Optimisation of Cutting Fluid Concentration and Operating Parameters based on RSM for Turning Ti–6Al–4V

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Research Article

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Abstract

The paper details experimental and optimisation results for the effect of cutting fluid concentration and operating parameters on the average surface roughness (Ra) and tool flank wear (V_B) when flooded turning of Ti-6Al-4V using water-miscible vegetable oil-based cutting fluid. Cutting fluid concentration, cutting speed, feed rate and cutting tool were the control variables. Response Surface Methodology (RSM) was employed to develop an experimental design and optimise Ra and V_B using linear models. The study revealed that cutting fluid concentration has a little influence on Ra and V_B performance while Ra was strongly affected by feed rate and cutting tool type. The developed empirical model also suggested that the best parameters setting to minimise Ra and V_B are 5%, 58 m/min, 0.1 mm/rev for cutting fluid concentration, cutting speed and feed rate, respectively, using H13A tool. At this setting, the predicted surface roughness and tool wear were 0.48 and 30 μm, respectively. In the same vein, tool life and micro-hardness tests were performed at the suggested optimum cutting condition with different cutting speeds. A notable decrease in tool life (82.3%) was obtained when a higher cutting speed was used.

1. Introduction

Cutting titanium is more demanding than other materials such as steel and stainless steel. Titanium-based alloys offer high strength-to-weight ratios (i.e., 40% lighter than steel alloys), high strength, high operating temperatures and exceedingly corrosion resistance, making them desirable materials to use mainly in aerospace applications. However, the same properties that give the alloys superior qualities also make them notoriously difficult to cut, owing to their low thermal conductivities, high dynamic shear strength and high hardness (e.g. up to 360 HV for Ti-6Al-4V), high chemical reactivity at elevated temperatures [1]. Low thermal conductivity (e.g. 7.3 W/m·K for annealed Ti-6Al-4V) causes accumulation of generated heat on the tooltip resulting in low surface quality and high tooling costs. The relatively low elastic modulus of titanium alloys (114 GPa) allows deflection of slender parts under high cutting force, promoting chatter and geometry problems. Additionally, in the absence of coolants, titanium alloys may have a great tendency to react with cutting tool materials in an atmospheric environment, negatively affecting the mechanical properties [2]. Thus, cutting fluids are crucial when machining titanium alloys. They are applied to the machining zone to minimise tool wear, improve surface finish and increase tool life [3]. Typically, mineral oil-based, synthetic, and semi-synthetic coolants are the most common fluids used in shop floors due to their chemical stability and reuse. However, the use of such fluids presents hazards to the environment and the operator (e.g. skin and respiratory systems diseases) due to the high amounts of hydrocarbons existent in these fluids [4, 5].

Recently, more attention was given to biodegradable fluids [6, 7]. The increase in global ecological consciousness and the niche market of biodegradable lubricants (7–10 % in US markets) allowed ecological friendly vegetable oil (VO) based fluids to replace conventional cutting fluid counterparts in machining industry [8–10]. Biodegradability with a high degradation rate of VO based cutting fluid is one of the main virtues over conventional cutting fluids. A biodegradation test (measuring the transformation of organic carbon to CO_2 under aerobic and composting conditions) was performed at 25°C for two weeks. The results showed that vegetable-oil based, pure rapeseed and synthetic ester oil are 100 % biodegradable, whereas mineral oil-based fluids were only 40 % biodegradable [11–13]. Additionally, owing to their tribological characteristics, vegetable oil-based cutting fluids have superb lubricity properties. This was attributed to the unique chemical structure of vegetable oil's molecule (e.g., heavy, long and dipolar). These molecules' ends have a little opposing polar charge that pulls the vegetable oil's molecule to a metallic surface and makes it strong enough to resist being rubbed out. Consequently, frictional energy is dropped, and hence, heat generation is reduced [14].

Homogeneity and super-dense characteristics are other distinctive properties of the vegetable oil's molecule, producing a thick, durable and hardy layer that provides the VOs with a greater capacity to withstand working loads [14, 15]. Vegetable oils base stocks have a high natural viscosity (275 cP at 23.9˚C). As the cutting temperature increases, the viscosity of vegetable oils drops more gradually than mineral oils counterparts. VOs remain more fluid than mineral oils while temperature decreases, facilitating faster drainage from chips and workpiece [16, 17]. The higher viscosity index of VOs (e.g. 222 for rice bran oil) [18, 19] helps the VOs provide steadier lubricity for a wide operating temperature range. VOs have a higher flash point (up to 224˚C) than mineral oil-based fluids counterparts (~ 131˚C), minimising smoke formation and fire threat. Higher flash point values allow employing the VOs based cutting fluids in high-temperature applications [20, 21]. They also have superior cooling performance owing to their high heat conductivities range (up to 0.172 W/m·K) [22], compared to 0.125 W/m·K for mineral oils [23], which is crucial for dissipating heat from the machining zones. Bermingham et al. [24] evaluated five different cutting strategies, including dry, flood (mineral oil-based), minimum quantity lubricant (MQL) VOs, laser-assisted milling (LAM), and MQL/LAM during milling of Ti-6Al-4V alloy at a cutting speed of 69 m/min. Higher tool life of 28 minutes was reported when MQL/LAM and MQL were used compared to flood (9 min), dry (4 min) and LAM (5 min). MQL using VOs also produced lower tool wear of 40 µm and MQL/LAM about 50 µm, while others achieved tool wear levels higher than 200 µm.

The palm oil performance using MQL and synthetic ester cutting fluids was also examined when drilling Ti-6Al-4V at a cutting speed of 100 m/min with a 0.1 mm/rev feed rate [25]. The results showed that palm oil MQL resulted in a lower cutting force of 1954 N compared with 2318 N for a synthetic ester with limited impact on tool life (314 seconds for both fluid types). This was attributed to the formation of a thin boundary lubrication film, which reduced friction in the tool-workpiece interface. Surface roughness was also evaluated when turning Ti-6Al-4V using different cutting fluid application methods, including dry, palm oil VOs and a mixture of palm oil with boric acid [26]. The minimum surface roughness of 1.42 µm was obtained using palm oil and chemical vapour deposition (CVD) coated tool at cutting speed of 79 m/min, a feed rate of 0.206 mm/rev and a depth of cut of 1 mm.

