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Research article

Effects of cooling conditions and grinding depth on sustainable surface grinding of Ti-6Al-4V: Taguchi approach

Kipkurui N Ronoh[1,]*, Fredrick M Mwema[1,2], Stephen A Akinlabi[3], Esther T Akinlabi[2], Nancy W Karuri[1] and Harrison T Ngetha[4]

[1] Department of Mechanical Engineering, Dedan Kimathi University of Technology, 657-10100 Nyeri, Kenya
[2] Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa
[3] Department of Mechanical and Industrial Engineering Technology, University of Johannesburg, Johannesburg, South Africa
[4] Department of Electrical and Electronics Engineering, Dedan Kimathi University of Technology, 657-10100 Nyeri, Kenya

* **Correspondence**: Email: kipkurui.ronoh@dkut.ac.ke; Tel: +254728660820.

Abstract: In this research, the effects of coolant types, cooling techniques, and grinding depth on the surface properties of the Ti-6Al-4V after surface grinding with white alumina wheel were investigated. Three coolant types namely sunflower oil, formulated sunflower oil-based emulsions and soluble cutting oil were applied to the grinding zone using two cooling techniques: wet cooling and minimum quantity lubrication. The grinding was undertaken at grinding depths of 0.005, 0.010 and 0.015 mm. An L_9 orthogonal array was used to design the experiments and undertaken the evaluation of the variable interrelationships. Surface hardness and surface morphology of the ground surfaces were determined using Vickers Macro-hardness tester and *Zeiss Axio Zoom V16* optical microscope, respectively.

Results from the signal-to-noise ratio analysis revealed that cooling technique has the most influence while the grinding depth has the least influence on the surface hardness of ground Ti-6Al-4V. The optimal parametric setting which gives the highest surface hardness of Ti-6Al-4V was identified from the main effect plots and were sunflower oil (SO), MQL_2 at a flow rate of 0.65 L/h and a grinding depth of 0.015 mm. Analysis of variance demonstrated that the individual contributions of coolant types, cooling techniques and grinding depths to surface hardness were 24.11%, 52.47% and 14.15%, respectively. The morphological investigations established that better surface finish was achieved through the application of sunflower oil-based emulsions in MQL cooling technique at a grinding depth of 0.005 mm.

Keywords: Ti-6Al-4V; coolant types; MQL; Taguchi; ANOVA; hardness; morphology

1. Introduction

Titanium and its alloy have many applications in biomedical, aerospace and chemical industries because of their excellent attributes. Titanium alloys especially Ti-6Al-4V, which was initially developed for use in aeronautical industries, is used widely for medical applications [1] due to its favourable characteristics such as excellent bio-corrosion resistance, lightweight, low Young's modulus, superior biocompatibility and high fatigue strength properties [2]. Some of the medical components manufactured from Ti-6Al-4V include hip implants, cardiac devices and bone plates, etc [1,2]. Ti-6Al-4V is composed of balanced titanium, 5.6–6.7 wt% of aluminium, 3.6–4.2 wt% of vanadium and interstitial elements such as iron and oxygen. It is categorised as α + β alloy as it has two phases which are α and β phases and some of its microstructures includes equi-axial, Widmanstätten and martensitic.

The hardness characteristic is one of the vital engineering requirements considered when choosing implant materials. Hardness has influence on the successful long-term implantation of the Ti-6Al-4V medical implants in human bodies. It has a relationship with tribological behaviour, yield strength, toughness and modulus of elasticity of the implant material [3]. In the tribological perspective, as the hardness increases, the abrasive wear resistance in the implant materials decreases. It is usually assumed that hardness value of the implant materials is similar to that of a bone when selecting it for biomedical application. As such, hardness test is commonly used on metallic implants to quickly evaluate their surface and mechanical properties.

Medical implants should have quality surfaces for successful implantation [4], and one way to achieve such surface is through grinding under appropriate conditions. Malkin and Guo [5] explained that grinding was a finishing process applied to mechanical components that require excellent surface quality, high tolerance and better surface roughness. The grinding process involves the integration of the ploughing, sliding and cutting action of the abrasive grains on the grinding zone [6]. Grinding modes are classified according to the morphology of ground surface as brittle, semi-brittle, semi-ductile and ductile modes. These modes depend on the lateral cracks which develop on the plane of the ground surface and the extent they penetrate into the surface [7]. Various grinding processes exist, some of which include surface grinding, internal grinding, cylindrical grinding and centreless grinding. Grinding can increase the hardness of the implant due to work hardening on the surface [8].

