Experimental Study on Cutting Force Comparison between Inner Cooling and Outer Cooling in Zig-zag Milling

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Abstract. The cutting force is a key factor that affects the milling performance. The performance of a kind of inner cooling mill with double straight channels developed by us was testified with an index of cutting force. Zig-zag milling experiments were done on CNC milling machine. Cutters with different diameters were carried out at different speeds for inner cooling and outer cooling. The average peak cutting forces per tooth were picked up. The results showed that forces of the outer cooling had been greater than that of inner cooling, and the bigger of the cutter, the more significant of their comparison, which means that inner cooling should be better than outer cooling, and the performance of the cutter was worthy. This work might play important roles in various cutting manufacturing factories and in milling research where inner cooling milling could be used instead of outer cooling.

1. Introduction

The inner cooling method in which we apply the cutting fluid by an internal channel of the tool on the work piece, is an excessive way to save the cutting fluid.

Inner cooling can be used for machining especially when the cutting depth exceeds 3mm. In inner cooling experiment researches, different tool structures (double straight channel, single straight channel and double helical channel) were used to check the cutting forces and tool wear on side milling, the results showed that milling cutter with double straight channel should have had approximately double cooling effect as being compared to double helical channel under cryogenic minimum quantity lubrication [1]. Islam et al. [2] noted that, the effects of inner cooling by cryogenic on the machining of hardened steel. Design, development of rotary liquid nitrogen applicator and investigation of machining performance under cryogenic and its comparison with dry and flood cutting were studied. The effect of the input cutting condition (cutting speed, feed rate and depth of cut) on the output (cutting force, surface roughness and tool flank wear) were analyzed. Result indicated that the following results cryogenic application via rotary applicator demonstrated improved cooling action. Cutting forces was reduced by cryogenic cooling. Liquid nitrogen increased the hardness of tool edges. The cutting speed and feed rate affected surface finish, cutting force and tool performance in various degree. Moreso, inner cooling research, Ferri et al. [3] reported that, the fluids performance, accurate control and influence through the inner geometry to control the heat generation. Results showed that among the three cutting parameters in inner cooling, the chip temperature depended significantly on the depth of cut rather than feed and cutting speed. The development of cutting force model is very important to tools development, optimization, and analysis of milling operations [4], [5].
M. Wan., etc. [6] explored the cutting force model of peripheral milling. (Yun & Cho, 2000) [7] Presented the new way to estimate the 3D force coefficients in which the constant cutting force coefficient of the milling cutter and the constant cutting force coefficient of the work piece is determined regardless of the angle of rotation of the tool or the cutting condition. These constants are used to calculate the cutting force. In the article “The impact of cooling methods on the maximum temperature of the processed object during side milling”, the highest temperature is measured by thermocouples. The cooling method has been noted to influence the cutting force coefficients (Nowakowski, Skrzyniarz, & Miko, 2017) [8]. In the paper “state of art of a cooling method for dry machining”, it was suggested that the cooling method in dry machining removes heat better. This, in turn, reduces the cutting resistance, focusing on the heat removal at the cutting tool tip, and improves the machining performance compared with wet machining and other methods (Ramachandran et al., 2017) [9]. In the article, “Dry machining: Machining of the future”, by P.S. Sreejith, B.K.A. Ngoi presented that dry machining without any fluid is more efficient due to the safety environment. The cost of coolants and lubrication in machining represents 16-20% manufacturing costs [10]. “The possibilities and limitation of dry machining” by Dr. Neil Canter states that for an open-faced operation like milling and boring dry machining were efficient while for closed face machining operation such as drilling, tapping and hole making dry machining is not recommended [11]. The use of minimum quality lubrication (MQL) or no coolant results in lots of subsurface damage and short tool service life (Beer, Özkaya, & Biermann, 2014) [13]. Can et al. [12] noted the performance of 316 stainless steel on High-Speed Milling by experimental study. The analysis concluded that the depth of cut and the feed significantly affected the milling force while speed was insignificant.

Though there are lots of researches on the cutting forces on different milling, additional knowledge is still needed to broaden the data baseline which can assist further researchers in their research work. This study is aimed at performance testing of a kind of self-developed inner cooling tool. The inner cooling tool used in our experiments was developed by our discipline. The content of this paper is to do an experiment, do the analysis of the cutting forces in zig-zag milling through inner and outer cooling method and then conclude. If the cutting forces are less so the milling is better so we can compare the forces of inner cooling and outer cooling. Furthermore, cutting forces for both inner and outer cooling at different diameters and different cutting speeds while the feed, cutting width and cutting depth remains same will be examined.

| Test No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---------|---|---|---|---|---|---|---|---|---|----|----|----|
| Cooling Method | Inner Cooling | Outer Cooling |
| Cutter Dia. (mm) | 12 | 16 | 20 | 12 | 16 | 20 | 12 | 16 | 20 | 12 | 16 | 20 |
| Spindle Speed (rpm) | 540 | 540 | 540 | 1080 | 1080 | 1080 | 540 | 540 | 540 | 1080 | 1080 | 1080 |