The cutting energy consumption of five cooling strategies, including minimum quantity lubricant (MQL) cooling mode using vegetable oils based fluid, flood, cooled air, cryogenic and dry cooling methods, have also been investigated when turning Ti-6Al-4V at different cutting speeds (90 and 120 m/min) and feed rates (0.1 and 0.2 mm/rev) utilising uncoated carbide cutting tool [27]. The results revealed that the use of MQL with VOs was associated with the least average cutting energy consumption in all cutting conditions of 0.012 kWh compared to flood (0.023 kWh), cooled air (0.022 kWh), cryogenic cooling (0.020 kWh) and dry condition (0.024 kWh). This was attributed to its superior lubricity property, which significantly reduced the cutting energy consumption. VOs based cutting fluids have also been examined when cutting other metallic materials such as steels. The performance of a formulated water-miscible VO-based cutting fluids at five different concentrations ratios including 5%, 10%, 15%, 20% and 25% was evaluated when turning heat-treated AISI 1040 [4]. The VO cutting fluids were benchmarked with dry cutting and the conventional mineral oil-based cutting fluid under constant cutting conditions of an average cutting speed of 62 m/min, a feed rate of 0.4 mm/rev and a depth of cut of 1 mm. The results showed that average surface roughness was reduced by 25% for the water-miscible VOs fluid with 10% concentration than dry machining and mineral oil-based cutting fluid.

Statistical modelling represents an inexpensive means for analysing key factors influencing parts' quality in different manufacturing processes. The use of techniques such as design of experiments (DoE), RSM, and ANOVA helped study the impact of parameters in many manufacturing processes [28, 29]. When a combination of several variables and their interactions affect desired outputs, RSM is beneficial for quantifying the relationship between such variables and the obtained response surfaces to optimise the process. RSM applied an experimental design to fit a model by least squares technique. Subsequently, the proposed model's adequacy is examined using the ANOVA tests [30–32]. Finally, the response surface plots are employed to locate the optimum setting of the studied variables. Process optimisation by RSM is faster for analysing experimental research results than other techniques such as the conventional one factor at a time technique.

This research was carried out to cover a research gap and study the effect of VO-based cutting fluids concentration and operating conditions on surface roughness and tool wear during flooded turning of Ti-6Al-4V. Statistical analysis has been adopted to optimise the machining parameters aiming to minimise both responses. Progression of Ra and tool wear with cutting distance and micro-hardness at different cutting speeds were also evaluated.

2. Experimental Details

2.1 Design of Experiments (DoE)

RSM was employed to generate the experimental plan. Analysis of Variance (ANOVA) was utilised to develop the relationship between the input and output parameters, identify the most significant parameters, and find the optimal setting of those parameters to achieve the intended objective function. The response surface, or process yield, "Y" can be expressed by the following second-order polynomial (regression) equation [1]:

$$Y = b_0 + \sum b_i x_i + \sum b_{ii} x_i^2 + \sum b_{ij} x_i x_j \qquad [1]$$

where x_i are the process variables or input parameters, the terms b_0, b_i, b_{ii}, and b_{ij} are the model coefficients that depend on the process parameters' main and interaction effects. The method of least squares was used to determine these constant coefficients. Design-Expert Software Version 7.0.0 (Stat-Ease Inc., Minneapolis, USA) was used to perform the analysis.

In this research, four variables (process parameters) were examined: the concentration of the cutting fluid, cutting speed, feed rate and the type of cutting tool. Each parameter was varied over 3 levels, as shown in Table 1. Accordingly, 27 parametric combinations (machining trails) were carried out. A depth of cut of 0.75 mm was maintained for all trials. Two output responses were considered in this study: the machined surface's roughness and tool wear.

Table 1
The range of matrix building parameters

Parameter	**Units**	**Levels**		
		1	**2**	**3**
Cutting fluid concentration	%	5	10	15
Cutting speed	m/min	58	91	146
Feed rate	mm/rev	0.1	0.15	0.2
Tool type	-	H10A	GC1115	H13A

2.2 Experiment work

Round bars of 24 mm diameter and 160 mm length were used as workpiece materials. These bars were made of Ti-6Al-4V Grade 5 alloy. Titanium Metal Limited, UK, supplied the workpiece materials. All turning trials were performed on a Graziano SAG12 Centre lathe. Each trial involved a cutting length of 120 mm, and a new insert tip was used. Three different indexable cutting tools materials (coarse grain uncoated carbide H13A, fine grain PVD coated GC1115 and medium to coarse grain uncoated carbide H10A were supplied by Sandvik Coromant having similar rhombic shapes, ISO designations (CNMG120408) and chip breaker geometry. A water-miscible vegetable oil-based cutting fluid (Vasco1000) containing 45% pure vegetable oil was used in all tests. Three concentration ratios were tested (5%, 10% and 15%) with a constant flow rate of 0.7 l/min. The bulk flood cooling mode was chosen to deliver the cutting fluid to the cutting zone through a single flexible hose. The intensity of the fluids was regularly monitored using a portable refractometer.

2.3 Measurement equipment

The average surface roughness (Ra) of the machined surface was measured using a Taylor Hobson Surtroni 3 + surface roughness tester. Ra test was conducted according to ISO 4287 and ISO 4288 and using 0.8 mm cut-off and an evaluation length of 4 mm. Alicona Infinite Focus G4 optical scanner was also utilised to capture the tool wear images. The scanning area was 5 mm x 1 mm in the axial and circumferential directions. Scans were obtained using 365.54 nm and 11.25 µm vertical (Z direction) and lateral (X and Y) resolutions. Additionally, circular samples of Ø 22.5 x 5 mm in thickness were cut, mounted, and ground to analyse the machined surface's micro-hardness. Micro-hardness was measured using BUEHLER Micromet II micro-hardness tester at the 30 µm interval between two consecutive measurements.

3. Results And Discussion

In statistical analysis, Least Square Fitting R^2 is used to describe the model fit. RSM method suggested that both the surface roughness and tool wear fit linear models with relatively high R^2 of 92% and 99%. The linear models representing the two responses can be described as functions of the cutting fluid concentration (c), cutting speed (v), feed rate (f) and cutting tool type, and are expressed as in equation [2]. The coefficients' values for the surface roughness and tool wear (for different tool types) are shown in Table 2 and Table 3.

$$Response = b_0 + b_1(c) + b_2(v) + b_3(f) \qquad [2]$$

Table 2
Response surface model coefficients for the values of surface roughness.

