Advances in Science and Technology Research Journal

Advances in Science and Technology Research Journal, 2027, 21(1), 393–410
https://doi.org/10.12913/22998624/235982
ISSN 2299-8624, License CC-BY 4.0

Received: 2026.07.13
Accepted: 2026.11.15
Published: 2026.12.01

Multi-scale analysis of chip compression ratio and deformation mechanisms during minimal quantity of lubrication assisted turning of AISI 1045 steel

Umidjon Mardonov[1*], Otabek Khasanov[1], Bekzod Yusupov[2], Jamshidbek Khasanov[3], Botir Saydumarov[4], Nargiza Ismatullayeva[5], Omil Kasimov[6], Dilshodbek Ergashev[3], Begijon Tojiboyev[7], Sarvar Tursunbaev[4]

[1] Department of Mechanical Engineering Technology, Tashkent State Technical University, 100095, Tashkent, Uzbekistan
[2] Department of Mechanical Engineering Technology, Almalyk State Technical Institute, 110100, Almalyk, Uzbekistan
[3] Department of Mechanical Engineering Technology, Andijan State Technical Institute, 170019, Andijan, Uzbekistan
[4] Department of Metal Technology, Tashkent State Technical University, 100095, Tashkent, Uzbekistan
[5] Department of Translation Studies, Linguistics and International Journalism, Tashkent State University of Oriental Studies, 100060, Tashkent, Uzbekistan
[6] Department of Vehicle Engineering, Tashkent State Transport University, 100167, Tashkent, Uzbekistan
[7] Department of Materials Science in Mechanical Engineering, Andijan State University, 170112, Andijan, Uzbekistan
* Corresponding author's e-mail: u.mardonov@tdtu.uz

ABSTRACT

In this manuscript, a multi-scale analysis combining the statistical analysis of the chip compression ratio and micro-scale evaluations of chip morphology was conducted. The individual and combined effects of spindle speed, feed, and depth of cut on the chip compression ratio were determined through experimental and statistical analysis methods. An uncoated carbide tool insert was used for machining operations, while natural olive oil was used for cutting fluid. The study used a full factorial design, analysis of variance, regression analysis, statistical modelling, graphical evaluation, and microstructural evaluation. The analysis of variance results showed that the parameters with the greatest influence on chip compression ratio were the feed and depth of cut, whereas spindle speed had a relatively minor impact. Increasing the feed reduced the chip compression ratio, while increasing the depth of cut had the opposite effect. The developed regression model demonstrated strong forecasting ability, with a high correlation among the R-sq, R-sq (adj), and R-sq (pred) values. Microstructural observations revealed a strong correlation between chip compression ratio reduction and chip morphology transition from continuous to segmented forms. Based on the combined statistical and microstructural analyses, depth of cut and feed were identified as the two dominant machining parameters governing the chip compression ratio and deformation mechanisms in minimum quantity of lubrication turning of AISI 1045. The study found that the influence of the minimum quantity of lubrication medium on the chip compression ratio at low feed and depth of cut values is significantly stronger, while its effectiveness is reduced in aggressive cutting modes.

Keywords: cutting parameters, chip compression ratio, chip morphology, MQL, turning, full factorial design.

INTRODUCTION

Due to intensified environmental standards, economic issues, and escalating demand for resource-efficient technologies, sustainable manufacturing is becoming one of the essential modern processing industries. Machining technologies, including turning, milling, and drilling, are widely applied methods in the manufacturing industry. Development of machining technologies that pay attention to today's sustainable manufacturing demands is one of the actual issues in mechanical engineering. Traditional cooling methods such as flood cooling are widely used in machining processes, and they have an effective role in reducing high cutting temperatures generated in machining processes. On the other hand, flood cooling technology requires an excessive amounts of metal working fluids. Such an excessive amount of chemical fluids (emulsions, synthetic oils, etc.) causes ecological and health issues, but most importantly, toxicity problems related to disposal [1–3]. Çalık and Uzun [4] emphasised the adverse environmental impacts and environment-human risks of the flood cooling method. According to their comprehensive review, there is a great demand for investigations of sustainable cooling strategies. Kesriklioglu [5] found that traditional flood cooling does not achieve significant temperature reduction in the chip-tool interface. He stated that flood cooling is not effective in continuous machining operations like turning. Because of these reasons, sustainable lubrication strategies are receiving increasingly more attention as an alternative to traditional cooling technologies. Minimal quantity of lubrication (MQL) has emerged as one of the most promising approaches among them because it has the ability to considerably lower the consumption of lubricating materials while keeping sufficient tribological properties during the machining operations [6-9]. Essentially, a small amount of oil is applied to the cutting zone in machining, and it helps to reduce friction at the chip-tool interface. This improves chip evacuation and increases the manufacturing efficiency by minimising environmental impacts.

The use of vegetable oils as a lubricating fluid is gaining significant interest in MQL machining due to their biodegradability, renewability, low toxicity, and excellent lubrication properties. Bai et al. [10] found that vegetable-based oils achieved lower milling force and better surface quality than synthetic cutting fluids, while Pervaiz et al. studied sustainable vegetable oil-based MQL technology in turning Ti6Al14V [11]. Olive oil, with its excellent viscosity, lubricity, and film-forming ability, is one of the suitable fluids to reduce friction and adhesion during the metal cutting process [12]. MQL systems with olive oil-based characteristics are appropriately used for turning operations when frictional contact and severe plastic deformation greatly influence the chip formation process [13, 14]. The stability and efficacy of the cutting process are influenced by the state of lubrication in machining operations, which also impacts chip flow, tool-chip contact area, heat generation, and material deformation mechanisms. The authors [15] said that surface quality and the chip morphology in milling operations is affected by lubrication methods in milling difficult-to-cut materials. In work [16], continuous lubrication with atomised cutting fluids resulted in better cutting performance of the turning tool. In addition, Cao et al. [17] found that the lubrication mechanism has a noticeable influence on tool microtexture.

Medium-carbon steels like AISI 1045 are commonly used in automotive, agricultural and mechanical engineering industries owing to the good combination of strength, machinability and low cost of this material [18]. However, machining of AISI 1045 steel is often accompanied by substantial plastic deformation, tool–chip friction, heat generation, and unstable chip geometry. Additionally, machining low-alloy steels such as AISI 1045 cast parts is difficult because of porosity after the casting process [19, 20]. These occurrences can adversely affect process stability and machining quality. For example, the authors of [21] employed the finite element method to improve the machinability of AISI 1045, while [22] studied a novel methodology using flood cooling in machining AISI 1045. Moreover, Khasanov et al. [23] found that a magnetic field influences the HSS tool performance in turning low-alloy steel, while Qasim et al. [24] used the Taguchi design and ANOVA to optimise the machining process of AISI 1045 parts. Analysis of chip formation thus helps in understanding the mechanics of material removal and deformation behaviour during cutting operation. In particular, Dung et al. [25] studied the chip formation with a combination of acoustic emissions and vibration signals in turning

SCM440. They found that tool wear was affected by chip formation, and chip formation patterns can be described by oscillations in the cutting zone. Rahman et al. [26] studied the chip morphology in nano-MQL conditions. They found that the depth of cut (DOC) largely affects the chip reduction coefficient, while a higher feed reduces a spiral-shaped chip. Moreover, lower shear strain and flow stress were reached under high cutting speeds, as found by Uysal and Jawahir [27]. The chip compression ratio is one of the most widely used indicators for characterising chip deformation, reflecting the degree of plastic compression of the chip during material removal. Since the chip compression ratio is directly related to the undeformed chip thickness, shear angle, material flow, and tool-chip friction, it is an important parameter for evaluating cutting performance and deformation mechanisms in turning processes. The authors of [28] found that undeformed chip thickness impacts specific energy in machining, and in [29], the authors studied the machining process under magnetically treated cutting fluid conditions, indicating chip formation. Moreover, Torchak et al. [30], discussed several methods of determining the chip compression ratio.

Machining parameters such as cutting speed, feed, and DOC strongly influence chip compression ratio. Earlier studies have shown that increasing feed considerably alters undeformed chip thickness and shear deformation characteristics [31, 32]. Particularly, Kose et al. [33] found that feed is the most influential parameter on tool stresses in machining operations. They studied the ceramic tool insert in turning Inconel 718. Moreover, DOC influences the material removal load and the geometry of the primary deformation zone [34, 35]. Likewise, cutting speed may influence chip formation through thermo-mechanical mechanisms, such as strain rate effects and thermal softening. Nevertheless, many investigations have been conducted on MQL-assisted turning. However, most studies have restricted themselves to assessing machining responses like surface roughness, cutting temperature, tool wear, and cutting force optimisation. There has been comparatively less attention to systematic analysis of chip deformation behaviour, especially chip compression ratio, under different cutting modes using statistically robust experiments [12, 21, 36].

Bibliometric analysis

The bibliometric analysis was conducted based on studies published in the Scopus database between 2020 and 2026. Recent directions were analysed using the Vos Viewer software (version 1.6.20) based on research keywords for cutting parameters, chip formation, MQL, and ANOVA (Figure 1a), and for chip formation and MQL (Figure 1b).

