A Comparative Study on the Micromachining Performance of Copper, Brass, and Aluminum

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Abstract

Besides steel, aluminium, brass, and copper are the three most frequently used engineering materials for various applications. Because of the ease of machinability and excellent mechanical and electrical properties, these materials are extensively used in manufacturing of micro-scale parts and components for the electronics and packaging industries. Micro-milling is the most popular machining process for fabricating micro-parts and components with excellent surface finish and dimensional accuracy. In this study, the authors investigated the micro-machining performance of copper, aluminium, and brass under the micro-milling process based on the machined surface quality at optimum machining speeds. The comparative machining performance study was conducted by machining reverse pyramid-shaped micro -features in all three materials using the same parameter settings. The objective during the trial-and-error experiments was to achieve the highest possible machining speed for different materials without any tool breakage.

In order to compare the performance, a suitable parameter setting was identified at which all three materials could be machined successfully at the maximum possible speed without any tool breakage. The surface quality of the machined slot was evaluated qualitatively, based on the surface finish of the slot, burr formation around the edges of the slots, and presence of any surface defects. The tool surface after machining was also evaluated for differences in tool wear for machining aluminium, copper, and brass. It was found that aluminium and brass could be machined at comparatively higher cutting speeds and depth of cut compared to copper. There was more frequent tool breakage when machining copper at higher speeds and depth of cut, due to the ductility of copper resulting in adhesion of materials around the tool edge. Brass was found to be comparatively easier to machine, due to the smaller chips generated and no visible adhesion to the cutting tool. At the same parameter settings, brass was found to generate a better surface finish with smooth edges and fewer surface defects compared to copper and aluminium. Finally, a feed rate of 30 mm/min, depth of cut of 0.3 mm, and a tool rotational speed of 2800 rpm were found to provide successful machining in three materials without any tool breakage, in addition to providing acceptable surface finish.

Introduction

In recent years, micro-scale devices and components made of different materials have become an integral part of many plastics, electronics, and semiconductor industries. Among the various manufacturing processes, machining is a well-established process used extensively in these industries for fabricating parts and components [1-4]. Micro-milling is one of the sustainable micro-machining processes that are used for manufacturing three-dimensional (3D) features on metals and ceramics [5-9]. Micro-milling is able to produce high material removal rates (MRR) and achieve high-quality surface finishes and dimensional accuracy with a new generation of miniaturized machine tools [9]. Because of the acceptable performance and reputation of mechanical micro -machining, various research studies have been conducted on the micro-milling processes and improvement of productivity in micro-milling. Several researchers have investigated the differences between conventional milling and micro-milling processes in terms of productivity [10], [11].

While conventional milling and micro-milling are operationally the same, the basic and essential differences between these processes are due to scale of operation [10], [11]. Özel et al. [10] evaluated the ratio of feed per tooth to radius of the cutter in both types of milling and concluded that it is much greater in micro-milling than conventional milling. The formation of the burr at the end of a cut is a similar phenomenon to chip formation. Burrs are unwanted because they can affect further assembly operations. Therefore, burrs should be removed in a de-burring process [12]. The burr removal process can be more easily applied to conventional milling than micro-milling. The de-burring process in micro-milling machining is very hard, as burr removal could harm the workpiece. Recently, micro-milling has been miniaturized to as small as 20 µm; as such, the conventional de-burring process cannot be conveniently applied to the micro-burrs. The scaled-down end mills and conventional machine tools have the same cutter geometries. Lee et al. [12] investigated the size and type of burrs formed in aluminium 6061-T6, stainless steel 304, and copper 110. They looked at five different types of burrs formed during processing such as entrance-side burrs at the down-milling side, top burrs from up- and down-milling, exit burrs at the bottom of the slot, and exit-side burrs at the up-milling side [12]. These kinds of burrs were important in the micro-milling process, because they could help the investigation of cutting parameters on burr formation.

There have been several research studies on the micro-milling of aluminium, copper, and brass, individually. Chu [13] conducted a series of experiments on micro-milling of aluminium 6061-T6 to study burr formation. He found that large feeds per tooth were responsible for large burrs in the feed direction, and that the cutting speed did not have an effect on burr formation. Mougo et al. [14] investigated the effect of the width of cut on the micro-milling performance of aluminium. They varied the width of cut to identity the influence of the minimum chip thickness on the resultant forces, and reported that width of cut lower than the tool diameter generated lower cutting forces and produced smoother surface finishes with fewer burrs. Liu and Wang [15] developed a new technology, micro-turn-milling, and applied it in the machining of aluminium alloy 2A12. It was reported that the surface roughness of micro-turn-milling was close to micro-turning and the surface profile of up-turn milling was better than that of down-turn milling. Monroy-Vázquez et al. [16] compared the superficial and dimensional quality of micro-features machined in aluminium, titanium alloys, and stainless steel. They reported that the micro-milling process was capable of offering quality features required on the micro-channeled devices. However, they also found that, among the three materials, stainless steel produced better surface quality in terms of burr formation and surface roughness.

