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ORIGINAL ARTICLE

An experimental analysis of process parameters to manufacture metallic micro-channels by micro-milling

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Abstract Miniaturisation of products is a current megatrend, and it presents a wider range of opportunities to expand manufacturing markets. Micro-device design and manufacturing is a growing area of scientific interest for large number of industrial fields. This paper reports the characterisation of micro-milling process to manufacture micro-channels in order to understand the behaviour of process parameters when a standard milling machine is used. This study is based on micro-channel manufacturing through a set of experiments varying parameters such as spindle speed (*N*), depth of cut per pass (a_p), depth (*d*), feed per tooth (fz) and coolant application. Materials used were aluminium and copper with a hardness of 21 HRB and 72 HRB copper, respectively. Results are obtained by evaluating dimensions, shape and surface finish of the micro-channel. The use of coolant in micro-milling is found to be a relevant factor to improve micro-channel-achieved dimensions and surface finish. In general, micro-channels in aluminium were found to achieve better quality than those in copper.

Keywords Micro-milling · Micro-channels

1 Introduction

Current manufacturing processes require changes and adaptation in order to face new challenges because traditional sectors such as automotive and mechanical equipments are decreasing its activity. Medical field with the intention of improvement quality of life is an emerging opportunity for manufacturing processes to take advantage of actual capabilities and transform them to contribute with healthcare [1]. The micro-manufacturing processes have become a growing area and have found widespread use in a variety of applications, such as biomedical devices, representing a niche market, creating the need to find alternative process to manufacture these components with low-cost, high-accuracy and high-quality surface finishing.

The advantages of micro-high speed machining in contrast with other processes such as silicon etching processes, energy beam and chemical used to manufacture the micro-devices systems are fewer material restrictions and the capacity to manufacture true three-dimensional features in comparison with other methods.

Micro-machining is defined as mechanical cutting of features with tool engagement less than 1 mm with geometrically defined cutting edges. This technology includes numerous characteristics of traditional machining; simultaneously, micro-machining increases a great number of issues mainly due to size or scale [2]. Productivity, dimensions, topography and quality surface finishing of micro-machining are affected by several factors such as

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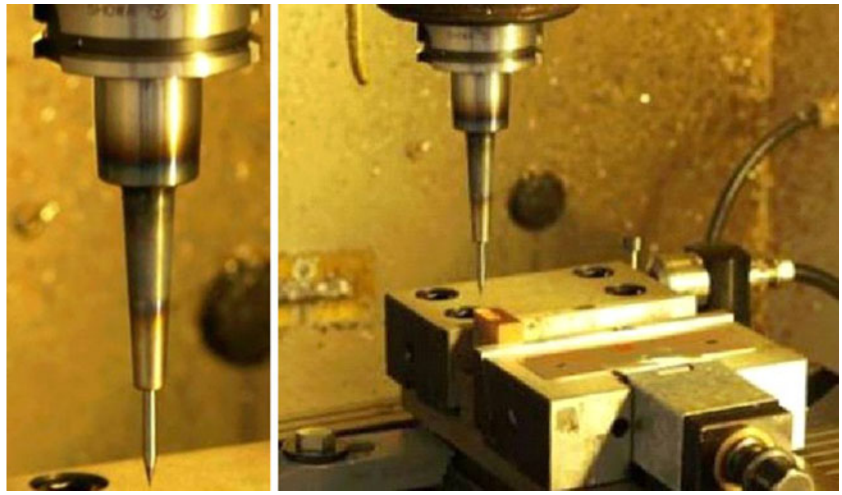


Fig. 1 Tool, tool holder and milling centre Deckel-Maho© 64V linear setup

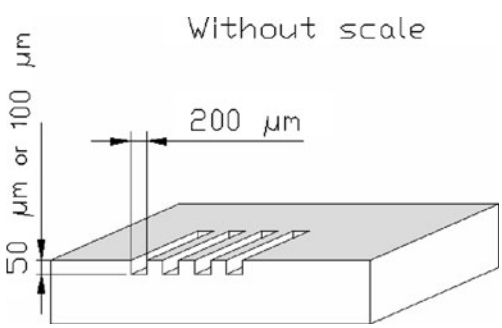


Fig. 2 Micro-channel design

microstructure, chip formation, tool wear, cutting forces, etc. The analysis of these factors has generated numerous researches.