Cutting fluids are used during grinding for the purposes of cooling of the ground surfaces, lubricating the cutting zone and cleaning of the ground workpieces [9]. There are various types of the cutting fluids and some include straight oil (mineral or vegetable oil), soluble cutting oil, semi-synthetic and synthetic fluids [10]. The cooling techniques for machining processes are divided into conventional cooling technique, i.e., flood cooling technique and non-conventional cooling techniques such as minimum quantity lubrication (MQL), cryogenic, minimum quantity cooling and lubrication (MQCL) and air cooling [11]. These non-conventional methods significantly reduce the amount of the cutting fluids, lower the manufacturing cost and keep the environment clean [12]. The MQL method applies atomised cutting fluid into the grinding zone at a typical pressure in a compressor of 4–6 bar through a nozzle [9,13]. In a typical MQL set-up, the range of the flow rate is 50–600 mL/h as stated by various authors [9,14–15]. This flow rate is much lower than the conventional cooling flow rate of 1.2×10^5 mL/h. Tschätsch and Anette [16] stated that the quantity used in MQL is in a range of 50 mL/h–1~2 L/h. Sustainable grinding by the use of biodegradable coolants delivered through minimum quantity lubrication (MQL) promises a better future in industrial applications [17]. It is an alternative to flood cooling as it improves the performance of ground medical implants through its better lubrication characteristics. Conventional cutting fluids are used during grinding in most industries; however, their use is now being questioned because of the problems they cause to the environment and health of the operators. As a result, it has led to the development of cleaner coolants such as vegetable oils which includes castor oil, sunflower oil, coconut oil, etc [18].

The quality of a ground surface depends on the types of coolant, cooling techniques, depth of grinding, speed, feed rate and among other parameters. Many experimental research works have been designed to investigate the effects of coolant types, cooling techniques and grinding depth on surface hardness during a grinding process. Tao et al. [19] carried out experiments to study the effects of grinding depth, wheel speed, abrasive size, and feed rate on surface quality of ground Ti-6Al-4V using silicon carbide wheel. They found out that the hardness increased as the grinding depth increased; this is because the loads increased and abrasive wear worsened, which led to an increase in grinding forces and eventually led to an increase in surface hardness. Sadeghi et al. [13] studied the grinding of grade 5 titanium alloy using synthetic and vegetable oil applied through minimum quantity lubrication. They noted that grinding using synthetic oils applied through minimum quantity lubrication technique produced better surface quality and lower grinding forces characterized by lower surface roughness, burnt-free surfaces and better surface morphology than the vegetable oils applied through minimum quantity lubrication. Deiab et al. [20] experimented on the sustainable turning of Ti-6Al-4V under six cooling strategies which were dry machining, wet cooling, minimum quantity lubrication (rapeseed oil), minimum quantity cooled lubrication (rapeseed oil), cryogenic cooling (liquid nitrogen) and cooled air lubrication. It was noted that the minimum quantity lubrication (vegetable oil) and minimum quantity cooled lubrication (vegetable oil) methods provide sustainable results in terms of surface roughness, tool wear and cutting energy consumption as compared to other cooling methods. Guo et al. [21] investigated surface grinding of Ti-6Al-4V alloy under three grinding environments (i.e., wet, minimum quantity lubrication and dry condition) using silicon carbide grinding wheel. They found out that grinding under minimum quantity lubrication generated the best surface finish with minimal surface damage as compared with grinding under wet and dry cooling methods due to the efficient cooling caused by good fluid penetration into grinding action zone.

Analyses of published results indicate that most investigators have concentrated on grinding of Ti-6Al-4V using conventional techniques and conventional coolants with a few on the sustainable technologies. Furthermore, there is a little focus on the optimization of grinding parameters during grinding of Ti-6Al-4V. In this study, the effect of different coolant types, cooling methods and grinding depth on the surface hardness and morphology during the dry, flood, and minimum quantity lubrication grinding of Ti-6Al-4V was investigated. Taguchi L_9 Orthogonal Array was used to select the input parameters and to optimize the number of experiments hence reducing the time of production and lowering the machining cost of the Ti-6Al-4V. The goal of this study is to investigate the effects of the coolant types, cooling methods and grinding depth on surface hardness during grinding of Ti-6Al-4V and to identify the optimal grinding conditions for maximizing the surface hardness of the implant. This study is novel because it involves the application of newly formulated sunflower oil-based emulsions, through locally improvised minimum quantity lubrication set up. The findings of this research provide a window for identifying optimal and cost-effective conditions of Ti-6Al-4V grinding. This will benefit local titanium machining industries in developing countries as it will increase their technical know—how as far as machining of titanium alloys using locally available machinery in a conventional way.