Tool Type	**H10A**	**GC1115**	**H13A**
Coefficient	**Surface roughness model**	**Surface roughness model**	**Surface roughness model**
b_o	+ 0.59048	+ 0.30825	-0.017302
b_1	+ 9.00000E-003	+ 9.00000E-003	+ 9.00000E-003
b_2	-3.09524E-003	-3.09524E-003	-3.09524E-003
b_3	+ 6.27778	+ 6.27778	+ 6.27778

Table 3
Response surface model coefficients for the values of tool wear

Tool Type	H10A	GC1115	H13A
Coefficient	**Tool wear model**	**Tool wear model**	**Tool wear model**
b_o	+ 14.06408	+ 2.57963	-9.13259
b_1	+ 0.15178	+ 0.15178	+ 0.15178
b_2	+ 0.62489	+ 0.62489	+ 0.62489
b_3	+ 19.03333	+ 19.03333	+ 19.03333

Table 4 shows the analysis of variance (ANOVA) F-values, p-values and percentage contribution ratio (PCR) for each of the studied process parameters for the surface roughness and tool wear. In statistical significance testing, the p-value is the probability of obtaining a test statistic at least as extreme as the one that was observed, assuming that the null hypothesis is correct. The null hypothesis (which assumes that all parameters have no significant effect) is rejected when the p-value is less than the predetermined significance level, which is 0.05 (95 per cent confidence level). This means that any factor has p-value less than 0.05 is considered to be a significant model parameter. This study indicated that the surface roughness was affected by the cutting speed, feed rate, and tool type, while the tool wear was affected by the fluid concentration, cutting speed, feed rate, and tool type. Also, the F-value gives a relative measure of the significance of the examined parameters. PCR is obtained for each parameter by dividing the squares term of this parameter by the total sum of squares and multiplying by 100. The higher the F-value and PCR, the stronger the effect of a given factor. It was clear that the feed rate had the most significant impact on the surface roughness among all the examined factors, owing to the largest F-value and PCR of 145 and 44%, respectively.

Moreover, the tool type and cutting speed were of less significance (especially the latter), with F-values of 68 and 28, respectively, and PCR of 41% and 8%. Finally, the effect of cutting fluid concentration on the surface roughness was shown to be insignificant. The ANOVA results had also demonstrated a remarkable influence of the cutting speed on the tool wear (F-value = 7140 and PCR = 85%). Tool type comes the second with F-value of 622 and PCR of 15%. Lastly, and despite the model's significant factors, both the fluid concentration and feed rate had relatively trivial effects on the tool wear with F-values of 5 and 8, respectively and PCR of only 0.1% each.

Table 4
ANOVA results for the average surface roughness and tool wear

Model Parameter	Surface roughness			Tool wear		
	F-value	p-value	PCR %	F-value	p-value	PCR %
Cutting fluid concentration	2.98	0.0987	0.9	5.33	0.0313	0.1
Cutting speed	27.91	< 0.0001	8.4	7140.16	< 0.0001	84.8
Feed rate	145.23	< 0.0001	43.6	8.38	0.0087	0.1
Tool type	68.18	< 0.0001	40.9	622.32	< 0.0001	14.8

3.1 Analysis of surface roughness

Figure 1 shows the effect of fluid concentration, cutting speed and feed rate on the surface roughness of the machined components for different tool types using linear models as suggested by the RSM. Cutting fluid concentration was found to have a marginal impact on surface roughness irrespective of the employed cutting tool. Regardless of the tool type, surface roughness increased consistently with increasing feed rate and decreasing cutting speed. However, the feed rate effect was shown to be more considerable, confirming the ANOVA results shown in Table 4. Increasing the feed rate from 0.1 to 0.2 mm/rev, at constant fluid concentration and cutting speed of 10% and 102 m/min respectively, and using H10A cutting tool, caused the surface roughness to rise from 1.03 to 1.86 µm. Increased feed rate did not secure sufficient time for the cutting fluid to carry away the heat from the machining zone, leading to high material removal rate but an accumulation of chips in the tool-workpiece zone, resulting in higher surface roughness.

On the other hand, increasing cutting speed from 58 to 146 m/min, at constant fluid concentration and feed rate of 10% and 0.15 mm/rev respectively, and using H10A cutting tool, resulted in a marginal drop of the surface roughness from 1.52 to 1.35 µm. This could be attributed to the higher cutting temperature that helps soften the workpiece material and minimises the cutting forces, leading to lower surface roughness. These findings coincide with Che-Haron et al. [33] for cutting Ti-6Al-4V, where the lower surface roughness was attained at higher cutting speeds. However, it is perceived that cutting speed should be controlled at an optimal level, as the impact of high cutting temperature would conspicuously influence the tool life, cutting force, chip formation and surface finish. Finally, the type of tool material was also significant. The lowest Ra was always associated with tool type H13A for the same fluid concentration, cutting speed and feed rate

3.2 Analysis of tool wear

The effect of the three numeric process parameters (fluid concentration, cutting speed and feed rate) on the tool wear is shown in Fig. 2 (a) to (c). Tool wear was found to have a linear function of the three parameters. Nevertheless, the main numeric factor that was found imposing the most significant effect on the tool wear was the cutting speed, and the relationship was positive. The cutting tool type was also found to influence tool wear considerably and H13A had the lowest tool wear. H13A outperformed the other tool materials in terms of both tool wear and Ra owing to its superior combination of high hot hardness, high toughness, and high transverse rupture strength properties [34]. Higher cutting fluid concentration was also found to increase tool wear with only a few microns marginally.

3.3 Optimisation of process parameters

According to the results detailed in Sect. 3.1 and 3.2, it can be seen that surface roughness and tool wear vary with the assessed parameters to different extents. Therefore, an optimisation study was carried out to explore the optimum setting of machining parameters. The desirable surface finish of the machined component can be achieved while prolonging the tool life. The objective function was set to minimise both the surface roughness and tool wear. The experimental data were analysed by design-expert software, and the genetic algorithm was used to predict the process parameters based on the set objective function. The response equations describing surface roughness and tool wear in terms of the critical process parameters (showed in Eq. (2)) and the related coefficients listed in Tables 2 and 3) were solved simultaneously.

Figure 3 shows the contour plot for the optimisation function to obtain minimum values for surface roughness and tool wear for a range of fluid concentrations and cutting speeds. The model suggested that the best parameters setting to minimise average surface roughness and tool wear were 5%, 58 m/min, 0.1 mm/rev for cutting fluid concertation, cutting speed and feed rate, using the tool type H13A. At this setting, the surface roughness and tool wear are predicted to be 0.48 μm and 30 μm.

3.4 Confirmation tests and the development of surface roughness and tool wear

To validate the results predicted by the design-expert for the optimal levels of machining parameters, additional three machining trials were carried out using 5% cutting fluid concertation, 58 m/min cutting speed, 0.1 mm/rev feed rate and H13A cutting tool (suggested optimised parameters for minimum surface roughness and tool wear). Table 5 shows the measured values of surface roughness and tool wear. As shown, the average values of the three samples' surface roughness and tool wear were 0.52 μm and 30 μm, respectively.

