



Article

Multi-Response Optimization and Experimental Investigation of the Influences of Various Coolant Conditions on the Milling of Alloy 20

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Abstract: This study investigates the machining processes of Alloy 20 under different cooling conditions: Minimum Quantity Lubrication (MQL), Carbon Dioxide (CO₂), and the hybrid MQL + CO₂ approach. The research focuses on optimizing the cutting parameters, understanding the surface characteristics, analysing the tool wear patterns, and evaluating the chip formation. Face-centred CCD-based response surface methodology (RSM) is applied in order to identify the optimized cutting conditions. Surface roughness, tool wear, and chip morphology are examined through SEM imaging. Surface roughness characteristics reveal distinctive characteristics for each coolant condition: MQL cooling results in a relatively rough surface with tool nose degradation, CO₂ cooling shows scratches on the surface and tool chipping, and MQL + CO₂ cooling yields a smoother finish with close and continuous chip formation under the optimized conditions. This study contributes valuable insights into the complex interactions between cutting parameters and coolants, aiding in the optimization of machining processes for improved outcomes of the machining of Alloy 20. Based on the RSM outcomes, the optimal parametric settings obtained are $V_c = 44$ m/min, $f = 0.04$ mm/rev, and $a_p = 0.43$ mm.



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Keywords: alloy 20; machining; minimum quantity lubrication (MQL); carbon dioxide (CO₂); hybrid coolant; optimization; response surface methodology (RSM); surface characteristics; tool wear; chip formation

1. Introduction

Supercritical Carbon Dioxide Cooling with Minimum Quantity Lubrication (scCO₂ + MQL) has proven to be highly beneficial in enhancing tool life and surface finish (R_a) while milling AISI 304L stainless steel. Wika et al. [1] found that scCO₂ + MQL increased tool life by 324% and improved R_a by 30% compared to flood cooling. The tool life was improved due to lower cutting temperatures, while the R_a was enhanced by reducing built-up edge formation. Cryogenic cooling using liquid nitrogen (LN₂) has also been shown to benefit stainless steel milling. Nalbant et al. [2] found that cryogenic cooling significantly impacts cutting forces (CF) compared to dry milling. This effect is especially pronounced at lower cutting speeds (V_c) and is attributed to the rapid cooling process inducing increased strain hardening. However, Paul et al. [3] found that cryogenic cooling reduced tool wear (TW) and improved R_a compared to dry and wet machining. These benefits are attributed to lower cutting temperatures and changes in chip formation. When comparing cooling strategies in the milling of medium carbon steel, Silva et al. [4] conducted research that

found that directing a reduced amount of cutting fluid to the cutting zone through reduced flow rate cooling resulted in the longest tool lifespan and the highest material removal rate (MRR). This study highlights the importance of exploring alternative methods in order to improve performance and achieve optimal results. The examination of worn tools showed that wear mechanisms were affected by the cooling strategy. Ho et al. [5] developed a novel cooling system-assisted MQL method using a thermoelectric cooling system. It improved surface roughness, reduced cutting forces and temperatures, and produced fewer tool marks than dry and MQL die steel milling. The study by Umbrello et al. [6] analysed the impact of cryogenic cooling on surface integrity during the hard machining of hardened steel. The outcome of that study indicates that cryogenic cooling typically results in improved surface integrity compared to dry hard machining. An et al. [7] found that scCO₂ with oil-on-water MQL reduced tool wear by 67.2% and improved the surface profile compared to scCO₂ alone during the milling of titanium alloy. Kang et al. [8] found that MQL improved tool life when compared to flood cooling and dry milling in high-speed end-milling hardened die steel. MQL was found to be beneficial for both TiAlN- and TiAlSiN-coated tools. Tapoglou et al. [9] found that cryogenic CO₂ coolant, when combined with other coolant options, can prolong tool life during milling. Sadik et al. [10] demonstrated that higher flow rates of cryogenic CO₂ coolant can improve tool life during the milling of titanium. These findings suggest that CO₂ cooling can manage tool wear when shoulder milling commercially pure grade 2 titanium. In summary, scCO₂ + MQL, cryogenic cooling, reduced flow rate cooling, cooling system-assisted MQL, and MQL have all been shown to improve tool life, surface finish, surface integrity, and productivity compared to dry and flood cooling strategies during the milling of stainless steel, medium carbon steels, die steels, and titanium alloys. These sustainable cooling techniques reduce cutting temperatures, provide lubrication, and modify chip formation, benefiting the milling process.

Sahu and Andhare [11] developed RSM models to relate power consumption, MRR, R_a , and tool wear to milling parameters. Multi-objective optimization using RSM and genetic algorithms found the optimal parameters of 133.5 m/min cutting speed, 0.14 mm/tooth feed rate (f), and 2.33 mm depth of cut (a_p). Hashmi et al. [12] also used RSM to develop a model relating R_a to milling parameters, finding the a_p to be the most significant. Sahu and Andhare [13] used RSM, teaching–learning-based optimization (TLBO), ‘JAYA’, and genetic algorithms to minimise R_a and CF when turning Ti-6Al-4V. RSM found the optimal machining parameters at higher V_c (171.4 m/min) and f (55.6 mm/min). Fuse et al. [14] combined RSM and a heat-transfer search algorithm to optimize abrasive waterjet machining parameters, maximising MRR (0.2304 g/min) and minimising both surface roughness (2.99 μ m) and kerf taper angle (1.72°). Abbas [15] used RSM and a TOPSIS-fuzzy approach to model and optimize high-speed turning, balancing R_a , flank wear, power consumption, and MRR. The optimal solution did not optimize each response, but balanced all. Abbas [16] used RSM and multi-objective optimization, based on ratio analysis integrated with regression and a particle swarm approach, to optimize high-speed machining, balancing lower R_a and higher MRR. Kumar et al. [17] used RSM and grey relational analysis to optimize the electrical discharge machining of Ti-6Al-4V, finding the discharge current most significant. An 18 A current, 100 μ s pulse on time, and 40 V were optimal. Research on high-speed milling of hardened steel under minimal-quantity lubrication with liquid nitrogen has shown promising results. The nitrogen–oil mixture can effectively reduce the milling force. Liao et al. [16] and Ravi [17] reported that MQL and cryogenic cooling with liquid nitrogen could improve tool life and R_a , and reduce CF. Lu et al. [18] showed that LN₂ cryogenic cooling can decrease CF and enhance R_a , particularly at high V_c . Duc et al. [19] discovered that MQL could also enhance R_a and CF during high-speed milling. Paschoalino et al. [19] developed a cyclic LN₂ injection system for MQL milling of Ti-6Al-4V alloy, leading to decreased R_a values and reduced liquid nitrogen consumption. In summary, the literature shows that RSM and various optimization algorithms can be combined to