Huo and Cheng [11] performed a series of experiments on micro-milling of oxygen-free, high-conductivity copper using tungsten carbide (WC), chemical vapour deposition (CVD) diamond, and single-crystal diamond micro-milling tools of 0.4 mm diameter. The purpose of the research was to study the influence of cutting parameters such as feed rate, cutting speed, and axial depth of cut on burr formation and surface roughness. Those authors reported that the optimal feed rate induced the best surface roughness. Filiz et al. [17] conducted a series of tests on 99.99% pure copper using the micro-milling process. Four feed rates (0.75, 1.5, 3, and 6 μm/flute) and three cutting speeds (40, 80, and 120 m/min) were considered for that study. It was found that the most important parameters in micro-milling were spindle speed, feed rate, and feed per tooth, which have a significant influence on micro-milling machining performance [17]. Prakash et al. [18] evaluated the effects of various parameters: axial depth of cut, cutting speed, and feed rate on tool life and flank wear. They found that feed rate did not influence tool life or flank wear; whereas, the depth of cut and cutting speed were effective on flank wear. Another study was performed by Mayor and Sodemann [19] to identify optimal parameters for maximum tool life. During that study, the authors used 100 μm end mills necked to 600 μm, with the workpiece under flood-like applications of an oil-based cutting fluid. The axial depth of cut and feed rate were varied with other parameters held constant, including radial depth of cut. The mean and variance calculated for each set of parameters and analysis of variance were performed. The analysis of variance revealed that tool life had a significantly stronger correlation with cutting parameter variations and maximum material removal from a distance or time [19].

Fard and Bordatchev [20] used the micro-milling of brass on ball-end mills to investigate the influence of tool direction on final surface geometry and quality in five-axis micro-milling. According to their findings on final surface geometry, changing the tool orientation can decrease the rubbing of the material at the bottom of the grooves. It was observed that the surface roughness at the bottom of the grooves improved significantly when a tool inclinational angle of 15 degrees was used in micro-milling. Similar findings were reported by the Copper Development Association [21], in which they suggested that the clearance behind the cutting edge should be enough to prevent a rubbing or burnishing action as an overall rule for copper alloys. Typically during micro-milling, having too much rake or clearance angle at high speeds produces extreme vibrations and digging in the workpiece [21]. Liu et al. [22] investigated micro-milling of brass to study the existence of minimum chip thickness. They conducted a comparative study between normal chip volume with different feed rates and brass chips with specific feed rates. They found that for low feed rates, the measured chip volume was much larger than the supposed chip volume, which showed that a chip could not be shaped with each pass of the cutting tooth. They also concluded that the chips were not formed with each pass of the tool. Egashira and Mizutani [23] investigated the micro-scale machinability of brass using both micro-drilling and micro-milling processes with a 10 μm diameter tool. They were able to drill micro-holes of 50 μm and micro-slots of 100 μm (length) x 20 μm (width), and reported that micro-features can be machined successfully in brass using both micro-machining processes.

Although there has been extensive research on the micro-milling of aluminium, brass, and copper, most of those studies have focused on machining performance of a single material. As all three materials are widely used in the micro-milling process, a comparative study on the machining performance of three materials will provide helpful insight and guidelines in the selection of suitable materials for different applications. Therefore, the authors of the current study conducted a comparative experimental investigation on the machining performance of copper, brass, and aluminium for machining micro-slots. The machining performance was evaluated in terms of machining speed, surface finish of the micro-slots, tool breakage, tool wear, and burr formation. An optimal parameter setting was identified that would provide improved machining performance for all three materials at the highest possible speed with considerably better surface finish and without tool breakage.

