Evaluation of Superficial and Dimensional Quality Features in Metallic Micro-channels by Micro-Milling.

ICOMM
2012
No. 70

K. Monroy[1], A. Attanasio[2], E. Ceretti[2], H.R. Siller[1], N. Hendrichs[1] and C. Giardini[2]
[1] K. Monroy, Industrial Engr., Tecnologico de Monterrey, Mexico; e-mail: A00971669@itesm.mx
[2] A. Attanasio, Mechanical Engr., University of Brescia, Italy; e-mail: aldo.attanasio@ing.unibs.it
[2] E. Ceretti, Mechanical Engr.,University of Brescia, Italy; email: elisabetta.ceretti@ing.unibs.it
[1] H.R. Siller, Mechanical Engr., Tecnologico de Monterrey, Mexico; e-mail: hector.siller@itesm.mx
[1] N. Hendrichs, Mechanical Engr., Tecnologico de Monterrey, Mexico; e-mail: nicolas.hendrichs@itesm.mx
[2] C. Giardini, Mechanical Engr.,University of Bergamo, Italy; email: claudio.giardini@unibg.it

ABSTRACT.

The miniaturization encourages the development of new manufacturing processes capable to conform features like micro-channels in order to use them for different applications, such as in fuel cells, heat exchangers and microfluidic devices. Many studies have been conducted on heat and fluid transfer in micro-channels, and they appeared significantly deviated from conventional theory, due to measurement errors and fabrication methods. Therefore, the present research focused on a set of experiments in micro-milling of aluminum, titanium and stainless steel varying parameters such as spindle speed (*N*), depth of cut per pass (a_p), channel depth (*d*), feed per tooth (f_z) and coolant application. The experimental results were analyzed in terms of dimensional error, channel profile shape deviation from rectangular and surface quality (burr and roughness). The micro milling process was capable of offering quality features required on the micro-channeled devices. Critical phenomena like run-out, ploughing, minimum chip thickness and tool wear was encountered as an explanation for the deviations in shape and for the surface quality of the micro channels. The application of coolant and a low depth of cut per pass were significant to obtain a better superficial quality features and a lesser amount of the dimensional error.

Keywords: micro-milling, micro-channels, fuel cells, heat exchangers, micro-fluidic devices.

I. INTRODUCTION

The demand for miniaturized meso-(100 μm-10 mm)/ micro-(0.1-100 μm) devices with high aspect ratios and superior surfaces has been rapidly increasing in diverse industries. There is a growing need for fast, direct, and mass manufacturing of meso/micro functional products [1, 2]. The motivation for small parts manufacturing has been the same since manufacturing was established: low-cost, high-accuracy and high-quality surface finishing in order to use these devices for different applications [3].

The micro-engineering is responsible for developing and manufacturing products with functional characteristics of at least one dimension on the order of micrometers [2]. Therefore micro-machining processes, like micro end milling, are in full expansion.

The micro end milling process is fast, cost efficient and can achieve good accuracy, low surface roughness, and high material removal rates (MRR) with feature sizes as small as 5-10 μm [4]. Appearing then, to be a flexible and the fast way to produce micro-forms for diverse applications, such as in fuel cells, heat exchangers and microfluidic devices

The interest in the use of micro-channel heat exchangers has arisen because they play an important part on the field of energy conservation, conversion and recovery. Its compacted size enabled by micro-channels, is improving the heat transfer and savings potential compared to the regular tube heat exchangers. The rate of heat transfer depends on the surface area to volume ratio, which means the smaller channel dimensions provide the better heat transfer coefficient, being this another motivation for the encouragement microfabrication technologies to increase the advantages generated from miniaturization of heat exchanger channels [5-14].

Fuel cells have been proposed as a possible power source to address issues that involve energy production and the environment. In particular, small fuel-cell systems are known to be suitable for portable electronic devices. The development of micro fuel cell systems can be achieved also by the application of microchannel technology, allowing them now to be small, efficient, modular, and potentially inexpensive [15].

