A comparative analysis of characteristics of cutting forces at micro-milling of hardened steels

B Z Balázs¹ and M Takács²

1,2 Budapest University of Technology and Economics, Faculty of Mechanical Engineering, Department of Manufacturing Science and Engineering, Budapest, Hungary

E-mail: balazs@manuf.bme.hu

Abstract. Micro-milling is one of the most important technologies to produce miniature components. Mainly due to the size reduction, the process has many special characteristics, such as the relatively large tool run-out, the relatively large deformation and the cutting edge radius of the micro-milling tool. The cutting force is often correlated to the phenomena mentioned above, its analysis is therefore often required. The main objective of the present paper is to analyze and compare the characteristics of cutting forces in micro-milling of different hardened steels. A systematic series of experiments were conducted on a hardened AISI H13 hot-work tool steel and a Böhler M303 martensitic corrosion resistance steel. The hardness of both materials is 50 HRC. A 500 µm diameter two fluted carbide micro end mill and a five-axis micromachining centre were applied. The effects of the cutting parameters are analysed by the analysis of variance (ANOVA). Experimental results show that the workpiece material has a significant influence on the cutting forces.

1. Introduction
Recently, the demand from many areas of the industry for miniature components is highly growing, which requires the development of micromachining technologies. Therefore, these processes become strongly researched [1-3]. One of the most essential machining technologies to produce micro components is micro-milling, which is capable of machining complex 3D geometries with high precision in a wide range of the materials [4, 5]. The tool geometries and the kinematics of micro-milling are similar to those used at macro dimensions. However, the knowledge cannot be directly adapted from macro dimensions due to the size reduction (to several orders of magnitude) [6]. Furthermore, the anisotropy and the grain size of the material become more significant in micro-dimensions [7], and the further problems are the relatively large run-out and the relatively large cutting edge radius (\(r_\beta\)) of the tool. The latter causes the problem of the minimum chip thickness (\(h_{min}\)). In the case of cutting below the \(h_{min}\) value, the ploughing is the main material removal mechanism [8], which can characterise by the high frictional forces [9]. In this case, the material is deformed elastically and plastically, and there is no chip formation [10]. The chip thickness changes continuously due to the kinematics of micro-milling, the ploughing effect is reduced, and the chip starts to form when the minimum chip thickness value is reached [10]. The value of \(h_{min}\) is considered by many researchers as a function of the cutting edge radius. The ratio of \(h_{min}/r_\beta\) is uniformly distributed between 0.2-0.4 [11, 12]. The cutting below the minimum chip thickness also reduces the surface quality due to the stronger ploughing effect [13].

The investigation of cutting forces and the effect of tool wear on them are also the subject of numerous scientific studies. Kuram and Ozcelik [14] investigated milling strategies on Ti6Al4V. They
observed that the increase in the rotational speed (12 000 – 28 000 rpm) reduced the tool wear at down milling and zig-zag strategy in the case of low feed rates (75 mm/min). However, it affected the tool wear negatively at the up milling strategy. Under these conditions, the surface quality improved, and the range of the \( F_x \) and \( F_y \) forces decreased (except the down milling). The cutting forces also depend on the milling strategy: the forces are smaller in the case of up milling than in the case of down milling, when machining AISI 1045 [15]. According to Mian et al. [16], the material of the workpiece significantly influences the chip formation, the deformation mechanisms of the workpiece and the flow, if the theoretical chip thickness is smaller than the cutting edge radius or the material grain size. Based on the experimental study by Gao et al. [9], a greater cutting edge radius may result in a greater negative effective-rake angle, which affects the shear and ploughing forces. These ploughing forces start to increase significantly below the minimum chip thickness, which entails a significant increase in the specific cutting force. Thus, the forces may increase due to the excessive reduction of the feed due to the ploughing phenomenon. Biró and Szalay [17] analysed the specific cutting force and identified a new boundary chip thickness in the range of micro chip formation. It was found by Aramcharoen and Mativenga [18] that the size effect is significant when the ratio of \( \frac{h_{\text{min}}}{F_p} \) is smaller than 1, in the case of micro-milling of a very fine-grain AISI H13.

