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EXPERIMENTAL INVESTIGATION OF FACE MILLING ALUMINUM ALLOY EN AW – 2011 T6 USING VARIOUS COOLING TECHNIQUES

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Abstract. *The main goal of this paper is to determine the influence of cooling technique on surface roughness during up and down face milling of aluminum alloy EN AW – 2011 T6. Along with dry machining, three cooling techniques were observed: cutting fluid (CF), minimum quantity lubricant (MQL) and cold compressed air (CCA). Thirteen experiments were conducted for each technique. Following the defined plan of the experiment, cutting speed and feed per tooth were varied. An optical profilometer was used to analyze arithmetic deviation of the profile (Ra) and arithmetic mean of the absolute height (Sa). Down milling produced up to 24 % lower Ra and Sa values in comparison to up milling. Increasing feed per tooth greatly increased surface roughness while increasing cutting speed led to a 12 % to 14 % decrease in surface roughness. Using the same cutting parameters, CCA produced the lowest, while CF produced the highest Ra and Sa values. Using the test results and regression analysis, mathematical models were generated allowing for precise Ra and Sa predictions. Optimization of the regression models was carried out with the goal of achieving the lowest surface roughness for each milling strategy and applied cooling technique.*

Key words: *Face milling, Minimum quantity lubricant, Cold compressed air, Dry machining, Surface roughness, Chip morphology*

1. INTRODUCTION

Milling is one of the most used machining processes that can precisely produce complex prismatic shapes. To remain competitive in today's manufacturing industry, it is paramount to reduce production costs. One of the most common cost saving measures involves

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increasing tool life. The easiest way to increase tool life is to reduce tool wear by introducing cooling, lubricating and flushing into the tool workpiece interface. This, most commonly, involves flooding the tool and workpiece with cutting fluids (CF). Although machining using CF provides effective cooling and lubricating, it leads to increased costs associated with cutting fluid filtration, storage, pumping, maintenance and recycling. Cutting fluids come in three major variants: oil, gas and water-based fluids. All three variants contain additives to increase machining performance. These additives are not biodegradable and present an environmental hazard so care must be taken when disposing of such fluids [1]. It has been proven that cooling fluids also present a health hazard to the machine tool operator. Many skin and lung illnesses have been documented over the years as a result of exposure to cutting fluids. Many dermatological illnesses can be traced back to an increased number of bacteria that are found in cutting fluids while inhalation of fluid vapors can lead to conditions such as: asthma, bronchitis and pneumonia [2,3,4].

These issues have led engineers to seek alternative cooling and lubricating techniques. Techniques such as: minimum quantity lubrication (MQL), cold compressed air cooling (CCA) and even dry machining are seen as viable alternatives to cutting fluids. Costs associated with cutting fluids sum up from 7 % to 17 % of the entire machining process expenses. The main appeal of alternative cooling techniques is the fact that they require a small amount or even no cutting fluid. Reducing or eliminating cutting fluids from the process provides a better surface finish, cleaner chips for recycling, lower maintenance costs, a healthier workpiece environment all the while being more environmentally friendly [5,6,7].

Due to low procurement costs, minimal cutting fluid use and favorable cooling and lubricating properties, MQL is seen as a leap in the metal machining industry. It involves spraying a fine mist of cutting fluid over the cutting zone using compressed air or gas. The mist forms a fine oil layer on the workpiece surface that provides lubrication while the cold air both cools and blows the hot chips away from cutting zone [6,8]. Dry machining has shown to produce no residue and a clean chip that can be easily sold or recycled. The process doesn't require any additional equipment, fluids or gasses which increase production cost thus ensuring a more competitive product on the market. On another hand, dry machining does not provide lubrication which leads to increased tool wear at the tool workpiece interface. To decrease tool wear, while still avoiding the use of harmful fluids, research has been put into study of cryogenic cooling techniques. These techniques use a liquefied gas such as N_2 or CO_2 to cool the cutting zone. Khanna et al. [9] compared surface roughness of dry, CF, MQL and cryogenic machined 15-5-PH stainless steel concluding that CF produces the finest surface, followed by cryogenic, MQL, and dry machining. Khanna et al. [10] also experimented on Inconel 718. Their study showed that cryogenic cooling produces a lower surface roughness than MQL, CF and dry machining. Shukla et al. [4] concluded that MQL produced a finer surface roughness of Al 6061 alloy than both CF and dry machining while an increase in feed rate had the most impact on surface roughness. Sreejith et al. [11] noted that an increase in coolant flow rate during MQL cooling produced a finer surface. However, machining using CF still produced a finer surface finish than MQL. They also showed that an increase in cutting speed negatively influenced surface quality. Combining alternative cooling techniques is also possible, as was shown by Yıldırım et al. [12]. By combining MQL and N_2 cryogenic cooling techniques, they achieved a better surface finish than those achievable with either MQL or cryogenic cooling. Race et al. [13] experimented on SA516 steel concluding that dry machining and MQL cooling outperform traditional CF techniques in terms of surface roughness. Milling strategy plays a crucial role in terms of surface roughness. This was proven by Iqbal et al. [14] during testing of Ti-6Al-4V under MQL, cryogenic CO_2 and liquid N_2 concluding that the roughness of an up milled surface is higher than a down milled surface regardless of cooling technique. Similarly, Vakondios et al. [15] experimented on Al 7075 – T6 using different milling strategies while varying cutting parameters. They concluded that milling strategies, as well as cutting parameters, greatly influence surface roughness. They also obtained mathematical models used to accurately predict surface roughness based on cutting parameters. Joshua et al. [16] also developed mathematical models for MQL and dry machining of Al 6061 using regression modeling. By varying cutting parameters and measuring surface roughness, they concluded that MQL produced a 20 % lower surface roughness than dry machining. Pramanik et al. [17] implemented alternative cooling methods for drilling processes by machining Al 6061. Surface roughness, power consumption, burr formation, diameter and circularity errors were observed under MQL, cryogenic LN_2 and air cooling. These experiments lead to conclusions that cooling techniques have a negligible influence on power consumption and product accuracy. However, an increase in both power consumption and surface roughness with increased feed rate was observed. Decreasing cutting speed led to higher surface roughness values. Effects of nano-MoS_2 particles added in MQL during turning of spherical graphite cast iron on machinability was investigated by Sertsoz and Kacal, [18]. Lawal et al. [6] experimented on AISI 9310 steel using a vegetable based MQL turning process. Their study showed that MQL outperformed traditional and alternative cooling techniques by up to 31.6 % in terms of surface finish while reducing cutting fluid related expenses. Jozić et al. [19] used Box-Behneken's experimental design and regression analysis to determine optimal cutting parameters during turning of 34CrNiMo6. Their findings showed that increasing the feed rate leads to a drastic increase in surface roughness while cutting speed has a far lower influence on the final roughness of the surface. Stojanković et al. [20] investigated the influence of cutting parameters on surface roughness of aluminum 6082-T6 alloy during end milling. They concluded that feed rate was the most influential cutting parameter on surface roughness. Increasing the feed rate led to an increase in surface roughness while increasing the cutting speed caused a decrease in surface roughness.