effectively optimize the high-speed machining of Alloy 20 for surface roughness and MRR. Higher V_c , lower f , and moderate a_p are generally found to optimize the responses.

Based on the literature available, it is clear that the milling of Alloy 20 is very scarce. No studies were reported on the milling of Alloy 20 under three different cooling conditions, and information regarding the optimization of the milling of Alloy 20 with RSM is also very difficult to find in the literature. This paved the way for us to carry out experiments with the optimized input parameters in order to study responses such as surface characteristics, tool wear, and chip formation. The following section contains the machining conditions used for milling Alloy 20.

2. Experimental Setup

For the milling experiments, a YCM EV20 CNC machine (Yeong Chin Machinery Industries Co. Ltd., Taiwan, China) was utilized. This machine has a maximum spindle speed of 8000 rpm and a power supply of 5.5 kW. These milling experiments used materials such as Alloy 20, which has $150 \times 100 \times 10$ mm dimensions. Tables 1 and 2 provide information on the workpiece chemical composition and the mechanical properties of Alloy 20, respectively. End milling was investigated in this study using a BAP-07H tool holder (Jining Qinfeng Machinery Hardware Co., Ltd., Jining, China) to secure the APMT 1135 PDTR (CS Cutoutil Hardware Tools Co., Ltd., Changsha, China) indexable titanium aluminium nitride (TiAlN)-coated cutting inserts with a nose radius of 0.8 mm.

Table 1. Chemical composition of Alloy 20.

Chemical Composition	
Elements in wt. %	Fe: 35, Ni: 38, Cr: 19, Cu: 3, Mn: 2, Mo: 2, Nb: 1, Si: 1, C: 0.07, P: 0.045, S: 0.035

Table 2. Physical properties of Alloy 20.

Physical Properties	
Tensile strength (MPa)	620
Density (g/cm^3)	8.05
Hardness (HV)	222

A detailed account of the input factor levels is provided in Table 3. The face-centred central composite design (CCD) utilized to construct the design matrix. The face-centred CCD comprises 20 points, including 15 non-centre points and 6 centre points, all used for each level of the categorical factor (surface roughness), resulting in 60 runs in the design matrix (as shown in Table 4). DOE and subsequent statistical analysis were carried out using Design Expert 13 software. Cutting speed (V_c), feed rate (f), and depth of cut (a_p) were selected as the milling parameters. The input factor levels were assigned based on a thorough literature survey and an assessment of the technical capabilities of the machine. In addition, trial experiments were conducted to find the input factors and the levels needed to mill Alloy 20, and the DOE was set based on the successful input parameters used when machining Alloy 20. A total of three trials were conducted on the input process parameter levels. Response surface methodology was utilized for establishing the designs of the milling experiments. Response surface methodology is a statistical technique that aids in determining the ideal mix of input parameters to produce the intended result. The experiments identified the most efficient combination of f , a_p , and V_c needed to produce the R_a required by using a literature review to determine the high and low input parameters. This allowed the experiments to produce the desired level of R_a .

Table 3. RSM input factors and levels.

Factor	Level				
	Type	Code	Low (−1)	Medium (0)	High (1)
Cutting speed (m/min)	Numeric	A	40	50	60
Feed rate (mm/rev)	Numeric	B	0.02	0.04	0.06
Depth of cut (mm)	Numeric	C	0.2	0.4	0.6

Table 4. Input parameters and surface roughness.

Run	Factor A	Factor B	Factor C	Environment	Response SR	Run	Factor A	Factor B	Factor C	Environment	Response SR	Run	Factor A	Factor B	Factor C	Environment	Response SR
1	50	0.06	0.7	MQL	0.961	21	50	0.06	0.7	CO ₂	0.993	41	50	0.06	0.7	Hybrid CO ₂ + MQL	0.919
2	50	0.06	0.4		0.607	22	50	0.06	0.4		0.632	42	50	0.06	0.4		0.565
3	50	0.06	0.4		0.64	23	50	0.06	0.4		0.665	43	50	0.06	0.4		0.598
4	50	0.06	0.4		0.617	24	50	0.06	0.4		0.659	44	50	0.06	0.4		0.575
5	50	0.06	0.4		0.637	25	50	0.06	0.4		0.662	45	50	0.06	0.4		0.595
6	50	0.09	0.4		0.753	26	50	0.09	0.4		0.778	46	50	0.09	0.4		0.711
7	50	0.06	0.4		0.636	27	50	0.06	0.4		0.661	47	50	0.06	0.4		0.594
8	50	0.06	0.0		0.961	28	50	0.06	0.0		0.993	48	50	0.06	0.0		0.919
9	60	0.08	0.2		0.859	29	60	0.08	0.2		0.897	49	60	0.08	0.2		0.806
10	40	0.07	0.2		0.95	30	40	0.08	0.2		0.986	50	40	0.08	0.2		0.912
11	33	0.06	0.4	MQL	1.135	31	33	0.06	0.4	CO ₂	1.18	51	33	0.06	0.4	Hybrid CO ₂ + MQL	0.992
12	67	0.06	0.4		0.78	32	67	0.06	0.4		0.825	52	67	0.06	0.4		0.727
13	60	0.04	0.2		0.613	33	60	0.04	0.2		0.651	53	60	0.04	0.2		0.56
14	40	0.04	0.2		0.862	34	40	0.04	0.2		0.898	54	40	0.04	0.2		0.824
15	60	0.08	0.6		0.751	35	60	0.08	0.6		0.789	55	60	0.08	0.6		0.698
16	40	0.08	0.6		1.065	36	40	0.08	0.6		1.101	56	40	0.08	0.6		0.974
17	40	0.04	0.6		0.948	37	40	0.04	0.6		0.984	57	40	0.04	0.6		0.91
18	60	0.04	0.6		0.88	38	60	0.04	0.6		0.918	58	60	0.04	0.6		0.827
19	50	0.02	0.4		0.533	39	50	0.02	0.4		0.558	59	50	0.02	0.4		0.491
20	50	0.06	0.4		0.636	40	50	0.06	0.4		0.661	60	50	0.06	0.4		0.594