From the bibliometric mapping shown in Figure 1, it can be seen that research related to machining in an MQL medium was primarily conducted on surface roughness of the part, tool wear, lubrication efficiency, and cutting temperature. In particular, surface quality was studied in almost all studies, while there is a lack of studies related to chip formation. Furthermore, although statistical methods such as analysis of variance (ANOVA) and design of experiments (DoE) are increasingly used to optimise machining processes, their application in the MQL environment remains limited for the systematic analysis of chip deformation during turning. Thus, the bibliometric results demonstrate significant research potential for studying the interaction between cutting parameters and chip deformation mechanisms using statistically validated approaches. Moreover, the interaction between cutting modes and CCR under vegetable oil-based MQL conditions, as well as chip morphology, has not been sufficiently studied.

Although numerous studies have investigated the effects of cutting parameters on tool wear, cutting forces and surface roughness under dry, flood and MQL conditions, limited attention has been given to the relationship between CCR and chip deformation mechanisms in MQL-assisted machining operations. Furthermore, the potential of CCR as an indicator of chip morphology evolution under MQL turning conditions remains insufficiently understood. Thus, studies on the statistical analysis of the individual and combined influence of cutting modes, and how their effects respond to MQL-assisted operations, remain a research gap in this area. In this study, the independent and combined effects of spindle speed, feed, and DOC on the CCR when turning AISI 1045 steel in an MQL environment using an olive oil-based lubricant and an uncoated carbide tool were investigated. Moreover, this study combines macro- and micro-scale analyses of chip morphology, statistical data analysis, and regression modelling to provide a complete understanding of the

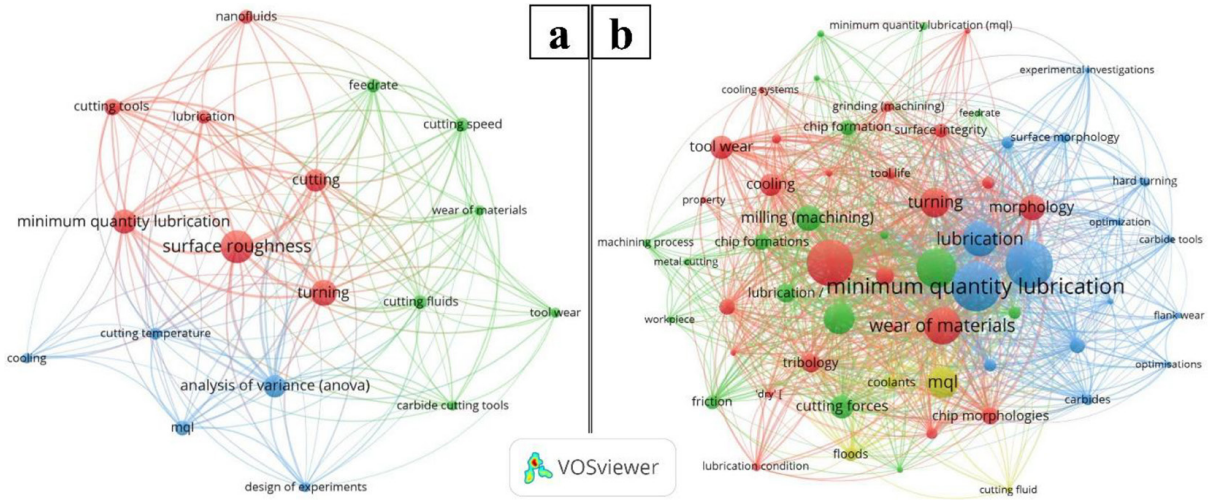


Figure 1. Bibliographic co-occurrence data generated by VOSviewer

chip formation mechanism and create a reliable basis for optimising cutting modes in the MQL-assisted turning process. ANOVA, regression modelling, residual analysis, and response surface plots were used to quantitatively assess the influence of spindle speed, feed, and DOC on CCR.

METHODS

Machining tests

To conduct the machining tests, a workpiece made of AISI 1045 steel, T15K6/YT5 (GOST 3882-74) grade uncoated carbide tool inserts (WNUM 080408) installed on an MWLNR2920 M08 2102-030729 type external turning tool holder, and a 16K20 screw-cutting machine tool were set up. The geometric parameters of the cutting tool insert and machine tool specifications are given in Table 1 and Table 2. The experiments were carried out under external longitudinal turning conditions using cylindrical AISI 1045 steel specimens with a diameter of 90 mm, and the machining operation was performed as a conventional turning process. During machining, the cutting tool engaged the external cylindrical surface of the workpiece under continuous longitudinal feed. A schematic illustration of the experimental setup and machining configuration is presented in Figure 2a.

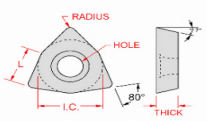
Table 2. 16K20 screw-cutting lathe parameters

Maximal spindle speed	1600 rpm
Longitudinal feed range	0.05–2.8 mm/rev
Transverse feed range	0.025–1.4 mm/rev
Distance between centres	1000 mm

Machining passes were conducted under MQL conditions, in which an oil nozzle was equipped with a mechanism to control air pressure and the amount of liquid added. This provides the air-liquid mixture (aerosol) for direct spraying into the cutting zone. The air pressure applied to the MQL medium was 203 KPa, and the volumetric flow rate of the cutting fluid was 200 ml/hour. Commercial food-grade olive oil was used as the MQL lubricant, with a dynamic viscosity of 84 mPa·s at 25 °C. The main input parameters (variables) chosen in this study were n – spindle rotational speed (rpm), f – feed (mm/rev), and DOC – (mm). The overall experimental study methodology and study conceptual framework are illustrated in Figure 2.

The chip deformation was quantitatively evaluated using the chip compression ratio (K), which represents the ratio between the chip thickness (a_{ch}) and undeformed chip thickness

Table 1. Geometric parameters of tool insert

	L, mm	Thickness, mm	Nose radius, (± 0.1)	Hole diameter	Holder type
	8.7	4.76	0.8	5.16	MWLNR2920 M08 2102-030729

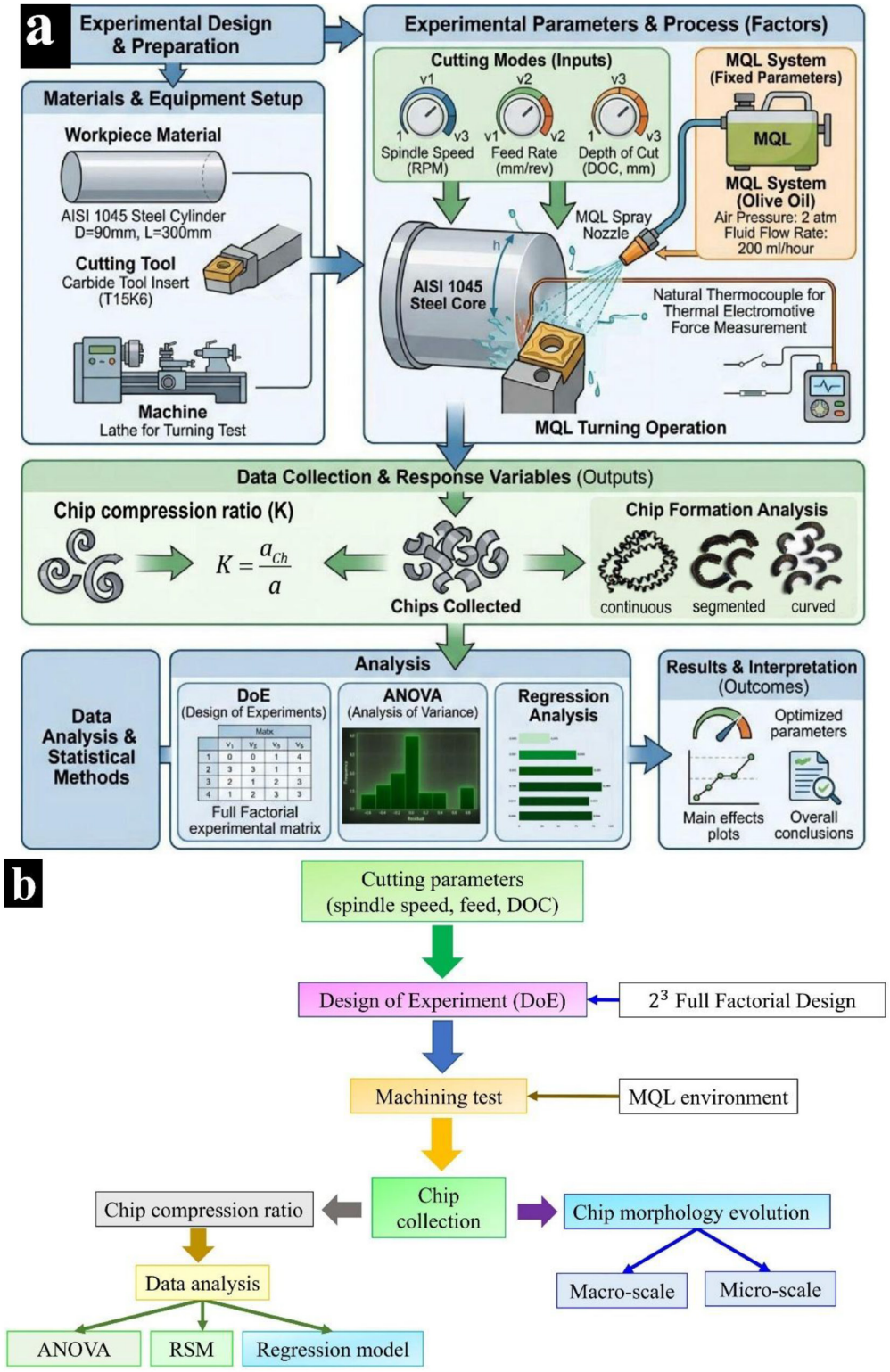


Figure 2. a) Schematic representation of the experimental workflow; b) study conceptual framework

