Process Capability of High Speed Micro End-Milling of Inconel 718 with Minimum Quantity Lubrication

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Abstract. The demand for micro-parts is expected to grow and micro-machining has been shown to be a viable manufacturing process to produce these products. These micro-products may be produced from hard-to-machine materials such as superalloys under little or no metal cutting fluids to reduce machining cost or drawbacks associated with health and environment. This project aims to investigate the capability of micro end-milling process of Inconel 718 with minimum quantity lubrication (MQL). Microtools DT-110 multi-process micro machine was used to machine 10 micro-channels with MQL and 10 more under dry condition while maintaining the same machining parameters. The width of the micro-channels was measured using digital microscope and used to determine the process capability indices, Cp and Cpk. QI Macros SPC for Excel was used to analyze the resultant machining data. The results indicated that micro end-milling process of Inconel 718 was not capable under both MQL and dry cutting conditions as indicated by the Cp values of less than 1.0. However, the use of MQL helped the process to be more stable and capable. Results obtained showed that the process variation was greatly reduced by using MQL in micro end-milling of Inconel 718.

1. Introduction

Micro-machining such as micro-milling machining is increasing applied in the production of micro-channels with dimensions below 1 mm as demands for 3-dimensional (3D) miniature components increase [1]. Micro-channel production is considered as an advanced technology and the market demand is very high considering the uses of these micro-products in electronic devices, medical devices and also in many miniature components and micro-parts of aerospace sector. The demand for parts and components made from so called super-alloys is expected to increase. Benefits of these materials may be taken advantage of in the manufacture of turbine engine, engines in energy sector, air-industry, cosmonautics, mining and for medical equipment. A synergy between the use of this class of materials and micro-machining may well be expected in the production of quality micro-products sought for now and more so in the future. One of these is Inconel 718 which is a high-strength, corrosion-resistive, precipitation hardened alloy which may be used in the temperature range from -252°C to +700°C in many applications [2].

In metal cutting processes both at conventional and micro levels, metal cutting fluids are required to serve as lubricants, coolants and chips flusher throughout a machining process [1,3]. High production machining typically generates high cutting zone temperature that might cause premature tool failure and wear [4]. Therefore the usage of cutting fluid is vital in order to keep the machining process running smoothly and ensuring a good work piece surface quality while prolonging the cutting tool life. Minimum quantity lubrication or MQL is the recent method used to deliver metal cutting fluids.
fluid to the tool-work interface. It was introduced to help reduce high machining cost as well as possibly eliminate health and environmental problems associated with the use of metal cutting fluids. On the extreme, dry machining may be carried out without using coolant or metal cutting fluid. In a review [3], MQL appears to be studied largely with the conventional machining processes and less with micro-machining processes.

While many studies were done on the use of MQL in machining process, smaller numbers were carried out on its use in micro-machining [1,3]. Those that did focused mainly on issues related to tool wear and surface finish [5,6]. In order to produce quality micro-products, stable and capable micro-machining processes are critical. There is a need to investigate characteristics of micro-machining processes such as the micro end-milling in terms of its stability and capability. To improve our understanding in this aspect, the process capability study was carried out on micro end-milling of Inconel 718 under MQL and dry cutting conditions.

2. Experiment
In this study, straight micro-channels were machined on Inconel 718 using micro end-milling available on Microtools DT-110 Integrated Multi-Process machine (see Figure 1). Ten (10) micro-channels were machined with a minimum quantity of Accu-Lube LB-2000 (LB-1) lubricant supplied by a Bluebe FK MQL system. Another set of 10 micro-channels was machined under dry cutting condition. Two-flute tungsten carbide end-mill cutters with diameter of 0.8 mm and nose radius of 0.1 mm were used. Table 1 provides the machining parameters used for both MQL and dry cutting conditions.

The width of each micro-channel was measured using a digital microscope with 400X magnification. Measurements were carried out at three (3) places along the length of each micro-channel and the average was calculated. QI Macros for Excel was used to analyze the results and determine the process capability.

3. Results and Discussion
The mean and standard deviation of the micro-channels for MQL and dry cutting conditions were 795.38 µm and 4.22 µm and 793.12 µm and 9.10 µm respectively. The mean width of the micro-channels machined under MQL cutting condition was closer to the targeted value of 800 µm that that under dry condition. Using the process capability of ± 5 µm during fabrication of micro-channels using a chemical etching method [7], the results clearly indicated that using MQL condition improved the capability of micro end-milling process of Inconel 718 in terms of accuracy and precision.

Figure 2 and 3 below showed the control charts developed for the machining process under dry machining and MQL conditions respectively. Machining under dry condition seems to be relatively less stable than under MQL condition as shown by the general downward trend in Figure 2. Both charts indicated the progressive wear of the cutters. However, the wear of the cutter used in dry machining of the workpiece appeared to be higher.

Dispersion in the width values of micro-channels machined under dry condition was found to be higher as indicated by the broader distance between the control limits in Figure 2. This serves as an evidence of a more consistent micro end-milling process when carried out using MQL.

The frequency distribution in Figure 4 obtained for dry cutting machining process indicated that 5 micro-channels were within the specification limits while the remaining 5 were out of tolerance. In the case of MQL, 7 out of 10 micro-channels were within the specification limits as indicated in Figure 5. The values of Cp for dry cutting and MQL conditions are 0.17 and 0.36 respectively. Values below 1.0 are indicative of incapable processes [8]. There are numerous factors that may contribute to the capability of a micro-machining process. However, based on apparently equal machining parameters, micro end-milling process of Inconel 718 using MQL was shown to be more capable. This may be explained by the lubricating effect presence hence resulting in less cutter wear.
Table 1. Experimental parameters

| Parameters            | Level   |
|-----------------------|---------|
| Depth of Cut (mm)     | 0.15    |
| Feed Rate (mm/min)    | 2       |
| Spindle Speed (rpm)   | 28,000  |

Figure 1. Micro Milling Setup with MQL

Figure 2. X-Bar chart for dry machining
Figure 3. X-Bar chart for MQL machining

Figure 4. Frequency distribution for dry machining
Figure 5. Frequency distribution for MQL machining

The centering of the machining process as indicated by the values of Cpk needs to be investigated further. Many factors may affect the stability of cutter during the machining process which may include vibration and machine dynamics. Further studies need to be carried out to focus on the factors affecting the capability hence quality of this increasingly important class of manufacturing process.

4. Summary
Micro-channels on Inconel 718 have been successfully machined using high-speed micro end-milling and the width of the micro-channels has been measured and analyzed using statistical process control tools. From the study the following may be concluded:

- Micro end-milling of Inconel 718 using MQL resulted in a more stable and consistent process as indicated by much smaller process dispersion compared to machining under dry cutting condition.
- Micro end-milling of Inconel 718 using MQL and under dry cutting condition were both shown to be incapable which may be attributed to numerous factors. However, the use of MQL clearly helped to make the process to be more capable.
- More studies need to be carried out in order to improve the understanding on significant factors affecting the capability hence the quality of the micro-machining processes.

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