Experimental Detail

A desktop micro-milling machine tool from "Denford" was used in this study to perform the experiments. The desktop milling machine was a compact, 3-axis CNC milling machine with totally enclosed interlocking guards. Figure 1 shows a photograph of the MicroMill with its different components. Variable spindle speeds and feed rates make the MicroMill ideal for cutting resistant materials such as wax, plastic, acrylic, aluminium, and free-cutting alloys. The travels of the machine bed in the X, Y, and Z directions were 228 mm, 130 mm, and 160 mm. The maximum values of spindle speed and feed rate were 2800 rpm and 750 mm/min, respectively. In this study, the depth of cut and feed rate were varied, while keeping the spindle speed at its maximum value 2800 rpm. As the higher cutting speed provides faster machining and the rotational speed of this desktop machine was limited, the maximum spindle speed was used. In order to machine copper, brass, and aluminium workpieces, tungsten carbide cutting tools with a diameter of 0.8 mm were used. Table 1 shows the machining conditions used in this study. After machining the micro-slots, the cutting tools were investigated using digital, reflected light, and scanning electron microscopes. Table 2 shows the sets of machining parameters used in this study and the comments on whether they resulted in successful or unsuccessful machining of a pyramid in copper, brass, and aluminium.

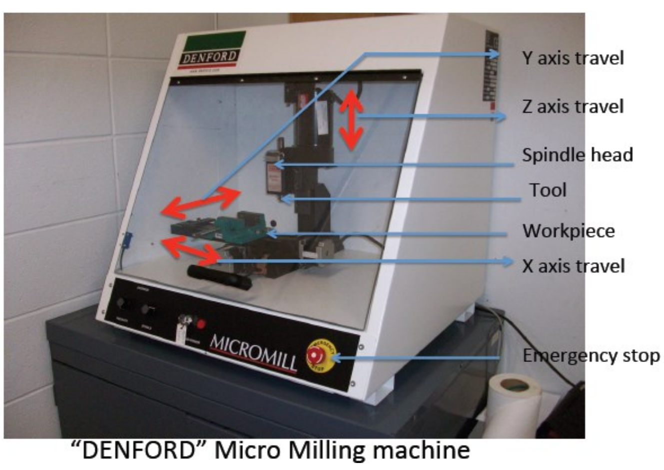


Figure 1. Photograph of the Desktop Micro-milling Machine Used in This Study

Table 1. Machining Conditions Used for Micro-milling of Aluminium, Copper, and Brass

Workpieces	Copper, Brass, Aluminium
Cutting tool	Tungsten Carbide (ϕ 1/32 inch or 0.8 mm)
Coolant	No coolant
Feed rate (mm/min)	20, 30, 40
Depth of cut (mm)	0.2, 0.3, 0.4
Spindle speed (rpm)	2800 (max. capacity)

Table 2. Sets of Machining Parameters Used on a Trial-and-error Basis and Their Outcomes

Run	RPM	Feed Rate	Depth	Cutter	Material	Successful
1	2800	40mm/min	0.4mm	0.8mm	Al	No
2	2800	30mm/min	0.4mm	0.8mm	Al	Yes
3	2800	30mm/min	0.4mm	0.8mm	Cu	No
4	2800	20mm/min	0.2mm	0.8mm	Cu	Yes
5	2800	30mm/min	0.2mm	0.8mm	Cu	Yes
6	2800	20mm/min	0.2mm	0.8mm	Brass	Yes
7	2800	30mm/min	0.2mm	0.8mm	Brass	Yes
8	2800	30mm/min	0.4mm	0.8mm	Brass	Yes
9	2800	40mm/min	0.4mm	0.8mm	Brass	No
10	2800	30mm/min	0.3mm	0.8mm	Brass	Yes
11	2800	30mm/min	0.3mm	0.8mm	Al	Yes
12	2800	30mm/min	0.3mm	0.8mm	Cu	Yes

Results and Discussion

Effect of Operating Parameters

In this study, the experiments were designed on a trial-and-error basis in order to determine a set of machining parameters for successful micro-milling of copper, brass, and aluminium. A reversed pyramid containing four square-shaped micro-channels was designed using CAD with the respective CNC codes generated such that the machine would run automatically. The objective was to identify a set of machining parameters that could successfully machine the materials at possibly higher machining speeds with improved surface finish. For all three materials, the machining conditions providing the highest possible productivity without any tool breakage, as well as the smoothest and most burr-free surface were identified. Table 2 shows the machining conditions of the 12 experimental runs used sequentially to find the most successful and optimum parameter settings for the micro-milling of copper, brass, and aluminium.