Table 5
Results of confirmation experiments

Experiment	Surface Roughness (μm)	Tool Wear (μm)
1	0.52	30
2	0.51	29
3	0.54	31
Av.	0.52	30

According to the confirmation tests, good agreement was found between the predicted and experimental values. The experimental results confirmed the applied RSM technique's validity for improving the machining performance and optimising the operating parameters.

Following the confirmation test, the progress of average surfaces roughness (Ra) and tool wear was evaluated as a function of cutting distance at the optimised fluid concentration, feed rate and tool type of 5% 0.1 mm/rev and H13A tool, with different cutting speeds. Tool life tests were also conducted at the same conditions. Figure 4 shows the progression of average surfaces roughness (Ra) with cutting distance at different cutting speeds. Generally, Ra ranged from 0.49 to 1.15 μm with the cutting length for different cutting speeds. This span was found lower and narrower than a corresponding Ra progression range of 0.8–2.5 μm achieved recently in Nath et al. [35] when 1.5 l/min conventional cutting fluid was flooded during turning Ti-6Al-4V using uncoated microcrystalline carbide tool. The surface roughness at the first stage (up to 240 mm) was independent of the cutting speed. After that, sharp increase in Ra was recorded at the higher cutting speed (146 m/min) with prolonging the cutting distance of up to 600 mm. This could be attributed to the precipitous tool wear due to the rise in temperature at the cutting zone. On the other hand, surface roughness values at the lower cutting speed (58 m/min) were found steadier. This tended to retain the geometry of the tool cutting edge for a more extended period. Figure 5 shows tool edge wear for the three tools used in this study.

3.5 Tool life test

Trials at the three cutting speeds were undertaken to perform extended tool life analysis. Tool life tests were accomplished at the optimised setting (0.1 mm/rev feed rate, 5% concentration ratio and H13A tool type). Tool rejection criteria were determined following ISO standards 3685 and 8688-2 for tool life testing. The machining test was ceased if one or a combination of the following took place: maximum tool flank wear (VB_B max of 0.3 mm), excessive chipping (i.e. flaking) or catastrophic fracture of the cutting edge. Tool life can be estimated with the relation:

$$Tool\ life = \frac{CD}{F_m} \qquad [3]$$

were CD is total Cutting Distance to reach flank wear criterion of 0.3 mm and F_m is feed rate in mm/min [37]. Figure 8 illustrates the comparison of tool life at cutting speeds tested. Optimum tool life of 12.13 minutes was associated with the least cutting speed of 58 m/min. This could be attributed to the reduction in temperature at the machining zone, which tended to preserve the insert tip's geometry for extended periods. Further, an argument could be made that if tool wear is of higher importance to the manufacturer than the surface roughness of the sample, a lower cutting speed could be used. However, this is unlikely as titanium alloys are often used for high precision parts where the quality, including surface finish, is paramount. In addition, the graph shows a dramatic drop in tool life at cutting speeds of 91 and 146 m/min. This indicates that the cutting speed has the most dominant effect on tool life regardless of the other process parameters used (i.e. feed rate, fluid concentration and tool type).

3.6. Analysis of micro-hardness results

Micro-hardness tests were also performed at optimised cutting conditions and at the lowest and highest cutting speeds of 58 and 146 m/min. Figure 9 shows the results of the micro-hardness measurements for 58 m/min cutting speed as a function of the distance below the machined surface (starting from 30 μm), where the dashed line stands for the nominal micro-hardness of the base material before the turning process. A notable increase in micro-hardness values was found near the surface (i.e., 330 HV at the beginning of the test, at 120 mm cutting distance, and 366 HV at the end of the test cutting 1080 mm). The micro-hardness was gradually reduced towards the specimen's interior until reaching nearly the base material nominal hardness (i.e., 297 HV). This could be attributed to the plastic deformation resulting from the cutting stresses. When cutting temperature increases, there is a greater tendency for plastic deformation of subsequent workpiece layer and hence increased micro-hardness [30]. It was suggested in an investigation by [31] that a hardening effect is usually occurred during the cutting process, most probably due to the high compressive stresses at the cutting edge. Additionally, abrupt heating and cooling might have contributed to the work hardening effect during machining [32]. A noticeable increment in the micro-hardness was observed when comparing the values obtained after the first and final cuts (330 and 366 HV, respectively) [33].

Figure 10 shows the micro-hardness results for the first and last cut at 146 m/min cutting speed. In general, micro-hardness dropped from 376 HV to 297 HV in the base metal at the end of the test (600 mm cutting length), while a drop from 350 HV to 270 HV was found at the beginning of the cutting test. It was noted that these values were within the acceptable hardness range for Ti-6Al-4V aerospace parts (i.e. 419.6 HV max and 284.4 HV min). The use of a worn tool is anticipated to increase the cutting temperature due to heat accumulation at the tooltip, leading to an increase in the work hardening effect during the machining process. However, the material below the top layer of the machined surface was softer, which might be attributed to the high-temperature and tempering effect at the cutting interface when turning Ti-6Al-4V [26].

Figure 11 shows micro-hardness results after different cutting distances in all investigated conditions at two different cutting speeds of 58 m/min and 146 m/min. Similarly, a rise of micro-hardness values with increased the cutting distance was seen. However, the highest micro-hardness measured was 376 HV when machining at the higher cutting speed of 146 m/min after the uncoated carbide H13A tool has failed. In contrast, at the lower cutting speed, a micro-hardness of 366 HV was recorded. It was also observed that when longer cutting was carried out with higher flank wear, the machined surface's disturbed layer's hardness increased significantly under all cutting conditions.

4. Conclusions

From the results obtained after flooded turning of Ti-6Al-4V at different operating parameters and cutting fluid concentrations using RSM, the following conclusions can be drawn:

- Fluid concentration has minimal or no impact on key machining indicators such as surface roughness and tool wear when machining titanium alloys using VO-based cutting fluid.
- Feed rate was suggested to be the main contributing factor for Ra having a PCR of 44%, followed by cutting tool type and cutting speed with PCR of 41 % and 8.4 %.
- Cutting speed was a critical factor affecting tool wear, with the highest PCR of 85%.
- Turning Ti-6Al-4V at a higher cutting speed produced slightly higher surface roughness with prolonging cutting distance.
- RSM indicated that the optimum combination of machining parameters required to minimise surface roughness and tool wear are cutting speed of 58 m/min, feed rate of 0.1 mm/rev, 5% fluid concentration and H13A tool type. At these values, the predicted surface roughness and tool wear would be 0.48 μm and 30 μm.

