Numerical and experimental analysis of surface roughness during the milling operation of titanium alloy Ti6Al4V.

Numerical and Experimental Analysis of Surface Roughness during the Milling Operation of Titanium Alloy Ti6Al4V

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***Abstract*—Titanium alloy (Ti-6Al-4V) has many industrial applications due to its excellent mechanical properties. However, its low thermal conductivity often results in surface and dimensional inaccuracies during machining operations. In this study, an experimental investigation was done to characterise the influence of milling parameters on the surface roughness of Ti-6Al-4V. The numerical experimentation involves the use of the Response Surface Methodology (RSM) with three factors namely: the speed, feed and depth of cut. The physical experiments were carried out using a DMU80monoBLOCK Deckel Maho 5-axis CNC milling machine and a carbide-cutting insert (RCKT1204MO-PM S40T). The comparative analysis of the results obtained indicate that the milling parameters and cutting conditions significantly influenced the surface finish of the titanium alloy. The results obtained from the physical experiments indicate an increase in the magnitude of the surface roughness when the cutting parameters exceed their optimal values. The machining parameters which resulted in the least surface roughness (Ra: 0.035 µm, Rz: 1.12 µm and Rq: 0.277 µm) under the air cooling condition were: cutting speed (265 m/min), feed per tooth (0.05 mm) and depth of cut (0.5 mm). Information on the effect of machining parameters on surface roughness will assist manufacturers in selecting the most feasible combination of the process parameters for producing titanium alloy (Ti-6Al-4V) parts with improved surface quality.**

***Index Terms*— process parameters, RSM, titanium alloy, surface roughness**

I. Introduction

The surface finish of a work piece is a measure of its surface quality and dimensional accuracy. The parameters used to machine a work piece may influence its mechanical properties and its ability to meet the required service and functional requirements. Hence, it is important to determine the effect of machining parameters on surface finish to avoid costly and time consuming rework. The topography and the surface layer characteristics of a work piece are some of the factors which influences its surface finish. The topography of a work piece surface examines the surface finish and roughness. The surface layer characteristics determine the properties of the surface layer in respect to the required functional requirements.

Nomenclature

T_d	Tool diameter (mm)
F_l	Flute length (mm)
F_n	Number of flute (mm)
L	Overall length (mm)
f_t	Feed per tooth (mm),
R	Radius of cutter (mm),
β	Helix angle (deg.)
α_1	Axial rake angle (deg.)
α_2	Radial rake angle (deg.)
Ra	Average surface roughness (µm)
Rz	Maximum height of profile (µm)
Rq	RMS of surface profile (µm)
y_i	Ordinate of the profile

There are several factors which affect the surface finish of a material during machining operations. These include: development of residual stresses, recrystallization, machining error, cutting tool geometry, plastic deformation, change in micro structure, finishing operations, lack of process control and uncontrolled cutting parameters amongst others [1-3].

Furthermore, machining at a high temperature can provoke chemical reactions between the cutting tool and the work piece. This results in geometrical inaccuracies, cracks or distortion [4-6]. In addition, the surface finish of a material also depends on the degree of its machinability. This relates to the ease with which a material can be machined to the desired surface finish. Materials which are difficult to machine are often prone to poor surface finish when compared to other materials that are easy to machine. Some researchers have reported on the challenges in the machinability of materials such as titanium alloy to the required finish conditions. Hence, the need for tolerancing in order to determine the limits at which the surface conditions of a work piece will no longer be acceptable for the required service conditions. An improved surface

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finish can be obtained by controlling the temperature and residual stresses that promote distortion optimization of the process parameters during the cutting operations, selecting the cutting tool with the appropriate orientation and using effective coolants [7-10]. There is also a need for real time diagnosis and process monitoring of the cutting operations for effective process control in order to provide real time tracking and adjustment. This helps to minimize errors and optimize the cutting performance [11-12]. In order to proffer solutions to the surface roughness as a challenge during the machining of titanium alloy, many works have been reported on the use of Design of Experiment (DoE), analytical and numerical techniques involving modelling and simulation [13-15]. For instance, Tlhabadira *et al.* [16] reported on the computer aided modelling and experimental validation of titanium alloy (Ti6AlV) during a milling operation. The study shows that computer aided approach validated via physical experimentations can be employed for investigating the process conditions for effective milling operation of titanium alloy. Mia *et al.* [17] studied the surface roughness and cutting forces using different techniques such as the Artificial Neural Network (ANN), Response Surface Methodology (RSM), and Analysis of Variance (ANOVA) in turning of Ti-6Al-4V under cryogenic jet applied flank and rake faces of the cutting tool. The study established a link between the magnitude of the cutting forces and the resulting surface roughness in the work piece. Furthermore, Ribeiro Filho [18] investigated the influence of cutting parameters on the surface quality and corrosion behaviour of Ti6Al4V in synthetic body environment (SBF) using Response Surface Method. This study revealed that the cutting parameters can significantly influence the surface finish and corrosion behaviour of titanium alloy. Similar findings on the effect of cutting parameters on surface integrity in milling Ti6Al4V were reported by Oosthuizen, *et al.* [19]. In addition, Kilickap *et al.* [20] performed mathematical modelling and optimization of cutting force, tool wear and surface roughness by using the Artificial Neural Network and the Response Surface Methodology in milling of Ti6242S while Revankar *et al.* [21] analysed surface roughness and hardness in titanium alloy machining with polycrystalline diamond tool under different lubricating modes. The findings from these studies show that the cutting parameters and cutting conditions have a significant effect on the machinability of titanium alloy to the desired quality.