The average surface roughness (R_a) of a specific area was measured at five different locations with the help of a portable test device TR200 model (TMTeck Instrument Co., Ltd., Beijing, China). The average of the measurements was considered as the surface roughness value. The device used could measure surfaces with a cut-off length of 0.8 mm and a traverse length of 4 mm. It is common practice in industries to utilize a small amount of lubricant within the workpiece interface via the Kenco MQL setup. The air pressure and flow rates typically used are 4 bars and 10 mL/h to 100 mL/h, respectively. For cryogenic conditions, a pressure regulator is utilized to regulate the flow of LCO₂ through a nozzle of approximately 20 kg/h throughput with a self-pressurized cylinder. Figure 1 illustrates a schematic view of the experimental conditions for the milling of Alloy 20.

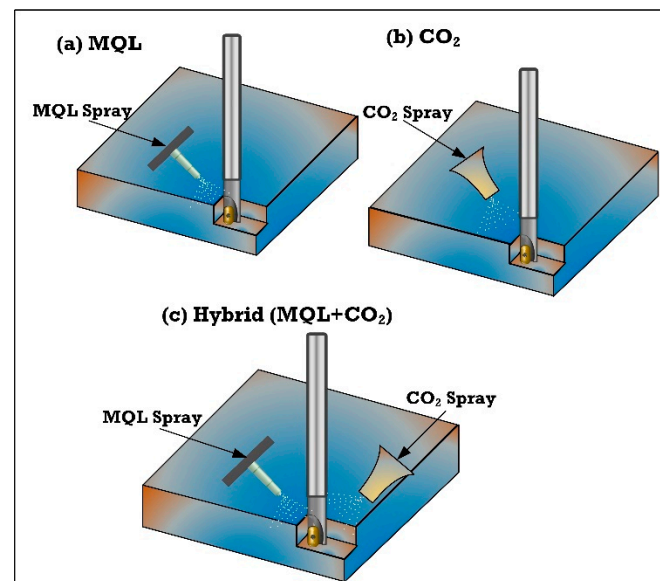


Figure 1. Schematic view of the experimental conditions.

3. Results and Discussion

3.1. ANOVA

ANOVA is a useful mathematical method for testing the significance of an experiment and analysing the response [20]. It helps to find out the significant parameters and signal-to-noise ratios present in minimized values of the control variables, so that the processing parameters can be optimized by ANOVA methods [21]. ANOVA can be applied in order to study the performance characteristics of machining process parameters such as cutting speed, feed, depth of cut, and width of cut, with consideration to multiple responses [22]. The experimental results—that is, the surface roughness observed for the three cooling environmental conditions of MQL, CO₂, and hybrid CO₂ + MQL—are exhibited in Table 4, while the ANOVA results for the different conditions are shown in Table 5, Table 6, and Table 7, respectively. In the analysis of variance (ANOVA) conducted for the three distinct coolant conditions, namely MQL (Minimum Quantity Lubrication), CO₂, and hybrid CO₂ + MQL, various cutting parameters were examined for their influences on the surface roughness. The results revealed noteworthy findings for each coolant condition.

Table 5. ANOVA response for MQL condition.

Source	Sum of Squares	df	Mean Square	F-Value	p-Value	
Model	1.46	9	0.1619	13.91	0.0002	Significant
A	0.2195	1	0.2195	18.86	0.0015	
B	0.1471	1	0.1471	12.64	0.0052	
C	0.0219	1	0.0219	1.88	0.2004	
AB	0.0003	1	0.0003	0.0254	0.8765	
AC	0.0015	1	0.0015	0.1268	0.7292	
BC	0.0535	1	0.0535	4.59	0.0577	
A ²	0.5081	1	0.5081	43.66	<0.0001	
B ²	0.0002	1	0.0002	0.0172	0.8983	
C ²	0.5895	1	0.5895	50.66	<0.0001	
Residual	0.1164	10	0.0116			Significant
Lack of Fit	0.1103	5	0.0221	18.31	0.0031	
Pure Error	0.006	5	0.0012			
Cor Total	1.57	19				

Table 6. ANOVA response for CO₂ condition.

Source	Sum of Squares	df	Mean Square	F-Value	p-Value	
Model	1.3	9	0.1441	14.69	0.0001	Significant
A	0.1802	1	0.1802	18.37	0.0016	
B	0.1243	1	0.1243	12.67	0.0052	
C	0.0181	1	0.0181	1.85	0.204	
AB	0.0002	1	0.0002	0.0163	0.9009	
AC	0.001	1	0.001	0.1053	0.7522	
BC	0.0436	1	0.0436	4.45	0.0612	
A ²	0.4814	1	0.4814	49.07	<0.0001	
B ²	0.0001	1	0.0001	0.0117	0.9159	
C ²	0.5247	1	0.5247	53.48	<0.0001	
Residual	0.0981	10	0.0098			Significant
Lack of Fit	0.0938	5	0.0188	21.95	0.0021	
Pure Error	0.0043	5	0.0009			
Cor Total	1.39	19				

Table 7. ANOVA response for hybrid CO₂ + MQL condition.