2. Aims and experimental conditions

The main aim of this research is the detailed experimental and theoretical investigation of micro-milling of such hardened steels, which can be used for micro-injection moulding tools. The industry requires not only the hardness of the materials; in many cases, the corrosion resistance is also important. Present paper deals with a detailed comparison of micro-milling of AISI H13 hot-work tool steel and a Böhler M303 martensitic stainless steel in terms of the cutting forces. Based on the certificate of the heat treatment, the hardness of both materials is 50±1 HRC. The chemical composition of the materials is shown in Table 1.

| Factors | \( f_x \) (µm) | \( a_p \) (µm) | Milling strategy | Material |
|---------|----------------|----------------|------------------|----------|
| Levels  | 7              | 3              | 3                | 2        |
| Values  | 1, 2, 4, 6, 8, 10, 12 | 25, 50, 100  | Up-, Down-, Full groove milling | AISI H13, Böhler M303 |

Full factorial experiments were designed and carried out (according to Table 2) to investigate the effect of the depth of cut, the feed per tooth and the milling strategies on the cutting forces of the micro-milling process. During the experiments, a cutting speed of 90 m/min was used, which correlates with...
3. Results and discussion

3.1. Cutting forces at groove milling

The characteristics of cutting forces provide indirect information on chip removal processes, and on material removal mechanisms, therefore, its analysis is often required [21–23]. Furthermore, cutting force is also in a close correlation to the deformation of the cutting tool [24], to the characteristics of surface roughness [25] and are essential for the foundation of process monitoring applications [26]. The influence of feed per tooth, depth of cut, and type of the material on the cutting forces can be seen in Figure 1.

![Figure 1. The influence of the feed per tooth, the type of the material, and the depth of cut on the (a) cutting force and on the (b) axial force component](image)

The ratio of the axial force to the cutting force \( \frac{F_z}{F_c} \) was also analysed in order to understand the changing of the specific axial force component of the process. This parameter describes whether the axial cutting force is large compared to the main cutting force, or not. It was found that the ratio decreases with the increasing of the depth of cut, and the increasing of the feed per tooth also reduces it slightly. For example, in the case of the AISI H13, \( a_p=25 \) µm, and \( f_z=1 \) µm factors were applied, the ratio is \( F_z/F_c=1.487 \), while, if the \( f_z \) is increased to 12 µm, the ratio decreased to \( F_z/F_c=1.175 \). In the case of \( a_p=100 \) µm, the values of the ratio are significantly smaller: \( F_z/F_c=0.946 \) (at \( f_z=1 \) µm), and \( F_z/F_c=0.544 \) (at \( f_z=12 \) µm). In contrast, when the \( a_p \) value is equal to the corner radius of the tool, there is a reduction in the values up to 4 µm feed per tooth value, however, the further increase of the feed results in a
smaller increase in the values. The possible reason for the relatively high $F_z$ component can be found in the relatively large corner radius of the cutting tool. The effect of the relatively small radius becomes more significant in micro sizes. The higher ratio of $F_z$ forces can result in a more stable cutting condition because the tool is loaded in the most rigid direction (axial). In contrast, the cutting force causes deflection of the micro-milling tool in a radial direction, which is one of the main problems in the case of micro tools with low stiffness.

The results were also analyzed by analysis of variance (ANOVA) using the Minitab program. The results obtained are shown in Figures 2. and 3. The $F_{crit}$=4.0847 at $p=0.05$ significance level. Based on the ANOVA results, the effect of all of the three examined factors is significant. For $F_x$, the effect of $a_p$ is the most significant ($F$-value: 2171.24, $P$-value: 0.000), followed by the feed per tooth ($F$-value: 966.38, $P$-value: 0.000), and by the workpiece material ($F$-value: 127.90, $P$-value: 0.000). The two hardened materials used have a uniform hardness of 50±1 HRC; in contrast, there are significant differences in cutting forces.

![Main Effects Plot for $F_x$](image1)

![Main Effects Plot for $F_z$](image2)