The primary objective of this current study was to identify parameters for successful machining of three materials at the highest possible speeds. Therefore, the rotational speed of the tool was set at the maximum capacity of the low-powered desktop micro-milling setup. As can be seen, the experiments started with the selection of the higher settings of depth of cut and feed rate, 0.4 mm and 40 mm/min, respectively. It can also be seen from run numbers 1 and 9 (see Table 2) that the parameter settings of 2800 rpm, 0.4 mm d.o.c., and 40 mm/min were not able to complete the machining of all of the slots successfully in aluminium and brass. Figures 2 and 3 show the optical images of the machined surfaces and cutting tools for machining aluminium and brass using settings of 2800 rpm, 0.4 mm, and 40 mm/min. Each figure includes the image of the target pyramid, a magnified image of the individual micro-slots, and an image of the cutting tool showing tool wear/breakage. It can be seen that the selection of a high depth of cut and feed rate was able to complete three out of four micro-slots successfully in aluminium, compared to two in brass. The topography of the individual slots in aluminium were also found be to better, when compared to those of brass as shown in Figures 2 and 3.

The machined surface of the individual slots in both aluminium and brass workpieces showed feed marks from the cutting tools, in addition to some form of surface defects. The burrs formed around the edge of the slots were found to be very irregular and rough. One common trend was observed in the failure of the cutting tool. For the machining of both aluminium and brass, the cutting tool was found to break in the middle of machining. This suggests that there was some reduction of tool sharpness while machining at the higher feed rate and depth of cut. The chipping from the cutting tool face can be confirmed from both Figures 2 and 3. For both cases, the tool wear mechanism was almost similar.

On the other hand, copper was found to be more difficult to machine, even at lower settings. As can be seen from Figure 4, an experimental run with spindle speed (s.s.) = 2800 rpm, f = 30 mm/min, and d.o.c. = 0.4 mm (run #3 in Table 2) was unable to complete the feature with five micro -slots. The cutting tool broke at the middle of the third slot (see Figure 4). Moreover, it can be seen from the image of the cutting tool that the wear mechanism of the cutting tool was also different for micro-milling of copper compared to that of aluminium and brass. Unlike cutting tool wear for machining aluminium and brass at higher settings of federate and depth of cut, no chipping from the cutting tool surface was observed in the cutting tool during the machining of copper. Instead, the cutting tool became very blunt, thus breaking the cutting tool tip. This was probably due to the higher amount of adhesion of the chips to the tool tip that prohibited the sharper cutting surface to come in contact during machining.

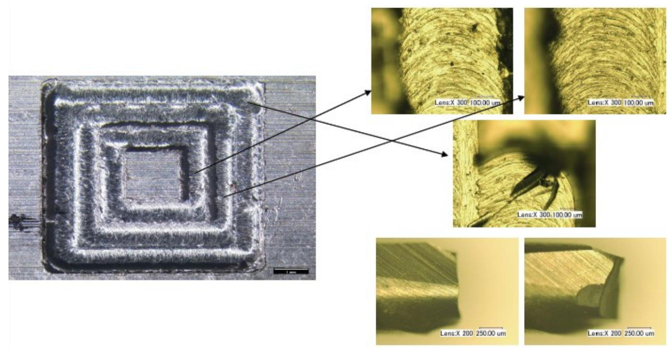


Figure 2. Machining of Aluminium at f = 40 mm/min, D.O.C. = 0.4 mm (Run #1 in Table 2): Image of Pyramid Shaped Structure (at left), and the Magnified images of Micro Slots (top right), and Cutting Tool (bottom right)

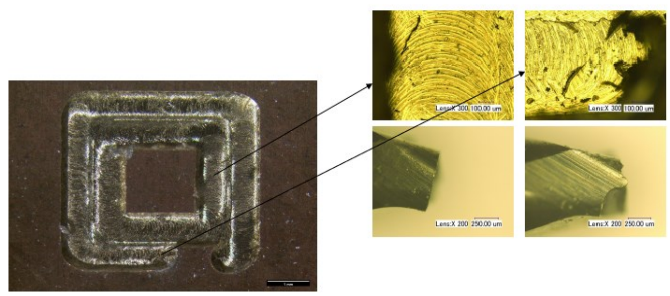


Figure 3. Machining of Brass at f = 40 mm/min, D.O.C. = 0.4 mm (Run #9 in Table 2): Pyramid Shaped Structure (at left) and Micro Slots and Cutting Tool (at right)

As copper is known to be very ductile, the heat generated during the dry machining of copper caused the copper chips to get attached to the cutting tool edges. As a result, the sharp cutting edge could not come in contact with the workpiece, resulting in breakage of the cutting tool. In addition, the chips were also found to get attached to the machined surface, due to the high ductility of copper, as can be seen from Figure 4. Besides the burrs at the edges, there was some adhesion of chips on the micro-slot surface for all of the individual slots. The chip analysis described in the following section also supports the adhesion of chips on the cutting tools and machined surface during the machining of copper.