From this brief literature overview, it is evident that there is space for additional research focusing on testing the influence of cooling technique and cutting parameters on surface roughness and chip morphology. Therefore, the goals of this paper are to investigate surface roughness and chip morphology of aluminum alloy EN AW – 2011 T6. This aluminum alloy was selected due to its good machinability. Along with dry machining, testing will be carried out using three cooling techniques: MQL, CF and CCA. Test results will be used to generate regression models needed for accurate roughness predictions. Proving the viability of alternative cooling techniques could greatly reduce health and environmental impacts associated with machining as well as ease recycling of metal chips.

2. Experimental Work

The main idea of this paper is to document the influence of cooling technique on surface roughness and chip morphology on a widely used aluminum EN AW – 2011 T6 alloy. Experimental research workflow and setup, shown in Fig. 1, consisted of up and down face milling, surface scanning and roughness measurement as well as chip morphology analysis. Twenty-six plates, measuring 100 mm x 30 mm x 10 mm, were face milled at varying cutting speed and feed per tooth combinations.

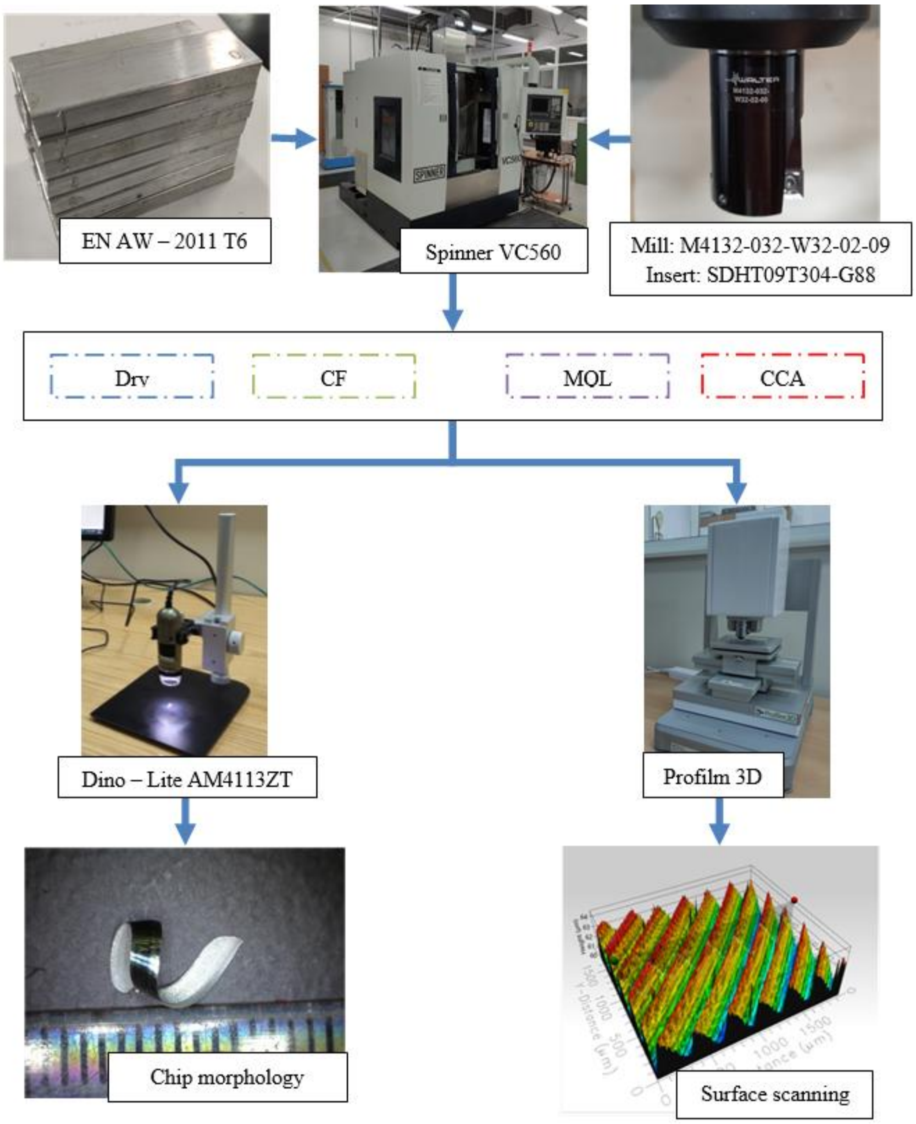


Fig. 1 Experimental setup and workflow

Along with dry machining, three cooling techniques were observed: CF, MQL and CCA. Rhenus TU 30 T coolant was used for CF and MQL experiments. Coolant properties are shown in Table 1.

Table 1 Rhenus TU 30 T technical data [21]

Concentrate		Emulsion	
Viscosity at 20 °C [mm²/s]	Content of mineral oil [%]	pH – value 5 %	Corrosion protection (DIN 51360/2)
Approx. 160	Approx. 18	9.4	4% grade 0

A vortex tube was used for CCA testing providing cooling temperatures as low as -34 °C [8]. Up and down face milling was performed using a two flute M4132-032-W32-02-09 mill manufactured by Walter AG. The end mill was equipped with SDHT09T304-G88 interchangeable carbide inserts. Experiments were carried out on a vertical machining centre, Spinner VC560. Cutting parameters were selected according to tool manufacturer specifications and machine tool limitations. Specified cutting parameters, shown in Table 2, were input into Design Expert software. Using response surface methodology implemented into the software, a central composite plan of thirteen cutting speed and feed per tooth combinations was generated. Axial (a_p) and radial (a_e) depths of cut were kept at a constant 1.5 mm and 32 mm, respectively.

Table 2 Cutting parameters

Minimal feed per tooth, $f_{t,min}$	0.05 mm/tooth
Maximum feed per tooth, $f_{t,max}$	0.25 mm/tooth
Minimum cutting speed, $v_{c,min}$	500 m/min
Maximum cutting speed, $v_{c,max}$	1000 m/min

Surface roughness of up and down milled specimen was measured using a Profilm 3D profilometer. Arithmetic deviation of the profile (*Ra*) and arithmetic mean of the absolute height (*Sa*) parameters were measured five times for each specimen and mean values are given in the results and discussion section of this paper. Arithemetic deviation of the profile (*Ra)* presents the absolute value of profile deviation from the profile center line within the observed length. Arithmetic mean of the absolute height (*Sa)* presents the mean of the average height difference of a measured plane. Measurements were carried out in accordance with the international standard ISO 8688 – 1 using an 800 µm cut off length. Scanning properties were kept constant throughout the testing. A Dino-Lite AM4113ZT digital microscope was used to study chip morphology [22].