2. Experimental work

2.1. Material

In this research, samples of the Ti-6Al-4V alloy with an average bulk hardness of 320.3 HV were used. This alloy has wide applications in biomedical and aerospace fields. The main composition of Ti-6Al-4V alloy is C 0.06–0.08%, V 3.13–4.05%, Al 5.33–6.1%, O 0.2%, Fe 0.4% and remaining is Ti. The samples used in the experiments were sliced through wire cut electrical discharge machining to the measurement of 25 mm × 25 mm × 6 mm. Before grinding, the surfaces were cleaned in water and acetone and air-dried. Some of the mechanical properties of the Ti-6Al-4V are shown in the Table 1.

Table 1. Mechanical properties of Ti-6Al-4V alloy.

Properties	Values
Average Bulk Hardness, HV	320.3
Tensile Strength (MPa)	890
0.2 % offset Yield strength (MPa)	800
Young's Modulus (GPa)	115
Density (g/cm^3)	4.5

2.2. Grinding conditions

The grinding experiments were undertaken using a precision surface grinder (Brierley, Chester, UK) model KGS 150. The machine operates at 1.1 kW power and a rated speed of 2855 rpm. The grinding set-up used in this work is shown in Figure 1. A grinding wheel, white alumina (Al_2O_3) abrasive designated as WA 80 M 5 V with dimensions of 180 mm × 19 mm × 31.75 mm was used to carry out the grinding process. A grinding wheel, white alumina (Al_2O_3) was used in this study because of the higher cost of the super-abrasives compared to the conventional abrasive wheel like alumina wheel [22]. At lower cutting conditions, conventional abrasive wheels are still encouraged because it gives good performance in terms of the surface finish [13,23]. Three types of cutting fluids namely sunflower oil (SO), sunflower oil-based emulsions (SOBE) and soluble cutting oil (SCO) were considered and applied under two minimum quantity lubrication (MQL_1 & MQL_2) and wet cooling techniques. These three cooling methods used, i.e., wet cooling, MQL_1 and MQL_2 had a flow rate of 72 L/h, 0.57 L/h and 0.65 L/h, respectively. The amount used in the MQL set-up in the study was in the upper percentile of the range of the typical MQL flow rate as stated by various authors [14–16] but the two flow rates were far less the conventional quantity used, which was 72 L/h [9,12]. The cutting and traverse speeds were maintained at constant values of 27 m/s and 6.7 m/s respectively in all the experiments. The grinding depths of 0.005, 0.010 and 0.015 mm were used. A down dressing of the wheel was performed after each of the grinding process using a diamond tip dresser.

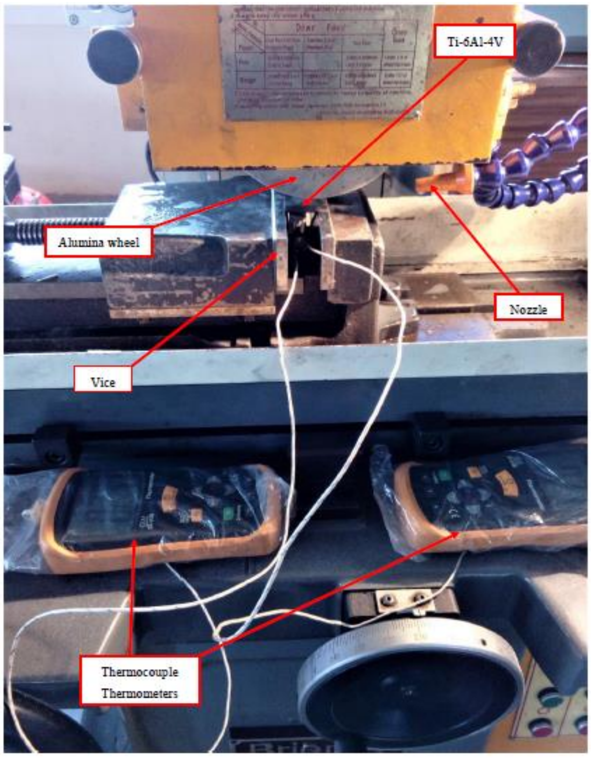

Figure 1. Surface grinding set up with the wet cooling method.