Vogler et al. [3, 4] worked the microstructure effects of single and multi-phase materials on surface generation and found two phenomena: the geometries effect of the tool and process geometry and the minimum chip thickness effects. At the same topic of research, Wang et al. [5] studied the effects of different metal phase grains, considering the workpiece with anisotropic properties in microscope. Mian et al. [6] investigated the micro-machinabilitty of multi-phase ferrite-pearlite and cutting tests in order to know the effects of tool edge radius, undeformed chip thickness and grain size on particular cutting force, burr size, surface finish and tool wear. Schmidt et al. [7] study the influence of material structure on the surface quality in micro-milling; particularly in mould fabrication of steel, the material has to be heat treated before the micro-end milling to obtain improved surface quality. Lee and Zhou [8] explore the effect of crystallographic orientation on the shear zone formation in micro-machining with a single crystal cutting model.

Furthermore, according to Dornfeld [2], the contribution of Kim et al. [9] is a study of ploughing under a certain

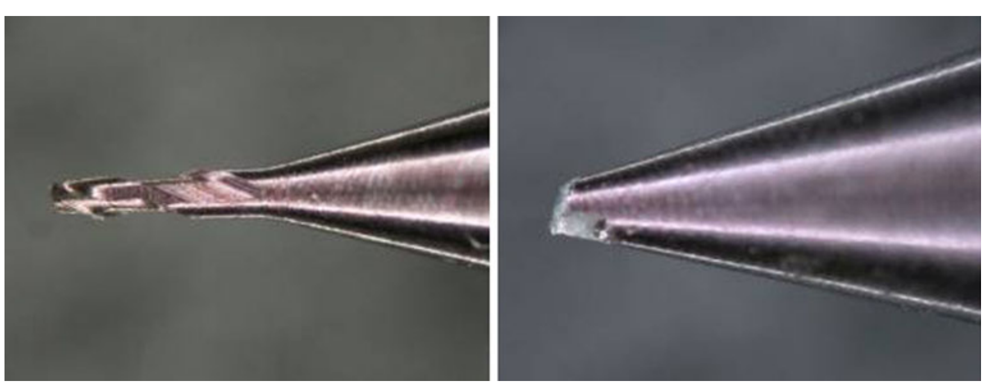


Fig. 3 Optical zoom comparison of new micro-tool and broken micro-tool

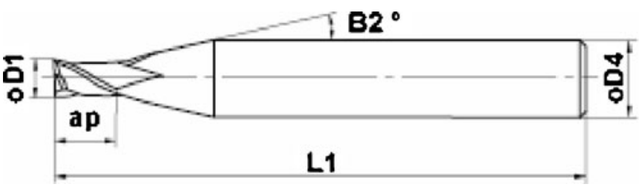


Fig. 4 Mitsubishi MS2SSD0020/CRNMSD0020S04 cutter schematically represented

depth of cut indicating that there exists a minimum chip thickness for chip formation.

Weule et al. [10] investigate the requirements for the micro-cutting of steel using tungsten carbide tools in order to know the interaction between the properties of the materials and the process parameters on the final part. Kim et al. [11] develop a static model of chip formation in micro-milling processes and have the capacity to describe the discontinuous chip formation observed at low feeds per tooth due to the dominance of the minimum chip thickness effect, and validate the model with experimental analyses. Focused also on process parameters, Lee and Dornfeld [12] conducted an experimental investigation in micro-slot milling considering burr shapes in aluminium and copper.

Other research works on modelling and simulate micro-machining processes. Chandrasekaran et al. [13] used molecular dynamics (MD) to simulate a nanometric cutting and propose a new method called length-restricted molecular dynamics. Komanduri et al. [14] also used MD simulations of nanometric cutting specifically to investigate burr formation and exit failure in metals. Bao and Tansel [15–17] propose analytical cutting force model for micro-end milling operations with tool run-out, and then this model was modified to represent tool wear, using estimations by genetic algorithms. Lee et al. [18] propose a mechanistic cutting force model for the precise prediction of the cutting force in micro-end milling with specific cutting conditions. Also Park and Malekian [19] examines the mechanistic modelling of the shearing and ploughing domain, cutting regimes to accurately predict micro-milling forces. Zhu et al. [20] study the selection of hidden Markov models structures for tool state estimation in the micro-milling of pure cupper and steel.