2. Experiments

All experiments were carried out on a CNC milling machine which had a maximum speed of 15000 rpm. The dynamometer was connected to the strain amplifier. The experimental system is shown in Fig. 2. Information about sampling points and waveform were saved into the personal computer. The cutting material (steel) was fastened on the dynamometer. The milling cutter used for the measurement was flat end mill cutter. The tool specification was D12x35x90, D16x45x100 and D20x50x110. The diameters of the cutter were 12mm, 16mm, and 20 mm with 4 teeth shown in Fig. 1. Tool material was tungsten carbide. Before the experiments, we were needed to design the experiment parameters. We knew that
cutting conditions affect cutting forces. It was not possible to observe the reaction of cutting forces to a variety of every parameter, so we were only deal with the spindle speed at different diameters while feed and cutting depth remained same throughout. In three different diameters tool experiments, cutting depth was designed 1mm, the Feed rate of 0.05 mm/tooth. The cutting width was 6mm. We will use zig-zag milling shown in Fig. 2. Firstly, the test # 1-3 and 7-9 experimental reading was done for the inner and outer cooling with a spindle speed 540 rpm. Secondly, the next test # 4-6 and 10-12 was done for the inner and outer cooling with a spindle speed 1080 rpm. Total 4 readings were taken at 12 mm cutter diameter. It was also same for 16mm and 20mm cutter diameters. So we were a total 12 test, 4 were taken at 12mm cutter diameter, 4 were taken at 16mm cutter diameter and 4 were taken at 20mm cutter diameter as shown in Table 1.

3. Cutting force analysis
The Subdirectory was analyzed in Matlab software. The noise was filtered by chebyshav’s type 2 low filter and the frequency domain spectrum were developed through Fourier transform tool FFT. In this paper for the convenience of the analysis, we will analyze the 1st test (Inner Cooling) and 7th test (Outer Cooling) where the cutter diameter was 12 mm and the rest were similar to this case. In additional arguments, it was not possible to put all spectral analysis in this paper. The average cutting forces were found from the wavelength in the time domain. In this analysis, we will use average forces. We have got from the experiment we don’t need to compute the resultant forces because in zig-zag milling the cutter cuts the material in only one direction so for the zig-zag milling cutting force/component force F only in one direction. In certain cases, we were found these average cutting forces in the feed direction(x-direction), in certain cases, the average forces were in the cutting width direction(y-direction). In Fig.3 and Fig.4, Original Noisy Signal shows the waveform in the time domain at cutter diameter 12mm and spindle speed 540 rpm. Firstly wavelength also involve the portion where cutter was not cut the material or was not in contact with the material so we were not needed that section. We were needed to examine when the cutting was stable. So we were needed to cut that section from the graph before observation. We perceived that it’s needed +5000 for inner cooling and +20004 for outer cooling to eliminate the unstable portion. Fig.3, Noisy signal indicate the forces in the feed direction after implementing the coding of uncut material at cutter diameter 12mm, spindle speed 540 rpm, Inner Cooling Case. Fig.4, Noisy signal graph shows that forces in the cutting width direction after implementing the coding of uncut material at cutter diameter 12mm, spindle speed 540 rpm, Outer Cooling Case.
Fig. 3 and Fig. 4, Noisy signal shows that the wavelength contains vibration/noise. Noise is a very important issue during machining because noise also affects the cutting forces. The frequency of the electromagnetic noise is 50 Hz.

May be this vibration caused by the eccentricity. Eccentricity effects the tool dimension and accuracy. Eccentricity maybe in spindle, cutting tool or tool holder. To resolve this problem we were designed a filter. We were designed a low pass chebyshev’s type 2 filter. As for design chebyshev’s filter, we needed 4 parameters. 1. Low-Pass Response 2. cut off frequency 3. A number of the filter 4. Band pass ripple. To design the low filter, stopband edge frequency/Cut off frequency should be two times the tool frequency. Tool frequency was observed from the amplitude spectrum.

Fig. 3 and Fig. 4, Second wavelength shows the filtered waveform in the time domain. We were needed to calculate the cutting forces. So we will enlarge the picture to see the cutter 4 teeth’s and wavelength height of 4 teeth’s. We were taken any 10 revolutions of the cutting tool and then noted down the height by the aim to find the cutting forces. Similarly, we calculated the tool cutting forces for remaining all reading. Since we have 4 tooth milling cutter, can easily observe in the Fig.3 and Fig.4, 4 tooth wavelength.

![Test # 1 (Inner Cooling Case, d=12mm and Spindle Speed 540 rpm)](image1.png)

![Test # 7 (Outer Cooling Case, d=12mm and Spindle Speed 540 rpm)](image2.png)

Table 2. Results

| Speed (rpm) | 540 | 1080 |
|-------------|-----|------|
| Cutter Dia. (mm) | 12  | 16  | 20  | 12  | 16  | 20  |
| Force for Inner Cooling (V) | 1.5627 | 1.0216 | 0.3063 | 1.8283 | 0.9137 | 0.4260 |
| Force for Outer Cooling (V) | 1.5696 | 1.1017 | 0.7258 | 1.8909 | 1.3488 | 0.6622 |

4. Conclusions

For zig-zag milling, the performance of the cutter plays an important role. We can observe from results at 12mm, 16mm, 20mm milling cutter diameter and cutting speeds 540 rpm, 1080 rpm respectively. By increasing cutter diameter inner cooling has been conquering than outer cooling for flat end milling cutter with the double straight channel. So inner cooling is better than outer cooling, especially for the bigger tool.

It was very dominant to find out the performance of an inner cooling tool that newly developed. For this purpose, we conducted different tests and the results concluded that the performance of the newly developed inner cooling tool is very good.

It is also noted that if the spindle speed is not great and other parameters are same then average cutting force are near to each other.
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