(*a*) (Equre 1) [37, 38]. In the present study, the experimental method of determining CCR was used. Undeformed chip thickness (*a*) was assumed to be equal to the feed per revolution (*f*). Considering the 95° cutting edge approach angle φ of the MWLNR2525-M08 tool holder, the undeformed chip thickness was calculated as $a = f \cdot \sin\varphi$. Since $\sin 95^0 \approx 0.996$, the undeformed chip thickness was practically equal to the feed per revolution. The deformed chip thickness was measured using a precision micrometre with a resolution of 0.01 mm. Experimental studies

included measuring chip thickness and determining the morphological characteristics of chips generated in the cutting process. For each experimental condition, three measurements were taken at different locations along the chip length, and the average value was used for the CCR calculation. The measurement uncertainty associated with chip thickness measurements was estimated to be ±0.01 mm, corresponding to the resolution of the micrometre. Each experimental condition was repeated twice according to the full factorial design, and the two experimental replicates were analysed independently. The corresponding CCR values obtained from each replicate were included separately in the statistical analysis. As a result, the experimental CCR is determined according to dependence (Equation 1):

$$K = \frac{a_{Ch}}{a} \tag{1}$$

CCR is an essential factor used in metal cutting processes to study and analyse the plastic deformation, machinability, and cutting performance. Subsequently, statistical and analytical methods such as DoE, ANOVA, and regression modelling were used to evaluate the truncation parameters of the collected data and their interactions. The obtained results were analysed using graphical and statistical tools; the influence of process variables was determined, and optimal processing conditions were determined. In the experiments, a special optical microscope of the AmScope PZ620 Series was used exclusively for qualitative observation and documentation of chip morphology and deformation features. Figure 3 shows the chip samples obtained from each turning pass.

CCR is influenced by several factors, including machining parameters (cutting speed, feed, and DOC) as well as tool geometry, particularly the rake face geometry and cutting-edge design. However, because the tool geometry was kept constant throughout this study, the present investigation focuses exclusively on the influence of the machining parameters on CCR.

Design of experiment

A full factorial design (FFD) was used to study the influence of cutting parameters on CCR in a vegetable oil-based MQL turning operation. The DoE consisted of three factors with two levels: A – spindle speed (n), B – feed (f), and C – DOC (a_p). The total number of combinations was $2^3 = 8$. To assess experimental error and improve the reliability of the statistical analysis, each experiment was replicated twice, for a total of 16 trials. No central points were included in the design,

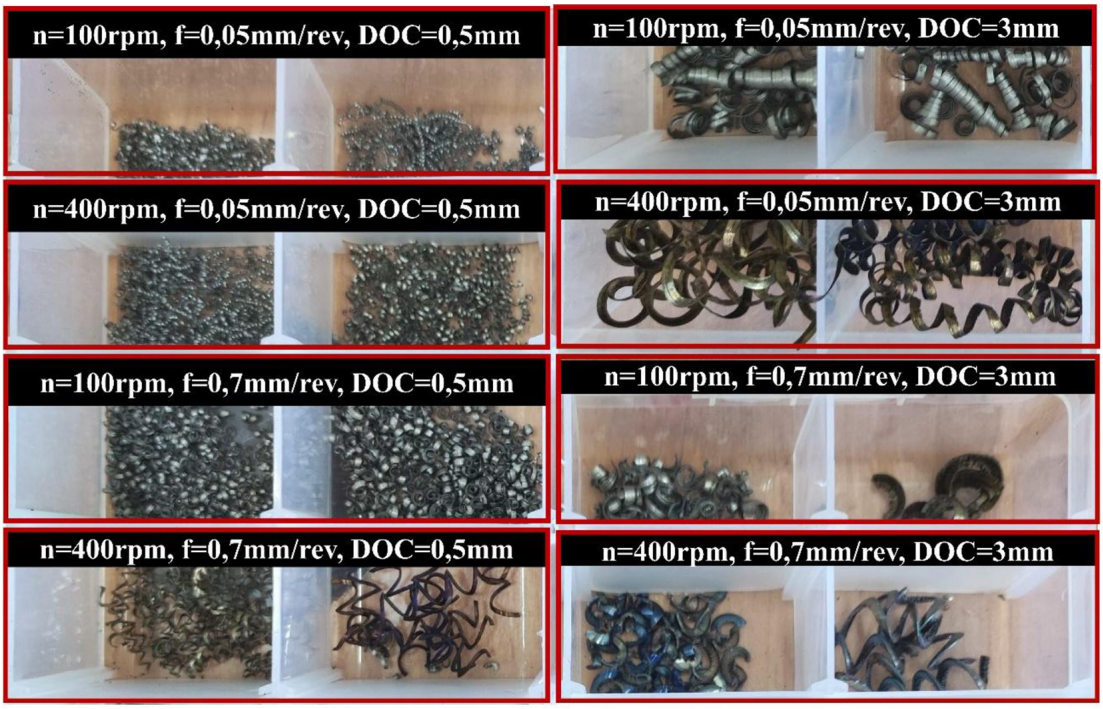


Figure 3. Chip samples obtained from turning tests

Table 3. Design summary for experimental tests

Factor	Symbol	Parameter	Unit	Low level	High level
A	n	Spindle speed	rpm	100	400
B	f	Feed	mm/rev	0.05	0.7
C	a_p	DOC	mm	0.5	3

and all experiments were conducted in a single block in random order. Table 3 presents the design summary.

RESULTS

Table 4 below represents the experimental results obtained from the 2^3 FFD. The table shows the random operating mode, the cutting parameters (n, f, and a_p), and the corresponding measured values of the chip compression ratio (K).

The results presented in Table 4 show that the CCR varied significantly with the selected cutting modes. Minor differences in K values are observed due to repeated experiments for identical parameter combinations, reflecting the inherent variability of the turning process. The results indicate that at low feed, chip deformation was high, whereas at higher feed, K values decreased significantly. In addition, the increase in CCR depends on the DOC and leads to increased material flow in the cutting zone. Based on these observations, preliminary conclusions can be drawn regarding the influence of cutting mode elements on chip deformation. Figure 4 presents the normal probability plot and Pareto chart (for standardised effects), which were used to determine the significance of the cutting parameters and their independent as well as combined effects on CCR. The normal probability plot shows that the effects corresponding to feed (B), DOC (C), and their interactions (AB and BC) deviate significantly from the baseline. Therefore, these effects are statistically significant for the value of K. However, the spindle speed lies closer to the line, indicating that this parameter has a relatively minor effect on CCR.

The foregoing considerations are also confirmed by the Pareto chart. It can be seen from Figure 4 that the standardised effects of C and B significantly exceed the critical reference line ($\alpha = 0.05$), which indicates that these factors are statistically very significant. DOC was found to be the factor with the strongest influence among all variables. The feed comes after the DOC, indicating their dominant role in CCR.

Table 4. Randomised design table, experimental chip coefficient ratio values

Run	A, rpm	B, mm/rev	C, mm	K
1	100	0.05	3.0	5.3
2	400	0.70	3.0	2.2
3	400	0.05	0.5	3.4
4	400	0.05	3.0	5.0
5	400	0.70	3.0	2.1
6	100	0.05	0.5	1.1
7	100	0.05	0.5	1.4
8	100	0.70	0.5	1.4
9	400	0.05	3.0	5.6
10	100	0.70	0.5	1.2
11	400	0.05	0.5	2.6
12	400	0.70	0.5	1.1
13	400	0.70	0.5	1.3
14	100	0.05	3.0	4.5
15	100	0.70	3.0	2.2
16	100	0.70	3.0	3.0

Furthermore, the interaction effects of feed with spindle speed (AB) and with DOC (BC) were also significant. This indicates the combined influence of process parameters on chip deformation characteristics. On the other hand, the main effect of spindle speed does not exceed the significance level, which implies that its influence is relatively weaker. These results confirm that feed and DOC primarily govern the CCR, while spindle speed plays a secondary role under the given machining parameters.

The primary influence of cutting parameters on CCR is illustrated in Figure 5. The lines in Figure 5 also confirm that both feed and DOC strongly influence CCR. Although the ANOVA results indicate that DOC has the greatest statistical contribution, feed produces the most pronounced change in chip compression behaviour by varying the undeformed chip thickness, while the effect of spindle speed is relatively minor. As seen in the figure, a sharp decrease in *K* was observed when the feed was increased from 0.05 mm/rev to 0.70 mm/rev. This phenomenon can be explained by an increase in the uncut chip thickness, which reduces relative plastic deformation in the shear zone. DOC, however, has a strong positive effect on chip deformation. As the input value of the DOC was increased from 0.5 mm to 3.0 mm, the response value of *K* also increased significantly, indicating greater material deformation due to higher cutting forces and an increased volume of the shear zone. As the spindle speed increased from 100 to 400 rpm, a very slight increase in CCR was observed, which once again confirmed that its effect was relatively small. This suggests that, within the chosen range, thermal effects linked to spindle speed are less significant than mechanical factors such as feed and DOC.