Finally, there are research studies like Kang and Ahn [21] which develop a research to verify the precision and cost efficiency of the micro-machining, demonstrating that it is feasible to manufacture moulding master with micro-machining in a rapid and cost-effective manner. Bissacco et al. [22] worked on experimental study applying micro-milling to the technology of microinjection moulding moulds in hardened tool steel. Ahn et al. [23] created a web-based Micro-Machining Service, named as MIMS; this

Table 1 Geometric characteristics of the Mitsubishi MS2SSD0020/CRNMSD0020S04 cutter

Corner geometry	S
Coating	MS/CRN
Tool interference corner (B2) [°]	15
Cutting diameter (D1) [mm]	0.2
Shank diameter (D4) [mm]	4
Overall length (L1) [mm]	40
Under shank length (L2) [mm]	7.8
Neck length (L3) [mm]	0.7
Length of cut (a_p) [mm]	0.3
Number of flutes	2

Table 2 Technical data of Cuttinsol 5 coolant

Theoretical content of mineral oil	Corrosion protection DIN 51,360, part 2 0% oxide to % concentration	PF value at 5% of concentration	Refractometer correction value
50	6	9.2	2

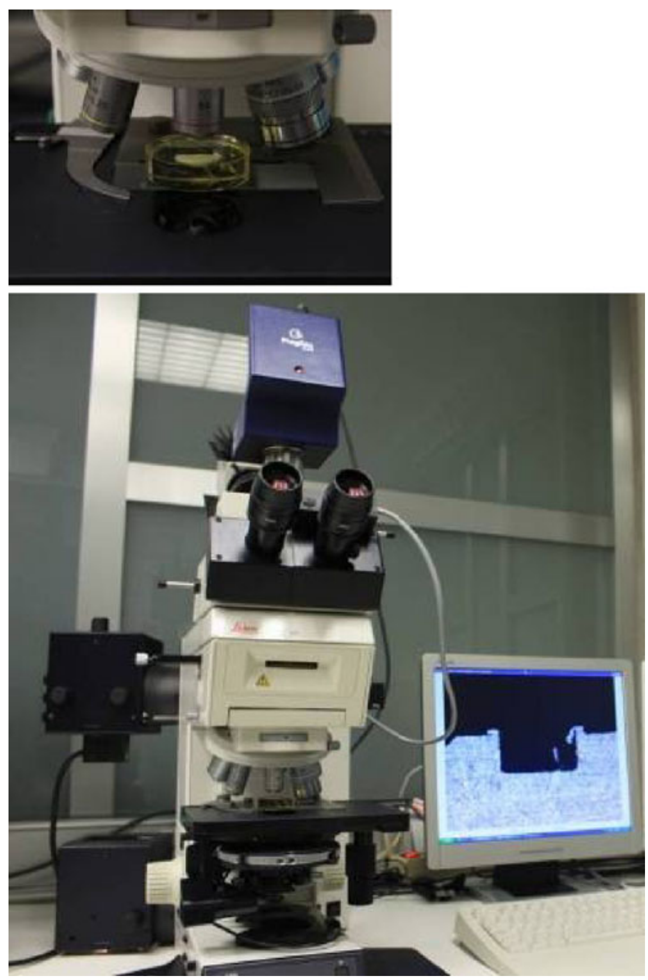


Fig. 5 Microscope LEICA DMR-XA

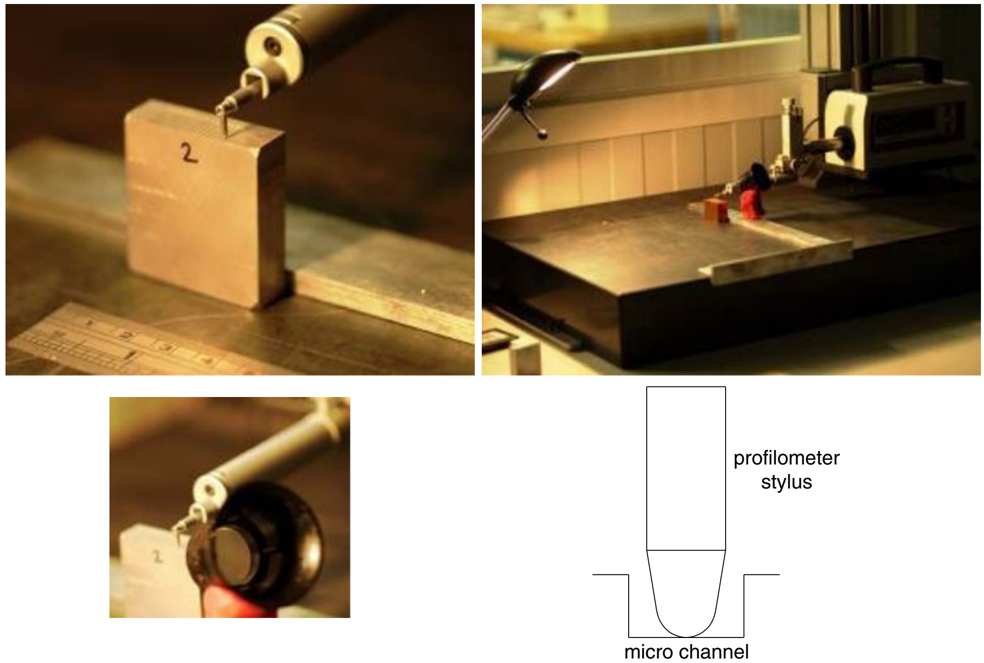


Fig. 6 Mitutoyo SV2000 Surftest equipment with lamp and magnifying glass

system provides time-effective process planning and fabrication of three-dimensional geometries in micro-scale. Jauregui et al. [24] have compared different manufacturing process, which includes machining based on not only the geometrical feature but also the process cost.