2.3. Design of experiment (DOE)

In the present work, three parameters and three levels were employed as shown in Table 2. Taguchi approach was used as the DOE to minimize the number of trials carried out. An L_9 Orthogonal Array was selected, and the Taguchi L_9 array matrix of controllable variables formed is shown in Table 3. The three levels of each input parameter were selected based on the number of available samples. Surface hardness and morphology measurements were taken on the samples for the evaluation of the output responses of the DOE. The surface hardness measurements were taken using LV800 MacroVickers Hardness Tester supplied by LECO Corporation which accommodates three objective lenses. Figure 2 shows the digital Vickers Hardness tester for the hardness testing experiments. The hardness of the samples ground with the three coolants under three cooling techniques was measured as per ASTM E92. A pyramid diamond indenter was used with a load of 9.8 N and a dwell time of 10 s. Five hardness values were obtained at different points on the ground sample, and their average was calculated for statistical accuracy.

Morphologies of the ground Ti-6Al-4V were captured using an optical microscope, *Zeiss Axio Zoom V16*, in reflection mode at magnifications of 50×. Reflections from ground Ti-6Al-4V surfaces were captured by AxioCam Mrc5 high-resolution CCD camera interfaced with a PC. Zeiss image analyser software installed on the PC was used to characterise the surface morphology of the ground Ti-6Al-4V.

Table 2. Types and levels of the grinding parameters.

Parameters	Types and levels of the grinding parameters		
	1	2	3
Coolants	Sunflower Oil, SO	Sunflower Oil-Based Emulsion, SOBE	Soluble Cutting Oil, SCO
Cooling Techniques	Wet	Minimum Quantity Lubrication, MQL_1	Minimum Quantity Lubrication, MQL_2
Grinding Depth (mm)	0.005	0.010	0.015

Table 3. Taguchi Orthogonal Array (L_9).

Trials	Input Parameters		
	Coolants	Cooling Techniques	Grinding Depth (mm)
1	SO	Wet	0.005
2	SO	MQL_1	0.010
3	SO	MQL_2	0.015
4	SOBE	Wet	0.010
5	SOBE	MQL_1	0.015
6	SOBE	MQL_2	0.005
7	SCO	Wet	0.015
8	SCO	MQL_1	0.005
9	SCO	MQL_2	0.010

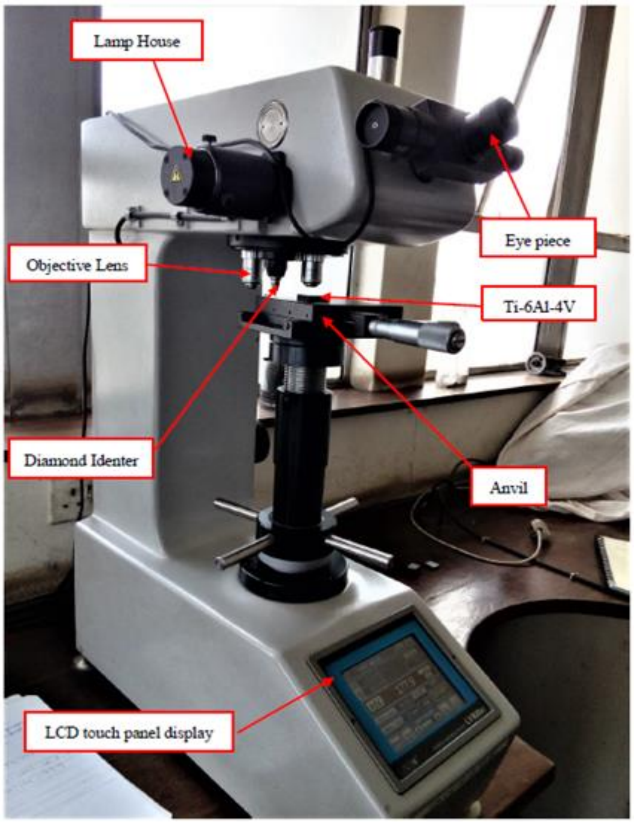

Figure 2. Vickers Macro-hardness set-up.