Many researchers are currently developing microchannel heat-exchangers, reactors, and separators as components for compact hydrogen generators for fuel cells [16]. It has been shown that microfabrication technology can be effectively applied for the miniaturization of fuel cells. Compact fuel cell power systems have potential applications in markets such as residential and commercial power, space exploration and defense. Automotive power systems are one of the most promising applications because of the variety and size of potential markets present in this field [15].

Moreover, microfluidic devices are now developing several applications in areas like medicine and biotechnology for the separation of molecules, transportation of DNA and, drug delivery systems. A microfluidic device can be identified by the fact that it has one or more channels with at least one dimension less than 1 mm. The principal function of a microfluidic device is the release and transportation of fluids. The fabrications techniques used to construct microfluidic devices are relatively inexpensive but highly elaborate [17]. An emerging application area for biochips is clinical pathology, especially the immediate point-of-care diagnosis of diseases, market valued in 2010 in $563 Million USD (Fig.1) and in general the microfluidic market its predicted to exceed the $3 Billion in 2014, accompanied by composed growth annual rates of 26% [18].

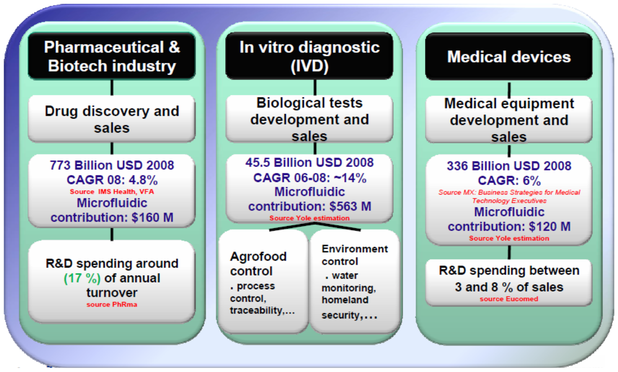


Fig. 1 Microfluidic Market Considerations [18]

The reduction in hardware volume on the latter mentioned devices were all possible by a micro-channel based design. The evolution of micro-channel-based devices is largely been triggered by advances in micro-fabrication technologies. The main geometric elements, micro-channels, have a variety of manufacturing processes and fabrication techniques documented in the literature (shown in Fig. 2): lithography, micro-end milling, a combination of wire electrodischarge machining (WEDM) & sandblasting, and abrasive water jet cutting [17]. In a previous study the capabilities of lithography, which is the conventional process for micro-channels, was compared with other processes. The evaluation consisted in a comprehensive study of surface quality and topography; also economical considerations were taken into account. The micro-milling process results showed that it can compete with lithography, in terms of achieving acceptable levels of product quality, surface finish and economics. Although, its application in micro-channeled devices is very limited on the literature, it can achieve surface roughnesses below 0.1% of the channel height [19].

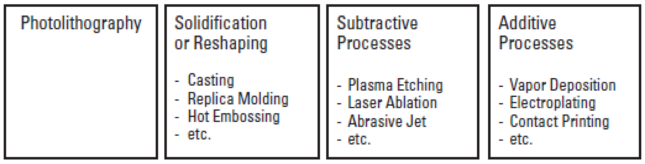


Fig.2 Broad categories of Microfabrication processes for Micro-channels [17].

The design principles of micro-channels on heat exchangers and microfluidic devices (including fuel cells), performance evaluated by heat transfers and fluid flow rates. Studies showed that the results on both flow rates appeared significantly deviated from conventional theory, which apparently are due to measurement errors and fabrication methods, including the surface roughness and channel shape [9][20]. Although the effect of surface roughness on the flow is well studied for over centuries, the exact effect has not been completely understood. For instance, at microscale level, it is impossible to obtain a completely smooth surface (without texture and burr) and it has also been shown that modern fluidic devices at micro levels routinely violate the 5% relative roughness threshold due to the inability to control the roughness of surfaces to sufficient levels[8] [21-22].