Source	Sum of Squares	df	Mean Square	F-Value	p-Value	
Model	1.73	9	0.192	12.4	0.0003	Significant
A	0.2508	1	0.2508	16.19	0.0024	
B	0.1806	1	0.1806	11.67	0.0066	
C	0.0237	1	0.0237	1.53	0.2442	
AB	0.0022	1	0.0022	0.1412	0.715	
AC	0.005	1	0.005	0.3231	0.5823	
BC	0.0827	1	0.0827	5.34	0.0434	
A ²	0.529	1	0.529	34.16	<0.0002	
B ²	0.0003	1	0.0003	0.0171	0.8987	
C ²	0.7507	1	0.7507	48.48	<0.0001	
Residual	0.1548	10	0.0155			Significant
Lack of Fit	0.1469	5	0.0294	18.43	0.0031	
Pure Error	0.008	5	0.0016			
Cor Total	1.88	19				

For the MQL cooling condition, the ANOVA indicated that cutting speed and feed rate are statistically significant factors affecting surface roughness. Additionally, the significance of the squared terms, specifically the square of V_c and the square of a_p , suggests that nonlinear effects play a role in the variation of surface roughness under MQL.

In the case of the CO₂ cooling condition, similar trends emerged. V_c and f were identified as significant contributors to R_a , aligning with the MQL condition and including squared terms, such as the square of V_c and the square of a_p , which further emphasized the role of nonlinear effects in shaping the R_a outcomes.

In the case of the hybrid CO₂ + MQL cooling condition, it showcased a consistent pattern. V_c and f maintained their significance in influencing R_a . The analysis revealed that the combined effect of “ f ” and “ a_p ” with the squared terms (square of V_c and square of a_p) is also statistically significant. This suggests that interactions between cutting parameters and additional nonlinear effects contribute significantly to surface roughness outcomes in the hybrid cooling condition. Regression models for the surface roughness of all the cooling environment conditions are presented in equations later in this section.

The ANOVA results consistently underscored the significance of “ V_c ” and “ f ” across all three coolant conditions—MQL, CO₂, and hybrid CO₂ + MQL—in influencing the surface roughness. Moreover, including squared terms and interaction effects in the analysis highlighted the complexity of the relationships between cutting parameters and R_a under varying coolant conditions. These findings provide valuable insights for optimizing

machining processes and selecting appropriate coolant strategies to achieve the desired surface quality in manufacturing settings.

$$\begin{aligned} Ra_{MQL} = & -3.92366 + 0.204982 \times v_c - 10.72522 \times f + 2.95831 \times a_p \\ & -0.030398 \times v_c \times f - 0.006790 \times v_c \times a_p + 20.43585 \times f \times a_p \\ & -0.001878 \times v_c^2 - 9.31556 \times f^2 - 5.05629 \times a_p^2 \end{aligned} \quad (1)$$

$$\begin{aligned} Ra_{CO_2} = & -3.78615 + 0.197866 \times v_c - 10.18814 \times f + 2.81039 \times a_p \\ & -0.022367 \times v_c \times f - 0.005682 \times v_c \times a_p + 18.46143 \times f \times a_p \\ & -0.001828 \times v_c^2 - 7.06642 \times f^2 - 4.77011 \times a_p^2 \end{aligned} \quad (2)$$

$$\begin{aligned} Ra_{MQL+CO_2} = & -4.17184 + 0.215096 \times v_c - 10.50105 \times f + 3.45640 \times a_p \\ & -0.082648 \times v_c \times f - 0.012504 \times v_c \times a_p + 25.41839 \times f \times a_p \\ & -0.001916 \times v_c^2 - 10.70429 \times f^2 - 5.70579 \times a_p^2 \end{aligned} \quad (3)$$

3.2. Response Surface

Response surface methodology (RSM) is an integrated optimization methodology of mathematical and statistical techniques used for modelling and optimizing response variables, incorporating quantitative independent variables [23]. RSM helps quantify the relationships between one or more measured responses and the vital input factors [24]. In this study, the investigation focused on the end milling method applied to Alloy 20, utilizing tool holders designated as BAP-07H and cutting inserts featuring TiAlN coatings. The objective was to explore the machining characteristics and surface quality under different cooling conditions, specifically MQL, CO₂, and a hybrid MQL + CO₂ approach. Figure 2 shows the surface roughness plots under different cutting parameters. The findings are summarized through the analysis of 3D response surfaces for each coolant condition. The response surface for MQL revealed that low R_a is associated with specific combinations of cutting parameters. A lower f and a higher V_c were optimal for achieving minimal R_a in the MQL coolant condition. The investigation into the CO₂ cooling condition demonstrated that low R_a is attained when employing a lower a_p in conjunction with higher V_c . This configuration was the optimal parameter combination for achieving superior surface quality in the CO₂ coolant environment. In the case of the hybrid MQL + CO₂ approach, the 3D response surface analysis indicated that low R_a is associated with specific combinations of f and a_p . The optimal conditions for minimizing R_a in this hybrid coolant environment were lower levels of f and a_p . These results contribute valuable insights into the intricate relationships between cutting parameters and R_a during end milling of Alloy 20 under different cooling conditions. The findings suggest that the optimization of machining processes can be achieved by tailoring cutting parameter combinations according to the specific coolant strategy employed, thereby enhancing the overall efficiency and quality of the machining operation, as shown in Figure 2.