This paper provides the needed insight for improving the milling as a micro-manufacturing process. It is highly useful to capture the influence of milling process parameters such as cutting speed, depth of cut per pass, depth and feed per tooth on desired dimensions, geometrical feature and quality surface finishing, which will help to develop a predictive system to identify the optimum set of process parameters. Considering all milling process parameters, it is important to identify which ones have more effect on resultant feature quality, and in what degree changing these process parameters will affect the feature quality. Therefore, this work will contribute to the understanding of the relations between process parameters and quality of the geometrical features on the final micro-features.

Table 3 Variable factors and factor levels of micro-milling of aluminium channels

		Factor levels	
		L1	L2
Variable factors	F1. Spindle speed [*N*], min^{-1}	10,000	12,000
	F2. Depth of cut per pass [a_p], µm	2	10
	F3. Channel depth [*d*], µm	50	100
	F4. Feed per tooth [f_z], µm/tooth	1.25	1.90
	F5. Coolant	Dry	Wet

2 Experimental setup

The milling centre that used to perform the experimentation was Deckel-Maho© 64V Linear (three-axis, vertical spindle and FANUC 180i controller). In order to minimise errors, heat-shrink toolholders were used in all experiments (Fig. 1).

The workpiece materials tested in this study were aluminium alloy with hardness of 21 HRB and copper alloy with hardness of 72 HRB. The experiments were carried out by machining micro-channels of 200 µm in width and depth of 50 or 100 µm (Fig. 2). GoELAN© software was used to generate the CAM Gcode.

A Mitsubishi© MS2SSD0020 end mill cutting tool of 200 µm diameter was tested for aluminium (Fig. 3), and a CRNMSD0020S04 end mill cutting tool of 200 µm was tested for copper. The tool designs for aluminium and copper are identical. Based on the supplier's suggestion, there is a different coating for each type of cutting tool (aluminium vs. copper).

One of the challenges in machining micro-channels is to establish the workpiece reference surface. The consequences associated with this issue are the tool breakage (as

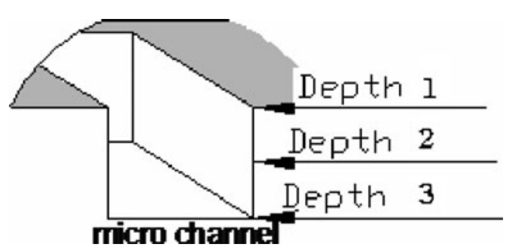


Fig. 7 Illustration widths at different depths

Table 4 Experimental results in aluminium

Test	N [min^{-1}]	a_p [µm]	d [µm]	f_z [µm/z]	Dry conditions		Wet conditions	
					Width [µm]	R_a [µm]	Width [µm]	R_a [µm]
1	10,000	2	50	1.25	189.40	1.607	189.40	1.607
2	10,000	10	50	1.25	149.27	2.214	149.27	2.214
3	10,000	2	100	1.25	179.33	2.606	179.33	2.606
4	10,000	10	100	1.25	181.87	3.347	181.87	3.347
5	10,000	2	50	1.90	202.80	1.429	202.80	1.429
6	10,000	10	50	1.90	210.17	1.056	210.17	1.056
7	10,000	2	100	1.90	204.47	1.796	204.47	1.796
8	10,000	10	100	1.90	210.20	0.864	210.20	0.864
9	12,000	2	50	1.25	186.37	1.525	186.37	1.525
10	12,000	10	50	1.25	182.93	1.535	182.93	1.535
11	12,000	2	100	1.25	171.20	1.227	171.20	1.227
12	12,000	10	100	1.25	174.07	3.916	174.07	3.916
13	12,000	2	50	1.90	204.77	1.445	204.77	1.445
14	12,000	10	50	1.90	196.63	1.021	196.63	1.021
15	12,000	2	100	1.90	208.73	0.722	208.73	0.722
16	12,000	10	100	1.90	214.43	1.140	214.43	1.140