These are difficulties and challenges from micro machining operations that can be attributed to material behavior in the micro scale, different cutting mechanisms compared to the macro scale, tool dynamics and vibrations, and tool wear and fragility. At this scale, the slightest variation in the manufacturing process will have a direct impact on the ability to produce conforming features of this type with an acceptable surface quality.

Therefore, the present article is intended to conduct a micro-milling experiment on metallic alloys in order to analyze its results in terms of surface quality and dimensional features to evaluate its performance as a technology in the prototyping of micro-channels. As a result, this work will also contribute to the understanding of the relations between process parameters and quality of the geometrical final micro-features of the channel with micro-milling.

2. EXPERIMENTAL METHODOLOGY

The micro-channels were machined in a fived axed CNC machining centre with a vertical spindle and a Heidenhain iTNC 530 Controller, shown in Fig.3.

Fig.3 CNC Machining Centre and Material Clamping

The experiments were conducted using an aluminum alloy with a hardness of 21 HRB, stainless steel 316L (AISI316L) and Ti6Al4V (Fig. 4). The materials were cutted into rectangular probes and fixed up in a standard clamp GERARDI VISE SERIES.

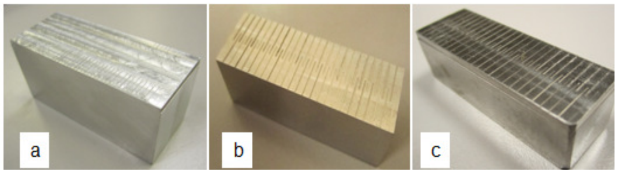


Fig. 4 Workpiece Probes: a) Al Alloy (56 mm x 23 mm) b) AISI316L (40 mm x 14 mm) c) Ti6Al4V (42 mm x 14 mm)

A Mitsubishi© MS2SSD0020 200 µm diameter end mill was used to machine rectangular profiled microchannels of 200 µm in width and two depths, 50 and 100 µm (Fig.5). One same end mill was employed to machine 16 channels, therefore three identical end mills were used for each material. Table 1 shows the geometric characteristics of the tool.

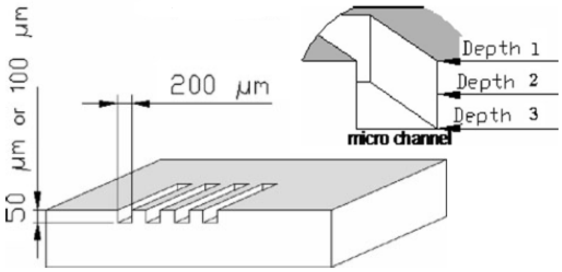
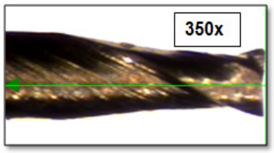
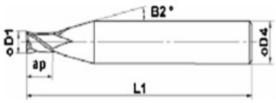


Fig. 5 Microchannel Design [23].

The toolpaths were generated with parametric programming in Gcode, as the channels were a linear design in an arrangement of 1 mm between each channel (Fig.5).

Table 1: Tool Specifications

Tool Specifications		Mitsubishi© MS2SSD0020
Material:	Solid Carbide	
Number of Flutes (z):	2	
Coating	CRN	
Diameter Dimensions		
Cutting Diameter (D1) [mm]	0.2	
Tolerance	0 - -0.02	
Shank Diameter (D4) [mm]	4	
Dimensions		
Overall Length (L1) [mm]	40	
Under Shank Length (L2) [mm]	7.8	
Neck Length (L3) [mm]	0.7	
Cutting Dimensions		
Length of cut (a_p) [mm]	0.3	
Other Dimensions		
Tool interference corner (B2) [°]	15	
Lead Angle 1(B3) [°]	30	

The design of experiments was defined as a two level half fractioned factorial with five variable factors; consequently a V resolution study ($2_V{}^4$) with three replicas was applied, totalizing 48 micro-channels per material. The same order of runs was used on the replicas, in order to have comparable results and to control tool wear. The variable factors of interest in the study are shown in Table 2.