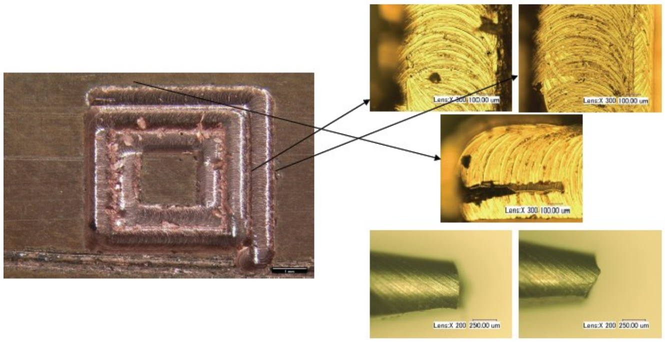


Figure 4. Machining of Copper at f = 30 mm/min and D.O.C. = 0.4 mm (Run #3 in Table 2): Pyramid-shaped Structure (at left) and Micro-slots and Cutting Tool (at right)

Although an experimental condition of s.s. = 2800 rpm, f = 30 mm/min, and d.o.c. = 0.4 mm were not able to machine copper successfully, it was able to machine both aluminium and brass without tool failure (see Figures 5 and 6). It can be seen from Figures 5 and 6 that between the two materials, brass provided a comparatively smoother surface on the micro-channels. There was burr formation around the edges of the micro-channels in both the brass and aluminium workpieces. No significant tool wear was observed in the tungsten carbide tool after machining four 5 mm x 5 mm square micro-slots in the brass workpiece. On the other hand, some adhesion of chips around the rake face of the cutting tool was observed after machining the same number of micro-slots in aluminium.

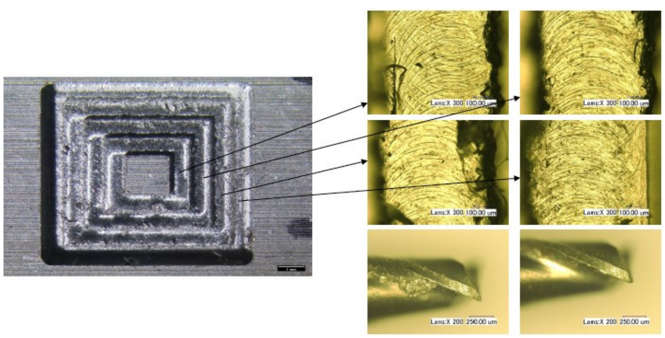


Figure 5. Machining of Aluminium at f = 30 mm/min and D.O.C. = 0.4 mm (Run #2 in Table 2): Pyramid Shaped Structure (at left) and Micro Slots and Cutting Tool (at right)

In order to obtain better surface finishes, the feed rate and the depth of cut were reduced to 20 mm/min and 0.2 mm without changing the spindle speed. It was found that the surface quality was improved significantly. It can be seen from Figures 7 and 8 that the machined slots had fewer burrs in both copper and brass. In addition, no significant tool wear was observed for machining both materials at the setting of 2800 rpm, 20 mm/min, and 0.2 mm. Brass produced a smooth and defect-free surface with fewer burrs around the edges. Although copper produced a comparatively poorer surface finish at 20 mm/min and 0.2 mm, the surface finish improved by increasing the feed rate one step. Figure 9 shows the improved surface finish of the slots, while machining copper at f = 30 mm/min and d.o.c. = 0.2 mm. On the other hand, increasing the feed rate to 30 mm/min, while keeping depth of cut unchanged at 0.2 mm during machining of brass (see Figure 10), resulted in a slight deterioration of the machined surface. This phenomenon can be explained by copper's higher ductility. Due to the higher ductility of copper, very low feed rates were not able to generate a smoother surface, whereas moderately higher feed rates at a lower depth of cut could generate better surface finishes during micro-machining of copper.

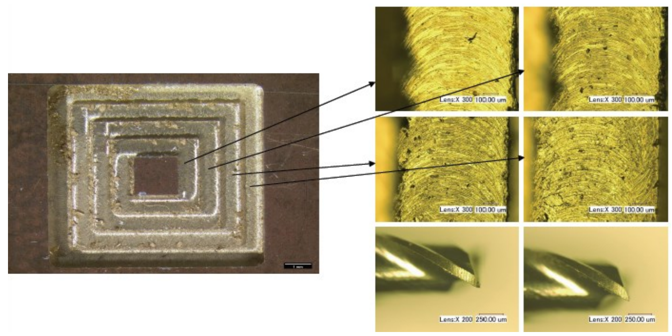


Figure 6. Machining of Brass at f = 30 mm/min and D.O.C. = 0.4 mm (Run #8 in Table 2): Pyramid Shaped Structure (at left) Micro Slots and Cutting Tool (at right)

