate cutting mechanics and physics involved. When dealing with a specific material and employing a particular machining setup (comprising cutting tools, machine tools, and cooling/lubrication conditions), the machinability—reflecting the ease or complexity of shaping a given material—is primarily influenced by the chosen cutting parameters. The assessment of material machinability involves diverse criteria categorized as fundamental (tool longevity, wear rate, surface quality) and supplementary (cutting forces, temperature, chip structure, etc.) [2].

The examination of chip structure provides insights into the stability of machining operations, often measured through various parameters like chip compression ratio (CCR), chip segmentation ratio, chip thickness, chip curling, and chip curvature radius [3, 4]. CCR, a quantifiable aspect of chip morphology [5], has been the focus of numerous studies across different engineering materials due to its utility as a measure of overall plastic deformation during machining [6]. Santos Jr. et al. [7] highlighted the significance of CCR as a post-machining parameter linked to the material's plastic deformation during chip formation, indicative of energy consumption

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during cutting. Additionally, it directly signifies the frictional dynamics at the chip-tool interaction zones, notably the rake surface [8].

Recent research has delved into the analysis of chip morphology. For instance, Hameed et al. [9] explored machinability indices such as CCR, shear plane angle, and specific cutting energy in conventional versus electropulsing-assisted turning of steel S235 and aluminum 6060. Chandra Behera et al. [3] conducted experimental research to grasp chip formation mechanisms in Inconel 718 turning using metallographic techniques. Kuruc et al. [10] analyzed the impact of feed rate and cutting speed on plastic deformation and CCR while turning C45 medium carbon steel and 62SiMnCr4 tool steel.

Furthermore, Younas et al. [11] scrutinized tool wear and energy consumption during the turning of Ti-6Al-4V alloys, emphasizing the strong influence of CCR, shear angle, and tool-chip contact length. Studies have also targeted optimizing cutting parameters regarding chip-tool interaction. Kumar et al. [12] utilized the Taguchi optimization approach to optimize turning conditions concerning CCR when machining titanium alloy. Mia et al. [4] introduced a grey relational-based Taguchi approach for multi-objective optimization of AISI 1060 steel turning process, considering CCR, effective shear angle, friction coefficient, and chip-tool interface temperature.

In the same vein, Singh et al. [13] performed chip morphology measurements and multi-objective optimization based on the RSM-desirability approach for turning AISI 4340 steel, focusing on CCR, surface roughness, and chip tooth height. Santos Jr. et al. [7] employed a genetic algorithm (GA) to determine cutting conditions that minimize machining force and CCR simultaneously when turning aluminum alloys.

The study focuses on analyzing how turning parameters impact chip compression ratio (CCR) during the machining of polyoxymethylene copolymer (POM-C). An empirical mathematical model was created using a face-centered central composite design, organizing depth of cut, feed rate, and cutting speed to understand their effects on CCR. The study aims to comprehensively explore these influences by systematically arranging these parameters within the design. The aim of applying this model was to identify correlations and patterns between the selected turning parameters and the resulting chip-compression ratio. In this way, the study should provide valuable insight into how variations in depth of cut, feed rate and cutting speed affect the chip compression ratio during the turning process of POM-C materials. This empirical approach enables a more detailed understanding of the complex dynamics between the machining parameters and the chip compression ratio, thus helping to optimize and improve machining processes for POM-C materials.

2. EXPERIMENTAL DETAILS

The longitudinal turning experiment was carried out on a universal lathe (POTISJE PA-C 30) in a dry machining environment. The test parts were in the form of a bar with a diameter of 100 mm, made of the polyoxymethylene (acetal) copolymer POM-C from Zell-Metall, Austria. The machining tests were carried out using a Walter VCGT160408FS-1 PCD insert on a Sandvik Coromant SVJBR 3225P 16 toolholder. The experimental tests were carried out in accordance with the face-centred central bonding plan and the cutting parameters given in Table 1. The cutting parameters were selected taking into account the recommendations for industrial plastics machining, the characteristics of the machine tool and the recommended cutting conditions for the insert.