Table 2 Variable factors and levels of micro milling in Aluminum, Steel 316, Ti6Al4V

	Aluminum		Titanium/Steel	
Variable Factor	L1	L2	L1	L2
F1. Spindle Speed [N],min^{-1}	10,000	12,000	10,000	12,000
F2. Depth of Cut per pass [a_p] µm	2	10	2	10
F3. Channel Depth [d], µm	50	100	50	100
F4. Feed per tooth [f_z], µm/fz	1.25	1.90	0.625	1.25
F5. Coolant	Dry	Wet	Dry	Wet

The metrology was executed in order to measure the response variables shown in Table 3.The burr measurement was made in a qualitative evaluation from images acquired with a non-contact Vision Measuring Machine; Mitutoyo Quick Scope QS200Z along with a QSPAK software for the compilation of images (Fig. 6).

Table 3 Metrology Response Variables

Response Variable	Measurement Type	Evaluation
1. Burr Formation	Qualitative	Evaluation from 1-5
2. Shape	Qualitative	ProfileShape
3. Dimension	Quantitative	Width Size [µm]
4. Roughness	Quantitative	Ra [µm]

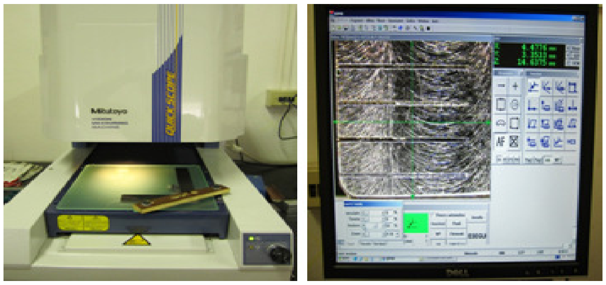
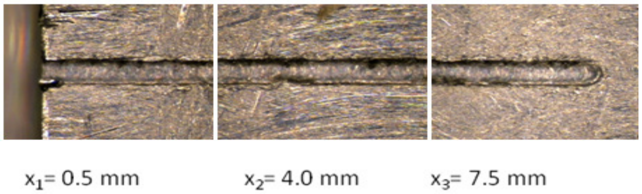


Fig. 6 Mitutoyo Quick Scope QS200Z and QUICKSOPE Software

Three images were taken from every channel varying the position of the channel for the image acquisition, taking snapshots at 0.5 mm, 4.0 mm and 7.5 mm, of the 8 mm channels. Consequently, a complete map of the top burr can be formed (shown in Fig. 7) and evaluated in a qualitative form by a given scale from 1-5 (5- No burr and 1-Excessive Burr).



x_1= 0.5 mm x_2= 4.0 mm x_3= 7.5 mm

Fig. 7 Channel Burr Formation Map

Before the profile measurement, a polishing process was made by metallographic means to assure the correct gathering of information, without the noise effects of burr and chip building on the entrance of the tool. As the workpieces were ready, the channel profile was measured through image capturing (Fig. 8). The profile analysis was performed in a qualitative way trying to categorize the final shapes derived by the process in each material.

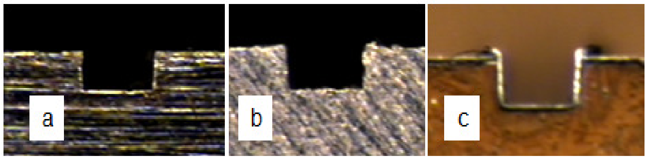


Fig. 8 Profile Picture a) Ti6Al4V b) AISI316L c) Al Alloy

The dimensional measurements were performed also by image acquisition. The measurements of the channel size were carried out in three different levels as in Fig. 5; in order to help in the form analysis and to record the deviation conformed to the nominal width channel size.

The measurements of surface roughness (Ra) on the floor surface of the micro-channel were conducted with a profilometer ZEISS SURFCOM 1500SD2 (Fig. 9), with a cut off of λc= 0.8 mm and a sampling ls= 4.0 mm, in accordance with ISO/DIS4287/1E using a Gaussian profile filter and no tilt correction.