3. Results and discussion

3.1 Influence of Cutting Parameters and Cutting Environment on Surface Roughness

3.1.1 Up Milled Surface Finish Analysis

Table 3 shows mean surface roughness values for: dry, CCA, CF and MQL up milled surfaces. Regression models for: dry machining, CCA, CF and MQL milling are given in Table 4 for both *Ra* and *Sa* parameters.

Table 3 Results of up milled surface roughness measurements

Run no.	v_c [m/min]	f_t [mm/tooth]	Dry machining		CCA		CF		MQL	
			Ra [µm]	*Sa* [µm]	*Ra* [µm]	*Sa* [µm]	*Ra* [µm]	*Sa* [µm]	*Ra* [µm]	*Sa* [µm]
1	750	0.009	0.088	0.099	0.057	0.048	0.077	0.076	0.045	0.050
2	500	0.050	0.331	0.336	0.317	0.321	0.321	0.277	0.304	0.309
3	1000	0.050	0.260	0.247	0.227	0.226	0.316	0.325	0.248	0.255
4	396	0.150	0.824	0.870	0.487	0.490	0.836	0.817	0.828	0.858
5	750	0.150	0.738	0.750	0.433	0.452	0.733	0.749	0.707	0.708
6	750	0.150	0.728	0.762	0.518	0.506	0.755	0.711	0.740	0.733
7	1104	0.150	0.810	0.810	0.706	0.768	0.949	0.911	0.832	0.836
8	750	0.150	0.717	0.743	0.427	0.383	0.886	0.922	0.691	0.733
9	750	0.150	0.764	0.819	0.366	0.374	0.839	0.875	0.761	0.803
10	750	0.150	0.781	0.783	0.369	0.355	0.822	0.872	0.721	0.752
11	1000	0.250	1.027	1.107	0.783	0.849	1.298	1.347	1.027	1.155
12	500	0.250	1.021	1.076	1.258	1.417	1.368	1.702	1.129	1.258
13	750	0.291	1.097	1.148	0.786	0.897	1.615	1.879	1.261	1.353

Table 4 Regression models of *Ra* and *Sa* surface parameters for up milled surfaces

Technique	Regression model	R^2	Equation no.
Dry machining	$Ra = 0.34519 - 7.44322*10^{-4} v_c + 5.66744 f_t + 7.66*10^{-7} v_c f_t + 3.9167*10^{-7} v_c^2 - 8.79081 f_t^2$	0.9935	(1)
	$Sa = 0.40838 - 8.28924*10^{-4} v_c + 5.48256 f_t + 1.193*10^{-3} v_c f_t + 3.857*10^{-7} v_c^2 - 8.40837 f_t^2$	0.9930	(2)
CCA	$Ra = 0.91490 - 2.96966*10^{-3} v_c + 5.28624 f_t - 3.845*10^{-3} v_c f_t + 2.34223*10^{-6} v_c^2 - 2.53281 f_t^2$	0.8277	(3)
	$Sa = 1.02164 - 3.38296*10^{-3} v_c + 5.40680 f_t - 4.734*10^{-3} v_c f_t + 2.69594*10^{-6} v_c^2 + 5.97812 f_t^2$	0.8327	(4)
MQL	$Ra = 0.32138 - 8.8903*10^{-4} v_c + 6.04079 f_t - 4.56*10^{-4} v_c f_t + 5.8747*10^{-7} v_c^2 - 5.1506 f_t^2$	0.9886	(5)
	$Sa = 0.3916 - 1.05798*10^{-3} v_c + 5.865 f_t - 4.83*10^{-4} v_c f_t + 6.9078*10^{-7} v_c^2 - 2.95762 f_t^2$	0.9949	(6)
CF	$Ra = 0.2219 - 6.3058*10^{-4} v_c + 5.48137 f_t - 6.52*10^{-4} v_c f_t + 5.1388*10^{-7} v_c^2 + 0.8767 f_t^2$	0.9935	(7)
	$Sa = -0.1782 + 1.04715*10^{-4} v_c + 7.05 f_t - 4.033*10^{-4} v_c f_t + 2.7538*10^{-7} v_c^2 + 7.4011 f_t^2$	0.9930	(8)

Coefficient of determination (R^2) shows how well the model fits measured results. An R^2 value closer to 1 is preferred as it indicates that the model covers a high amount of variability of the response data around its regression line. For example: *Ra* model generated for dry machining has an R^2 value of 0.9935 indicating that 99.35 % of measured data fits the regression model.

Using the test results and regression models, surface plots showing the influence of cutting speed and feed per tooth on up milled surface roughness parameters were generated. A comparison of surface plots using dry machining, CCA, CF and MQL cooling techniques are shown in Figs. 2 and 3, for both *Ra* and *Sa* parameters respectively.

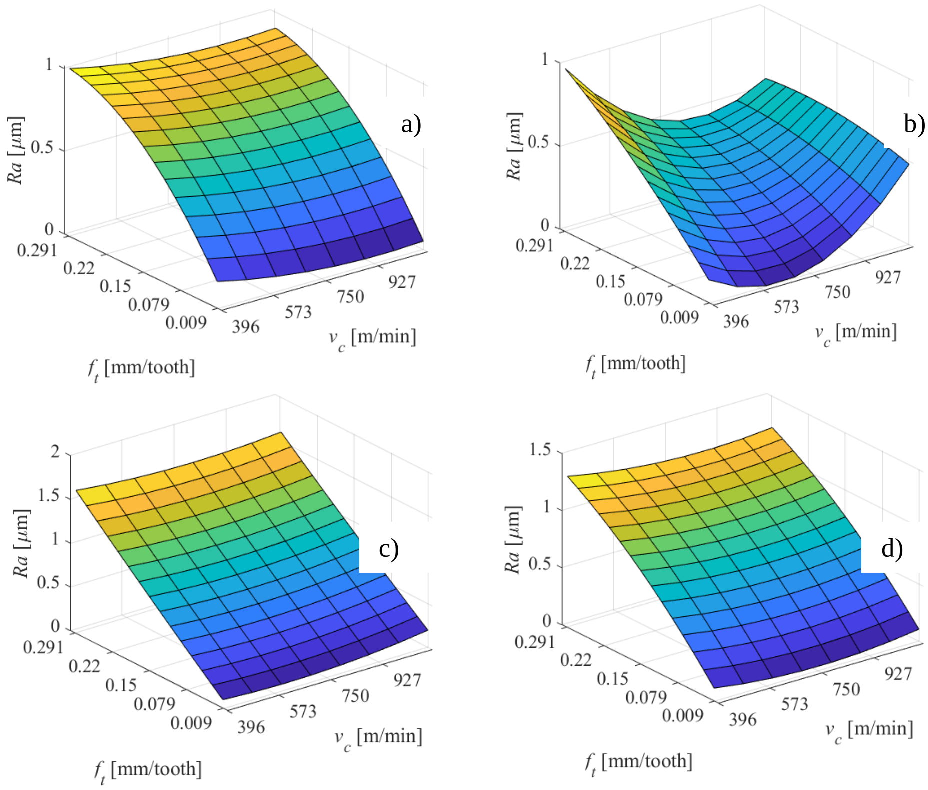


Fig. 2 Influence of feed per tooth and cutting speed on surface roughness *Ra* using dry machining a) and cooling techniques: b) CCA, c) CF, d) MQL