Figure 6 shows the interactions between the studied cutting parameters and CCR. It was established that certain interaction lines are not parallel, and there are significant correlations between the feed and DOC, as well as the feed and spindle speeds. The interaction between feed and spindle speed (feed × rpm) indicates that the effect of feed on CCR depends on spindle speed. When the feed was at the lowest value (0.05 mm/rev), CCR was significantly higher, especially at high spindle speed values. However, it can be observed that when the feed is increased (0.70 mm/rev), the difference between feed and spindle speed becomes insignificant. This indicates that the dependency of CCR on the spindle speed decreases at higher feeds. Furthermore, the interaction between DOC and feed becomes clearly evident. At low feed, increasing the DOC from 0.5 mm to 3.0 mm led to a sharp increase in CCR. In contrast, at higher feeds, the increasing rate of K with DOC is relatively lower. This indicates that the effect of DOC on CCR is strongly dependent on the feed value, which confirms the coupled mechanical behaviour during chip formation. Similarly, the RPM-DOC interaction had a relatively weak effect, indicating that these two parameters have a limited combined effect on the feed-related interactions. Overall, Figure 6 indicates that feed plays a key role in governing the interaction effects, particularly with DOC, whereas the ANOVA results identify DOC as the factor with the greatest statistical contribution to CCR.

Figure 7 presents three-dimensional response surface plots generated from the fitted regression

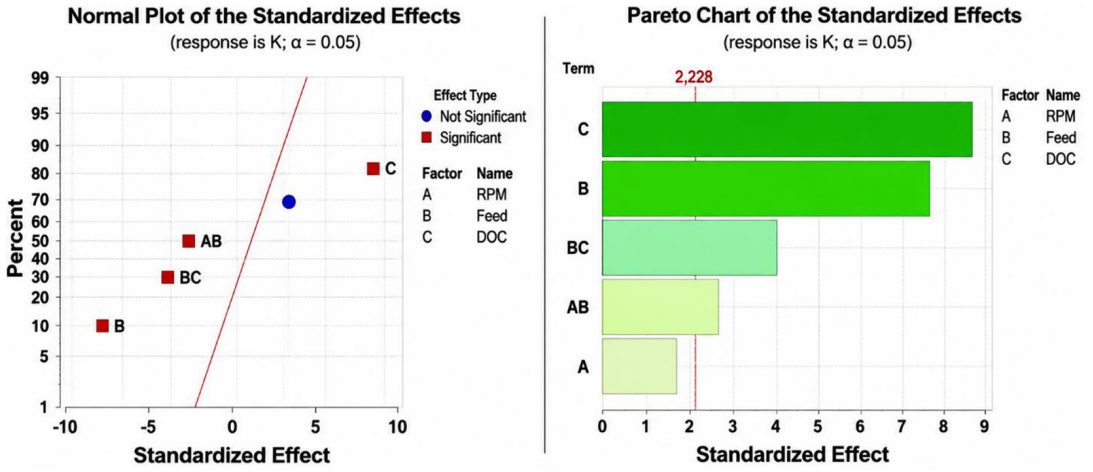


Figure 4. Normal plot and Pareto chart of standardised effects for chip deformation (K)

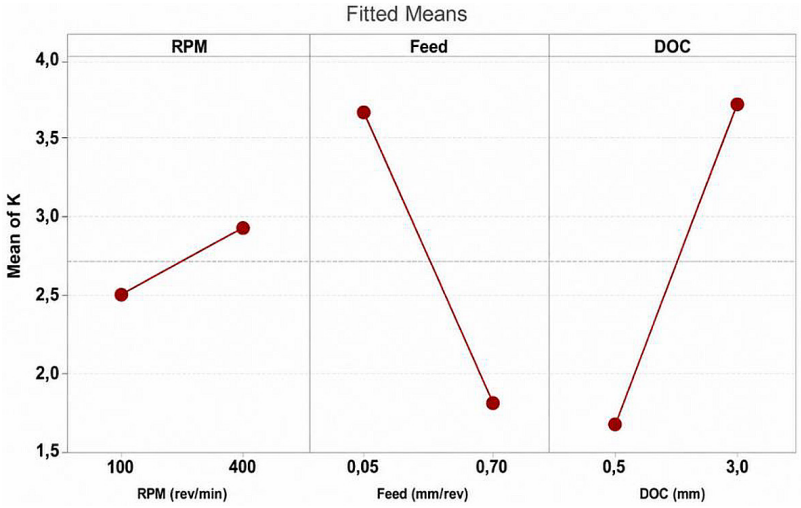


Figure 5. Main effects plot showing the influence of spindle speed, feed, and DOC on chip deformation (K)

model that illustrate the combined influence of cutting parameters on CCR. These graphs allow for a more detailed observation of the combined effect of cutting modes. Furthermore, these images enable the identification of areas corresponding to the maximum and minimum CCR.

An examination of the three surface plots reveals a strong combined effect of feed and cutting depth. Figure 7a shows that CCR reaches its maximum at a low feed and a large cutting depth, which indicates that strong plastic deformation occurred under these conditions. However, regardless of the cutting depth, the CCR decreased significantly feed was increased. This growth confirms the high impact of the feed on CCR. It is clear from the surface plot of feed and spindle speed that CCR is highly sensitive to the feed, while the effect of spindle speed is relatively moderate (Figure 7b). CCR was slightly increased by improving spindle speed at lower feed values. But, the influence of spindle speed became negligible at high feed. This suggests that the influence of spindle speed is dependent on the feed. In contrast, the spindle speed-DOC surface diagram shows a relatively weaker interaction effect (Figure 7c). Although CCR increases with the DOC, the change along the spindle speed axis is relatively small. From this, it can be seen that the combined effect of spindle speed and DOC is less significant compared to the thrust-related interactions.

Overall, the response surface plots indicate that maximum CCR occurs at a low feed and a high DOC when turning in a vegetable oil-based

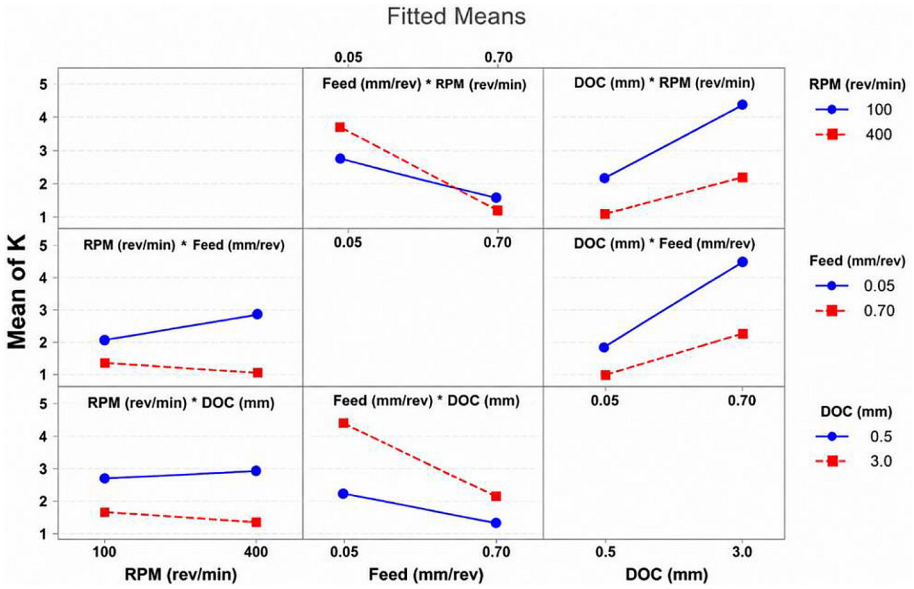


Figure 6. Interaction plots of the combined effects of cutting parameters on chip deformation

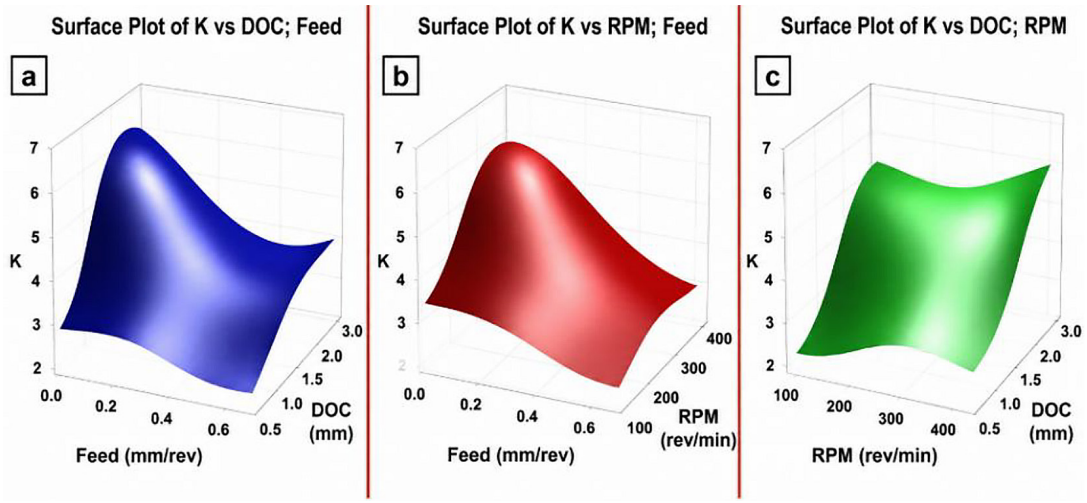


Figure 7. Response surface plots of the combined effects of cutting parameters on CCR: (a) feed and DOC, (b) feed and spindle speed, and (c) spindle speed and DOC

MQL environment. Conversely, minimum CCR occurs at a high feed and a low cutting depth mode. As a result, response surface plots further illustrate the principal role of the feed, particularly through its interaction with DOC in controlling chip deformation under MQL turning conditions.