Fig. 9 SURFCOM 1500SD2 Profilometer

The accuracy of the roughness measurements was defined by a perfect alignment of the channel path with the x-axis movement of the stylus of the profilometer. The reduced size of the microchannels was a challenge for the roughness measurements; as if the alignment was not carefully done it will create trembling movements due to the friction of the stylus with the microchannel walls. Consequently, the alignment was possible by a CELESTRON 44302-A hand-held digital microscope that permitted to observe the profilometer stylus inside the center of the microchannel and allowed to capture video and magnified images (shown in Fig.10).

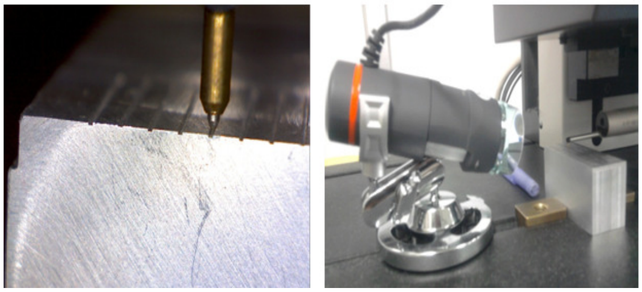


Fig. 10 Alignment and Celestron Portable Microscope

A gage R&R test was carried out to the profilometer to validate the data. The results show sufficient different categories to distinguish adequately between parts and a low study variation on repeatability, 7.09% which according to the AIAG guidelines the measurement device is acceptable.

3. RESULTS

A total number of a hundred and forty-four micro channels have been machined with micro-milling by following the experimental plan discussed in section 2. The results gathered from the measurements were analyzed by material and observing the following:

- The mean average roughness and the range of roughness results
- The mean burr formation evaluation and burr evaluation by tool.
- The channel size mean and size by level, analyzing its percentage error deviation relative to the nominal size.
- The channel depth, analyzing its percentage error deviation relative to the nominal size (50 or 100 µm)
- The predominant profile shape resulted from the process by material.

A. ALUMINUM ALLOY

- The roughness ranged from 0.095 to 2.5 µm.
- The mean burr evaluation was 3.10 out of 5 (being 5 the ideal).
- The depth of cut per pass and coolant application are the most important factors to consider in order to minimize the top burr formation of the micro channels (Fig. 11). Observing in the 2-way interactions of the depth of cut per pass versus all other factors, in all cases with the lowest level, 2 µm, the top burr formation is lower. In the interaction of the coolant with all other factors, in all cases in wet conditions, the top burr formation decreases.

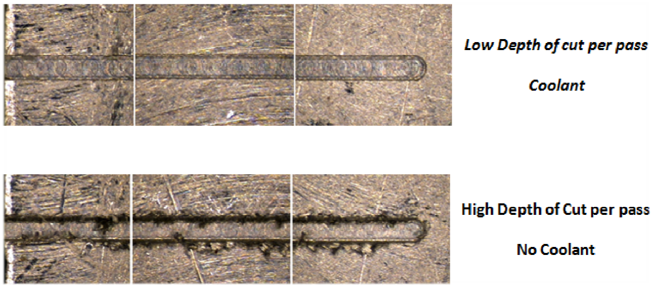


Fig. 11 DOC per pass and Coolant influence in burr formation of AL Alloy

- The minimal burr formation was with a 2 µm depth of cut per pass and in wet conditions.
- The use of coolant is the most important factor to consider in order to minimize the roughness (Fig. 12). It's evident the strong coolant influence, as in all cases in wet level of coolant the roughness is at the minimal.

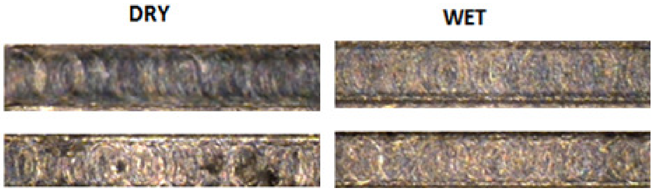


Fig. 12 Coolant application for minimizing roughness

- It was found a tendency of larger dimension on the top of the channel compared to mid and bottom. Performing a trapezoidal shape regularly (shown in Fig. 13), which it was proved statistically. Performing the ANOVA analysis independently, it resulted that at all levels of the channel was affected by the depth of cut per pass may caused the deflection of the tool, producing irregular micro channels.