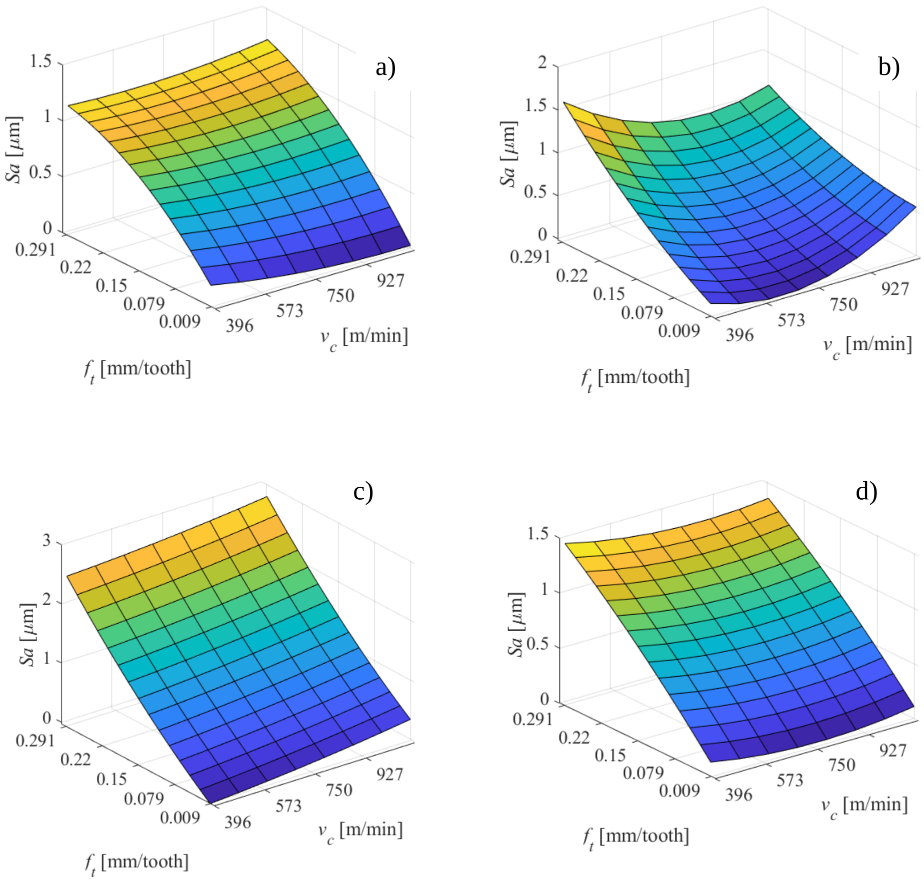


Fig. 3 Influence of feed per tooth and cutting speed on surface roughness *Sa* using dry machining a) and cooling techniques: b) CCA, c) CF, d) MQL

3.1.2 Down Milled Surface Finish Analysis

Table 5 shows mean surface roughness values for: dry, CCA, CF and MQL down milled surface. Regression models for: dry machining, CCA, MQL, and CF tests were generated using the selected central composite plan and test results. Regression models, given in Table 6 for both *Ra* and *Sa* parameters, are used for accurate surface roughness predictions.

Table 5 Results of surface roughness measurements for down milled surface

Run no.	v_c [m/min]	f_t [mm/tooth]	Dry machining		CCA		CF		MQL	
			Ra [µm]	*Sa* [µm]	*Ra* [µm]	*Sa* [µm]	*Ra* [µm]	*Sa* [µm]	*Ra* [µm]	*Sa* [µm]
1	750	0.009	0.083	0.110	0.050	0.059	0.076	0.084	0.050	0.089
2	500	0.050	0.264	0.240	0.228	0.273	0.277	0.251	0.309	0.202
3	1000	0.050	0.251	0.230	0.223	0.212	0.325	0.275	0.255	0.250
4	396	0.150	0.896	0.808	0.447	0.453	0.817	0.877	0.858	0.765
5	750	0.150	0.647	0.754	0.412	0.445	0.749	0.587	0.708	0.580
6	750	0.150	0.713	0.746	0.448	0.466	0.711	0.590	0.733	0.599
7	1104	0.150	0.909	0.759	0.686	0.652	0.911	0.968	0.836	0.806
8	750	0.150	0.838	0.613	0.374	0.356	0.922	0.918	0.733	0.645
9	750	0.150	0.749	0.624	0.366	0.439	0.875	0.749	0.803	0.580
10	750	0.150	0.555	0.596	0.362	0.429	0.872	1.342	0.752	0.515
11	1000	0.250	1.137	1.097	0.644	0.822	1.347	1.342	1.155	0.833
12	500	0.250	1.189	1.010	1.002	1.073	1.702	1.534	1.258	1.012
13	750	0.291	1.310	1.052	0.737	0.827	1.879	1.773	1.353	1.340

Table 6 Regression models of *Ra* and *Sa* surface parameters for down milled surfaces

Technique	Regression model	R^2	Equation no.
Dry machining	$Ra = 0.38891 - 9.02496 * 10^{-4} v_c + 4.94105 f_t + +5.94 * 10^{-4} v_c f_t + 4.976 * 10^{-7} v_c^2 - 6.41 f_t^2$	0.9666	(9)
	$Sa = 0.53975 - 1.31824 * 10^{-3} v_c + 4.55264 f_t + +9.72 * 10^{-4} v_c f_t + 7.84 * 10^{-7} v_c^2 - 5.2315 f_t^2$	0.9656	(10)
CCA	$Ra = 0.934 - 2.74826 * 10^{-3} v_c + 3.96665 f_t - -2.217 * 10^{-3} v_c f_t + 2.0672 * 10^{-6} v_c^2 + 0.7825 f_t^2$	0.8187	(11)
	$Sa = 0.98805 - 2.7625 * 10^{-3} v_c + 3.17097 f_t - -8.84 * 10^{-4} v_c f_t + 1.98566 * 10^{-6} v_c^2 + 1.60787 f_t^2$	0.8548	(12)
MQL	$Ra = 0.47323 - 1.34772 * 10^{-3} v_c + 4.70435 f_t - -1.297 * 10^{-3} v_c f_t + 9.96109 * 10^{-6} v_c^2 + 0.2005 f_t^2$	0.9478	(13)
	$Sa = 0.32467 - 1.06477 * 10^{-3} v_c + 5.00538 f_t - -2.264 * 10^{-3} v_c f_t + 9.121 * 10^{-6} v_c^2 + 2.15344 f_t^2$	0.9329	(14)
CF	$Ra = 0.691 - 1.9257 * 10^{-3} v_c + 5.3568 f_t - -3.86 * 10^{-4} v_c f_t + 1.307 * 10^{-6} v_c^2 - 2.117 f_t^2$	0.9427	(15)
	$Sa = 0.7483 - 2.2195 * 10^{-3} v_c + 4.292 f_t - -2.264 * 10^{-3} v_c f_t + 1.6817 * 10^{-6} v_c^2 + 10.82312 f_t^2$	0.9656	(16)

The generated models have a high R^2 value which means the models can reliably predict surface roughness parameters. For example: the model generated for dry machining has an R^2 value of 0.9666 for *Ra* surface parameter. This means that 96.66 % of measured data fits the generated model.