Declarations

Ethical Approval: This paper does not contain any studies with human participants or animals performed by any of the authors.

Consent to Participate: Authors agree to the authorship order.

Consent to Publish: All authors have read and agreed to the published version of the manuscript.

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Availability of data and materials: The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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Figures

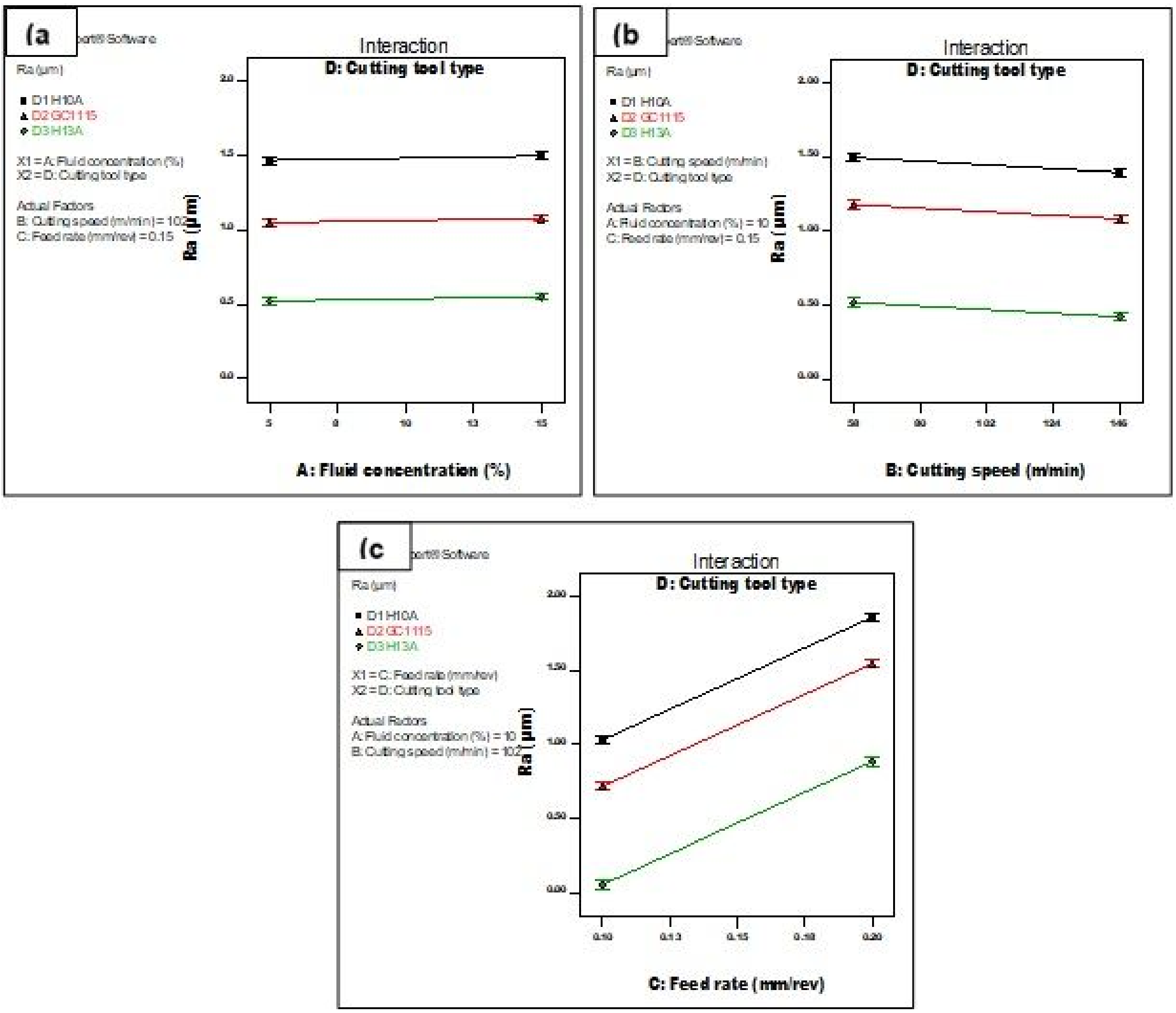

Figure 1

Effect of machining parameters on surface roughness. (a) cutting fluid concentration, (b) cutting speed, and (c) feed rate