Table 1. Cutting parameter levels used in the experiment

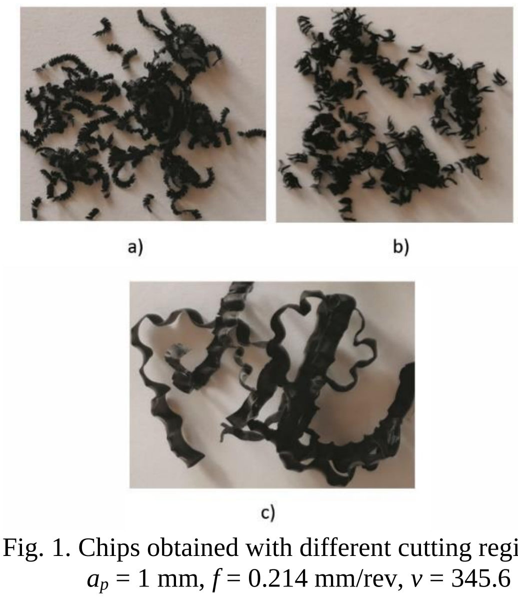
Parameter	Level 1	Level 2	Level 3
Depth of cut a_p [mm]	1	2.5	4
Feed rate f [mm/rev]	0.049	0.214	0.392
Cutting speed v [m/min]	188.5	345.6	510.5

The realization of the experiment, among other important performances, made it possible to estimate CCR (Rc) as the ratio of actual chip thickness (t_2) to the un-deformed (uncut) chip thickness (t_1) [6, 14]:

$$R_c = \frac{t_2}{t_1} = \frac{t_2}{f \cdot \sin \kappa} \quad [1]$$

where f is the feed rate and κ is the cutting edge angle.

In Equation 1, the un-deformed chip thickness is affected only by the feed rate given that the tool cutting edge angle was held constant during experimentation (κ = 93°). The actual chip thickness was measured using a Mitutoyo digital micrometer with measurement range of 0 - 25 mm and a resolution of 0.001 mm. After each experimental trial, the chips were collected and randomly selected for measurement of chip thickness. Three measurements were taken in order to obtain average chip thickness for all cutting conditions. Some of measured chip samples are shown in Figure 1.



a) b)

c)

Fig. 1. Chips obtained with different cutting regimes: a) a_p = 1 mm, f = 0.214 mm/rev, v = 345.6 m/min; b) a_p = 2.5 mm, f = 0.392 mm/rev, v = 345.6 m/min; c) a_p = 4 mm, f = 0.049 mm/rev, v = 510.5 m/min

As given in Equation 1, the resulting CCR in turning is higher than 1 because the actual chip thickness is greater than the corresponding un-deformed chip thickness, due to the frictional conditions existing at the chip-tool interface and the plastic deformation of the chip [14]. Higher CCR values require more work to carry out the process [10] and therefore indicate a higher demand for plastic energy for chip formation [3]. This means that the chip has encountered tremendous constraints in sliding across the rake face of the tool, affecting chip movement, and has thus become thicker and vice versa [7].

3. EMPIRICAL MODEL

The experiment and the subsequent collection of measurement data led to the development of a second-order mathematical model that establishes the relationship between the rotation parameters (a_p, f and v) and the chip compression ratio (CCR). This model has the following form:

$$R_c = 1.303 + 0.125 \cdot a_p - 0.18 \cdot f - 0.026 \cdot v + 0.105 \cdot a_p^2 - 0.012 \cdot f^2 + 0.05 \cdot v^2 + 0.0125 \cdot a_p \cdot f + 0.026 \cdot a_p \cdot v - 0.073 \cdot f \cdot v \quad [2]$$

It should be noted that in addition to considerably high values of coefficients of determination (R^2=0.94,R_pred^2=0.66,R_adj^2=0.89) and p value much less than 0.05, residuals were scattered randomly without any significant pattern around zero, which indicates that the developed empirical model is suitable for prediction and analysis of the change in CCR values with respect to independent variables (a_p, f and v).

4. RESULTS AND DISCUSSION

The graphical visualization presented in Figure 2 showcases the model that has been developed to predict the Chip Compression Ratio (CCR). This graphical representation serves as a comprehensive tool to delve into and analyze the intricate relationships and effects of various factors, such as the depth of cut, feed rate, and cutting speed, on the resulting CCR. By visually depicting these relationships, the figure aids in gaining a deeper understanding of how alterations in the depth of cut, feed rate, and cutting speed interact and influence the resultant Chip Compression Ratio in the turning process of POM-C material.