In an effort to enhance sustainability and machininability of titanium alloy, numerical methods for predicting temperature and surface hardness were reported [22]. This include developing a model for the optimizing energy consumption during the milling operation of titanium alloy (Ti6Al4V) [23]. Existing work has demonstrated the use of modelling and simulation tools such as Abaqus which were validated using physical experimentations to establish the optimum range of process parameter during the the milling operation of titanium alloy [24]. The modelling and optimization of the cutting parameters for the milling operation of titanium alloy has also been reported [25].

The machining parameters required for meeting the service and functional requirements of the titanium alloy (Ti6AlV) are still under investigation and have not been fully highlighted in literature. This paper aims to fill this gap by investigating the surface roughness during the milling operation of titanium alloy using the Response Surface Methodology (RSM). The succeeding sections present the materials and employed, results and discussion as well as conclusion and recommendations.

II. Materials and Method

The physical experiments were investigated using a DMU80monoBLOCK Deckel Maho 5-axis CNC milling machine and a mill cutter (SF550: HRC 40-HRC 50). A solid rectangular work piece of the titanium alloy (Ti6Al4V) was screwed to the stationary dynamometer (KISTLER 9257A 8-Channel Summation of Type 5001A Multichannel Amplifier) and mounted directly to the machine table. The Response Surface Methodology (RSM) was employed for the design of the numerical experiment with the range of the process parameters as follows: cutting speed (250-270 m/min), feed per tooth (0.05-0.30 mm) and axial depth of cut (0.50-3.0 mm). The choice of RSM was due to its ability to feasibly combine process parameters within the optimum range. The range of process parameters was determined based on previous studies [26-29]. These process parameters are varied over different levels while the surface roughness serves as the response of the designed experiment. The RSM produced 20 feasible combinations of the process parameters whose responses in terms of surface roughness (average surface roughness, Ra; average value of the maximum height of the profile, Rz; and average Root Mean Square (RMS) of surface profile Rq).

The numerical approach employed for this study is the Response Surface Methodology (RSM) and Central Composite Design (CCD). RSM and CCD have proven to be a suitable technique for the determination of most feasible combinations of process parameters and their cross effects on the response of the designed experiment [27].

Thus, the RSM with the Central Composite Design (CCD) were used to determine the feasible combination of process parameters for the milling operation. The general second-order polynomial RSM (full quadratic model) used for the experimental design is expressed as shown in (1) [30].

$$R_u = \beta_0 + \sum_{i=1}^{n} \beta_i X_{iu} + \sum_{i=1}^{n} \beta_{ii} X_{iu}^2 + \sum_{i<j}^{n} \beta_{ij} X_{iu} X_{ju} + \varepsilon_u, \quad (1)$$

Where: *Ru* is the corresponding response and β_0, β_1, β_{ii} and β_{ij} represent the regression coefficients. The terms X_{iu} and X_{ju} are coded values of the ith and jth input parameters *(i<j)*, while ε_u is the residual error.

The Design Expert software (version 11) was used for designing the RSM with CCD experiment. The summary of the experimentation design involving the three process parameters namely: cutting speed, feed per tooth and depth of cut is presented in Table I.

TABLE I. SUMMARY OF THE NUMERICAL EXPERIMENTATION

Notation	Independent Variables	Levels		
		-1	0	1
A	Cutting speed (m/min)	250	260	270
B	Feed per tooth (mm)	0.50	0.40	0.30
C	Depth of cut (mm)	0.50	1.75	3.00

The machining data were collected with the aid of the stationary dynamometer (KISTLER 9257A 8-Channel Summation of Type 5001A Multichannel Amplifier) and the Data Acquisition System (DAQ) connected to the computer. The temperature during the cutting operation was measured with the aid of a professional infrared video thermometer with LCD display and camera function (MT 696) with infrared temperature range of -50-1000℃. The experimental set up is shown in Fig. 1.

During the cutting operation, cooling, was achieved with the aid of compressed air, which was supplied through the pipes and discharged from a nozzle to the interface of the cutting tool and work piece interface. The essence is to reduce the cutting temperature at the cutting tool and workpiece interface. This enables a comparative analysis between the magnitude of the surface roughness under the cooling and no cooling conditions.

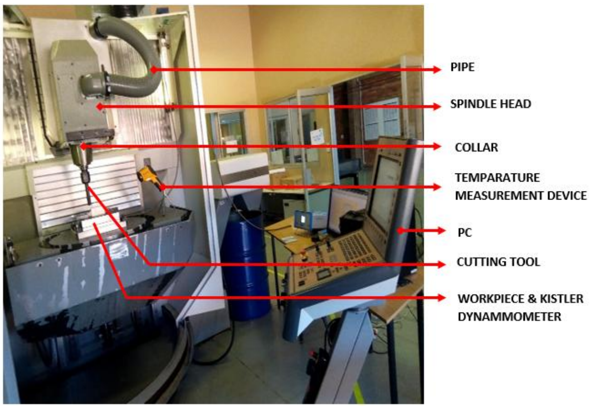

Figure 1. The physical experimental set up [22].