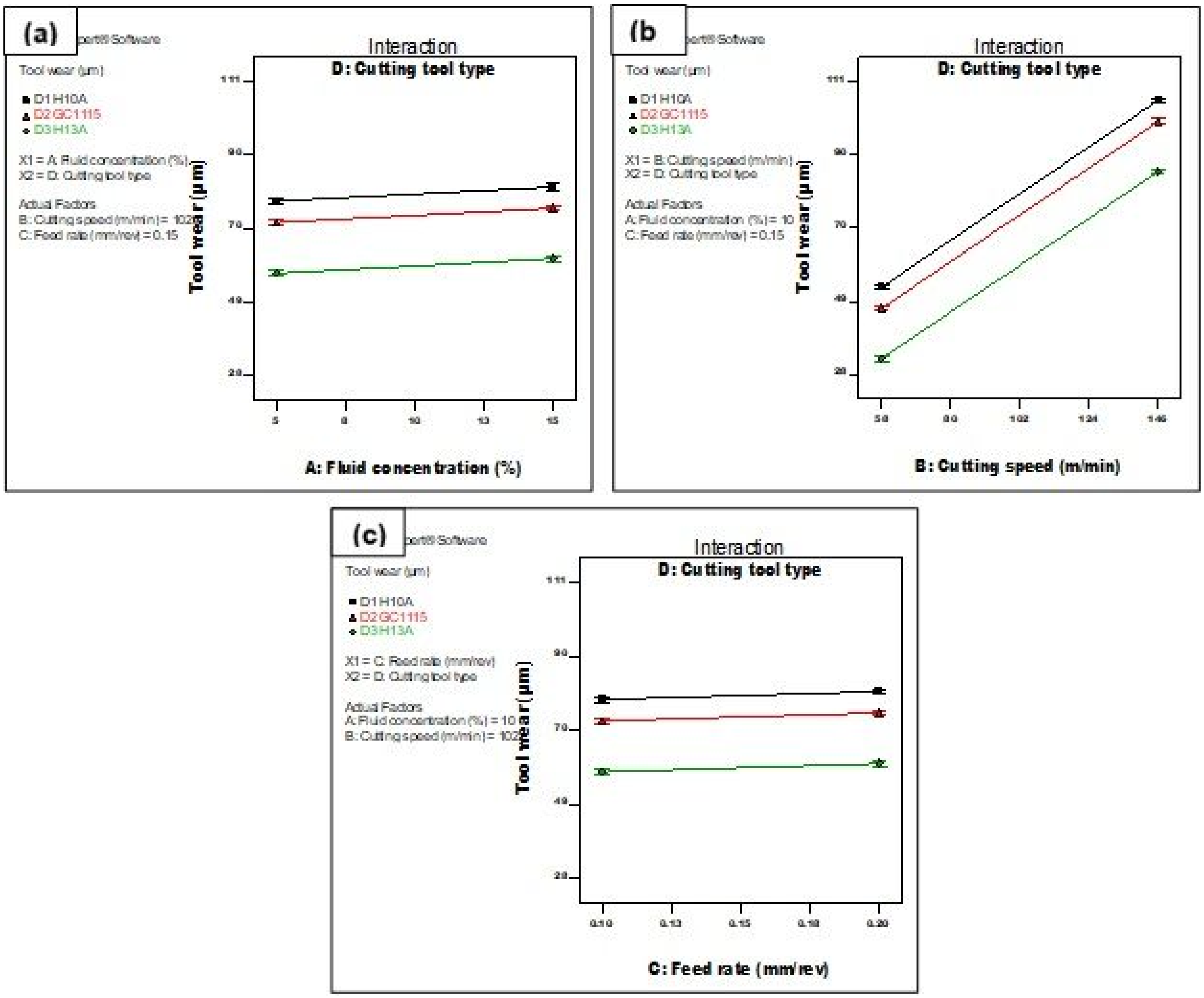

Figure 2

Effect of machining parameters on tool wear. (a) cutting fluid concentration, (b) cutting speed, and (c) feed rate

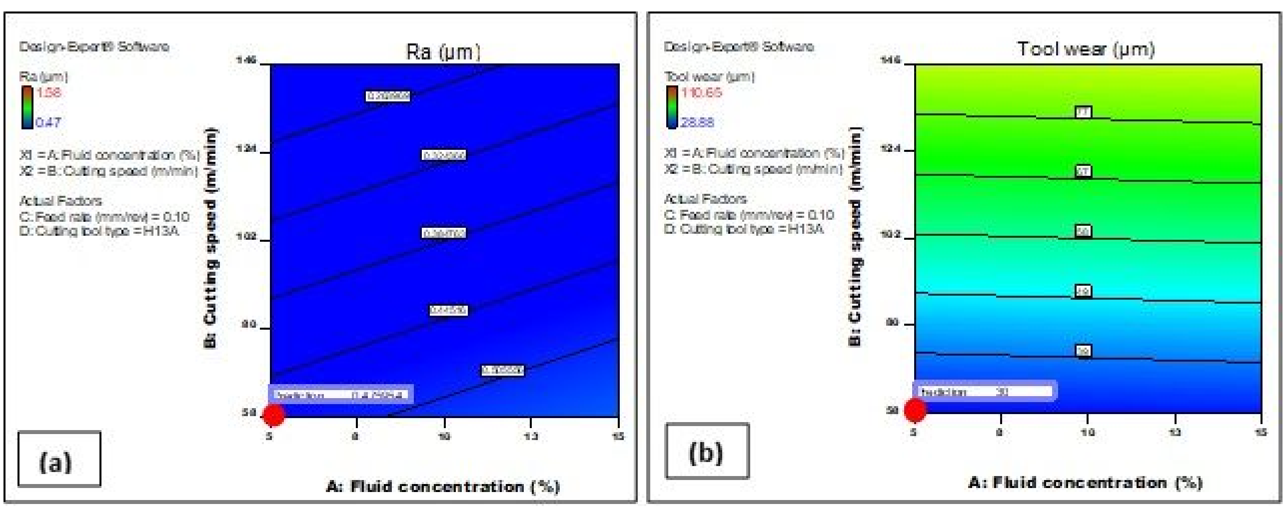

Figure 3

Predicted optimum fluid concentration and cutting speed (at a feed rate of 0.1 mm/rev and using a tool type H13A) that fulfil the desired surface finish and tool life; (a) minimum surface roughness and (b) minimum tool wear.