2.4. Signal-to-noise (S/N) ratio

Taguchi method is used to get a solution by a plan of experiments, and it examines the experimental results using the *S*/*N* ratio statistical technique. S/N ratio is used to reduce the variations in the process and shows the most influential factor affecting the output response. In this method, "signal" denoted by (*S*) shows the desired value (mean) for the output response while "noise" denoted by (*N*) shows the undesired value [24]. There are three types of analysis applicable to *S*/*N* ratios: "smallest is the best", "largest is the best" and "nominal is the best" [25]. In this case, the higher-the-better case was used for surface hardness since the aim was to get the best surface properties after grinding. The combination of optimal parameters is predicted from main effects plot of S/N ratio and is given by the highest value of S/N ratio. The ranking shows the significance level of each parameter [26]. The S/N ratios for the hardness were computed using the following equation:

$$S/N = -10\log\left(\frac{1}{m}\sum_{i-1}^{m} {}^{1}/_{x_i^{2}}\right) \quad (1)$$

where S/N is the value of the signal-to-noise ratio for the "highest is the best" scenario, x_i is the measured quality characteristic of the i^{th} repetition, and m is the repetition trials.

2.5. Analysis of variance, ANOVA

ANOVA is a statistical technique that shows the individual interactions of the controllable input parameters [25]. In this study, it was used to establish statistically significant input parameters and percent contribution of these parameters to the surface hardness. The ANOVA was used to analyse the effects of coolant types, cooling techniques and grinding depth on the surface hardness. ANOVA was performed at the 95% confidence level, i.e., a 5% significance level and hence a *P*-value of less than 0.05 shows that controllable input parameter is statistically significant on the hardness [27] while the *P* value of more than 0.05 shows that controllable input parameter is statistically less significant on the hardness.

3. Experimental results and discussion

3.1. Experimental results

The experimental results obtained were tabulated as shown in Table 4 after surface grinding. The surface hardness was obtained using LV800 Macro Vickers Hardness Tester. Table 4 contains the response output (surface hardness) and the average S/N ratio of each parameter level in the last two columns respectively. When the input factors and their effects on the hardness are considered, the surface grinding of Ti-6Al-4V has been studied using main effect plots with the help of a Taguchi Method and the ANOVA. Due to the heat generation and mechanical effect at the grinding zone, work-hardening and surface-softening can occur simultaneously on the ground surface [28]. The surface hardness of a ground work-piece is an engineering parameter that significantly affects the service reliability of the workpiece.

Table 4. Hardness data from the experiments and S/N ratios values.

Trials	Input Parameters			Output Response	Response Table
	Coolants	Cooling Techniques	Grinding Depth, (mm)	Vickers Macro-Hardness, HV	S/N Ratio for Hardness
1	SO	Wet	0.005	319.60	50.0921
2	SO	MQL_1	0.010	320.78	50.1242
3	SO	MQL_2	0.015	322.66	50.1749
4	SOBE	Wet	0.010	320.22	50.1090
5	SOBE	MQL_1	0.015	321.16	50.1344
6	SOBE	MQL_2	0.005	320.72	50.1225
7	SCO	Wet	0.015	319.06	50.0775
8	SCO	MQL_1	0.005	319.86	50.0992
9	SCO	MQL_2	0.010	320.70	50.1220

3.2. Signal-to-noise ratio analysis of surface hardness

The signal-to-noise (S/N) ratio is a quality feature in the Taguchi technique, and the optimal level of input factors is the largest value obtained from the S/N ratio. The main effects plot for S/N ratio for the hardness of ground Ti-6Al-4V is shown in Figure 3. From Figure 3, it was noted that the cooling technique was the most influential input parameter on the surface hardness among the three input factors, whereas the grinding depth is the least influential input parameter. The optimal parametric setting which gives highest surface hardness of Ti-6Al-4V was identified from the main effect plots and were sunflower oil (SO) as cutting fluid, MQL_2 as cooling technique and grinding depth of 0.015 mm.

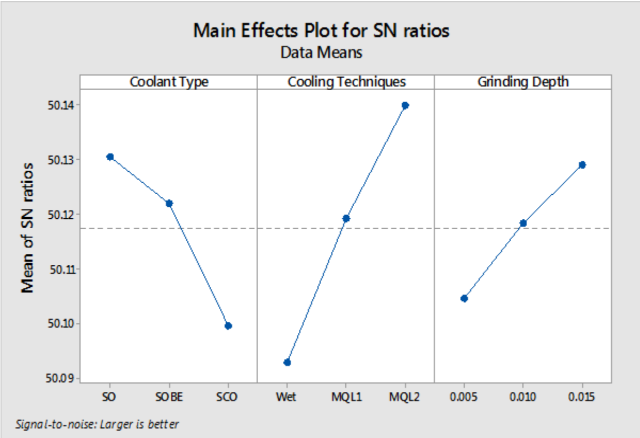

Figure 3. Main effects plot for S/N ratio of the hardness.