Regression analysis

Using experimental data, a regression model in uncoded units was developed to predict CCR as a function of the cutting parameters (n, f, a_p) (Equation 1).

$$K = (3.93 - 6.92 \cdot f) \cdot 10^{-3} \cdot n + \\ + (0.95 - 1.14 \cdot a_p) \cdot f + 1.25 \cdot a_p + 0.586 \quad (1)$$

where: n – spindle speed in rpm, f – feed in mm/rev, and a_p – DOC in mm.

The regression equation reveals the quantitative relationship between the cutting parameters and CCR. The positive coefficient of the DOC shows that increasing the DOC leads to a significant increase in CCR. This corresponds to an increase in the material removal rate and higher cutting forces. The coefficient associated with the feed is also positive in the linear model. However, the strong negative interaction between Feed×DOC indicates a decrease in the overall effect of the feed under combined conditions. This, in turn, confirms that the feed plays a dominant and complex role in CCR. Equation 2 shows that the spindle speed coefficient is relatively small, confirming the low contribution of cutting speed to CCR within the selected range. This corresponds to the previous observations from the analysis of main effects and interactions. The negative value of the rpm-feed interaction indicates that a simultaneous increase in both parameters results in a decrease in CCR, which emphasises the combined thermo-mechanical nature of the cutting process.

Based on the foregoing, the developed regression model confirms that CCR is primarily governed by the feed and DOC, while spindle speed has a secondary effect. This model can be effectively utilised in turning processes under MQL conditions to predict CCR within the investigated experimental domain and to support the selection of machining parameters under similar MQL turning conditions. The coded coefficients used in developing the regression model (Equation 1) and their statistical significance were also analysed. The analysis results are summarised in Table 5.

As shown in Table 5, the feed and the DOC have the most significant impact on CCR, with very low p-values ($p<0.05$). The negative coefficient of the feed (-0.900) indicates that its increase leads to a considerable decrease in CCR. The DOC (+1.025), with a positive coefficient, indicates that it results in higher deformation of the chip. The spindle speed does not have a statistically significant effect ($p=0.119$). This implies that in the chosen range, the spindle speed has less effect on the CCR compared to the feed and the DOC. Moreover, the importance of the combined state of the cutting parameters also becomes clear from the table. The interaction between spindle speed and

Table 5. Statistical significance of the coded coefficients

Term	Effect	Coef.	SE Coef.	T-Value	P-Value	VIF
Constant		2.712	0.117	23.12	0.000	
RPM	0.400	0.200	0.117	1.70	0.119	1.00
Feed	-1.800	-0.900	0.117	-7.67	0.000	1.00
DOC	2.050	1.025	0.117	8.74	0.000	1.00
RPM*Feed	-0.675	-0.338	0.117	-2.88	0.016	1.00
Feed*DOC	-0.925	-0.462	0.117	-3.94	0.003	1.00

feed is statistically significant (p=0.016), indicating that a simultaneous increase in both spindle speed and feed further reduces chip deformation. Likewise, the interaction between the feed and the DOC is highly significant (p=0.003), which indicates that the effect of the feed on CCR is strongly dependent on the DOC. The variance inflation factor (VIF) values for all terms were equal to 1.00; this confirms that there is no multicollinearity in the developed model and that the input values are independent. Statistical data were used to assess the adequacy and predictive ability of the developed regression model, and the results are presented in Table 6. The relatively low value of standard error (S=0.469) indicates the validity of the model, which fits the experimental data well. Moreover, there is a minor deviation between the predicted and experimental values.

The regression analysis shows that both feed and DOC are the primary determinants of CCR. According to the ANOVA results, DOC exhibited the greatest statistical contribution, whereas feed strongly influenced chip thickness and deformation behaviour. This was followed by DOC, while cutting speed showed a lower influence on CCR. The results support the mechanics of chip formation, and they state that chip thickness (which varies with feed) is a determining factor of the amount of plastic deformation.

A residual analysis was conducted to evaluate the adequacy of the developed regression model for CCR during turning (Figure 8). First of all, the normal plot results were analysed to confirm the validity of the normality assumption required for ANOVA and regression analysis. According to the normal probability plot, all the residuals tend to lie on an approximately

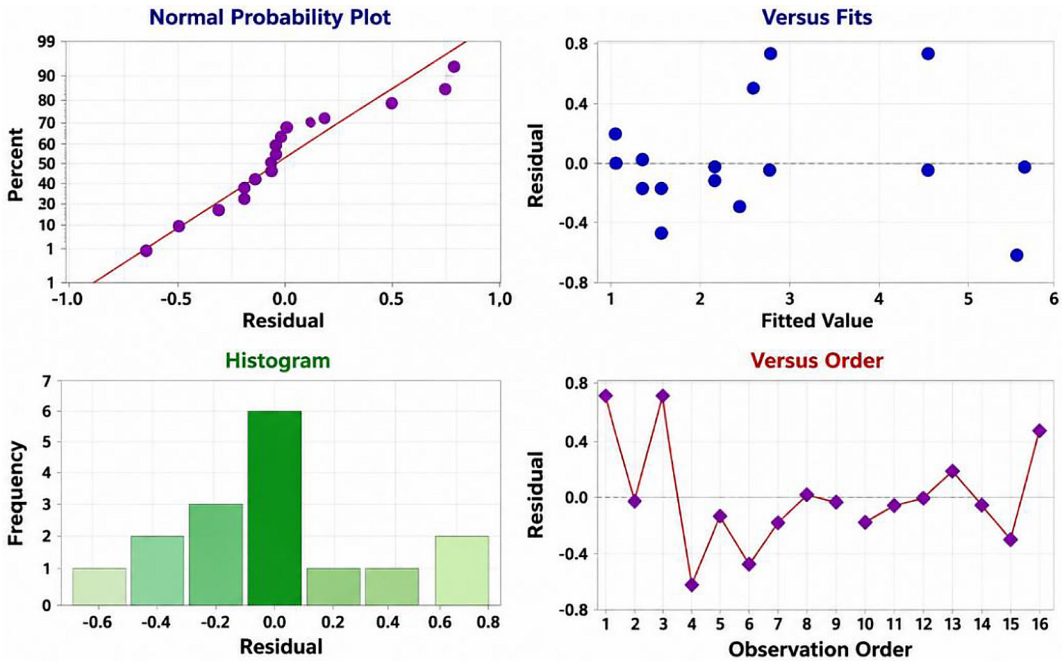


Figure 8. Residual plots of CCR: (a) normal probability plot, (b) residuals versus fitted values, (c) histogram of residuals, and (d) residuals versus observation order

Table 6. Regression model summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.469308	94.18%	91.27%	85.11%

straight line, showing normal distribution. The residual histogram supports this finding, exhibiting a roughly symmetric distribution centred around zero without evident asymmetry or outliers. The plot of residuals vs fitted values shows scatter and does not show any clear pattern or funnel shape. This indicates the variances are constant and the test for heteroscedasticity is not present in the model. Besides, the plot of residuals versus order of observation showed no patterned trends. As a result, we can confirm that the residuals are independent and not affected by time or experiment order. Consequently, the independence of the residuals and the absence of time-dependent or experimental sequence effects can be confirmed.

Based on the obtained results, the developed regression model, which aimed to predict CCR under specified cutting regimes, is statistically adequate and reliable. Therefore, the regression model is satisfactory for further analysis on the effect of cutting parameters, as well as interpretation.

Analysis of variance

A statistical test was performed on the generated regression model developed using the selected critical factors as predictors through ANOVA. The ANOVA results are provided in Table 7. According to the table, it can be seen that the lack of fit criterion is not statistically significant (p=0.097). This shows that the model fits the experimental data and does not show significant lack of fit. In addition, the presence of pure error, resulting from the repetition of experiments, increases the reliability of the statistical analysis.

The significance of the model developed based on the obtained results was also confirmed by the ANOVA results presented in Table 7, with an F-value of 32.38 and a p-value of less than 0.001. These results confirm that the regression model reliably represents the variation in CCR. Furthermore, the linear terms also showed a high significance level ($p<0.001$). Despite showing no variation in CCR values at the maximum spindle speed of 3860 rpm (p=0.119), a statistical analysis concluded the spindle speed to be insignificant. It is likewise evident that the reciprocal effects of the cutting modes are significantly different (p=0.002). In particular, the reciprocal effect of feed and DOC is the most significant (p=0.003), and the interaction of spindle speed and feed also has a considerable effect (p=0.016). Furthermore, the statistical indications in Tables 4 and 5 confirm that the developed regression model is accurate and reliable for analysing and predicting CCR under the given machining conditions.