Table 5 Micro-channels in aluminium using different parameters in dry conditions

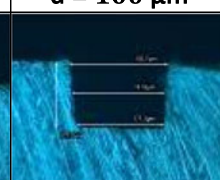
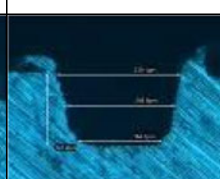
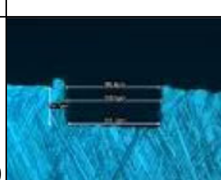
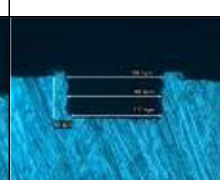
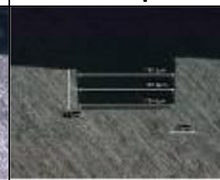
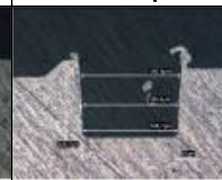
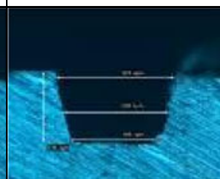
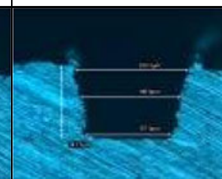
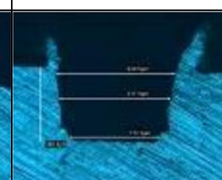
	Dry conditions				
	a_p = 2 µm		a_p = 10 µm		
	d = 50 µm	d = 100 µm	d = 50 µm	d = 100 µm	
N=10,000 min^{-1}					f_z=1.25 µm/z
					f_z=1.90 µm/z
N=12,000 min^{-1}					f_z=1.25 µm/z
					f_z=1.90 µm/z

Table 6 Micro-channels in aluminium using different parameters in wet conditions

	Wet conditions				
	a_p = 2 µm		a_p = 10 µm		
	d = 50 µm	d = 100 µm	d = 50 µm	d = 100 µm	
N=10,000 min^{-1}					f_z=1.25 µm/z
					f_z=1.90 µm/z
N=12,000 min^{-1}					f_z=1.25 µm/z
					f_z=1.90 µm/z