The response table for S/N ratios for hardness is shown as Table 5, and the larger is better approach was used. From the analysis of the response table, it can be noted that cooling techniques have the maximum percentage of contribution to hardness, followed by the coolant type and finally the grinding depth as indicated by S/N ratio analyses.

Table 5. Response table for S/N ratios for hardness.

Level	Coolant Type	Cooling Techniques	Grinding Depth
1	50.13	50.09	50.10
2	50.12	50.12	50.12
3	50.10	50.14	50.13
Delta	0.03	0.05	0.02
Rank	2	1	3

3.3. Means for hardness

As a result of the heat generation and mechanical effect at the grinding zone, work-hardening and surface-softening can occur simultaneously on the ground surface [28]. The interaction of the surface grinding conditions influence the hardness of the surface and subsurface layers [29]. Yang et al. [28] explain that the increase of micro-hardness will lead to the improvement of the fatigue life which is a good requirement for implant materials. Main effects plot for the means of hardness were plotted using hardness values. As observed in Figure 4, the hardness of the Ti-6Al-4V increases in a somehow linear manner as grinding depth increases. Change in grinding depth affects the grinding forces that will subsequently affects hardness of ground surface. With increase in grinding depth, many abrasive grits participates in the grinding process. The loads on each abrasive grain increases aggravating abrasive wear, and raising the frictional heat. This change produces a great plastic deformation, which generates a hardened layer leading to an increase in surface hardness subsequently. Work hardening phenomenon on the deformed grains near subsurface of the Ti-6Al-4V increases hardness of the ground samples than that of base material [30]. Generally, the hardening effect on the surface of the ground samples of the Ti-6Al-4V is due to high plastic flow rate at the higher grinding depth combining with the heat generation at the grinding zone [13]. Malkin and Guo [5] explained that, the values of the hardness values also increases as grinding depth increases. This increment was probably related to the generation of a martensitic layer due to much heat generation on the surface of the work-pieces subjected to grinding. These results were the same as the findings reported by Tao et al. [19].

In terms of the cooling techniques, the wet cooling has a negative influence on the hardness as it reduces the hardness of the ground surface. Similar findings were observed by [13,22] who discussed that in wet cooling. The layer thickness with micro-hardness disturbance generated is higher as compared to the MQL cooling technique. In wet cooling, the access of the grinding fluid to the grinding zone is not perfect; hence, there is an increase in heat generation. Increase in heat led to the higher plastic deformation resulting in surface softening and microstructural damage. In wet cooling technique, the pressure of the coolant is not high (approximately 0.1 MPa) to forcefully pushed the coolant to break the gas barrier into the grinding zone for effective cooling, lubrication and cleaning of the abrasive wheels. Ineffective penetration of the coolants results in the observed reduction in hardness of the ground Ti-6Al-4V samples ground using the wet cooling technique as shown in Table 4. When compared with the hardness of the bulk material (320.3 HV) stated in section 2.1, the hardness of the samples ground under wet cooling technique is reduced. This is also observed in Figure 4 where the hardness of the samples is lowest for the wet cooling technique.

In the MQL technique, application of cutting fluids gives superior performance over wet cooling technique. This performance is attributed to the capability of the coolant to reach the cutting zone due to the compressed air which pushes the tiny oil droplets into the grinding zone [22], small size of the particles in mist which improves penetration of the coolants, and large surface to volume ratio for each droplet provides the possibility of rapid vaporization [9]. Effective penetration of the grinding fluids results in the observed increase in the hardness of the ground Ti-6Al-4V samples from the hardness of the bulk material samples as shown in Table 4. This is also observed in Figure 4 where the hardness of the samples is highest for the MQL cooling techniques.