The findings depicted in Figures 2a) and 2b) notably illustrate that an incremental rise in the depth of cut consistently leads to a nonlinear increase in the Chip Compression Ratio (CCR), irrespective of the specific values of the cutting speed and feed rate. This observation aligns with a related study conducted by Singh et al. [13], wherein they also noted that, when maintaining constant values for cutting speed and feed rate, the CCR gradually amplifies with an escalation in the depth of cut. This correlation stems from the increased material removal from the workpiece due to a higher depth of cut. It's important to note that any augmentation in the depth of cut or feed rate contributes to an enlargement of the cross-sectional area of the undeformed chip. Consequently, this tendency results in a decrease in the CCR, as a larger undeformed chip cross-section requires more energy for compression, thus affecting the overall Chip Compression Ratio.

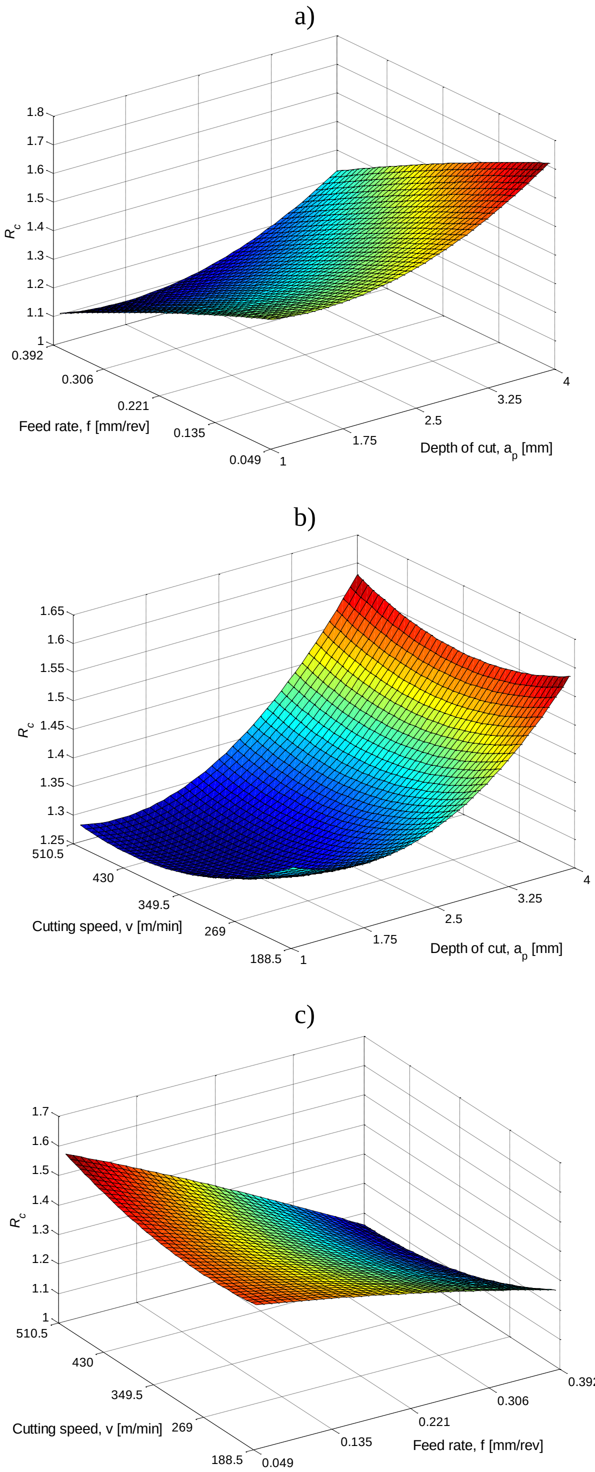


Fig. 2. Surface plots of CCR: a) interaction of depth of cut and feed rate, b) interaction of depth of cut and cutting speed, c) interaction of feed rate and cutting speed

The trend of a near-linear decrease in the Chip Compression Ratio (CCR) corresponding to an escalation in the feed rate is discernible in Figures 2a) and 2c). This decrease can be attributed to the augmented thickness of the undeformed chip resultant from an increased feed rate. At lower feed rates, there's a notable increase in plastic deformation within the chip. This phenomenon arises due to a more pronounced strain-hardening effect occurring when the feed rate is lower, resulting in a thinner unreformed chip being removed. Moreover, this effect is compounded by the size effect elucidated in reference [2] and the higher specific cutting pressure highlighted in [15]. An interesting observation is that higher cutting speeds accentuate the decline in CCR, primarily due to the effect induced by the increase in feed rate. Astakhov and Shvets [6] also posit that the impact of feed rate might vary at different cutting speeds. However, in the machining of steels, a prevalent trend of decreasing CCR with an escalation in the feed rate across various cutting speed values is evident. Similar conclusions were drawn by Chandra Behera et al. [3] in their study on turning Inconel 718. They highlighted that the increased cutting speed leads to a rise in chip velocity, subsequently reducing friction at the chip-tool contact point [16], potentially contributing to the observed decrease in CCR with increased feed rate.