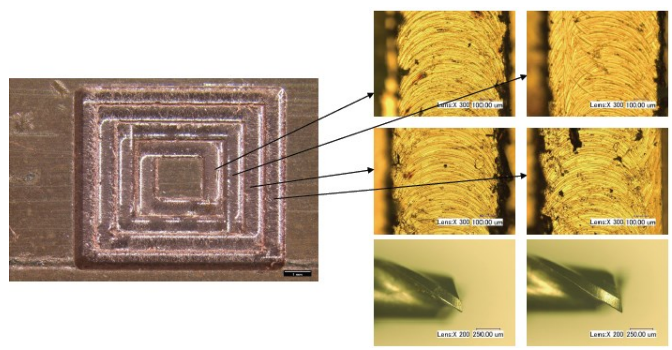


Figure 7. Machining of Copper at f = 20 mm/min and D.O.C. = 0.2 mm (Run #4 in Table 2): Pyramid Shaped Structure (at left) Micro Slots and Cutting Tool (at right)

Finally, it was found that all three materials could be machined successfully without any tool failure via any combination of parameters up to a feed rate of 30 mm/min and a depth of cut of 0.3 mm. It was found the surface finish of the micro-slots in copper started to deteriorate at the settings of 2800 rpm, 30 mm/min, and 0.3 mm (see Figure 11), whereas the surface quality of slots were still acceptable in brass and aluminium (see Figures 12 and 13). Therefore, considering all the performance parameters, a spindle speed of 2800 rpm, f = 20 mm/min, and D.O.C. = 0.2 mm were found to be the optimum parameters capable of machining all three materials successfully with less burr formation and a defect-free surface finish. Copper was able to generate slightly better surface finishes at 2800 rpm, f = 30 mm/min, and D.O.C. = 0.2 mm, whereas brass and aluminium were found to produce slightly poorer quality surface finishes compared to those produced using the optimum parameters noted above.

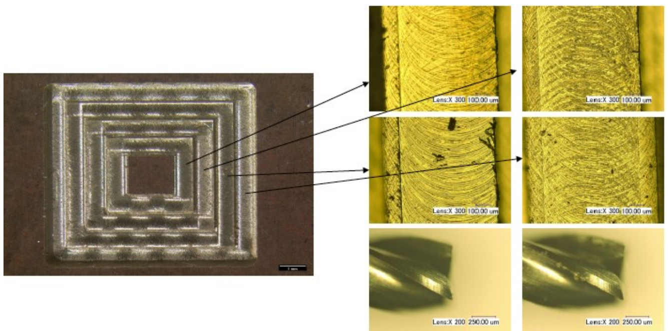


Figure 8. Machining of Brass at f = 20 mm/min and D.O.C. = 0.2 mm (Run #6 in Table 2): Pyramid Shaped Structure (at left) and Micro slots and Cutting Tool (at right)

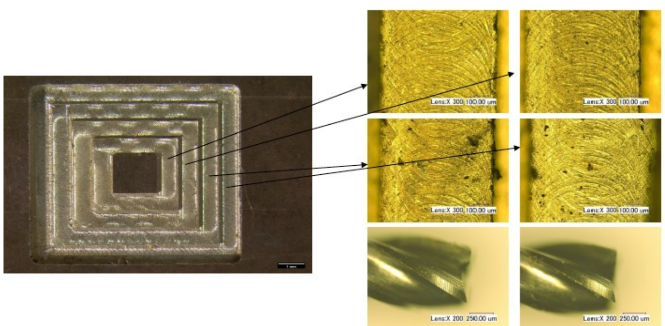


Figure 9. Machining of Brass at f = 30 mm/min and D.O.C. = 0.2 mm (Run #7 in Table 2): Pyramid Shaped Structure (at left) and Micro Slots and Cutting Tool (at right)

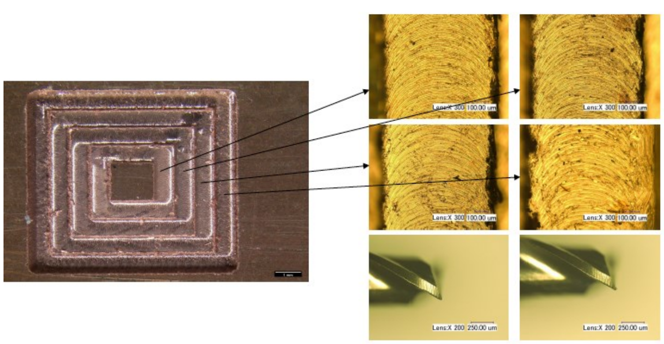


Figure 10. Machining of Copper at f = 30 mm/min and D.O.C. = 0.2 mm (Run #5 in Table 2): Pyramid Shaped Structure (at left) and Micro Slots and Cutting Tool (at right)