Using the test results and regression models, surface plots showing the influence of cutting speed and feed per tooth on up milled surface roughness parameters were generated. A comparison of surface plots using dry machining, CCA, CF and MQL cooling techniques are shown in Figs. 4 and 5 for both *Ra* and *Sa* parameters, respectively.

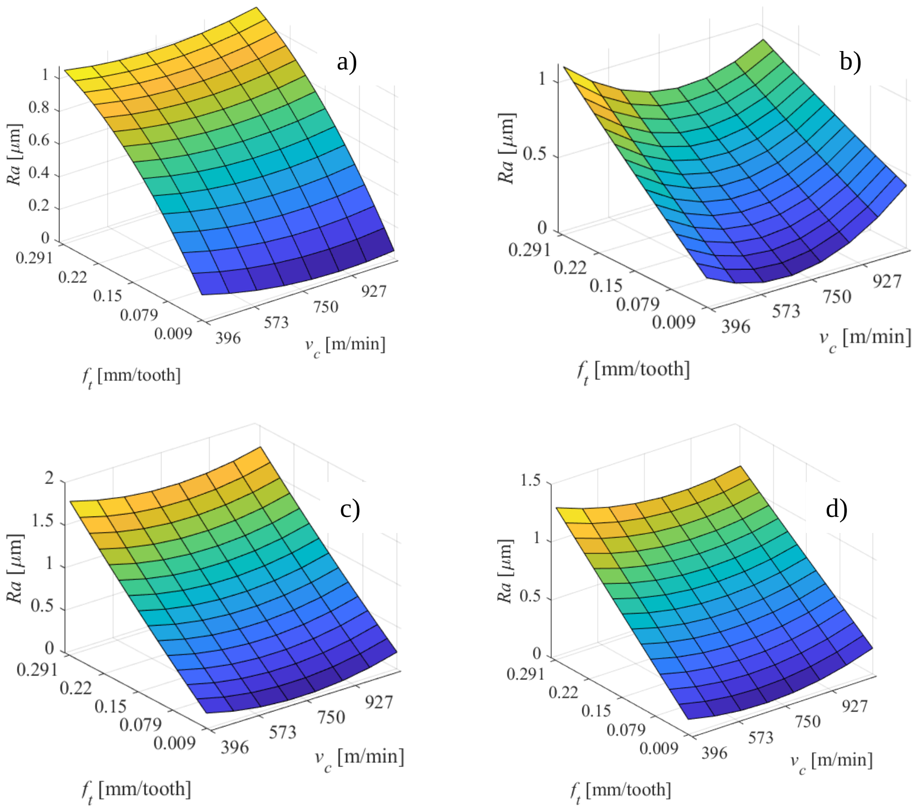


Fig. 4 Influence of feed per tooth and cutting speed on surface roughness *Ra* using dry machining a) and cooling techniques: b) CCA, c) CF, d) MQL

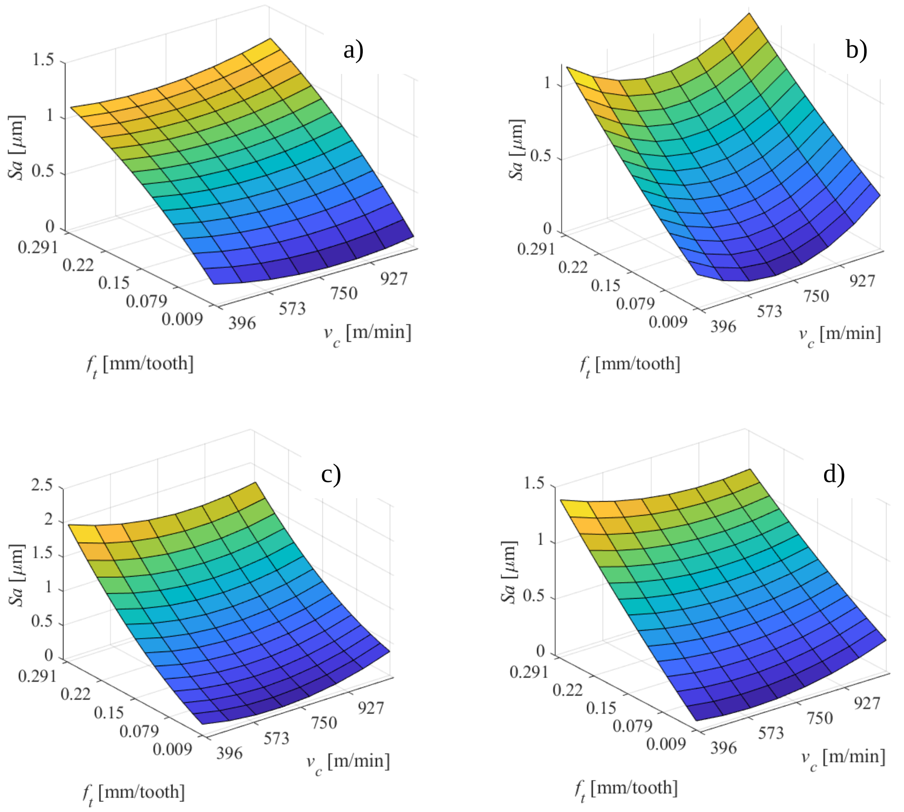


Fig. 5 Influence of feed per tooth and cutting speed on surface roughness Sa using dry machining a) and cooling techniques: b) CCA, c) CF, d) MQL

3.1.3 Discussion

From the test results, it can be concluded that, generally, up milling provides a higher surface roughness than down milling. Observing tests conducted at a cutting speed of 750 m/min and feed per tooth of 0.15 mm/tooth, down milling produced a 24 % lower surface roughness when compared to up milling. Similar findings were reported by Iqbal et al. [14]. During up milling, chip cross section is at its lowest at the initial contact point between the tool and workpiece. Due to the low chip cross section, the tool must be forced into the cut leading to burnishing on the workpiece surface. Burnishing generates additional heat which can cause the chips to weld on the rake face changing the tool geometry and leading to higher surface roughness values. During down milling, chip cross section starts at its maximum and later decreases as the tool leaves contact with the workpiece. High chip cross section at the initial contact point of the tool and workpiece makes cutting easier, reduces burnishing and leads to a lower surface roughness value.