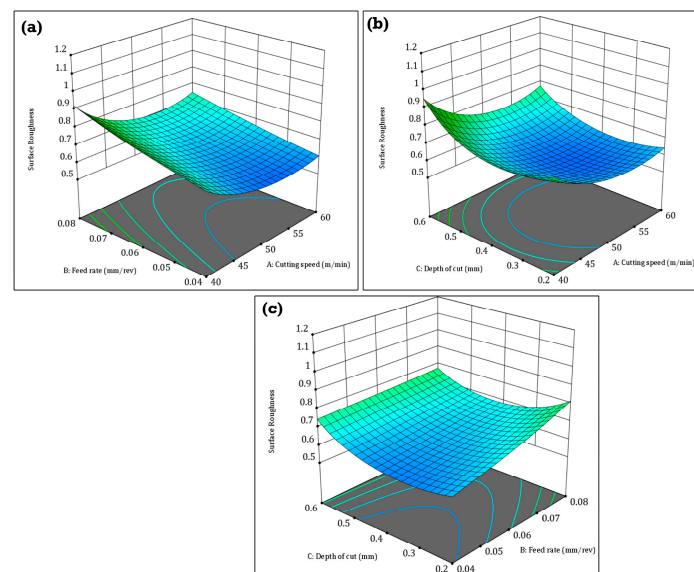


Figure 2. (a–c) surface roughness plots under different cutting parameters.

3.3. Normal Probability Plot

Normal probability plots can be used to study the influences of factors. According to the normal probability plot, the points close to the line fitted to the middle group of points represent estimated factors with no significant effect on the response variable. In contrast, the points away from the straight line probably represent more important factors affecting the research objectives [25]. Figure 3a represents the normal probability plot for MQL, Figure 3b represents the normal probability plot for CO₂, and Figure 3c represents the normal probability plot for MQL + CO₂. In the context of the experiments involving the end milling of Alloy 20 under various cooling conditions (MQL, CO₂, and MQL + CO₂), a critical aspect of the analysis was the examination of external studentized residuals of the normal percentage probability (Figure 3). As per the normal probability plot, the points that are close to the line fitted to the middle group of points represent the estimated factors that do not demonstrate any significant effect on the response variable. On the other hand, the points that appear far away from the straight line are likely to represent the ‘real’ factor effects on the surface integrity, tool wear, and chip formation. From Figure 3, it has been established that the main input factors A, B, and C and their factor interactions are quite far away from the straight line and are considered to be significant. The external residuals represent the differences between observed and predicted values, adjusted for the influence of individual data points. The assessment involved plotting these external residuals against the normal percentage probability, aiming to understand the distributional characteristics of the residuals. The findings from this analysis indicate a trend of almost linear behaviour for the MQL, CO₂, and MQL + CO₂ conditions. The nearly linear alignment of points on these plots suggests that the external residuals exhibit a distribution close to normal across the different coolant conditions. The relationship between external residuals and normal percentage probability is critical to validating regression model assumptions. The almost linear pattern observed across these plots for the MQL, CO₂, and MQL + CO₂ conditions supports the assumption of normality in the distribution of residuals. This is a key prerequisite for reliable statistical inferences derived from regression analyses. In summary, examining the external residuals with a normal percentage probability reveals an almost linear trend for the MQL, CO₂, and MQL + CO₂ conditions used in the experiments, as shown in Figure 3. This observation strengthens the statistical validity of the analyses, affirming the reliability of the regression models employed to investigate the end milling process of Alloy 20 under different cooling strategies. The adherence to normal distribution assumptions enhances the credibility of parameter estimates and the subsequent inferences drawn from the regression models.

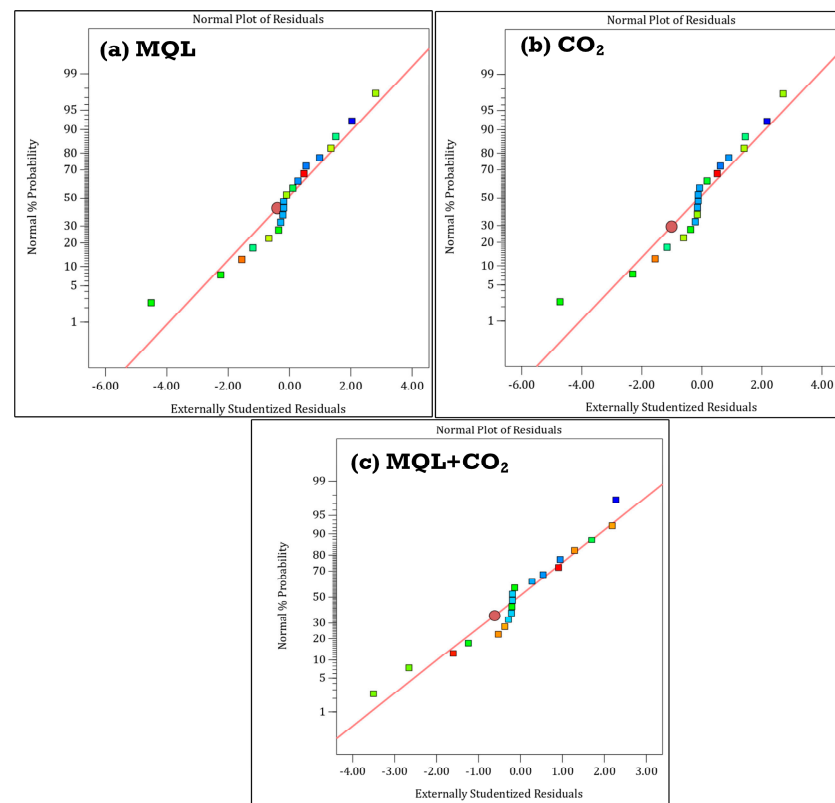


Figure 3. Normal % probability under different conditions.

3.4. Optimization

With the response surface methodology optimization, the recommended cutting conditions for Alloy 20 were obtained as follows: V_c of 44.3514 m/min, f of 0.04502 mm/rev, and a_p at 0.435244 mm. Figure 4 indicates the optimal conditions obtained through RSM, and the following discussion is based on these obtained optimal conditions. Under these optimized parameters, the anticipated R_a values are 0.693654 for MQL, 0.665265 for CO_2 cooling, and 0.620885 for the hybrid MQL + CO_2 approach. These values signify the expected outcomes of surface roughness corresponding to the optimized cutting parameters for each respective coolant condition. The optimization process through RSM emphasizes the importance of tailoring cutting parameters to specific coolant strategies in order to achieve enhanced surface quality during the machining of Alloy 20.