A 3 flute 12 mm diameter mill cutter (Fig. 2) was employed during the milling operation and the specifications is shown in Table II.

Figure 2. The mill cutter.

TABLE II. THE CUTTING TOOL SPECIFICATIONS

Symbol	Parameter	Value
T_d	Tool diameter (mm)	12
F_l	Flute length (mm)	45
F_n	Number of flute	3
L	Overall length (mm)	100
β	Helix angle (deg.)	15
α_1	Axial rake angle (deg.)	15
α_2	Radial rake angle (deg.)	15

Equation 2 represents the average roughness (Ra) from measured profiles while (3-5) are formulas expressing the approximations of maximum height of profile (Rz) in milling operations.

Hence, the average surface roughness (Ra) and the peak to valley (Rz) for peripheral is expressed by (2-3) respectively.

$$R_a = \frac{1}{N}\sum_{i=0}^{N} y_1 \quad (2)$$

$$R_z = \frac{f_t^2}{8(\pm\frac{f_t \times N_t}{\pi})} \quad (3)$$

From Equation 3, conventionally the up milling takes the positive sign while the negative sign is used for the down milling.

For a circular path, (4) hold thus;

$$R_z = \frac{f_t\,(cos\beta)^2}{8(R)} \quad (4)$$

For face milling operation, (5) is expressed as follows;

$$R_z = \frac{f_t}{tan\theta_c - cot\alpha} \quad (5)$$

Where: y_i is the ordinate of the profile, f_t is the feed per tooth (mm), N_t is the number of teeth, R is the radius of cutter (mm), θ_c is the corner angle (deg.), β is the helix angle (deg.) and α is the rake angle (deg.).

The Root Mean Square (RMS) which measures the deviation of the profile due to irregularities (Rq) is expressed as shown in (6).

$$R_q = \sqrt{\frac{1}{L}\int_0^l y^2 dx} \quad (6)$$

Where: L is the length of the surface measured (mm), y is the profile curve or irregularities while dx is the distance along L (mm).

The chemical composition, mechanical and thermal properties of the titanium alloy (Ti-6Al-4V) are presented in Tables III and IV respectively.

TABLE III. CHEMICAL COMPOSITION OF TITANIUM ALLOY (TI-6AL-4V) [31]

Element	Percent weight (wt. %)
Al	6
Fe	0.25
O	0.2
Ti	90
V	4

TABLE IV. MECHANICAL AND THERMAL PROPERTIES OF TITANIUM ALLOY (TI-6AL-4V) [31]

S/N	Properties	Value
	Mechanical	
1.	Density (kg/m^3)	45000
2.	Brinell's hardness (BH)	334
3.	Yield strength (MPa)	880
4.	Ultimate tensile strength (MPa)	950
5.	Bulk modulus (GPa)	150
6.	Modulus of elasticity (GPa)	113.8
7.	Poison's ratio	0.342
8.	Shear modulus (GPa)	44
9.	Shear strength (MPa)	550
	Thermal	
1.	Specific heat capacity (J/g℃)	0.5263
2.	Thermal conductivity (W/m.K)	6.7
3.	Melting point (℃)	1660
4.	Coefficient of thermal expansion (K^{-1})	8.70

Fig. 3 and 4 show the machined work piece and the Mitutoyo SJ – 201 surface roughness tester used for measuring the surface roughness. Three different types of surface roughness were determined namely: the average roughness (Ra), the maximum height of the profile (Rz) and the RMS of the surface roughness profile (Rq). The average roughness (Ra) is the roughness parameters which measures the deviation of a surface from its ideal form while the maximum height of the profile (Rz) is a measure of the maximum height of the profile. This is the difference between the largest five peaks and valleys within the sampling length. The surface roughness profile error (Rq) is a function of the Root Mean Square (RMS) of the profile irregularities. The measurements were replicated three times for each category of the surface roughness. The average value are computed as the magnitude of the average roughness presented in Table IV.

Figure 3. The machined titanium alloy work pieces.

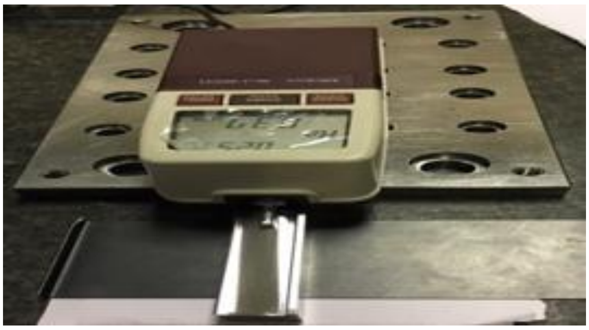

Figure 4. The Mitutoyo SJ – 201, surface roughness tester.