Conducted tests give a good insight on how feed per tooth influences surface roughness. By observing tests with feed per tooth of 0.009 mm/tooth, 0.15 mm/tooth and

0.291 mm/tooth at a constant cutting speed of 750 m/min, an increase in surface roughness was observed with increasing feed per tooth. For example: during dry up milling the surface roughness parameter *Sa* increased from 0.09884 μm at 0.009 mm/tooth to 1.148 μm at 0.291 mm/tooth. Similar behavior was noted for all other cooling techniques. By increasing the feed per tooth, the cusp height increases. Such effect is shown in Fig. 6. The cusp, presented as the hatched surface, increases in both height (*h*) and length (*l*) with increasing feed per tooth which negatively influences surface roughness values. This effect will be more closely examined in section 3.3 using an optical profilometer.

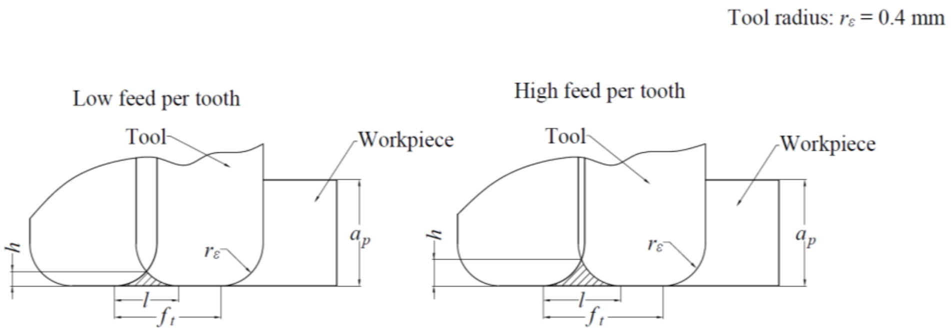


Fig. 6 Influence of feed per tooth on the cusp height

Observing the influence of cutting speed on surface roughness, a 12 % to 14 % decrease in roughness was noted with increasing cutting speed. Similar findings were reported by Rahman et al. [23], Iqbal et al. [14] and others. Low cutting speeds lead to increased plastic deformation of the workpiece which cause higher surface roughness. The fact that higher cutting speeds lead to a decrease in surface roughness can be attributed to increased workpiece deformation rate. High deformation rates don't allow for a high amount of plastic deformation of the chip. Speeds higher than 1000 m/min produced a rougher surface than was expected. These are most likely caused by increased adhesion of material on the cutting surfaces such as noted by Sreejith et al. [11].

By comparing surface roughness values, shown in Tables 3 and 5, it was observed that CCA cooling produced a considerably finer surface finish than other techniques. Minimum quantity lubricant came in second best followed by dry machining and CF. The effectiveness of CCA could be attributed to increased cooling capacity of the technique. High mobility of the chilled compressed air moving in and around the tool workpiece interface provides effective cooling which leads to a better surface finish. Minimum quantity lubricant uses a fine mist of cutting fluid which both cools and lubricates the cutting zone. Superior surface qualities of CCA and MQL could additionally be attributed to an increased air flow over the cut surface which could aid in forming a finer passive aluminum oxide layer on the workpiece surface. Poor surface roughness achieved by dry milling could be attributed to increased heat generated leading to material adhesion on the tool faces.

Analyzing generated models, it was observed that feed per tooth has the most impact on surface roughness parameters regardless of cooling technique or milling strategy.

Cutting speed has a much lower impact on *Ra* and *Sa* surface roughness parameters. Generated models were used to optimize the machining process. Goals of the optimization were to determine optimal cutting parameters while keeping *Ra* and *Sa* values low. Optimal cutting parameters and predicted surface roughness parameters are shown in Table 7.

Table 7 Optimal cutting parameters

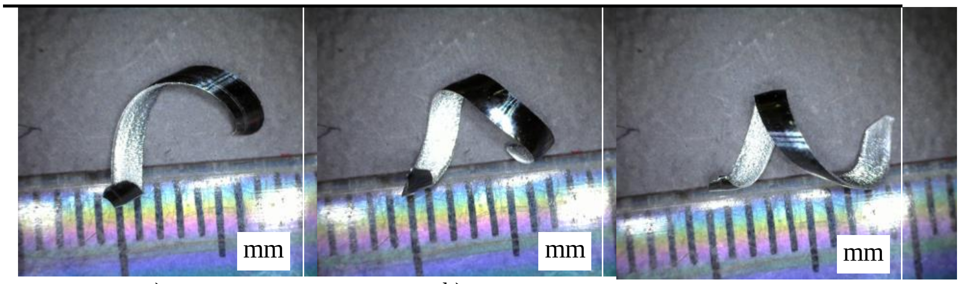
Cutting technique	Milling strategy	Optimal v_c [m/min]	Optimal f_t [mm/tooth]	Predicted *Ra* [µm]	Predicted *Sa* [µm]
Dry machining	Up milling	878	0.05	0.289	0.284
	Down milling			0.237	0.244
CCA	Up milling	687	0.05	0.119	0.093
	Down milling			0.146	0.160
MQL	Up milling	721	0.05	0.259	0.256
	Down milling			0.208	0.205
CF	Up milling	677	0.05	0.285	0.253
	Down milling			0.236	0.185

3.2 Influence of Cutting Parameters and Cutting Environment on Chip Morphology

3.2.1 Influence of Cutting Speed on Chip Morphology

Table 8 shows three different chips produced by dry machining at varied cutting speeds of: 396 m/min, 750 m/min and 1104 m/min and a constant feed rate per tooth of 0.15 mm/tooth.

Table 8 Morphology of dry machined chips with varied cutting speeds at feed per tooth of 0.15 mm/tooth: a) 396 m/min, b) 750 m/min and c) 1104 m/min

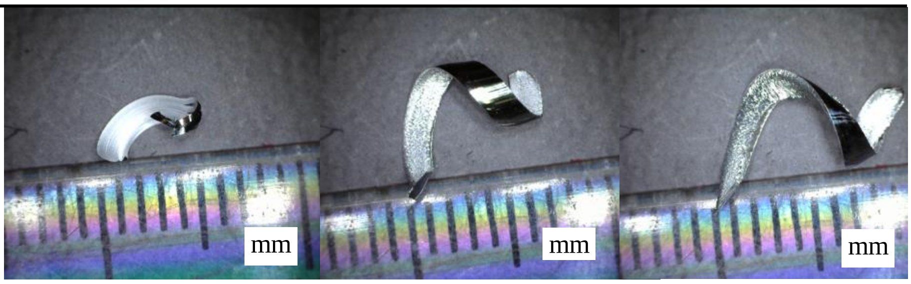


	a)		b)		c)	
	Up milling	Down milling	Up milling	Down milling	Up milling	Down milling
Ra [µm]	0.824	0.896	0.738	0.647	0.810	0.909
Sa [µm]	0.870	0.808	0.750	0.754	0.810	0.759

3.2.2 Influence of Feed Per Tooth on Chip Morphology

Table 9 shows three different chips produced dry machining at varied cutting feeds per tooth of: 0.009 mm/tooth, 0.15 mm/tooth and 0.291 mm/tooth. Cutting speed was kept at a constant value of 750 m/min.