The empirical model created displayed strong statistical validity by correlating predicted CCR values with actual experimental data. Although the experimental CCR values seemed confined within the 1.1 to 1.6 range, this range aligns with typical conditions for both finishing and medium machining operations. This narrow span was expected due to POM-C's notably lower specific cutting force compared to materials like steels, aluminum alloys, and cast irons.

The analysis underscored the depth of cut as the primary factor impacting CCR, followed by the feed rate, cutting speed, and the interplay between cutting speed and feed rate. A direct relationship between depth of cut and CCR was evident, while cutting speed and feed rate exhibited an inverse correlation, with some interaction observed between the two.

The models developed to predict CCR can function as objective functions for optimization problems in turning processes, particularly in minimizing objectives. This methodology presents significant improvements to the overall process. Notably, it was discovered that minimizing CCR and maximizing Material Removal Rate (MRR) are not conflicting goals. However, achieving these objectives necessitates a delicate balance with other vital machining performance factors, like surface roughness and the creation of favorable chip forms.

Figure 2 b) and c) shows that the effect of the cutting speed on the resulting CCR is least pronounced and that it has a variable character. Namely, as shown in Figure 2 b), an increase in the cutting speed up to approximately 350 m/min results in CCR decrease, but afterwards, an increase in the cutting speed again increases CCR, and that increase is higher for greater values of the depth of cut. One may notice that for a constant feed rate there is a combination of cutting speed and depth of cut which produces minimal CCR. Research by Astakhov and Shvets [6] showed that in machining copper, steel, and aluminum, for a constant feed rate and depth of cut (f = 0.07 mm/rev, a_p = 1 mm), there exists a particular cutting speed which results in minimal CCR. The conducted machining test also confirmed the existence of variable influence of cutting speed on the CCR. It has been pointed out that the cutting speed influences the energy spent on the deformation of the chip through the temperature, dimensions of the deformation zone adjacent to the cutting edge and velocity of deformation.

Further, from Figure 2 c) one may notice that there exists a certain level of interaction between the cutting speed and feed rate. Namely, for low feed rates, and increase in the cutting speed leads to a slight increase in CCR, however, for high feed rates, and increase in the cutting speed results in a decrease in CCR. The experimental investigation by Yilmaz et al. [17], showed that increased cutting speed influences the chip formation by producing less thick chips, and this may justify the observed decrease of CCR for higher cutting speed.

Figure 2 shows that there are significant effects of both feed rate and depth of cut on CCR. The combination of high feed rate and low depth of cut decreases CCR, while CCR attains higher values when using higher depth of cut values and minimum feed rate values. These observations are in line with the results of Singh et al. [13]. The authors explained this phenomenon mainly due to dominating effect of material removal rate, which is directly linked with depth of cut.

5. CONCLUSION

The experimental study delved into the Chip Compression Ratio (CCR) during the turning process of unreinforced polyoxymethylene copolymer (POM-C) utilizing a PCD cutting tool. The empirical model developed to predict CCR showed statistical validity, aligning well with actual experimental data. Despite the CCR values ranging from 1.1 to 1.6, seemingly narrow, this span is typical for the varied experimental conditions, covering finishing and medium machining operations.

This constrained range was expected due to POM-C's lower specific cutting force compared to other materials. Depth of cut emerged as the most influential factor on CCR, followed by feed rate, cutting speed, and their interaction. Depth of cut exhibited a direct proportional relationship with CCR, while cutting speed and feed rate showed inverse proportionality with some interaction.

These empirical models can function as objective functions for optimization problems in turning processes, offering comprehensive enhancements. Notably, it was found that minimizing CCR and maximizing Material Removal Rate (MRR) aren't conflicting objectives, yet they must be balanced with critical machining factors like surface roughness and chip formation. Achieving an optimal balance among these factors is vital for effective machining performance.

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