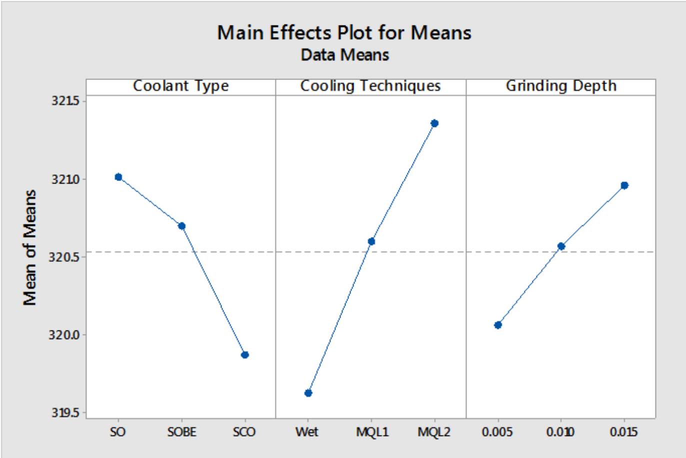

Figure 4. Main effects plot for the means of the hardness.

3.4. Analysis of variance (ANOVA)

The ANOVA was used to illustrate which input parameter significantly influences the surface hardness [31]. The ANOVA results are used to determine if the main input factors and/or interaction factors are statistically significant or not on the output response(s) [25]. ANOVA was applied to the experimental results using Minitab 17 software, and the Table 6 shows the ANOVA results.

Table 6. ANOVA table for surface hardness undertaken at 95% CL.

Source	Degree of Freedom	Seq. SS	Contributions, (%)	Adj. Sum of Squares	Adj. Mean Squares	F-Value	*P*-Value
Coolant Types	2	2.0812	24.11	2.0812	1.0406	2.60	0.278
Cooling Techniques	2	4.5294	52.47	4.5294	2.2647	5.66	0.150
Grinding Depth	2	1.2214	14.15	1.2214	0.6107	1.53	0.396
Error	2	0.8001	9.27	0.8001	0.4000		
Total	8	8.6321	100				

ANOVA was carried out on the hardness of the Ti-6Al-4V, and the test was done at 95% confidence level. This level means 5% is the significant level where the controllable factor is significant on the corresponding response if *P*-value is less than 0.05 and less significant on the corresponding response if *P*-value is more than 0.05. From Table 6, it can be seen that the contributions of coolant types, cooling techniques and grinding depths to surface hardness were 24.11%, 52.47% and 14.15%, respectively. In light of these data, the most important input parameter affecting the surface hardness was the cooling techniques. The error rate was 8.63% for the surface hardness and was considerably low. This error meets the requirement which states that the error level for accurate statistical assessment should be less than 20 percent [25]. It was also observed that despite all the three input factors have less significance on surface hardness; they have an influence on surface hardness in the following order: cooling technique (0.150), coolant types (0.278) and grinding depth (0.396). From these findings, it can be stated that the input parameters have less significant effect on hardness of Ti-6Al-4V at 5 % significance level.

3.5. Surface morphology

Micrographs were recorded using a *Zeiss Axio Zoom V16* optical microscope to characterize the surface morphology after the surface grinding process. The letters on each sample show sample (a) to sample (i) ground under different grinding conditions as indicated in Table 3 in the section 2.3 in the methodology. The ground surface of the Ti-6Al-4V presented various surface features which due grinding under various conditions. Because the regions examined were randomly selected, the morphologies in Figure 5 makes sense statistically in showing the distribution of surface defects. Surface defects types mainly involved grinding marks, ploughing grooves, smeared materials, surface burning and micro-cracks [32]. The optical images of each sample are shown in Figure 5a–i and the letters a to i marked correspond to the trials carried out as per Taguchi Orthogonal Array. In abrasive machining of the materials, the abrasive grains interact with a work piece in three stages of material deformation which are cutting, ploughing and rubbing [13]. The grinding process in all the samples was dominated by the cutting action, and this was due to the active participation of the grains. As shown in Figure 5, grinding marks were a dominant defect on the ground surface and were characterised by a linear arrangement of parallel lines that were produced by abrasive grits.

The second major surface defects on the ground surfaces of the Ti-6Al-4V were ploughing grooves. As shown in Figure 5a,c,e,f, there were shallow ploughing grooves along the grinding direction. These grooves developed as a result of ploughing effects of hard particles on the wheel surface. During grinding, energy used in ploughing deforms the work-piece material without removing it [14]. It is usually characterised by a flow of material sideways from the cutting path into grooves or ridges. Another surface defects observed on the ground surface were micro-cracks. Micro-cracks occurred on the ground surface due to the instantaneous cracking and burning of lubricant oil while grinding [14]. These micro-cracks are what were observed in Figure 5a,d,i. These micro-cracks can also be attributed to the inadequate cooling capacity of the coolants. Cooling of the grinding zone depends on the type of the cooling technique used. In Figure 5a,d, the cooling technique used was wet cooling method and it is known that wet cooling is not an appropriate cooling method when grinding materials. Due to that, micro-cracks occurred in samples ground under wet cooling technique.