III. RESULTS AND DISCUSSION

The results obtained for the combination of the machining parameters and measured average roughness from the work piece after the cutting operation with and without intermittent cooling are presented in Tables 5 and 6. The machining operations were carried out with and without intermittent cooling in order to determine the effect of cooling on the surface roughness of the work piece.

Tables V and VI shows that the magnitude of the average roughness under air cooling and no cooling conditions. An increase in the magnitude of the cutting parameters (speed of cut, feed rate and depth of cut) beyond their optimum values resulted in increased surface roughness. The depth of cut is the perpendicular distance between the cut and uncut surfaces of the work piece, which is a measure of the thickness of the material removed during the machining operation. The higher the depth of cut beyond the optimum value, the lower the degree of the surface finish and vice versa. This is because the shear angle (angle of deformation) and the heat affected zone is a function of the depth of cut. Thus, an increase in the depth of cut beyond the optimum value (0.5 mm) increases the heat affected zone and the shear angle thereby producing a corresponding increase in the magnitude of the cutting force.

TABLE V. THE CUTTING PARAMETERS AND THE SURFACE ROUGHNESS (AIR COOLING)

Run	Cutting speed (m/min)	Feed per tooth (mm)	Depth of cut (mm)	Average surface roughness Ra (μm)	Average value of the maximum height of the profile Rz (μm)	Average RMS of surface profile Rq (μm)
1	260	0.30	1.80	0.400	2.02	0.523
2	270	0.05	1.25	0.380	2.16	0.480
3	260	0.15	1.50	0.466	2.26	0.590
4	260	0.20	0.50	0.402	2.36	0.571
5	275	0.20	2.00	0.400	2.22	0.546
6	260	0.25	1.50	0.398	2.57	0.587
7	250	0.07	2.50	0.393	2.55	0.493
8	260	0.09	1.60	0.458	2.31	0.585
9	265	0.10	1.50	0.436	2.61	0.539
10	270	0.20	1.55	0.052	2.67	0.365
11	275	0.07	0.55	0.060	2.17	0.406
12	250	0.09	0.10	0.043	2.19	0.433
13	260	0.20	0.65	0.040	2.12	0.453
14	265	0.30	2.50	0.039	1.78	0.367
15	270	0.05	2.40	0.046	1.45	0.366
16	275	0.15	2.60	0.038	1.24	0.383
17	265	0.20	2.4	0.035	1.12	0.277
18	260	0.25	1.80	0.060	1.833	0.486
19	270	0.08	1.75	0.046	1.75	0.457
20	250	0.06	3.00	0.050	2.173	0.433

TABLE VI. THE CUTTING PARAMETERS AND THE SURFACE ROUGHNESS (NO COOLING)

Run	Cutting speed (m/min)	Feed per tooth (mm)	Depth of cut (mm)	Average surface roughness Ra (μm)	Average value of the maximum height of the profile Rz (μm)	Average surface profile Rq (μm)
1	260	0.30	1.80	0.578	2.896	0.602
2	270	0.05	1.25	0.429	2.683	0.576
3	260	0.15	1.50	0.685	2.750	0.640
4	260	0.20	0.50	0.416	2.780	0.566
5	275	0.20	2.00	0.687	2.670	0.654
6	260	0.25	1.50	0.433	2.206	0.520
7	250	0.07	2.50	0.588	2.476	0.587
8	260	0.09	1.60	0.326	2.056	0.516
9	265	0.10	1.50	0.782	2.894	0.673
10	270	0.20	1.55	0.468	1.800	0.690
11	275	0.07	0.55	0.689	2.764	0.763
12	250	0.09	0.10	0.056	1.700	0.313
13	260	0.20	0.65	0.064	2.468	0.458
14	265	0.30	2.50	0.053	2.230	0.496
15	270	0.05	2.40	0.068	2.576	0.557
16	275	0.15	2.60	0.065	1.653	0.356
17	265	0.20	2.4	0.056	1.926	0.446
18	260	0.25	1.80	0.080	2.785	0.651
19	270	0.08	1.75	0.070	2.087	0.346
20	250	0.06	3.00	0.084	2.564	0.447

Cutting force increases with an increase in the residual stress and cutting temperature. This tends to promote frictional activities and temperature increase as well as material's deposition on the rake face of the tool. This causes the development of built up edges with an increase in the surface roughness of the material [32].

Fig. 5 shows the effect of cooling and cutting speed on the average surface roughness during the cooling and non-cooling cycles. The results obtained indicated that the average surface roughness reduces with intermittent air-cooling. However, intermittent cooling causes an increase in the machining cycle time when compared to the non-cooling cycles. The cutting speed measures the speed at which the tool approaches the work piece for material removal. From Fig. 5, an increase in the magnitude of cutting speed beyond the optimum results in an increased surface roughness for the cooling and non-cooling cycles. This is because an increase in the cutting speed increases the energy requirements of the process. Thus, bringing about heat generation at the work piece-tool interface. The generation of heat at the work piece-tool interface without cooling is detrimental to the cutting tool life and the surface finish of the work piece. It also makes the overall cutting process less sustainable in terms of energy consumption and environmental impact. Without cooling, residual stresses tends to build up within the work piece material, thus, resulting in an uneven surface.