Table 9 Morphology of dry machined chips with varied feed per tooth at a cutting speed of 750 m/min: a) 0.009 mm/tooth, b) 0.15 mm/tooth and c) 0.291 mm/tooth



	a)		b)		c)	
	Up milling	Down milling	Up milling	Down milling	Up milling	Down milling
Ra [μm]	0.088	0.083	0.738	0.647	1.097	1.137
Sa [μm]	0.099	0.110	0.750	0.754	1.148	1.097

3.2.3 Discussion

Chips between the tool and workpiece cause excess heating, higher friction and serve as a barrier at the point of contact which can have a negative impact on surface roughness. For this reason, smaller chips are preferred as they are easier to evacuate from the cutting zone. Low feeds per tooth produced high amounts of thin and short chips. Increasing feed per tooth produced a longer and thicker chip with clear signs of increased deformation. Similar cases were reported by Joshua et al. [16], Shukla et al. [4] and others. Table 9 a) shows a delaminated chip produced by dry milling at a feed per tooth of 0.009 mm/tooth and cutting speed of 750 m/min. Delamination of the chip could be caused by prolonged contact between the tool and workpiece causing excess heating of the chip and its serration at the end of the cut. A similar occurrence was reported by Khanna et al. [10] during dry turning of Inconel 718. Cutting speed has a limited influence on chip morphology as only length and pitch of the chip changed while the thickness remained unchanged. Chips produced by alternative cooling techniques showed little to no cutting fluid residues which made them easier to analyze and recycle.

3.3 Specimen Surface Scanning

Using a Filmetrics profilm 3D optical profilometer it was not only possible to measure various surface roughness parameters but to generate a 3D model of the analyzed surfaces.

Figs. 7–9 show scans of dry down milled surfaces at a constant cutting speed of 750 m/min with varied feeds per tooth of 0.009 mm/tooth, 0.15 mm/tooth and 0.29 mm/tooth. All surfaces were scanned using the same scan settings.

From Figs. 8 and 9, it is clear that feed per tooth greatly impacts workpiece surface. As was shown in section 3.1.3, an increase in feed per tooth increases the height and length of the cusp height that leads to an increase in surface roughness measurements. Similar observations were made observing the three tested cooling techniques.

Figs. 10 and 11 show 3D surface scans of down milled dry machined surfaces. The specimen in the figures below were machined using a constant feed per tooth of 0.15 mm/tooth and cutting speed of 396 m/min and 750 m/min. No visible changes in the length of the surface were observed in the figures above. Comparing the graph in Figs. 10 and 11, a decrease in the height of the profile was noted, indicating a decrease in surface roughness with increased cutting speed. Cooling techniques produced comparable results to the ones mentioned above.

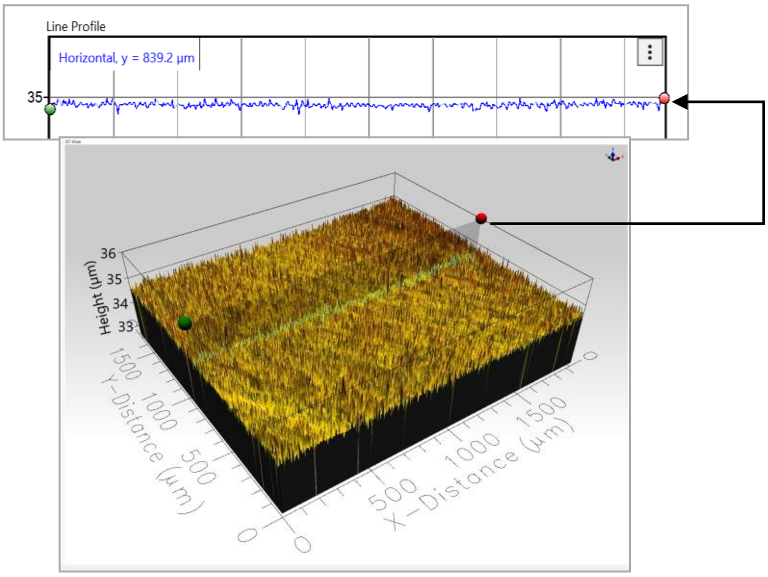


Fig. 7 Surface scan of dry down milled specimen at 750 m/min and 0.009 mm/tooth. Surface roughness measured for this test were *Ra* = 0.083 µm and *Sa* = 0.110 µm

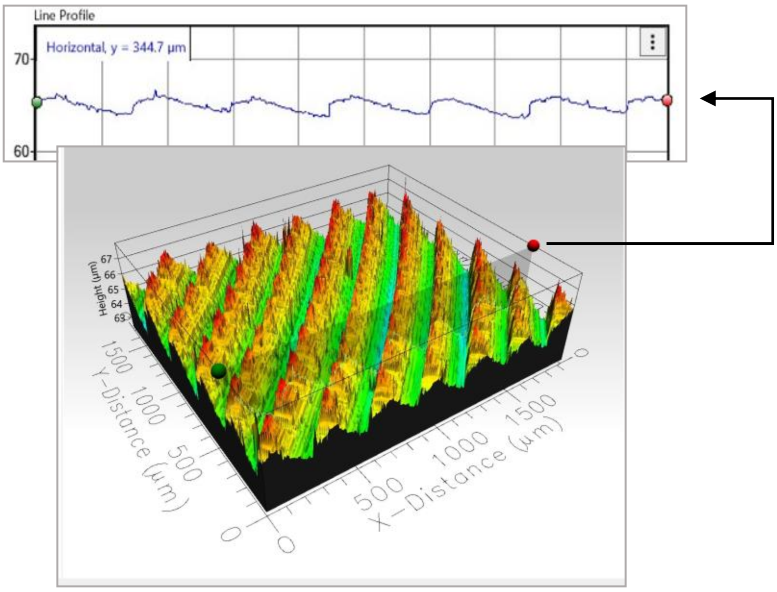


Fig. 8 Surface scan of dry down milled specimen at 750 m/min and 0.15 mm/tooth. Surface roughness measured for this test were *Ra* = 0.647 µm and *Sa* = 0.754 µm