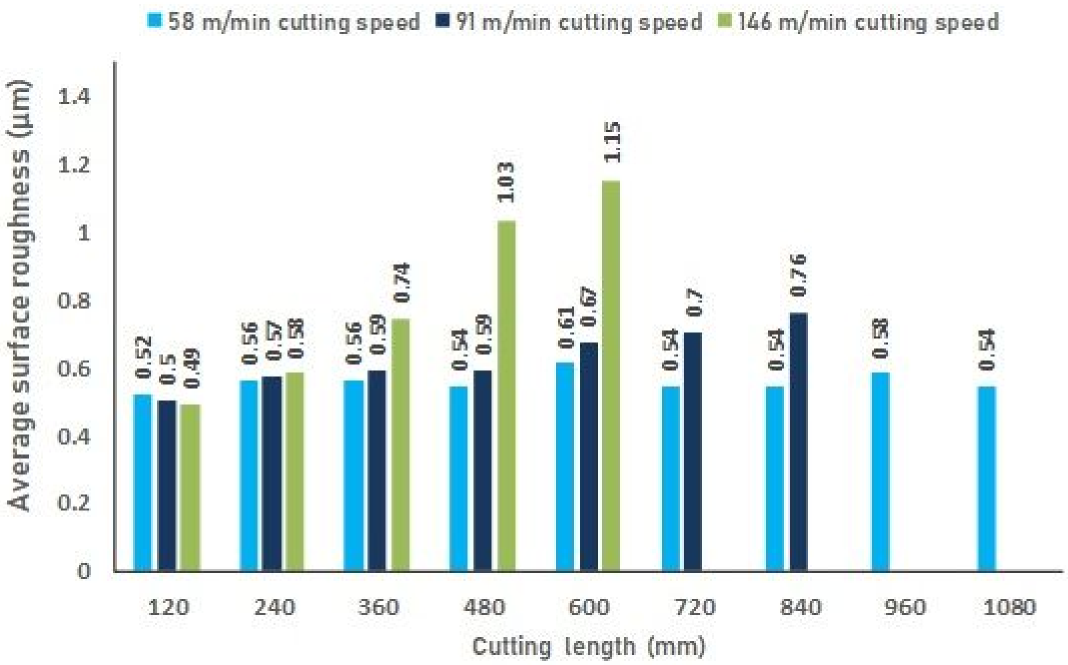

Figure 4

Ra results versus cutting length at different cutting speeds

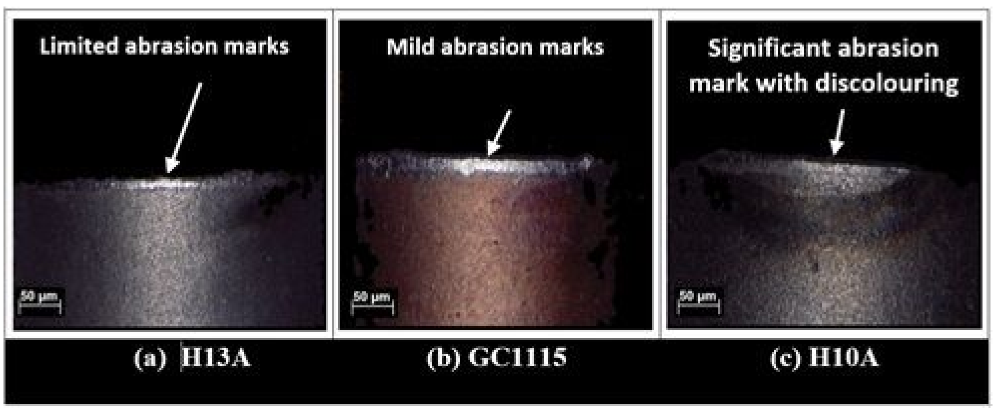

Figure 5

Images of abrasion marks on tested tips at cutting speed of 58 m/min, 0.1 mm/rev feed rate and 5% concentration ratio.

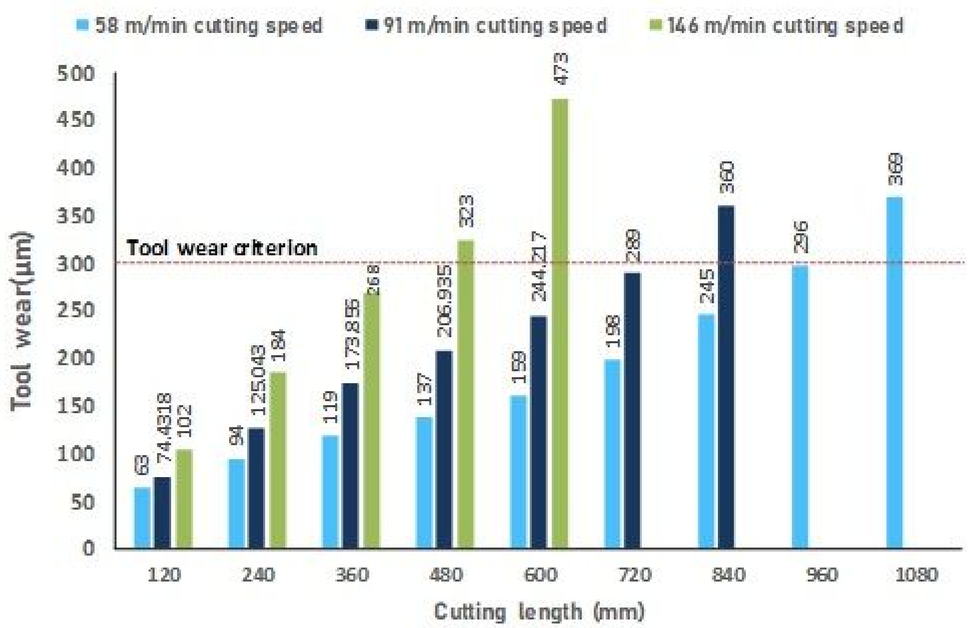

Figure 6

Tool wear results versus cutting length at different cutting speeds

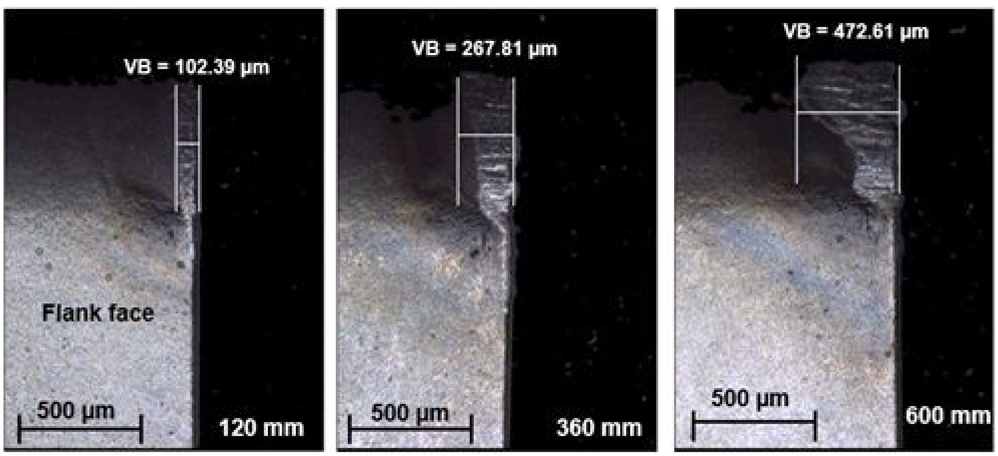

Figure 7

Images of flank wear on H13A at 120, 360 and 600 mm cutting distance of 146 m/min cutting speed, 0.1 mm/rev feed rate and 5% concentration ratio

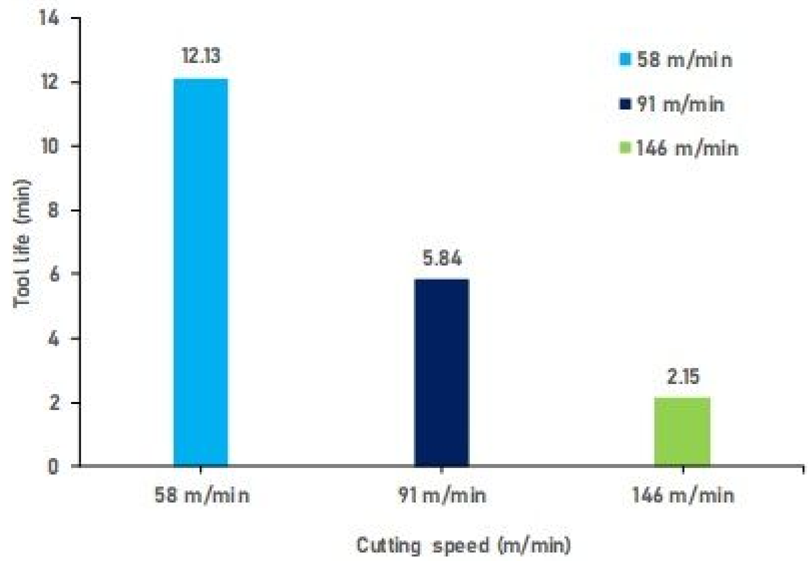

Figure 8

Comparison of tool life obtained for different cutting speeds and at optimised cutting parameters (0.1 mm/rev feed rate, 5 % fluid concentration ratio and H13A tool type).