Fig. 6 also shows the effect of cooling and cutting speed on the maximum height of the profile. The largest peaks for the heights and valley for 20 samples were measured during their cooling and non-cooling cycles. The results obtained indicate appreciable reduction in the magnitude of the surface roughness during the cooling cycle as compared with the non-cooling cycles. In addition, an increase in the magnitude of the cutting speed beyond the optimum value brings about an increase in the magnitude of the surface roughness.

Fig. 7 shows the Root Mean Square Error of the work piece profile with respect to the cutting speed. The deviation from the desired surface profile increases with an increase in the magnitude of the cutting feed during the cooling and non-cooling cycles. The deviation signals an increase in the magnitude of irregular surface profile which is more pronounced during the non-cooling cycles due to the build-up of residual stresses as a result of increase in temperature.

Fig. 8 shows the effect of feed rate on the average surface roughness during the cooling and non-cooling cycles. The feed rate measures the distance moved by the cutting tool in one revolution. When the feed rate increases beyond the optimum value (0.05 mm), the surface roughness increases and vice versa. This may be due to increasing temperature across the tool-chip interface which promotes the development of built up edges and chip fracture. Some feed marks were observed in the work piece, which indicates the presence of surface profiles which are not properly machined thereby increasing the surface roughness. The introduction of intermittent air cooling produced significant reduction in the magnitude of the surface roughness for the cooling cycles.

Fig. 9 shows the effect of cooling and feed rate on the maximum height of profile. The height of work piece profile irregularities increases with an increase in the magnitude of the feed rate beyond the optimum value. The irregularities were more pronounced during the cooling cycles when compared to the cooling cycles.

Fig. 10 shows the effect of cooling and feed rate on the Root Mean Square (RMS) of the surface profile. With an increasing magnitude of the feed rate beyond the optimum without cooling, the RMS was pronounced which contributes to the increasing value of the surface roughness.

Fig. 11 and 12 show the surface roughness (average surface roughness, Ra; average value of the maximum height of the profile, Rz; and average surface profile Rq) under the air cooling and no cooling condition. For the cutting operation under both the air cooling and no cooling conditions, the results indicate that the magnitude of surface roughness decreases from the maximum height of the profile (Rz) to the average RMS of surface profile (Rq). The average surface roughness (Ra) has the least magnitude of roughness (Ra: 0.035 μm) for the cooling condition. The results also show that the magnitude of surface roughness was higher under the no cooling condition when compared to the air cooling condition for all the three types of surface roughness measured. This phenomenon can be traced to increased frictional activities especially in the shear zone during the cutting tool and work piece engagement in the absence of cooling. Abele and Frohlich [33] cite high thermal stress of titanium alloy due to its low thermal conductivity as one of the reasons for its poor surface finish during machining operations. The authors recommend the use of effective cooling strategy to minimise the thermal stress.

Furthermore, the milling operation is characterised by a cyclic nature of cutting force and chip formation mechanism. If the work piece is not adequately clamped the increasing temperature of the cutting tool can cause distortion. Distortion can also take place when the optimum cutting force is exceeded [34]. The cutting-tool and work piece distortion can increase the surface roughness due to vibration and cutting tool or work piece displacement. Ezugwu [35] explains that the low modulus of elasticity of titanium alloy is responsible for the material's deflection under high cutting force, thus causing springback. The selection of the cutting tool with coatings and right orientation, use of rigid machines with adequate clamping of the work piece, as well as the use of optimum cutting force are some of the ways to minimise vibration and chatter during the machining operation of titanium alloy [33, 35].

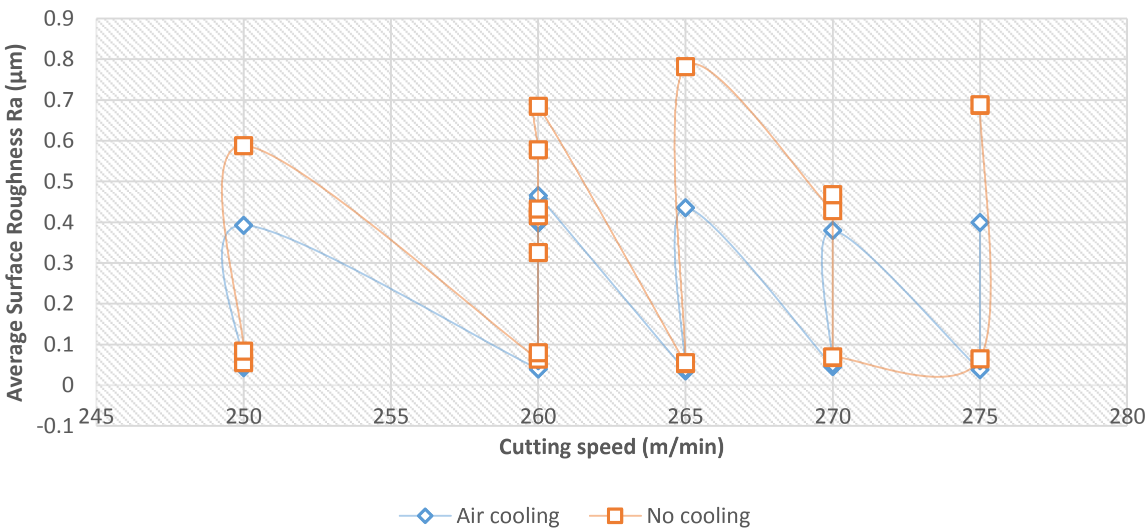

Figure 5. The effect of cooling and cutting speed on the average surface roughness.