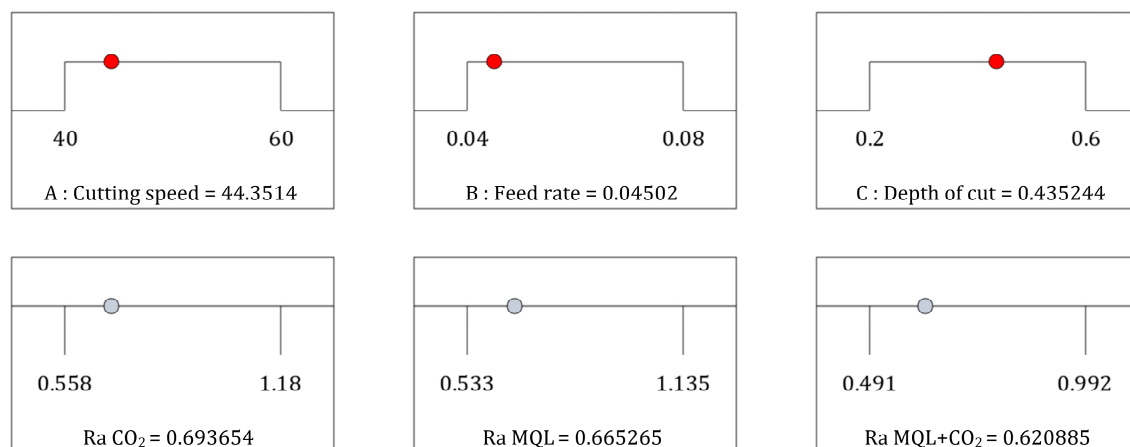


Figure 4. Optimum conditions obtained from RSM.

3.5. Surface Integrity

SEM analysis was performed to determine the best of the optimal parametric levels that were obtained using the optimization methods. Microscopic surface defects caused during the machining process also impact the macroscopic parts' properties. The surface integrity is critical to functionality, longevity, and overall performance [26]. And the surface integrity directly influences corrosion and fatigue resistance [27]. MQL effectively reduces shear stresses caused by friction during machining [28]. Cryogenic machining can effectively change the deformation mechanism of the machining process, which has a certain effect on the hardness and subsurface microstructure of the material [29]. This section compares the surface integrity given by different cooling methods to determine the optimal cooling method.

Figure 5 shows a cross-section layer of the machined surface under optimal machining conditions. The surface topography analysis conducted under the optimum cutting conditions provides valuable insights into the quality and characteristics of the machined surfaces for each respective cooling environment. In the case of MQL, the surface topography reveals a comparatively rough texture. This suggests that despite the optimization efforts, the MQL cooling condition tends to result in surface irregularities and variations, potentially influenced by the specific lubrication and cooling characteristics associated with this method. Conversely, the surface topography under CO₂ cooling conditions exhibits a different characteristic, showcasing a pattern of scratches on the machined surface. This pattern implies that the CO₂ coolant environment, while optimized for other machining parameters, may introduce some scratching effects on the workpiece surface. Under the hybrid cooling condition of MQL + CO₂, the surface topography appears to be notably smooth. This indicates that the combination of Minimum Quantity Lubrication and Carbon Dioxide as coolants, under the specified optimized cutting parameters, contributes to achieving a smoother surface finish compared to the other individual coolant environments. In summary, the surface topography analysis provides a nuanced understanding of the effects of different cooling environments on the machined surfaces under optimized cutting conditions. While MQL results in a relatively rough surface, CO₂ introduces scratches, and the combination of MQL + CO₂ yields a smoother surface finish. These observations underscore the influence of coolant strategies on the final surface characteristics of the machined Alloy 20 workpieces.

Upon conducting scanning electron microscopy (SEM) imaging for the machined samples made using the three coolants mentioned above, under the specified cutting parameters, distinct features on the machined surfaces became evident. Figure 6 shows the SEM of machined surfaces; $V_c = 44$ m/min, $f = 0.04$ mm/rev, and $a_p = 0.43$ mm. In the case of MQL, the SEM images reveal a surface characterized by scratches and damage. Scratches indicate potential abrasions or irregularities on the surface, possibly influenced by the lubrication and cooling dynamics associated with MQL. The damage observed suggests that the machining process under MQL conditions may be subject to some surface deterioration. Similarly, the SEM images for Carbon Dioxide (CO₂) cooling conditions exhibit surfaces marked by scratches and damage. This consistent observation of scratches implies that the CO₂ coolant environment, despite the optimized cutting parameters, introduces a scratching effect on the workpiece surface. The damage observed may also signify potential challenges associated with this cooling method in maintaining surface integrity. Under the hybrid cooling condition of MQL + CO₂, the SEM images showcase a surface characterized by fine feed marks. These fine feed marks indicate a smoother surface texture than the scratches observed in the other conditions. This suggests that the combined effects of MQL + CO₂ as coolants under the specified optimized cutting parameters contribute to mitigating scratching and damage, resulting in a finer and more refined surface finish. In summary, SEM imaging provides a detailed visual representation of the machined surfaces under different coolant conditions. While the MQL and CO₂ conditions exhibit surfaces marked by scratches and damage, the hybrid MQL + CO₂ condition demonstrates a surface with fine feed marks, indicating a smoother and more

refined outcome. These SEM observations further support the influence of coolant strategies on the surface characteristics of machined Alloy 20 workpieces, as shown in Figure 6.