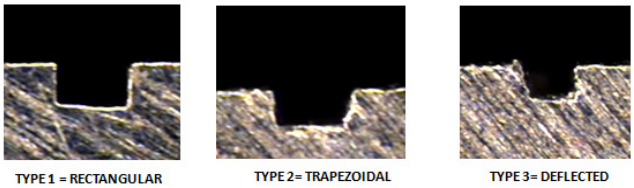


Fig. 13 Common Categorized Profiles in Al Alloy

- The dimensional error in depth was 8.34% and 11.89% in width.

B. AISI 316L

- The roughness ranged from 0.022-0.5840 μm. The AISI316L recorded the minimal roughness measurements of all three materials.
- The mean burr evaluation was 3.31 out of 5 (being 5 the ideal). Out of all the three materials the steel was the material with less burr formation on the channel edges.
- The depth of cut per pass was most influencing factor to minimize the top burr formation of the micro channels (Fig. 14). The minimal burr formation was with a 2 μm depth of cut per pass.

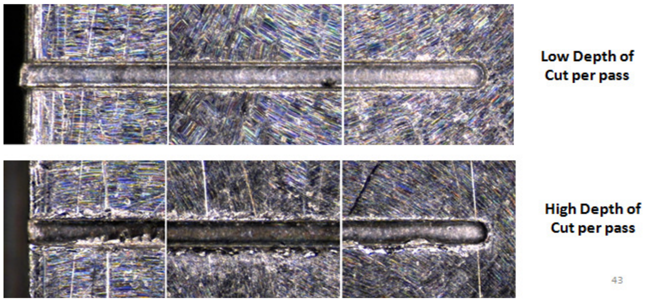


Fig. 14 Depth of cut per pass influence in burr formation of AISI316L

- The use of coolant is the most important factor to consider in order to minimize the roughness (Fig.15). It's evident the strong coolant influence, as in all cases in wet level of coolant the roughness is at the minimal.

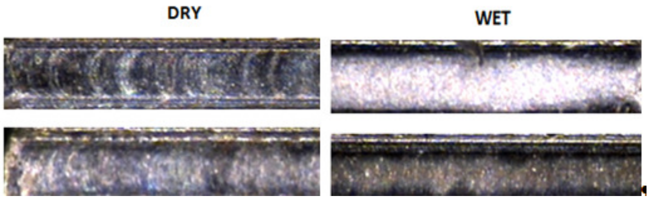


Fig. 15 Coolant application for minimizing roughness in AISI316L

- The dimension at three different levels on the channel (top, middle and bottom) can give a basic explanation of the shape of the profile of the channel. It was found a tendency of larger dimension on the top of the channel compared to mid and bottom. Performing a trapezoidal shape regularly, as shown in Fig. 16.