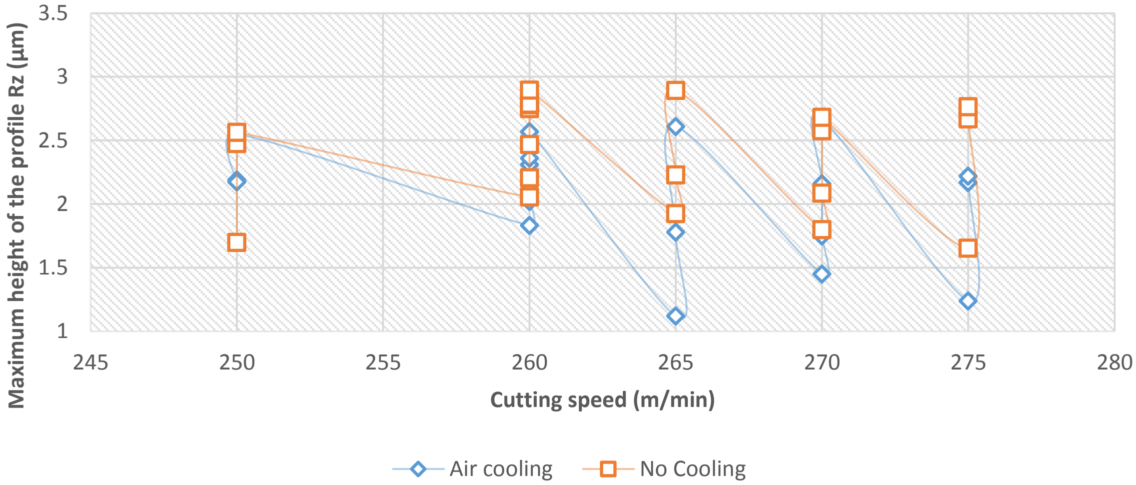

Figure 6. The effect of cooling and cutting speed on the maximum height of the profile.

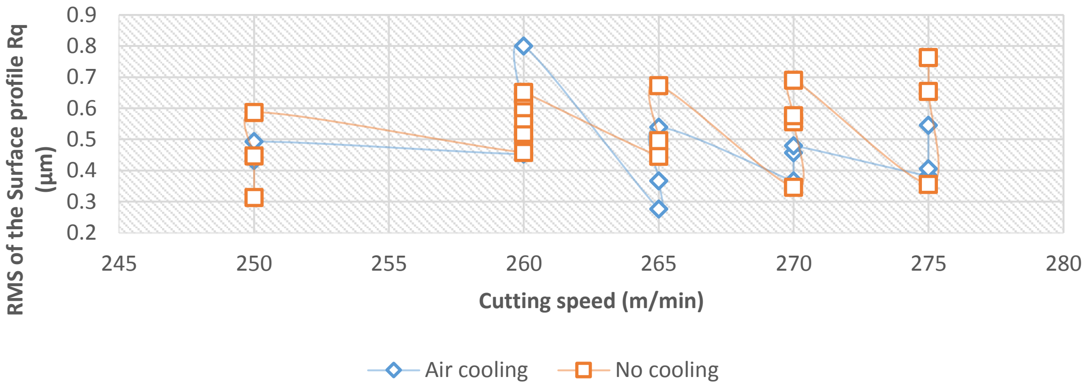

Figure 7. The effect of cooling and cutting speed on the RMS of the surface profile.