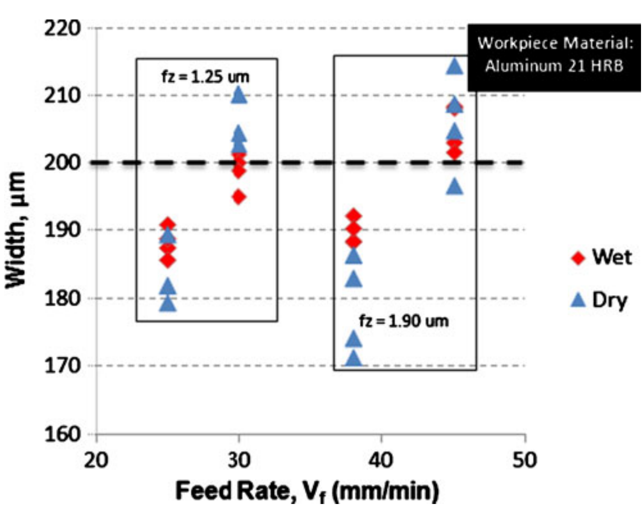


Fig. 8 Influence of feed rate on width dimensional feature in aluminium

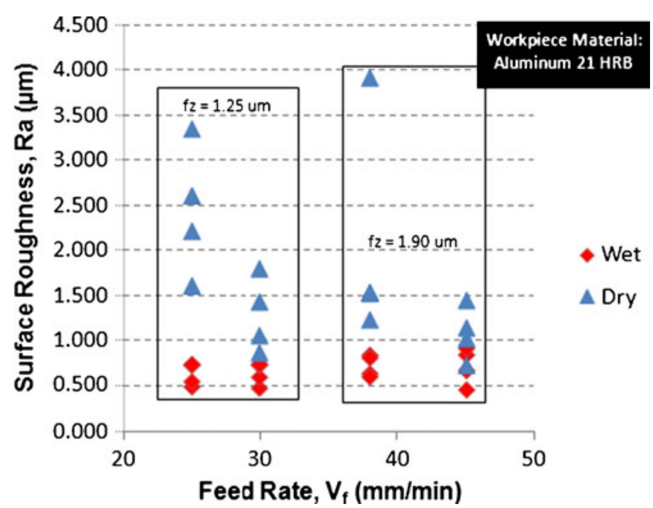


Fig. 9 Effect of feed rate and depth of cut on surface finish in aluminium

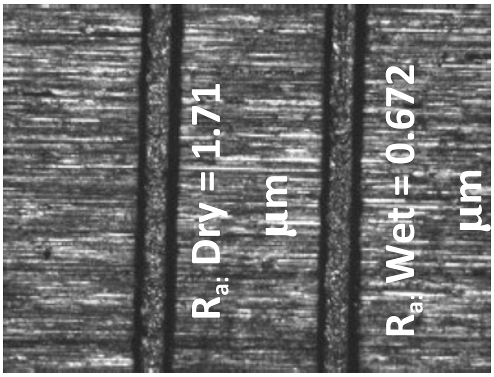


Fig. 10 Top view of micro-channel in aluminium

shown in Fig. 3) or machining in the air and not achieve contact with the workpiece. Figure 4 and Table 1 show geometric features of the tools.

A conventional coolant based on mineral oil was used (CUTTINSOL 5 by COLGESA©). Table 2 shows the technical data of CUTTINGSOL 5.

Dimensional measurements were performed with an optical microscope LEICA DMR-XA attached to NIKON F90 and RICOH X-RX3000 camera bodies and digital video with a SONY DXC950-P of 3CCD camera (Fig. 5) for the collection of digital images. These images were numerically processed using the Quartz PCI© software, version 5. Measurements were done with destructive tests.

The measurement of surface roughness parameter R_a on the micro-channel bottom surface was conducted with a stylus instrument (Mitutoyo SV2000 Surftest equipment), with a cut off of 0.8 mm, in accordance with ISO/DIS 4287/1E. The ability to obtain the most precise and rapid surface measurements by profilometer is affected due to the reduced scale of micro-channels. As a consequence, the profilometer stylus inside micro-channel cannot be seen with the naked eye. In order to compensate this difficulty, a magnifying glass and an intense illumination in the direction of the workpiece are required. Figure 6 illustrated the process of measuring the surface finish at micro-channel bottom surface.

The variable factors of interest in this study are shown in Table 3. The design of experiments was defined as full factorial with five variable factors and two levels per variable factor. The response variables are the surface roughness, R_a [μm] at the bottom of the micro-channel, micro-channel width dimension [mm] and micro-channel shape as indicated in Fig. 2.

3 Results and discussion

A total number of 32 micro-channels were machined with micro-milling process on a standard milling machine by following the experimental plan discussed in Table 3. The geometrical features and surfaces are inspected using the imaging system described in Section 2.

In order to obtain the measure of micro-channel width, three measurements are conducted at different depths, as illustrated in Fig. 7. The value reported in the results table is the average of these three measures.

3.1 Aluminium workpiece

Table 4 presents five different inputs (spindle speed, axial depth of cut, final axial depth, feed per tooth and coolant) and two measured outputs on the machined features (width and surface finish). The dimensions and shape of the micro-channels produced with micro-milling process exhibit variations. Tables 5 and 6 show the micro-channels in aluminium produced with the different combinations of variable factors.

By mere visual inspection, the pictures in Tables 5 and 6 clearly indicate the adverse effect on micro-channel shape as feed per tooth is increased. When the feed per tooth increases, geometrical shape tends to be rounded in the lower corners, and the micro-channel loses the rectangular shape. A preliminary appreciation also indicates that the use of coolant helps to control the rectangular shape of the micro-channels.

The effect of feed rate (V_f) on width dimensional feature in aluminium is summarised in Fig. 8. The feed rate (V_f) given in Fig. 8 is the combination of spindle speed (N) and feed per tooth (f_z) set in Table 3. The combination of lower feed rate and coolant produces a more stable process, with

Table 7 ANNOVA for width in aluminium

Factor	*DF*	SC sec.	SC adjust.	Mc adjust	*F*	*P*
N	1	61.00	61.00	61.00	0.84	0.369
a_p	1	49.01	49.01	49.01	0.67	0.420
d	1	47.00	47.00	47.00	0.64	0.430
f_z	1	3,673.53	3,673.53	3,673.53	50.34	0.000
Coolant	1	117.81	117.81	117.81	1.61	0.215
Error	26	1,897.17	1,897.17	72.91		
Total	31	5,845.51				

Table 8 ANNOVA for R_a in aluminium

Factor	*DF*	SC sec.	SC adjust.	Mc adjust.	*F*	*P*
N	1	0.8690	0.0869	0.0869	0.2600	0.6150
a_p	1	0.2326	0.2326	0.2326	0.6900	0.4130
d	1	0.9948	0.9948	0.9948	2.9600	0.0970
f_z	1	2.2398	2.3298	2.3298	6.6700	0.0160
Coolant	1	8.7132	8.7132	8.7132	25.9700	0.0000
Error	26	8.7243	8.7243	0.3356		
Total	31	20.9916				