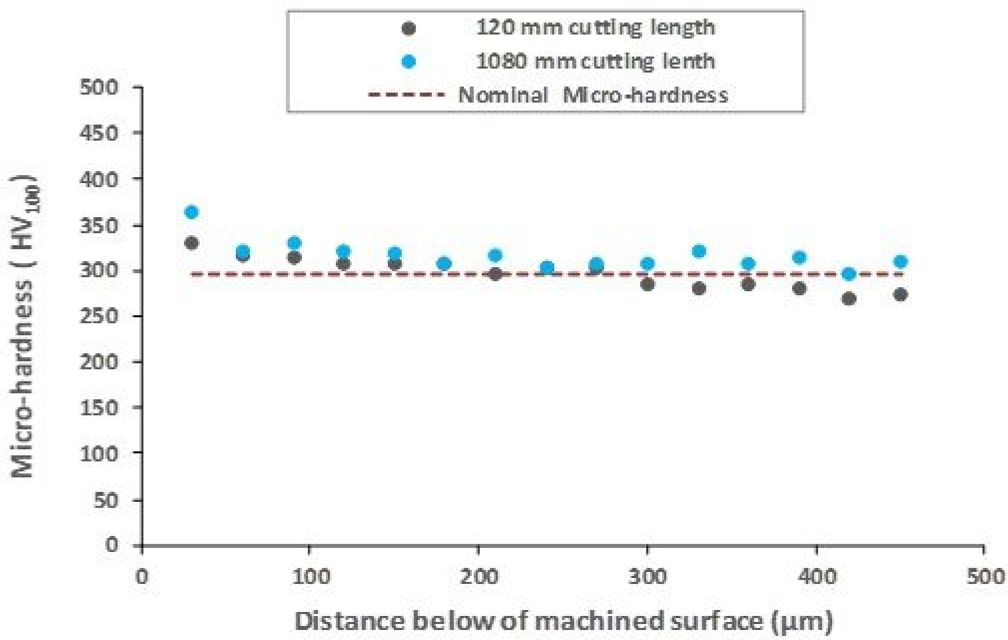

Figure 9

Micro-hardness results beneath the machined surface at cutting speed of 58 m/min, 0.1 mm/rev feed rate, 5% concentration ratio and H13A tool type

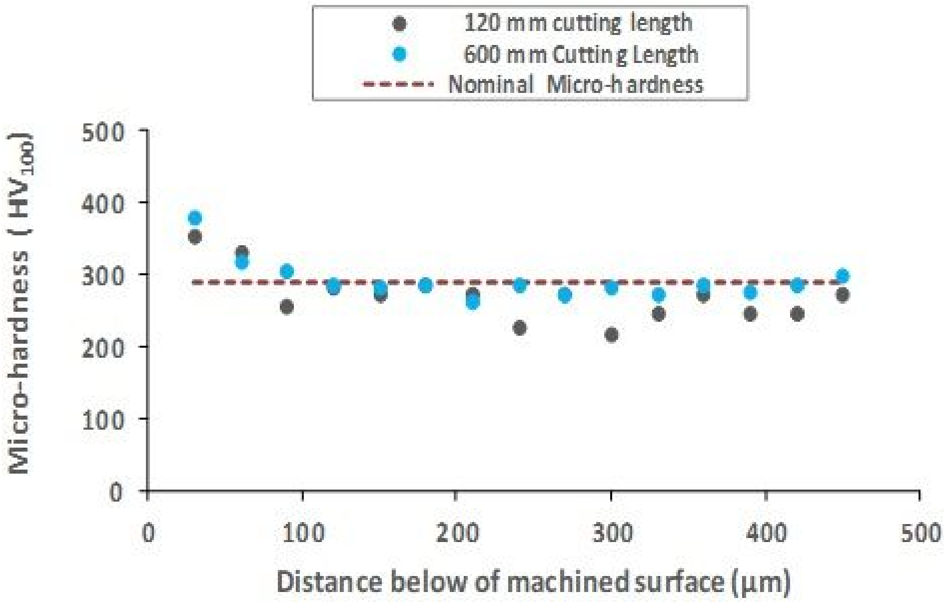

Figure 10

Micro-hardness results beneath the machined surface at cutting speed of 146 m/min, 01 mm/rev feed rate, 5% concentration ratio and H13A tool type.

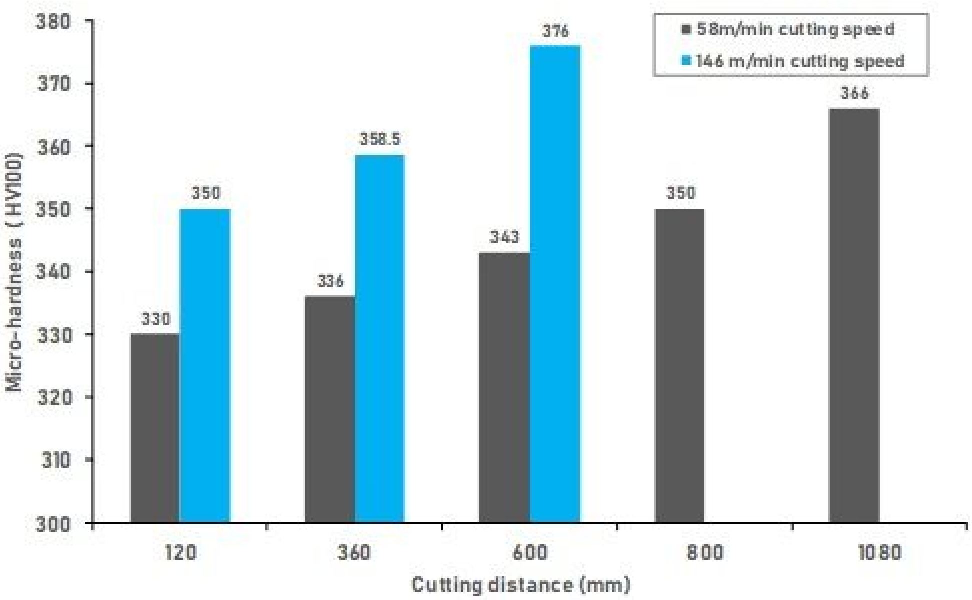

Figure 11

Micro-hardness results versus cutting distance at cutting speeds of 58 and 146 m/min, 0.1 mm/rev, 5% concentration ratio and H13A tool type