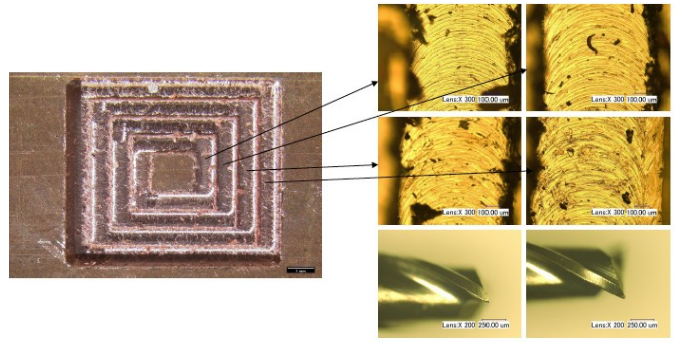


Figure 11. Machining of Copper at f = 30 mm/min and D.O.C. = 0.3 mm (Run #12 in Table 2): Pyramid Shaped Structure (at left) and Micro Slots and Cutting Tool (at right)

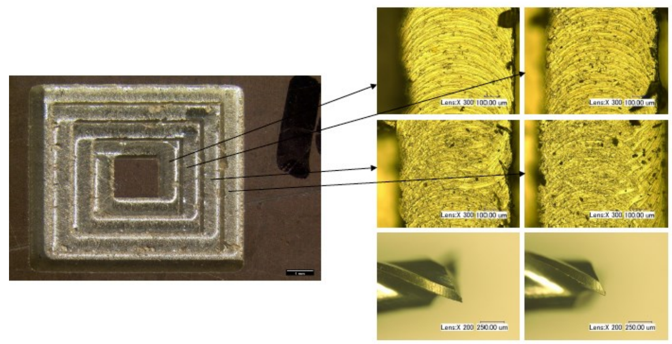


Figure 12. Machining of Brass at f = 30 mm/min and D.O.C. = 0.3 mm (Run #10 in Table 2): Pyramid Shaped Structure (at left) and Micro Slots and Cutting Tool (at right)

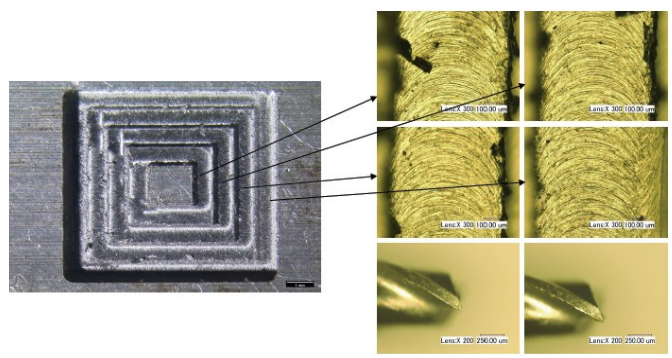
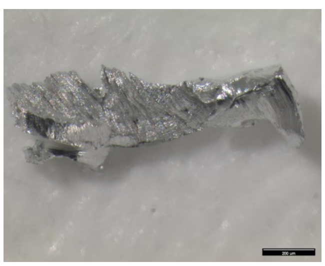


Figure 13. Machining of Aluminium at f = 30 mm/min and D.O.C. = 0.3 mm (Run #11 in Table 2): Pyramid Shaped Structure (at left) Micro Slots and Cutting Tool (at right)

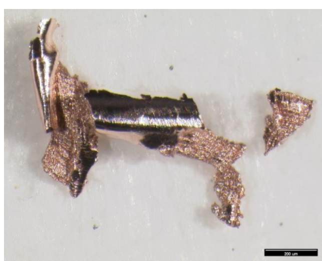
Study of Chip Morphology

In this study, the chips were collected at different settings of cutting parameters to investigate the chip morphology and correlation to surface finish and tool wear. It was observed that for almost all settings of parameters, the chips generated during the micro-milling of copper and aluminium were continuous type, whereas the chips produced during the machining of brass were mostly discontinuous type. Figure 14 shows the optical images of the chips formed at a tool rotational speed of 2800 rpm, f = 30 mm/min, and depth of cut of 0.3 mm. The most important reason for the continuous nature of chips in copper is its ductility. During the dry machining of copper at higher feed rates and depth of cut, a significant amount of heat was generated, due to the friction between cutting tool and workpiece surface. Due to this heat, the copper became more ductile, thus promoting the continuous chips with the travel of cutting tool along a path.