Chip formation

Morphological characteristics of chip samples obtained from experiments conducted under various cutting modes, magnified several times, are presented in Figure 9. The results illustrate that the curvature, segmentation, surface texture, and deformation intensity of the chips vary significantly relative to the spindle speed, feed, and DOC. Figure 9 presents a sample (a-h) from the experiments conducted in each cutting mode, along with its images and morphological analysis at 7X, 50X, and 100X magnifications. Table 8 provides information on which cutting mode environment corresponds to the designations shown in Figure 9.

From the chip images in Figure 9 (a_1–a_4), it can be seen that at the lowest cutting mode in the experiments (100 rpm, 0.05 mm/rev, 0.5 mm), shorter spiral and discontinuous chips were formed compared to other modes. In this case, the low cutting temperature and the decrease in tool feed reduce the plastic softening of the material being cut, resulting in a brittle type of chip separation and the fragmentation of the chip morphology. A significant change in chip formation was observed when the spindle speed was increased from 100 to 400 rpm (Figure 9, b_1–b_4) without changing the feed and DOC. In this case, the chips took on a relatively longer, ribbon-like, and partially continuous shape. Compared to the images of sample a_1-a_4, the edges of the chips in sample b_1-b_4 were observed to be less fractured. This can be explained by the improved stability of

Table 7. Analysis of variance results

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	5	35,6550	7.1310	32.38	0.000
Linear	3	30,4100	10,1367	46.02	0.000
RPM	1	0.6400	0.6400	2.91	0.119
Feed	1	12,9600	12,9600	58.84	0.000
DOC	1	16,8100	16,8100	76.32	0.000
2-Way Interactions	2	5.2450	2.6225	11.91	0.002
RPM*feed	1	1.8225	1.8225	8.27	0.016
Feed*DOC	1	3.4225	3.4225	15.54	0.003
Error	10	2.2025	0.2203		
Lack-of-fit	2	0.9725	0.4863	3.16	0.097
Pure error	8	1.2300	0.1537		
Total	15	37,8575			

Table 8. Chip morphology image compatibility with cutting modes

Row	RPM	Feed	DOC
a	100	0.05	0.5
b	400	0.05	0.5
c	100	0.7	0.5
d	400	0.7	0.5
e	100	0.05	3.0
f	400	0.05	3.0
g	100	0.7	3.0
h	400	0.7	3.0

the chip flow at high spindle speed values, which might be associated with thermal softening. Significant changes in chip geometry were observed when the feed was increased to 0.7 mm/rev at low spindle speeds and DOC (Figure 9, c_1–c_4). At the same time, the chips turned into thick, clearly curved and spiral-arc. Consequently, as the feed increases, the thickness of the non-deformed chip increases, resulting in an increase in compressive stress and plastic deformation in the primary deformation zone. From the samples in Figure 9 d_1–d_4, it can be seen that screw-like long chips with relatively identical geometry are formed. Compared to samples a and c, the surface of these samples was relatively smoother and more stable. At the same time, a high spindle speed improved the duration of chip evacuation, while the high feed mode maintained sufficient material flow for stable chip twisting.

The next four cases (Figure 9, e–h) present microscopic images of chip samples obtained at a cutting depth of 3 mm under various spindle speeds and feeds. Consequently, a low spindle speed and a high DOC value at a given feed led to a significant thickening and shortening of the chip (Figure 9, e_1–e_4). This is because a large DOC increases the contact area at the chip-tool interface, leading to a rise in cutting forces. Furthermore, the uneven surface and traces of material adhesion shown in Figure 9, e_4, indicate the presence of strong friction and local adhesion during chip formation. The fact that shear force is present when selecting the highest spindle speed and DOC clearly substantiates the ribbon-like nature of the chips, as shown by the samples in Figure 9, f_1–f_4. High spindle speed and DOC cause intensive deformation of the material. Serrated, highly deformed segmented chips with rough fractures were observed in the g samples (Figure 9, g_1–g_4).

Here, images of the sample formed under the influence of a low spindle speed relative to the maximum feed and DOC can be seen. The micrographs revealed clearly localised shear, irregular fracture zones, and unstable chip curvature. The most severe chip deformation was observed at the highest cutting parameters selected for the experiments (400 rpm, 0.7 mm/rev, and 3 mm DOC) (Figure 9, h_1-h_4). Although the chip exhibits a curved morphology, traces of dense-layered shear and severe deformation lines are clearly visible on its surface. A simultaneous increase in all cutting parameters is likely to increase the cutting temperature, deformation rate, and friction at the chip-tool interface. These observations may indicate reduced effectiveness of lubricant penetration under the investigated cutting conditions.

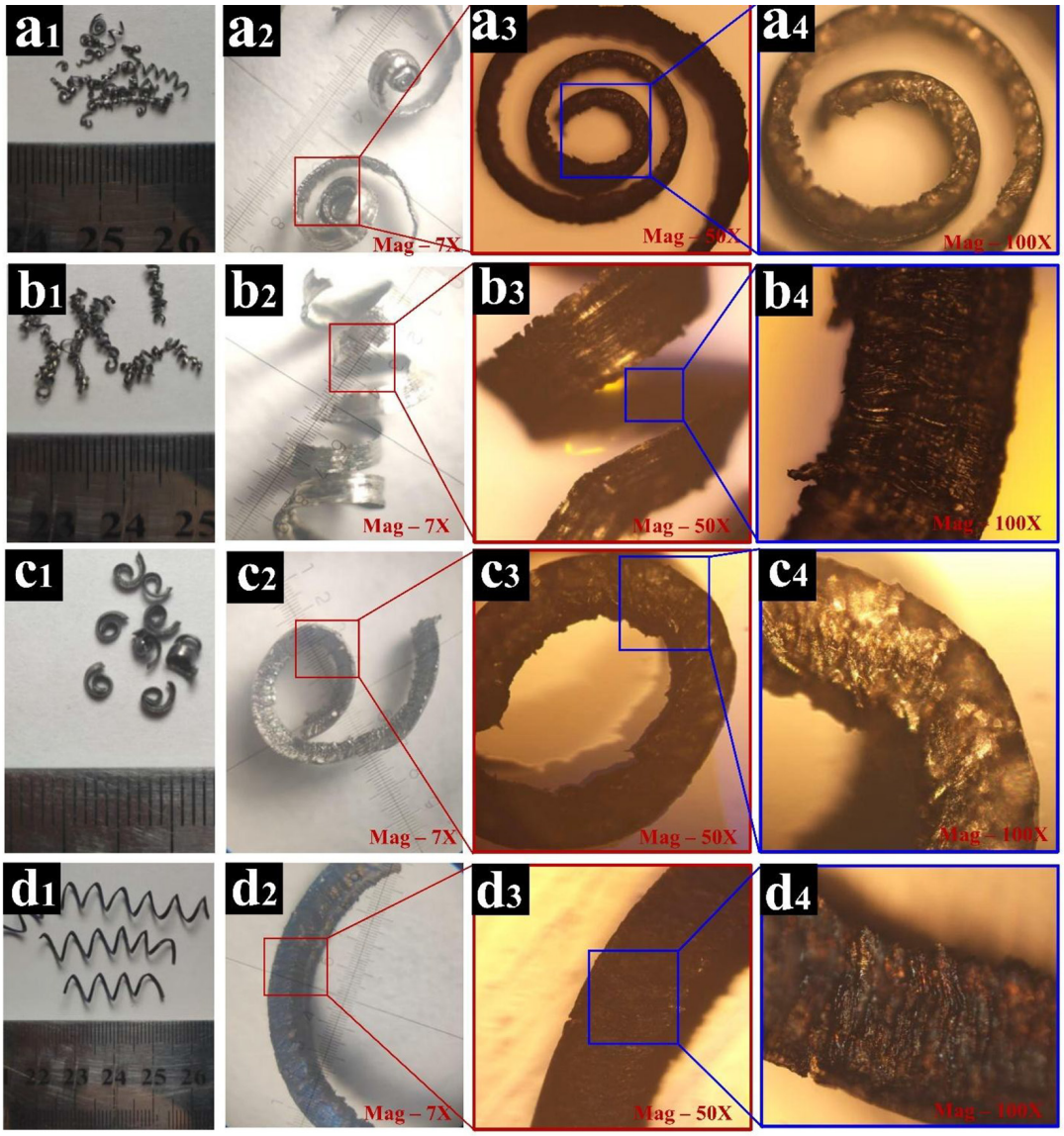


Figure 9. Macroscopic chip morphologies under different cutting parameters at multiple magnifications

In all the microscopic images, the formation of chips is evident through traces of shear deformation, lamellar structures, and the ruggedness of the chip edges. This indicates the occurrence of plastic deformation during the MQL turning. Thus, this kind of change in chip morphology can be attributed to the combined effect of the feed and DOC, which influences both the chip thickness and its shear zone.