Table 9 Experimental results in copper

Test	N [min^{-1}]	a_p [µm]	d [µm]	f_z [µm/z]	Dry conditions		Wet conditions	
					Width [µm]	R_a [µm]	Width [µm]	R_a [µm]
1	10,000	10	50	2	154.23	1.507	278.60	1.327
2	10,000	10	100	2	149.80	2.051	252.73	1.774
3	12,000	10	50	2	136.23	1.896	135.63	1.871
4	12,000	10	100	2	153.30	1.830	178.07	1.314

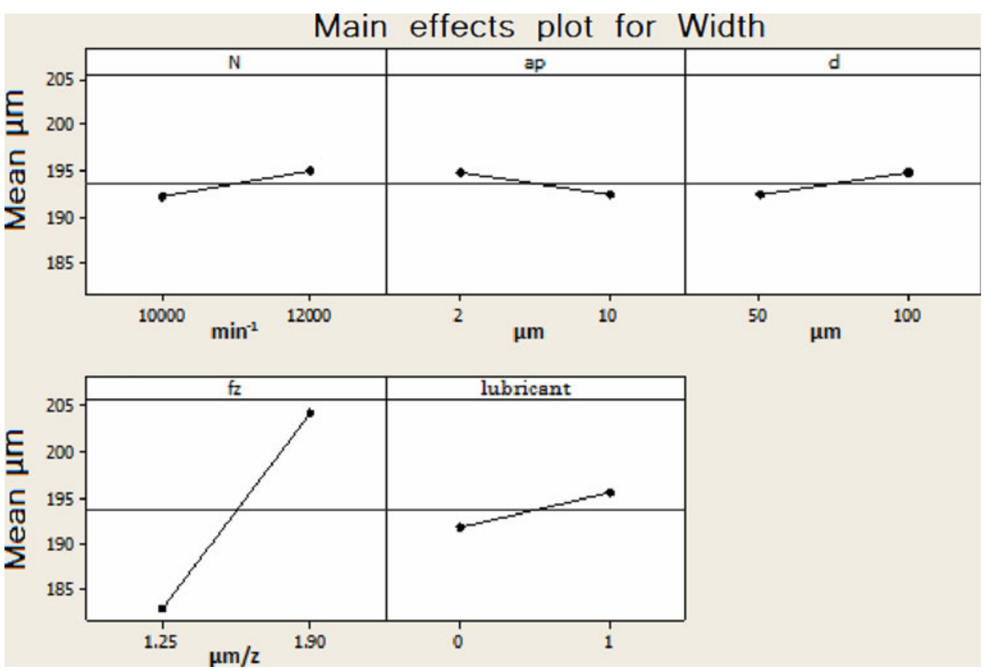


Fig. 11 Graphs of main effects for width in aluminium

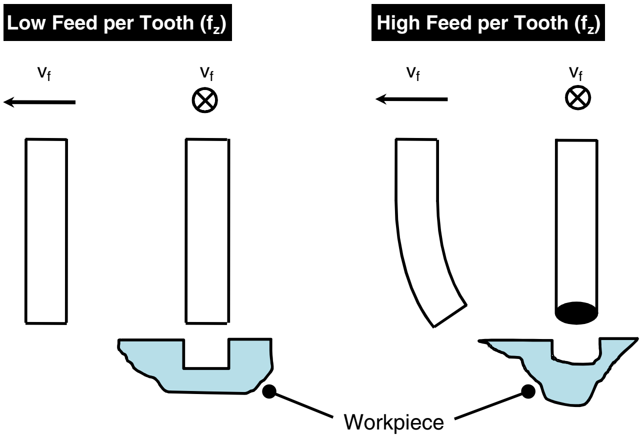


Fig. 12 Tool deflection effect on micro-channel shape

average width of micro-channel approaching closer to the target of 200 µm. Note: When the average micro-channel width is lower than 200 µm, it means that the shape is trapezoidal (tapered) or rounded at the bottom.

The effect of feed rate on the surface finish at the bottom of the micro-channel is summarised in Fig. 9, using aluminium as workpiece material. Similar to the study of micro-channel width, the use of coolant provides a more stable process, achieving a lower level of surface roughness. As further evidence of the positive effect of coolant, Fig. 10 shows the top view of micro-channels and the surface roughness average values obtained in aluminium.