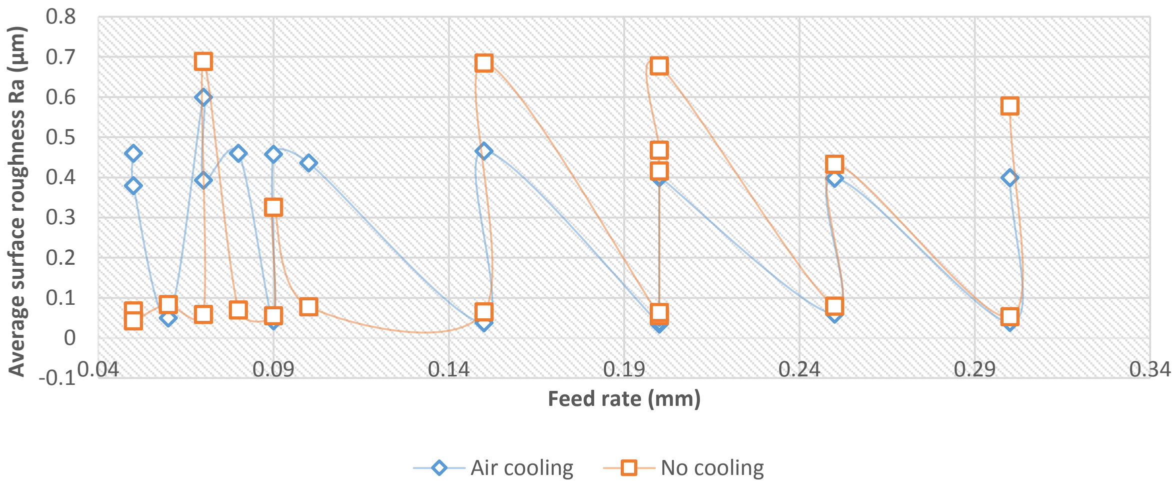

Figure 8. The effect of cooling and feed rate on the average surface roughness.

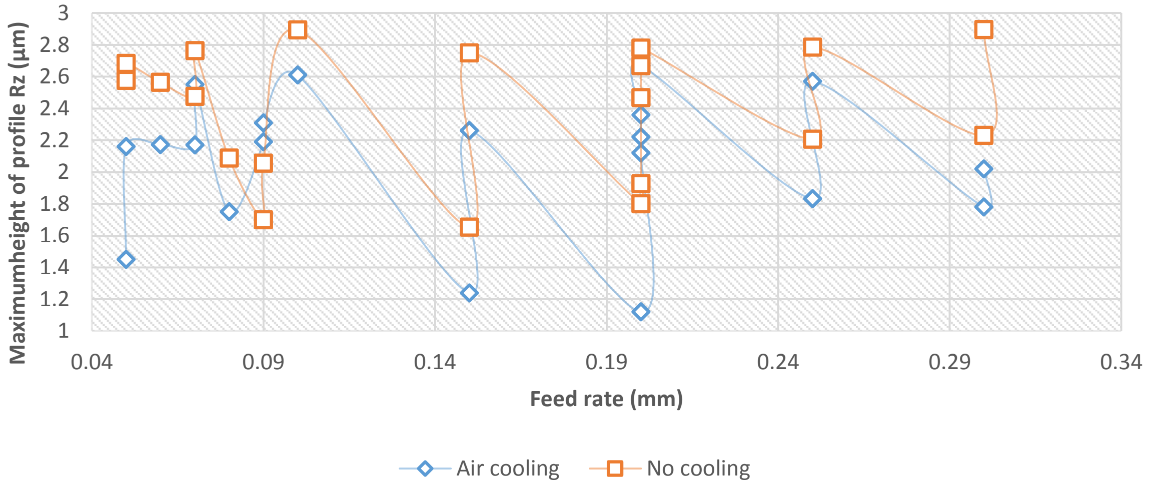

Figure 9. The effect of cooling and feed rate on the maximum height of profile.

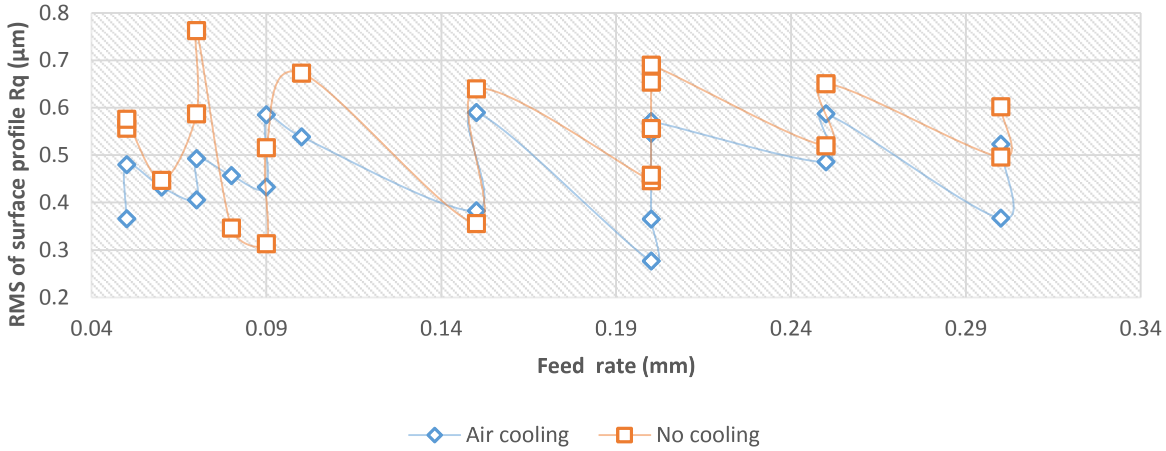

Figure 10. The effect of cooling and feed rate on the RMS of the surface profile.