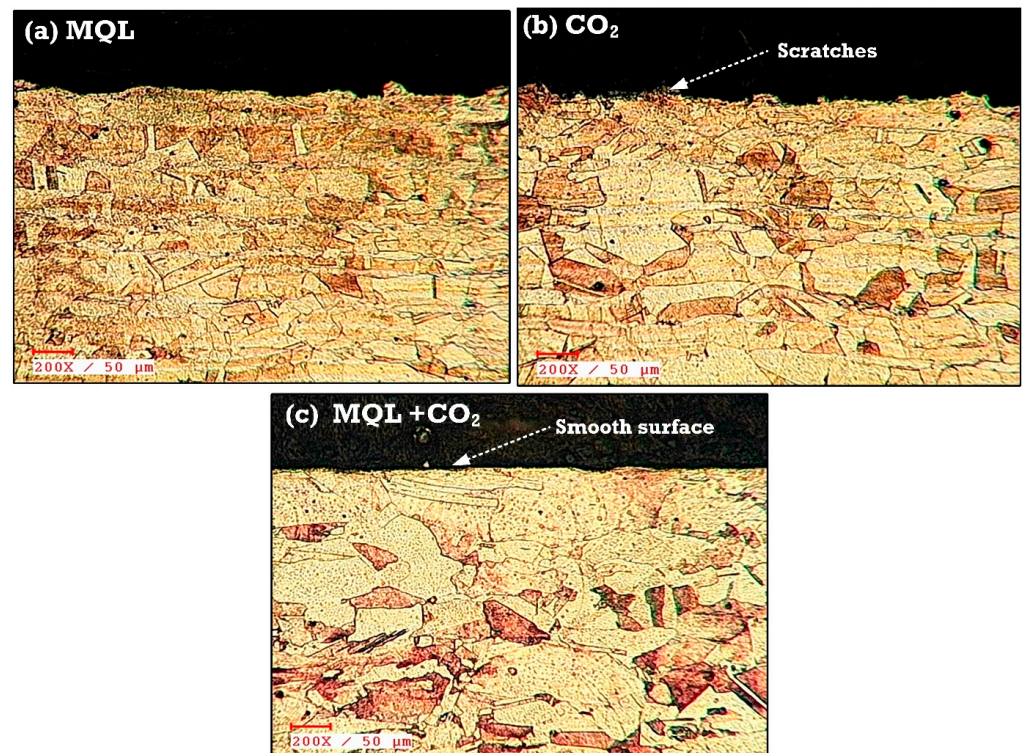


Figure 5. Cross-section layer of machined surface; $V_c = 44$ m/min, $f = 0.04$ mm/rev, and $a_p = 0.43$ mm.

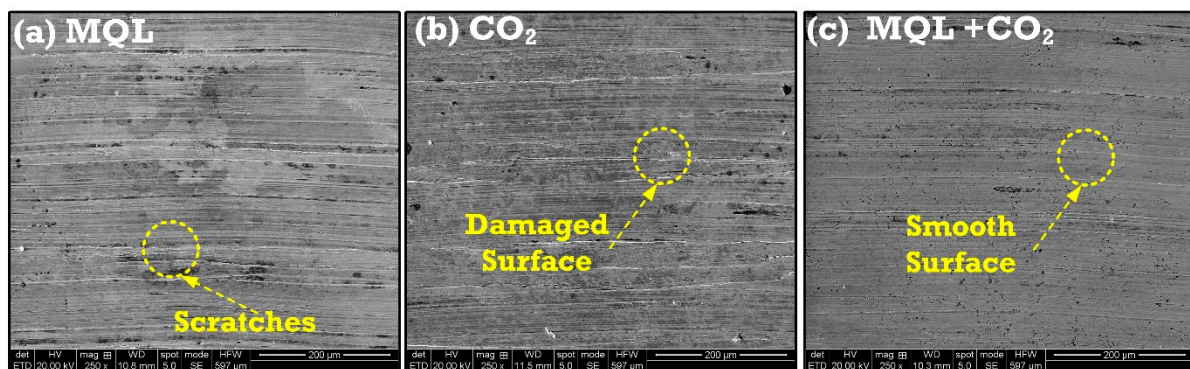


Figure 6. SEM of machined surfaces; $V_c = 44$ m/min, $f = 0.04$ mm/rev, and $a_p = 0.43$ mm.

3.6. Chip Formation and Cutting Tool Wear

During the cutting process, the cutting speed and cooling method greatly impact tool wear. The increase in temperature in the cutting area of the tool causes the main cutting edge to move and deform, thus increasing tool wear [30]. Chip formation is also affected by the machining conditions, and chip formation can damage the face of the tool, which also increases tool wear. Lubrication and cooling are effective ways to reduce tool wear [31]; lubrication methods will form a lubrication film on the tool face, which greatly protects the tool; in addition, CO₂ cooling can effectively penetrate the chip area and introduce a good cooling effect. This section explores the practical impacts of new cooling methods on chip formation and tool wear. Figure 7 shows the chip morphology; $V_c = 44$ m/min, $f = 0.04$ mm/rev, and $a_p = 0.43$ mm. Examining chip formation (Figure 7) during machining processes under various cooling conditions provides essential insights

into the material removal mechanisms and overall cutting performance. Distinct chip formation characteristics were observed under the specified cooling conditions (MQL, CO₂, and hybrid CO₂ + MQL). Under the MQL cooling condition, chip formation was comparatively discontinuous. This suggests that the chips produced during machining under MQL are not consistently continuous, but exhibit breaks or interruptions. The discontinuous nature of chip formation under the MQL condition may be attributed to the specific lubrication and cooling dynamics associated with this method, influencing the material flow and chip morphology. In the case of the Carbon Dioxide (CO₂) cooling condition, chip formation was observed to be greater and discontinuous. The chips generated under CO₂ are larger than those of MQL and exhibit similar continuity interruptions. The bigger and discontinuous nature of chips under the CO₂ condition may indicate specific thermal and mechanical interactions between the coolant and the workpiece material, leading to variations in chip morphology. Contrastingly, under the hybrid cooling condition of MQL + CO₂, chip formation was noted to be close and continuous. This suggests that the chips produced under the hybrid CO₂ + MQL condition are closely connected and exhibit a more continuous flow. The close and continuous chip formation in the hybrid condition may result from the combined effects of Minimum Quantity Lubrication and Carbon Dioxide, providing a balance between lubrication, cooling, and chip evacuation, thereby influencing the overall chip morphology. The observed chip formation characteristics vary across the different cooling conditions. MQL is associated with comparatively discontinuous chips; CO₂ produces bigger and discontinuous chips; and the hybrid MQL + CO₂ condition results in close and continuous chip formation. These findings offer valuable insights into the complex interplay between cutting parameters, coolant strategies, and chip morphology, contributing to a comprehensive understanding of the machining processes under different cooling environments [32].