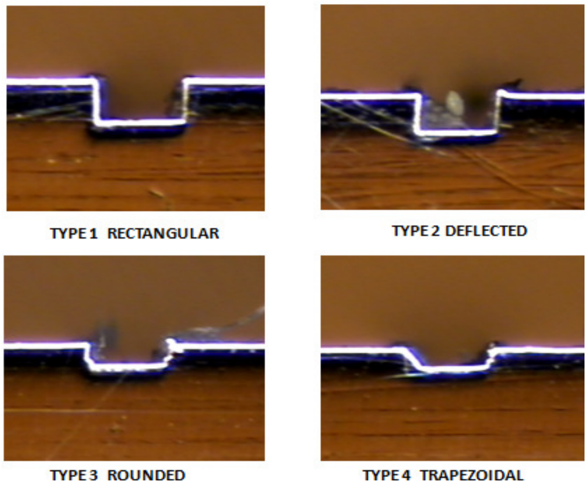


Fig. 16 Common Categorized Profiles in AlSI316L

- The dimensional error in depth was 4.98% and in width 11.80%. The steel give the most accurate dimensional depth measurements above all and an influence of more deviated measurements were found on less depth channels.
- The dimension of the channel also affected the middle level width, which it can be said that in smaller channels (50 μm) the problem of deflection it's more visible. This is validated by the images in which it can be seen a greater deformation of the material on small channels.
- The channels width measurements where is always less than the nominal radius of the tool. It can be inferred that the tool real diameter was smaller than 200 μm.

C. TI6AL4V

- The roughness ranged from 0.043-0.574 μm.
- The mean burr evaluation was 3.125 out of 5 (being 5 the ideal).
- The depth of cut per pass was most influencing factor to minimize the top burr formation of the micro channels (Fig.17). The minimal burr formation was with a 2 μm depth of cut per pass.

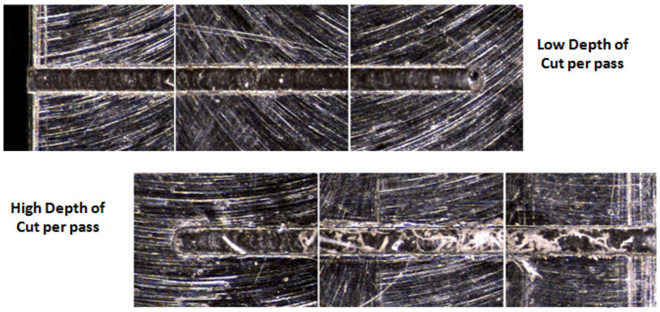


Fig. 17 Depth of cut per pass influence in burr formation of Ti6Al4V

- The burr formation was also described by the tool wear, as it can be seen on the time series graphs where the trend is negative as the use of the tool increases.
- A low of depth of cut per pass accompanied by a high feed per tooth can minimize the roughness (Fig. 18).

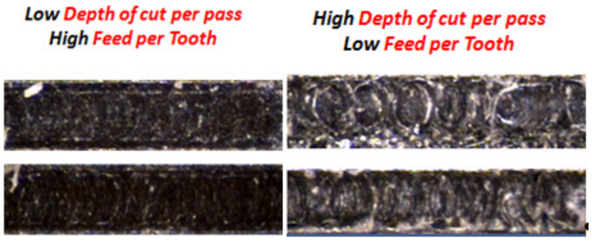


Fig. 18 Depth of cut per pass and Feed influence in surface roughness of Ti6Al4V

- In the evaluation of the Titanium workpiece, a statistical difference was founded only on the bottom level on the channel; in the upper and middle level of the channel statistically satisfied the nominal measurement of 200 µm, being the always the lower level of the channel the smallest dimension. Being Titanium the material with the most regular profiled shape channel (See Fig. 19).

Fig. 19 Common Categorized Profiles in Ti6Al4V

- The dimensional error in depth was 11.62% and in width 5.33%. The titanium reversed the error percentages giving the most accurate width measurement above all.