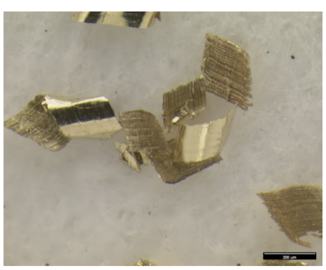
However, as more and more continuous chips were formed, they tended to attach to the cutting tool edge, due to the heat generated during the machining process. As a result, the sharp edges of the cutting tools could not come in contact with the workpiece surface, resulting in digging and rubbing actions rather than cutting. The rubbing and digging action of the cutting tool resulted in significant tool wear and/or tool breakage. This is why copper was found to be the most difficult material to cut in micro-milling using higher cutting speeds, feed rate, and depth of cut. On the other hand, discontinuous nature of chips during the micro-milling of brass made it suitable for successful machining at comparatively higher machining speeds.



(a) Aluminium



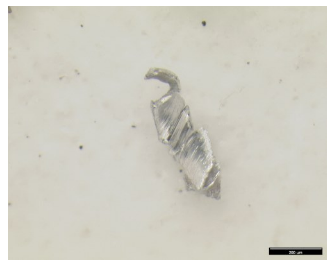
(b) Copper



(c) Brass

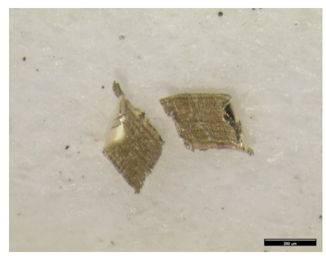
Figure 14. Optical Images of Chips Generated in Different Materials, while Machining at a Parameter Setting of Spindle Speed of 2800 rpm, f = 30 mm/min, and Depth of Cut of 0.3 mm

The chip morphology was also found to be influenced by the depth of cut. It was found that the continuity of the chips decreased with a reduction in the depth of cut, thereby reducing the chance of chip adhesion to the cutting tool. As a result, premature tool failure was significantly reduced at lower settings of depth of cut. With the reduction of the depth of cut, the chip became less continuous for all three materials. Although the chips formed in copper and aluminium were still found to be continuous, as can be seen in Figure 15, the adhesion of chips to the cutting tool was not common at reduced settings of depth of cut.



(a) Aluminium

(b) Copper



(c) Brass

Figure 15. Optical Images of Chips Generated in Different Materials at a Spindle Speed of 2800 rpm, f = 20 mm/min, and Depth of Cut of 0.2 mm

Conclusions

The following conclusions can be drawn from this experimental study of the micro-milling of copper, brass, and aluminum:

- Among the three different materials, brass produced the best surface finish, followed by aluminum and copper at the same parameter settings. Copper was able to produce comparable surface finishes at comparatively lower machining speeds, feed rates, and depth of cut.
- Brass was found to be more easily machined by maintaining improved surface finish at comparatively higher cutting speeds and depth of cut. Brass showed

good machinability in micro-milling, due to its discontinuous chip formation and minimum adhesion to the tool.

- Copper was found to be comparatively difficult to machine by micro-milling, due to the buildup of chips and adhesion of chips to the tool edges. The higher ductility of copper was found to be responsible for the poor machinability of copper.
- Tool wear and, hence, tool breakage increased with the increase of cutting speed and depth of cut for all three materials. With the increase of depth of cut and feed rate, more rubbing or digging action took place rather than cutting, resulting in more frequent tool breakage.
- The chips became more continuous at higher depth of cut for all three materials, increasing the chance of adhesion to the edge of the cutting tools. The adhesion phenomenon prohibited the sharp rake surfaces to come in contact with the workpiece, thereby increasing premature tool failure.
- The chip morphology analysis suggests that brass produces discontinuous types of chips during the micro-milling operation, making it better than copper and aluminum. However, by selecting appropriate machining parameters, copper and aluminum can also be machined with comparable surface finishes.

Future Research

This research provides useful information in the field of mechanical micro-machining and opens up the field for more extensive and in-depth research on micro- and nano-scale machining of these three materials. Future research should focus on the modelling of cutting forces for micro-milling of brass, copper, and aluminium and establish the co-relationship with this experimental investigation. An in-depth analysis of the findings of this study should be conducted by investigating the changes of materials at the atomic and molecular levels. The study of molecular structural changes of materials before and after machining could explain the machinability of the materials. In addition, the mechanical property changes of the materials at the micro- and nano-scale, due to machining, should also be investigated in future studies.

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