A more in-depth analysis of the micro-channel average width and bottom surface roughness was conducted. Tables 7 and 8 summarise the results of the ANOVA analysis. Table 9 reveals that feed per tooth is the most significant factor in micro-channel average width. Figure 11 shows graphs of main effects for micro-channel average width. One potential explanation for this correlation is the tool deflection. Figure 12 shows a schematic explanation for the rounding of the micro-channel bottom. As the feed per tooth increases, the cutting tool deflects, producing an elliptical projecting of the cutting tool end. Therefore, the average micro-channel width is reduced as the feed per tooth increases.

According to Table 8, the results suggest that R_a is mainly influenced by feed per tooth and coolant. The main effect graph for surface roughness at micro-channel bottom is shown in Fig. 13.

Table 10 Micro-channels in copper using different parameters in dry conditions

	Dry Conditions		
	a_p = 10 µm		
	d = 50 µm	d = 100 µm	
N=10,000 min^{-1}			f_z=2.00 µm/z
N=12,000 min^{-1}			f_z=2.00 µm/z

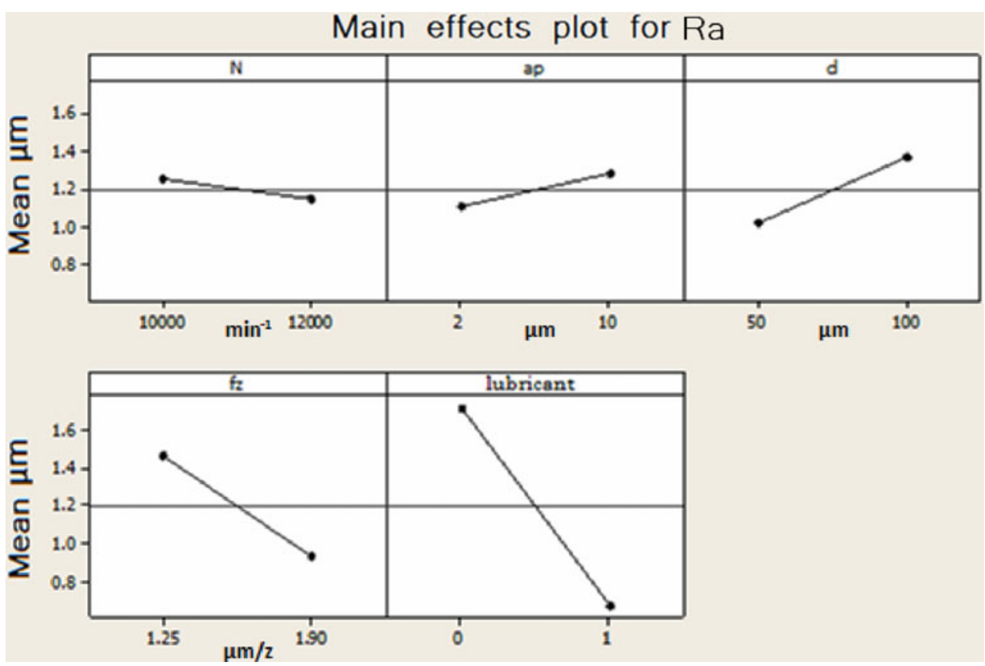


Fig. 13 Graphs of main effects for R_a in aluminium

3.2 Copper workpiece—preliminary study

A preliminary study was performed in copper using similar parameters and cutting tool (the only difference is the coating tools) as those used for aluminium. Table 9 presents five different inputs (spindle speed, axial depth of cut, final axial depth, feed per tooth and coolant) and two measured outputs on the machined features (width and surface finish).

Table 10 shows the micro-channels in copper produced by using different parameters. The results in copper suggest that width dimensional feature and rectangular shape are difficult to achieve (see Table 10). A significant difference in material hardness (72 HRB for copper vs. 21 HRB for aluminium) might be the explanation for the process instability. It is clear that micro-channel manufacturing is a delicate process. Further research is required in copper alloys.

4 Conclusions

In this study, surface finishing, shape and dimensional features of micro-channels have been investigated in micro-milling process with standard milling machine, for aluminium and copper workpieces. Results suggest that standard machine tools are capable of applying micro-milling in order to produce micro-channels. In general, this study finds better results when micro-channels were carried out in aluminium compared with copper. Some specific conclusions can be drawn as follows:

1. In aluminium workpiece (hardness, 21 HRB), the average micro-channel width is better controlled in aluminium using higher feed rates.
2. In aluminium workpiece (hardness, 21 HRB), the use of coolant provides better results in terms of average micro-channel width and micro-channel bottom surface roughness.
3. Micro-channels performed in copper lack the intended rectangular shape. Further research is needed to better control the micro-channel manufacturing in copper alloy with a hardness near 72 HRB.

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