DISCUSSIONS

Ben Salim et al. [37] found that the cutting speed with feed is strongly affected in orthogonal dry turning cutting of AISI D2 steel and their combined effect is insignificant. In our work, it is based on the fact that feed and DOC have a strong effect, and the combined effect of feed and spindle speed is also important. Zhang et al. [39] studied chip control in the hard machining of AISI 1045 in dry medium. They studied the effect of the macro-geometry of the PCBN cutter on chip morphology and believe that low cutting speed leads to the formation of a continuous chip regardless of what DOC is in the feed. In contrast, in our work, it was found that increasing the spindle speed without changing the feed and DOC in the MQL environment led to the formation of a continuous chip. This confirms that the influence of cutting parameters on chip formation varies depending on the MQL medium. Additionally, Elshafaa Abdelnasser et al. [40] studied the chip formation

mechanism in precision turning of TC4 in a dry environment. They emphasised that higher DOC at cutting speeds results in a high tangling of chips with a snarled curve. However, according to our study, in MQL-assisted hard turning operations, high spindle speed and DOC resulted in a segmented chip form. Consequently, the influence of cutting modes on chip formation in the MQL medium differs from other environments, indicating a high need for research in this field.

In the present study, a combination of macro- and micro-scale evaluations supported by statistical data analysis was employed to investigate CCR in turning under a vegetable oil-based MQL environment. Analysis of the obtained results indicates that chip deformation is mainly governed by the tool feed and DOC. Statistical data analysis of ANOVA and regression model indicated that feed and DOC are the most influential factors affecting CCR, and an individual effect of the spindle speed showed a lower influence. According to the results of interaction analysis, the effect of feed significantly depends on other parameters in the experimental study.

Based on regression analysis of the experimental results, a mathematical model was developed. The adequacy of the model (Equation 2) was highly rated through residual analysis and model summary statistics, indicating that the model possesses strong predictive capabilities. The regression model allows for predicting the outcomes of correctly selecting cutting parameters for turning operations while using an MQL environment, or the results that can be achieved using pre-selected cutting parameters. This model can be used for training AI systems and in the algorithms of automated manufacturing systems. However, it should be noted that the results of this model have high accuracy within the experimental environments and do not guarantee the achievement of the same results in other environments.

The statistical data evaluations were directly confirmed by the macro- and micro-scale analysis of the chips (Figure 9). The results indicate that spindle speed, feed, and DOC interact significantly to affect chip morphology during MQL-assisted turning. A low spindle speed in the MQL environment primarily led to the formation of discontinuous and segmented chips, whereas the opposite condition increased chip continuity. Higher feed and DOC values increased the material removal load, which in turn significantly intensified chip compression, the tendency toward segmentation, and surface deformation. Among the parameters studied, feed and DOC had the greatest impact on chip thickness and segmentation state, while spindle speed significantly affected chip continuity and surface smoothness. Such as, several researchers have verified that the lubricating effect under MQL conditions reduces friction at the tool-chip interface. Consequently, smoother chips and reduced adhesion are achieved [37–40].

Quantitative evaluation of the experiments reveals that the chosen machining parameters mainly affect chip deformation. CCR in the examined cutting conditions varied between 1.1 and 5.6, roughly a 409% rise from minimum to maximum. Conversely, the combined impact of feed and DOC brings about the biggest changes in phenomena. Increasing the DOC from 0.5 mm to 3.0 mm under low-feed conditions (0.05 mm/rev) increased the CCR from 1.1–1.4 to 4.5–5.6, indicating a near fourfold increase in chip deformation. In contrast, as feed shifted from 0.05 to 0.70 mm/rev, the CCR was significantly reduced, even at higher values of DOC. As evidenced, feed is very effective in suppressing chip compression under MQL conditions. The quantitative results conform to the ANOVA and regression analyses, showing that feed and DOC were the statistically most important factors. On the other hand, the spindle speed had a very low impact in the range examined. The elevated R^2 = 94.18% indicates a very good regression model for predicting the relationship between machining parameters and CCR, which can help select parameters for MQL-assisted turning of AISI 1045 steel.

Role of MQL environment

The main reason for the difference in the results of this study from previous studies [38–40] is related to the influence of the MQL medium. It is known that an increase in DOC and Feed during oblique cutting increases the contact area at the chip-tool interface, which makes it difficult for the lubricating element to reach the friction surface. Low feeds and DOC may indicate reduced lubrication effectiveness, which can ease the friction and chip flow. Nevertheless, increasing the feed and the DOC increases the material removal rate, contact pressure, and heat level significantly, resulting in a much lower relative contribution of the lubricant film. When these conditions exist, plastic deformation and shear localisation increasingly dominate, thus triggering the

transition from continuous chips to segmented and discontinuous chips. As a result, the evolution of chip morphology was mainly attributed to the cutting parameters. However, high shear forces and shear deformation in the high feed and DOC conditions reduce the effectiveness of the lubrication film generated by the MQL. The reduction of the influence of the MQL environment on the CCR at high feed and cutting depths can also be seen by the proximity of our results to the results of previous dry machining work [40]. Consequently, at low feed and DOC values, the influence of the MQL medium on the CCR is significantly stronger. This is due to the influence of a lubrication film produced by the MQL at the chip-tool interface. Based on this, the use of MQL technology in finishing operations with a small cutting depth yields high efficiency.

Despite the thermal effects of MQL-assisted turning, mechanical factors are still dominant. As a result, spindle speed has a weak influence on chip formation. The reported finding was that the efficiency of the MQL environment decreased with increasing DOC. In short, it is clear that controlling feed and DOC during MQL-assisted turning can improve chip morphology for better machining productivity.

CONCLUSIONS

In this study, the influence of cutting parameters on CCR during the turning of AISI 1045 steel in a vegetable oil-based MQL environment was investigated using a 2^3 full factorial design approach, combined with statistical and qualitative chip morphology analysis.

The statistical study revealed that feed and DOC were the dominant factors. The obtained results of the interactive influence of feed and DOC ($p=0.003$) and spindle speed and feed ($p=0.016$) confirmed that CCR is influenced by the combined action of the investigated machining parameters rather than by their individual effects alone.

Analysis of the experimental data showed that the CCR ranged from 1.1 to 5.6, representing an approximately 409% increase across the investigated machining conditions. Feed and DOC were identified as the dominant factors governing chip deformation, whereas spindle speed had only a minor influence. The developed regression model demonstrated high predictive capability (R^2 = 94.18%, R^2adj = 91.27%, R^2pred = 85.11%), indicating its suitability for predicting CCR within the investigated machining range.

Analysis of macro-scale chip morphology showed that lower spindle speeds tend to produce more segmented chips, while higher speeds favour more continuous chip formation under the tested MQL conditions. Increasing feed and DOC resulted in more distinct shear features and chip segmentation, indicating greater plastic deformation with higher mechanical stresses. These qualitative insights align with the statistical data and support the impact of cutting parameters on chip deformation. Nonetheless, additional quantitative microstructural studies are needed to verify the specific deformation mechanisms involved.

Acknowledgement

The authors express their gratitude to the technicians of the Metal Technology department for their assistance in conducting the experiments.

REFERENCES

1. Adler D., Hii W., Michalek D., Sutherland J. Examining the role of cutting fluids in machining and efforts to address associated environmental/health concerns. Mach Sci Technol. 2006 Jun;10(1):23–58. https://doi.org/10.1080/10910340500534282
2. Pereira L., Sad C., Castro E., Filgueiras P., Lacerda V. Environmental impacts related to drilling fluid waste and treatment methods: A critical review. Fuel. 2022 Feb;310:122301. https://doi.org/10.1016/j.fuel.2021.122301
3. Pervaiz S., Kannan S., Kishawy A. An extensive review of the water consumption and cutting fluid-based sustainability concerns in the metal cutting sector. J Clean Prod. 2018 Oct; 197:134–53. https://doi.org/10.1016/j.jclepro.2018.06.190
4. Çalık B., Uzun G. A Comprehensive Review of Cooling and Lubrication Techniques in Machining: Efficiency and Sustainability Perspectives. Eng Perspect. 2026 Mar 26;6(2):260–76. https://doi.org/10.64808/engineeringperspective.1808611
5. Kesriklioglu S. Ineffectiveness of flood cooling in reducing cutting temperatures during continuous machining. Int J Adv Manuf Technol. 2022 Oct;122(9–10):3957–68. https://doi.org/10.1007/s00170-022-10093-7
6. Cabanettes F., Faverjon P., Sova A., Dumont F., Rech J. MQL machining: from mist generation to tribological behavior of different oils. Int J Adv Manuf Technol. 2017 Apr;90(1–4):1119–30. doi:

https://doi.org/10.1007/s00170-016-9436-0

7. Uslu G., Korkmaz M, Elkilani R., Gupta M., Vashishtha G. Investigation of tribological properties of Inconel 601 under environmentally friendly MQL and nano-fluid MQL with pack boronizing. Lubricants. 2024 Oct 14;12(10):353. https://doi.org/10.3390/lubricants12100353
8. Mardonov U., Khasanov O., Yang Y., Yatskevich O., Akramov M., Abdullaev B. Studying the effect of diverse lubricating and cooling environments in turning gray cast iron. International Journal of Mechatronics & Applied Mechanics. 2025; 2(22): 213–223. https://doi.org/10.17683/ijomam/issue22.v2.22
9. Cagan S., Venkatesh B., Buldum B. Investigation of surface roughness and chip morphology of aluminum alloy in dry and minimum quantity lubrication machining. Mater Today Proc. 2020;27:1122–6. doi: https://doi.org/10.1016/j.matpr.2020.01.547
10. Bai X, Zhou F, Li C, Dong L, Lv X, Yin Q. Physicochemical properties of degradable vegetable-based oils on minimum quantity lubrication milling. Int J Adv Manuf Technol. 2020 Feb;106(9–10):4143–55. https://doi.org/10.1007/s00170-019-04695-x
11. Pervaiz S., Ahmad N., Ishfaq K., Khan S., Deiab I., Kannan S. Implementation of sustainable vegetable-oil-based minimum quantity cooling lubrication (MQCL) machining of titanium alloy with coated tools. Lubricants. 2022 Sep 24;10(10):235. https://doi.org/10.3390/lubricants10100235
12. Zamiruddin N., Sani A., Rosli N. Oil viscosity effects on lubricant oil film behaviour under minimum quantity lubrication. IOP Conf Ser Mater Sci Eng. 2021 Mar 1;1092(1):012029. https://doi.org/10.1088/1757-899X/1092/1/012029
13. Das I., Zaman P. Response modeling and optimization of process parameters in turning medium carbon steel under minimum quantity lubrication (MQL) with vegetable oil and oil blends. Lubricants. 2024 Dec 12;12(12):444. https://doi.org/10.3390/lubricants12120444
14. Saleem M., Mehmood A. Eco-friendly precision turning of superalloy Inconel 718 using MQL based vegetable oils: Tool wear and surface integrity evaluation. J Manuf Process. 2022 Jan;73:112–27. https://doi.org/10.1016/j.jmapro.2021.10.059
15. Günay M., Korkmaz M. Understanding the relationship between surface quality and chip morphology under sustainable cutting environments. Materials. 2024 Apr 16;17(8):1826. https://doi.org/10.3390/ma17081826
16. Zhang W., Cao T. Cutting performance of a tool with continuous lubrication of atomized cutting fluid at the tool-chip interface. Int J Adv Manuf Technol. 2023 May; 126(1–2): 117–30. https://doi.org/10.1007/s00170-023-11116-7
17. Cao T., Li Z., Zhang S., Zhang W. Cutting performance and lubrication mechanism of microtexture tool with continuous lubrication on tool-chip interface. Int J Adv Manuf Technol. 2023 Mar; 125(3–4):1815–26. https://doi.org/10.1007/s00170-023-10821-7
18. Kholmirzaev N., Turakhodjaev N., Saidmakhamadov N., Tadjiev N., Khasanov J., Yusupov B.,..., Juraev J. (2024, December). Improvement of the technology of melting of low alloy steel alloy in an electric arc furnace. In Materials Science Forum. 2024 December; 1139: 3-9). Trans Tech Publications Ltd. doi: https://doi.org/10.4028/p-2AMBsZ
19. Kholmirzaev N., Turakhodjaev N., Saidmakhamadov N., Khasanov J., Bektemirov A., Sadikova N. Effects of titanium (Ti) contents on the wear resistance of low-alloy steel alloys. In E3S Web of Conferences. 2024; 525:03003. EDP Sciences. https://doi.org/10.1051/e3sconf/202452503003
20. Saidmakhamadov N., Turakhodjaev N., Tursunbaev S., Kholmirzaev N., Saydumarov B., Khasanov J.,... Gaybullaev M. Obtaining high-quality foundry products from low-alloy steel alloys. In AIP Conference Proceedings. 2026, March; 3390 (1):080011. AIP Publishing LLC. https://doi.org/10.1063/5.0321874
21. Davim J., Maranhão C. A study of plastic strain and plastic strain rate in machining of steel AISI 1045 using FEM analysis. Mater Des. 2009 Jan; 30(1):160–5. doi: https://doi.org/10.1016/j.matdes.2008.04.029
22. Mardonov U., Madaminov S., Jeltukhin A., Meliboev Y. The influence of magnetically treated lubricating-cooling fluids on turning AISI 1045. Journal of Engineering and Technological Sciences. 2026. 58(2):217–226. https://doi.org/10.5614/j.eng.technol.sci.2026.58.2.5
23. Khasanov S., Mardonov U., Ongboyev A., Ismatov M. Influence of a magnetic field on HSS tool wear/life and the intensity of external machining environments in turning. International Journal of Mechatronics and Applied Mechanics. 2024:(16):163–170. https://doi.org/10.17683/ijomam/issue16.19
24. Qasim A., Nisar S., Shah A., Khalid M., Sheikh M. Optimization of process parameters for machining of AISI-1045 steel using Taguchi design and ANOVA. Simul Model Pract Theory. 2015 Dec;59:36–51. https://doi.org/10.1016/j.simpat.2015.08.004
25. Hoang D., Thien N., Pham T., Nguyen T. Combined analysis of acoustic emission and vibration signals in monitoring tool wear, surface quality and chip formation when turning SCM440 steel using MQL. EUREKA Phys Eng. 2023 Jan 19;(1):86–101. https://doi.org/10.21303/2461-4262.2023.002509
26. Abdur Rahman K., Sethy P., Khatai S., Kumar R., Panda A., Ranjan Mishra R., et al. Chip morphology assessment in turning of hardened AISI 52100 steel under ZnO nanofluid environment. J Phys

Conf Ser. 2024 Aug 1;2818(1):012045. https://doi.org/10.1088/1742-6596/2818/1/012045

27. Uysal A., Jawahir I. Analysis of slip-line model for serrated chip formation in orthogonal machining of AISI 304 stainless steel under various cooling/lubricating conditions. J Manuf Process. 2021 Jul;67:447–60. doi: https://doi.org/10.1016/j.jmapro.2021.05.009
28. Balogun V., Mativenga P. Impact of un-deformed chip thickness on specific energy in mechanical machining processes. J Clean Prod. 2014 Apr;69:260–8. https://doi.org/10.1016/j.jclepro.2014.01.036
29. Umidjon M., Jeltukhin A., Meliboyev Y., Azamat B. Effect of magnetized cutting fluids on metal cutting process. In International Conference on Reliable Systems Engineering (pp. 95–104). Cham: Springer International Publishing. 2022, August. https://doi.org/10.1007/978-3-031-15944-2_9
30. Storchak M. Determination of chip compression ratio for the orthogonal cutting process. J Manuf Mater Process. 2024 Sep 1;8(5):190. https://doi.org/10.3390/jmmp8050190
31. Kroft L., Povolny M., Mezulianik J. Effect of Feed and Depth of Cut on Chip Shape. In: Katalinic B, editor. DAAAM Proceedings [Internet]. 1st ed. DAAAM International Vienna; 2023 [cited 2026 May 20]. p. 0154–60. doi: https://doi.org/10.2507/34th.daaam.proceedings.021
32. Korkut I., Donertas M. The influence of feed rate and cutting speed on the cutting forces, surface roughness and tool–chip contact length during face milling. Mater Des. 2007 Jan;28(1):308–12. https://doi.org/10.1016/j.matdes.2005.06.002
33. Kose E., Kurt A., Seker U. The effects of the feed rate on the cutting tool stresses in machining of Inconel 718. J Mater Process Technol. 2008 Jan;196(1–3):165–73. https://doi.org/10.1016/j.jmatprotec.2007.05.019
34. Li B., Jiang X., Yang J., Liang S. Effects of depth of cut on the redistribution of residual stress and distortion during the milling of thin-walled part. J Mater Process Technol. 2015 Feb;216:223–33. https://doi.org/10.1016/j.jmatprotec.2014.09.016
35. Sadílek M., Dubský J., Sadílková Z., Poruba Z. Cutting forces during turning with variable depth of cut. Perspect Sci. 2016 Mar;7:357–63. https://doi.org/10.1016/j.pisc.2015.11.055
36. Mia M., Dey P., Hossain M., Arafat M., Asaduzzaman M., Shoriat Ullah Md, et al. Taguchi S/N based optimization of machining parameters for surface roughness, tool wear and material removal rate in hard turning under MQL cutting condition. Measurement. 2018 Jul;122:380–91. https://doi.org/10.1016/j.measurement.2018.02.016
37. Salem S., Bayraktar E., Boujelbene M., Katundi D. Effect of cutting parameters on chip formation in orthogonal cutting. J Achiev Mater Manuf Eng. 2012;50(1).
38. Astakhov V., Shvets, S. The assessment of plastic deformation in metal cutting. J. Mater. Process. Technol. 2003;146:193–202. https://doi.org/10.1016/j.jmatprotec.2003.10.015
39. Zhang X., Wu S. Chip control in the dry machining of hardened AISI 1045 steel. Int J Adv Manuf Technol. 2017 Feb;88(9–12):3319–27. https://doi.org/10.1007/s00170-016-8989-2
40. Abdelnasser E., El-Sanabary S., Nassef A., Barakat A., Elkaseer A. Influence of technological parameters on chip formation and chip control in precision hard turning of Ti-6Al-4V. Micromachines. 2023 Oct 23;14(10):1973. https://doi.org/10.3390/mi14101973