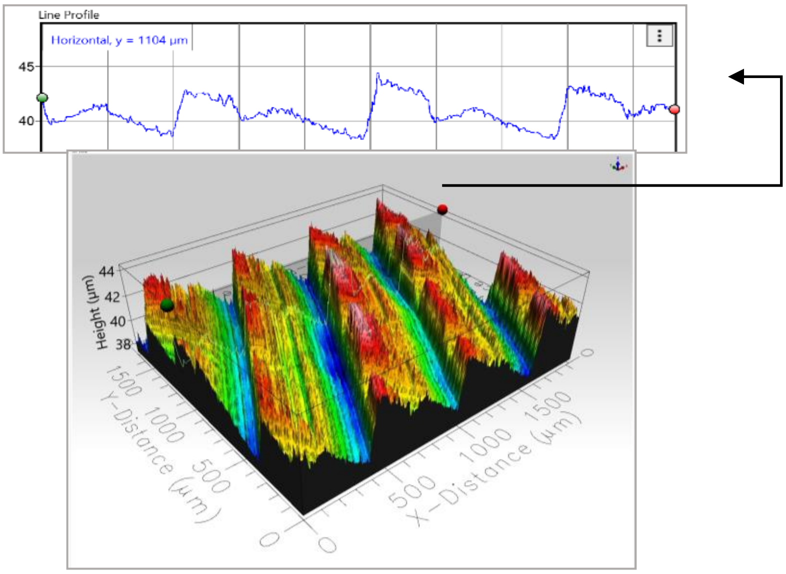


Fig. 9 Surface scan of dry down milled specimen at 750 m/min and 0.29 mm/tooth. Surface roughness measured for this test were *Ra* = 1.310 µm and *Sa* =1.052 µm

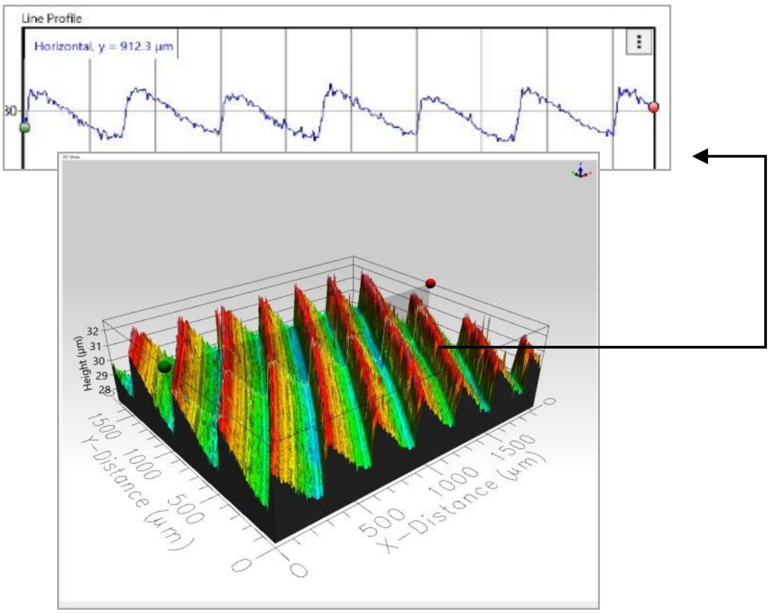


Fig. 10 Surface scan of dry down milled specimen at 396 m/min and 0.15 mm/tooth. Surface roughness measured for this test were Ra = 0.896 µm and Sa = 0.808 µm

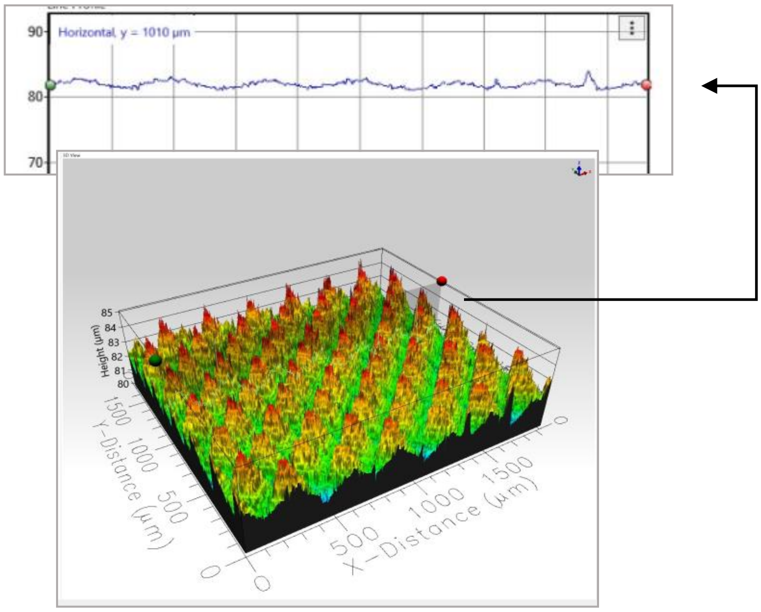


Fig. 11 Surface scan of dry down milled specimen at 750 m/min and 0.15 mm/tooth. Surface roughness measured for this test were Ra = 0.647 µm and Sa = 0.754 µm

4. CONCLUSIONS

Surface roughness and chip morphology of aluminum alloy EN AW – 2011 T6 using four cutting environments were examined in this paper. Along with dry machining, three cooling techniques were tested: cold compressed air, minimum quantity lubrication and cutting fluid. From these experiments, the following was concluded:

- Down milling provides up to 24 % lower surface roughness than up milling. This is a result of a higher chip cross section at the entry point of the tool as compared to a low chip cross section such is produced by up milling. A lower chip cross section at the entry point leads to burnishing of the workpiece surface. Burnishing generates excess heat which can cause chips to weld to the rake face of the tool thus negatively influencing surface roughness.
- Feed per tooth greatly influences surface roughness of the workpiece. Increasing feed per tooth produces a rougher surface due to an increased cusp height.
- Decreasing cutting speed leads to an increase in surface roughness due to increased plastic deformation of the workpiece material.
- Cold compressed air cooling produced the lowest surface roughness. Increased cooling capacity of the chilled air produced by the vortex tube reduces heat generated. Surfaces machined using MQL cooling performed worse than CCA but outperformed dry and CF cooled tests. This could be due to increased air flow over the cut surface which could aid in forming a finer aluminium oxide layer on the workpiece surface. Dry machining produces a rougher surface finish than the latter, most likely, owing to increased adhesion of workpiece material on the machined surface.
- Feed per tooth greatly influence chip morphology. A low feed per tooth produces high amounts of short and thin chips. Increasing feed per tooth increases the length and thickness of chips. Lower surface roughness parameters could be attributed to smaller chip sizes that do not obstruct the cutting zone and produce less heat at the tool workpiece interface.

The influence of tool wear was not observed in this paper due to very short machining times of the test. In future research, multiple passes will be implemented to induce observable tool wear.

Continuation of research should move in direction of cost analysis. Cost comparison between dry machining, CF, MQL and CCA comparing tool wear, surface roughness, cutting fluid usage and chip recyclability would give a clearer insight on the viability of alternative cooling techniques.

Finally, an increase in surface roughness was noted at high cutting speeds which were not expected. An investigation will be conducted in future research focusing on measuring tool vibrations that could cause such results.

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