Figure 7. Chip morphology; $V_c = 44$ m/min, $f = 0.04$ mm/rev, and $a_p = 0.43$ mm.

Figure 8 shows the rake wear; $V_c = 44$ m/min, $f = 0.04$ mm/rev, and $a_p = 0.43$ mm under the optimal machining conditions. In the examination (Figure 8) of the cutting conditions for the specified tool under various coolant environments, distinct tool wear patterns were observed. Under the Minimum Quantity Lubrication (MQL) cooling condition, the tool exhibited nose degradation and peeling signs. The occurrence of nose degradation suggests that the cutting edge of the tool's nose, which plays a crucial role in initiating the cutting process, experienced wear and deterioration. Also, peeling indicates that the tool material's layers are being separated or peeled away. These wear characteristics under the MQL condition may be attributed to the specific lubrication and cooling properties associated with MQL, potentially leading to increased friction and wear on the tool's cutting surfaces. Conversely, the tool chipped under the Carbon Dioxide (CO₂) cooling condition. Chipping forms small, localized fractures or chips on the tool's cutting edges. The presence of chipping under the CO₂ condition suggests that the tool may have experienced excessive localized force or stress during machining, resulting in the formation of chips on the tool's edges. The cooling dynamics of CO₂ may influence the heat dissipation and chip formation processes, contributing to the observed chipping. Under the hybrid cooling condition of MQL + CO₂, the tool exhibited signs of chipping similar to those observed in the CO₂ condition. Chipping in the CO₂ and hybrid CO₂ + MQL conditions suggests that certain

machining forces or conditions common to both coolant strategies contribute to this specific wear pattern on the tool. Analysing tool wear patterns under different coolant conditions reveals distinct characteristics. MQL is associated with nose degradation and peeling, while CO₂ and the hybrid MQL + CO₂ condition exhibit signs of chipping on the tool's cutting edges. These wear patterns provide valuable insights into the interactions between cutting parameters, tool materials, and coolant strategies, informing the optimization of machining processes for improved tool performance and longevity.

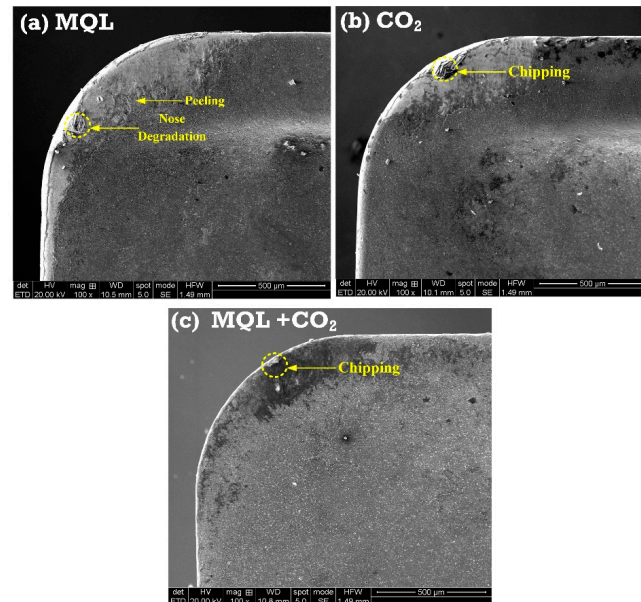


Figure 8. Rake wear; $V_c = 44$ m/min, $f = 0.04$ mm/rev, and $a_p = 0.43$ mm.

4. Conclusions

In conclusion, the comprehensive investigation into the machining processes of Alloy 20 under various cooling conditions—Minimum Quantity Lubrication (MQL), Carbon Dioxide (CO₂), and the hybrid MQL + CO₂—has provided valuable insights into the intricate relationships between cutting parameters, surface characteristics, tool wear patterns, and chip formation. The key findings are summarized as follows:

1. Based on the RSM outcomes, the optimal parametric settings obtained are $V_c = 44$ m/min, $f = 0.04$ mm/rev, and $a_p = 0.43$ mm, for which the R_a value for MQL is $0.665 \mu\text{m}$, the R_a value for CO₂ is $0.693 \mu\text{m}$, and the R_a value for MQL + CO₂ is $0.620 \mu\text{m}$.
2. Surface roughness outcomes varied under different cooling conditions, with MQL exhibiting a relatively rough surface, CO₂ showing scratches, and the hybrid MQL + CO₂ resulting in a smoother finish under the optimized cutting parameters.
3. Tool wear patterns were distinctive for each coolant condition. MQL was associated with nose degradation and peeling, while CO₂ and the hybrid condition displayed signs of chipping, indicating the influence of coolant strategies on tool performance.
4. Chip formation characteristics varied significantly. MQL resulted in comparatively discontinuous chips, CO₂ produced bigger and discontinuous chips, and the hybrid MQL + CO₂ condition yielded close and continuous chip formation. These observations underscore the diverse effects of coolant strategies on material removal processes.
5. Scanning electron microscopy (SEM) images revealed surface features corresponding to the coolant conditions. The MQL and CO₂ conditions showed scratches and damage, while the hybrid condition demonstrated fine feed marks, indicating a smoother surface.
6. The application of response surface methodology (RSM) identified optimized cutting conditions, providing specific parameter values for cutting speed, feed rate, and depth

of cut. These optimized conditions were associated with minimized surface roughness for each coolant condition.

7. The findings highlight the nuanced interplay between cutting parameters, coolant strategies, and machining outcomes. The optimization of cutting conditions is essential for achieving the desired surface quality, tool longevity, and chip characteristics during the machining of Alloy 20. This study contributes to a broader understanding of coolants' effects on machining processes and provides valuable insights for optimizing machining operations in manufacturing settings.

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