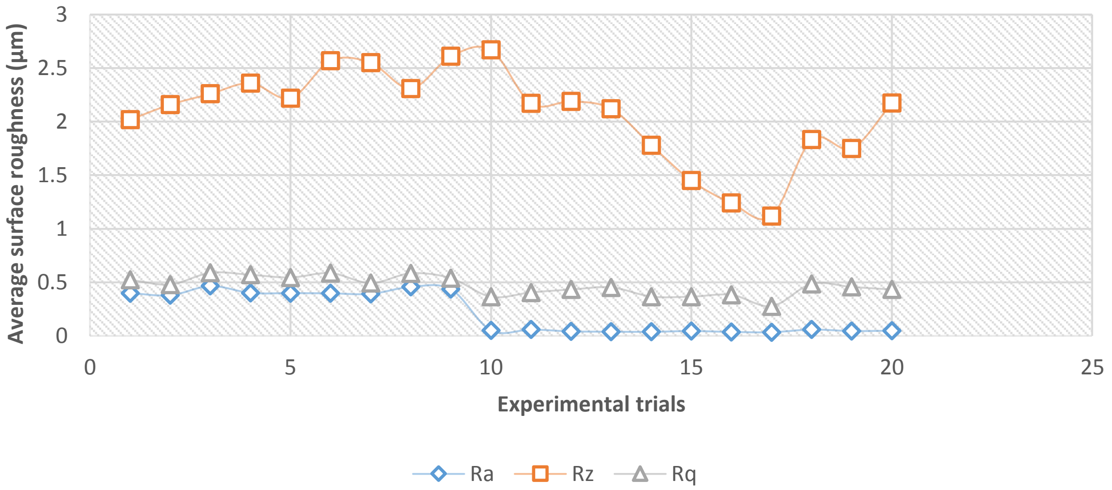

Figure 11. The average surface roughness (Air cooling).

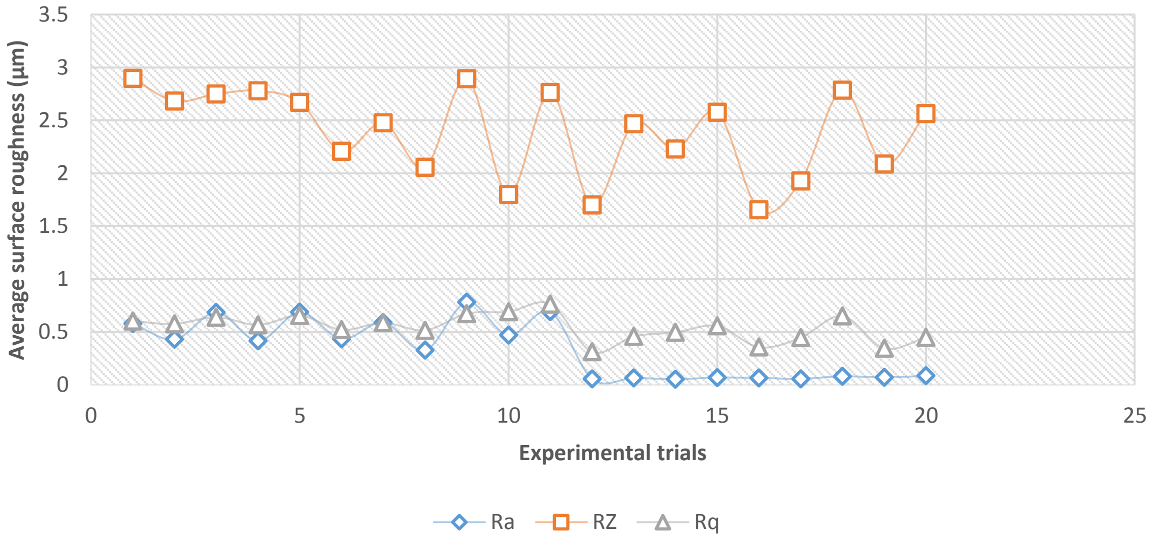

Figure 12. The average surface roughness (No cooling).

IV. Conclusion

This study determines the effect of cooling conditions and milling parameters (cutting speed, feed rate and depth of cut on the surface roughness) on the surface roughness during the milling operation of Ti-6Al-4V The results obtained indicate that the optimum value of the process parameters which resulted in the least surface roughness (Ra:0.035 µm, Rz:1.12 µm and Rq 0.277 µm) under the air cooling condition were: cutting speed (265 m/min), feed per tooth (0.05 mm) and depth of cut (0.5 mm). An increase in the value of the speed of cutting, feed rate and depth of cut beyond this optimal values result in a corresponding increase in the magnitude of the surface roughness. A combination of an optimal values of the cutting speed and feed rates with low depth of cut produces better surface finish and thus recommended for this nature of machining operation. Furthermore, the results indicate that the magnitude of surface roughness decreases from the maximum height of the profile (Rz) to the average RMS of surface profile (Rq) while the average surface roughness (Ra) has the least magnitude of roughness under the cooling and no cooling conditions. In addition, the introduction of the air cooling condition reduces the magnitude of the surface roughness with reduction in feed marks and profile irregularities which increases the surface roughness. The study provides information on the combination of the most feasible cutting parameters and cutting conditions which promotes the surface quality of the titanium alloy (Ti-6Al-4V). Hence, the work finds application in the manufacturing industries, which employ the titanium alloy for product development. Future studies, can consider the development of mathematical models for the optimisation of the surface roughness of titanium alloy during milling operation. In addition, the effect of tool wear on the findings of this study can be investigated as part of future studies.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

The work is a product of the collective efforts of all the authors.

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