Burning of the ground surface of any metallic sample is an indication of the insufficient coolant for effective cooling and lubrication during the process. Grinding heat generated in the grinding process of Ti-6Al-4V played a critical role in the ground surface. High temperature is responsible for the surface burning. Liang et al. [32] discussed that the grinding temperature responsible for the burning effect on the machining of the Ti-6Al-4V is approximately 1100 ℃. In Figure 5g, there were burnt areas on the surface, which is likely due to ineffective cooling by the wet cooling method. Small black spots were also clearly visible in Figure 5b, which is a feature showing smearing/re-deposition of material. The adhered material particles were primarily small-sized debris of microchips which got welded on the ground surface due to high temperature [32]. This can be the result of Ti-6Al-4V’s comparatively high chemical reactivity and ductility [17]. As shown in Figure

5h, there were possible cases of chattering during grinding of sample 8 (Figure 5h) as indicated by the "discontinuities" in the grinding marks. These marks are general indications of the abrasive wheel lifting from material surface and then re-engaging back to the surface of the material during the grinding process.

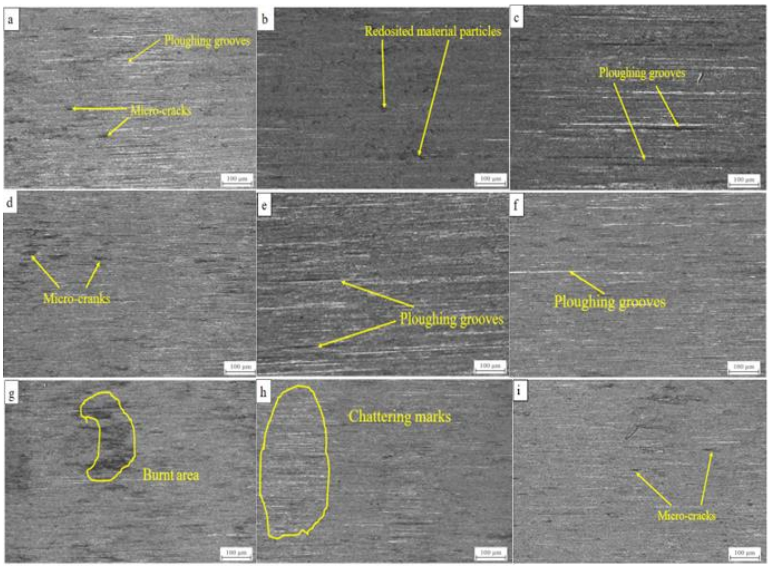

Figure 5. Morphology of the ground samples under magnification of 50×.

4. Conclusion

In this study, Ti-6Al-4V alloy pieces were ground under three input parameters and the individual influence of grinding depths, cooling techniques and coolant types on the surface hardness of Ti-6Al-4V alloy after surface grinding was determined. Taguchi method was used as a design of experiment method where the orthogonal array gave the design matrix. The highest S/N ratio gives the optimal input parameters for grinding Ti-6Al-4V. In that case optimal parametric setting for maximizing the surface hardness of Ti-6Al-4V is sunflower oil (SO) as cutting fluid, MQL_2 as cooling technique and grinding depth of 0.015 mm. Considering the ANOVA, it was noted that the contributions of coolant types, cooling techniques and grinding depths to surface hardness were 24.11%, 52.47% and 14.15%, respectively. In light of these data, the most important input parameter affecting the surface hardness was the cooling techniques.

This study suggested the optimized conditions of surface grinding of the Ti-6Al-4V to get the best morphological surface and hardness value. The findings of this research provide a window for identifying optimal and cost-effective conditions of Ti-6Al-4V grinding that can be used to reduce machining costs of this essential biomedical material. This could be recommended to be used in machining medical implant at titanium implant industry. This study is novel because it investigates the individual influence of grinding parameters on the surface hardness of the Ti-6Al-4V. It is also novel because it involves the application of newly formulated sunflower oil-based emulsions, through locally improvised minimum quantity lubrication set up in grinding of the Ti-6Al-4V.

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Conflict of interests

The authors declare no conflict of interests in this paper.

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