4. DISCUSSION

- All the materials top burr formation were affected by the depth of cut. Lekkala et. Al [24], realized a similar experiment on Al alloy and stainless steel in which the ANOVA analysis also showed the same trend on significant influence of DOC on the burr formation, proposing vibrations as the possible explanation. But on the contrary, in its study stainless steel burr appeared in larger than in the aluminum.
- In the case of Ti6Al4V, the burr formation was minimized by a lower DOC (2µm), contrasting in a study of Schueler [25] applying the same DOC massive burrs formations occurred. Literature assures that as the depth of cut increases, the tool is pushed further beneath the surface of the work material; this would in turn impress the grooves on the surface being machine because of the increased cutting load.
- Bisacco et al. [2], highlighted the ploughing phenomenon, that could explain the behavior of Ti versus burr formation where it ocurred a plastical deformation when the depth of cut was lower than a critical chip thickness. Kim et al. [26] classified the deformation in two types, the forced deflection of the tool and the elasto-plastic deformation of the work-piece material
- The burr formation in all materials can also be explained by the tool wear which is one of the most important aspects of machining. As in Lee et al. and Schmidt [27-28], the burr size in stainless steel was related to the amount of tool wear. If built-up edge is encountered on the tool, the tool can continue to cut for a long time without wear, but affecting the dimensions.
- In Ti6Al4V, the roughness was minimized by a lower depth of cut per pass (2µm) and high feed rates (25 & 30 mm/min); which can be explained that with a cutting depth so small and high load, the material cutting does not exist any longer, only deforming the material plastically, making ploughing of the material.
- These results are supported by studies conducted by Yang and Chen [29], which encountered that an increase of the depth of cut worsens the surface roughness, these were also similar to Ginta et al. [30] as varying cutting conditions in the same Ti alloy (Ti6Al4V). Korkut and Donertas [31], even stated a linear model where the increase on depth of cut, increased the surface roughness.
- Run out it's another issue with greater impact in micro machining. Due to the lower strength in the micro tool, causing less stiffness and vibrations, generating higher roughness or deflection of the tool. The deviation of the desired shape of the profiles can be due to this phenomenon creating a tool deflection, greatly affecting the chip formation and accuracy.
- According to Dornfeld [3], a typical flood of coolant is generally not suitable for micro machining. First, because the flow pressure may influence the cutting tool behavior and the removal of excess working fluid after micro machining is challenging. However, in the present experiments the presence of coolant was strongly proposed to minimize the roughness, clearly seen in all three materials.
- Muthukrishnan et al. [32], shows the influence of coolant in micro milling of Ti6Al4V. Their results validated the present results showing better roughness in wet machining as, with coolant prevents the formation of built up edge which damaged the surface.

5. CONCLUSIONS

In the present study, dimensional features and surface finishing in burr and roughness were evaluated as a result of micromilling materials as Aluminum, Steel 316L and Ti6Al4V. Results suggest that micro milling offers a process capable of offering quality features required on the microfluidic devices (all three applications). The conclusion remarks from the present research study can be summarized as follows:

- The surface roughness determines the microchannel flow capability because it helps to describe its effect in the friction and pressure behavior of the fluid. The literature focuses on the heat transfer evaluation by roughness; however the present contributes with the manufacturing sight of the parameters needed in micro-milling to obtain the desired roughness, dimensions, profile shape and an appropriate surface by the burr formation analysis.

- In general, the better surface quality in terms of burr formation and roughness was obtained with AISI316L, although Ti6Al4V had the best behavior for the formation of the geometric rectangular shape profile.
- There is a general affinity in the machining process of developing v-shaped microchannels non-conforming with the appropriate rectangular profile desired. A further research is needed to better understand the behavior of the tool with the material, since this deviation affects the heat and fluid flow.
- In all three workpieces, the burr formation can be controlled by a low depth of cut per pass.
- Titanium, surface quality is entirely defined by using lower depths of cut per pass.
- The application of coolant was critical to get a better quality superficial features which avoided the built up edge formation and heating of the material.
- A low depth of cut per pass (2μm) will minimize the burr formation in all materials, and it influence also the accuracy on the dimensional measurements.
- The dimensional measurements give us the idea of the profile formed. The deviated shapes, encountered there trapezoidal, regular and deflected. These profiles can be explain by the possible run out of the tool, tool wear and built up edge.
- The milling centre showed an adequate performance for prototyping microfluidic devices, even accomplishing the industrial requirements.
- Critical phenomena encountered like run-out, ploughing, minimum chip thickness and tool wear explained the deviations in the form, dimensions and diminishing of surface quality on the micro channels.

ACKNOWLEDGEMENTS

Authors would like to express their gratitude to IREBID: FP7-PEOPLE-2009-IRSES-247476 for financing this research work. This study was supported by CONACYT, Mechanical and Industrial Engineering Department of the University of Brescia and the Center for Innovation in Design and Technology from Tecnológico de Monterrey.

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