**Figure 2.** Main effects plot for (a) $F_x$ and (b) $F_z$

| Source             | DF | Adj SS  | Adj MS  | F-Value | P-Value |
|--------------------|----|---------|---------|---------|---------|
| Model              | 7  | 144.686 | 20.6694 | 477.15  | 0.000   |
| Linear             | 3  | 139.920 | 46.6399 | 1076.68 | 0.000   |
| $a_p$              | 1  | 94.054  | 94.0537 | 2171.24 | 0.000   |
| $f_z$              | 1  | 41.862  | 41.8618 | 966.38  | 0.000   |
| Material           | 1  | 5.540   | 5.5405  | 127.90  | 0.000   |
| 2-Way Interactions | 3  | 15.166  | 5.0555  | 116.71  | 0.000   |
| $a_p$*$f_z$        | 1  | 14.317  | 14.3170 | 330.51  | 0.000   |
| $a_p$*Material     | 1  | 0.839   | 0.8388  | 19.36   | 0.000   |
| $f_z$*Material     | 1  | 0.008   | 0.0084  | 0.19    | 0.662   |
| 3-Way Interactions | 1  | 0.007   | 0.0072  | 0.17    | 0.685   |
| $a_p$*$f_z$*Material| 1  | 0.007   | 0.072   | 0.17    | 0.685   |
| Error              | 34 | 1.473   | 0.0433  |         |         |
| Total              | 41 | 146.159 |         |         |         |

On average, 30% higher forces were measured in the case of the AISI H13 material was applied than the Böhler M303 one. The possible reason could be found in the different structures of the different workpiece materials. The main effect of the material is 0.7 N for the $F_x$ and 0.65 N for the $F_z$ in the investigated parameter range. So, the demand in the industry of the corrosion resistance of the materials could result in even better conditions in terms of the cutting forces. The interaction plots are shown in Figure 3. The values shown in Table 3 show that the interaction between the depth of cut and the feed per tooth, and between the $a_p$ and the material is statistically significant.
Figure 3. Interaction plot for (a) $F_c$ and (b) $F_z$

The results of ANOVA are similar in the case of the $F_z$ force component to the results of $F_c$ forces. The main effects plot for $F_z$ is shown in Figure 3b. The most significant factor is the feed per tooth (F-value: 331.22, P-value: 0.000), followed by the depth of cut (F-value: 187.31, P-value: 0.000), and by the workpiece material (F-value: 115.22, P-value: 0.000).

3.2. Cutting forces at different milling strategies

This chapter deals with the comparison of the milling strategies (up milling and down milling) with special regards to the forces measured during the machining. The influence of the feed per tooth, depth of cut, and type of the material on the cutting forces can be seen in Figure 4.

Figure 4. The influence of the feed per tooth, the type of the material, and the depth of cut on the (a) cutting force and on the (b) axial force component

The trends of the cutting forces and the axial forces are similar to the results of the full groove milling process, as was expected before, the forces increase with the increasing of the chip cross-section. In the case of $F_z$ component is concerned, a significant increase was observed at both materials and both milling strategies, at $a_p=50$ $\mu$m and after $f_z=4$ $\mu$m. This change occurs when the ratio of chip thickness to the cutting edge radius is $h/r_e=1\pm\delta$ (where $\delta$ is an experimental error). The possible reason for these phenomena could be found in the different dominant material removal mechanisms (shear and ploughing) appearance.
The ratio of \( F_z/F_c \) was also analyzed in the case of up milling and down milling. A decrease of the ratio was also observed with the increases of the feed per tooth and with the increases of the depth of cut (Figure 5.). However, there is an exception at \( \alpha_p=50 \, \mu m \) (this depth of cut is equal to the corner radius of the tool), which proper reason needs additional experiments in the future. There is a minimum point at both strategies when the feed per tooth value is 4 \( \mu m \) (which is equal to the assumed cutting edge radius of the tool). In the case of the hot-work tool steel, the ratio is on average 11% lower at up milling than at down milling. In contrast, it is on average, 5.5% lower at down milling in the case of Böhler M303.

![Figure 5. The influence of feed per tooth, depth of cut and strategy on the \( F_z/F_c \).](image)

![Figure 6. Main effect plots for (a) \( F_c \) and (b) \( F_z \).](image)

Based on the results of the analysis of variance, the effect of all of the four analysed factors is statistically significant. The related F-values and P-values are shown in Table 4, ordered by the size of their effect. The interactions in terms of the analysed factors are also statistically significant in the case of \( F_c \). Nevertheless, the effect of the interactions are statistically not significant in the case of the \( F_z \) component is concerned.

|   | \( F_c \)          |   | \( F_z \)          |
|---|--------------------|---|--------------------|
|   | Factor | F-value | P-value | Factor | F-value | P-value |
|   | \( \alpha_p \)     | 2913.09 | 0.000    | \( f_z \) | 196.01  | 0.000   |
|   | \( f_z \)          | 1421.38 | 0.000    | \( \alpha_p \) | 127.79 | 0.000   |
|   | Material           | 89.45   | 0.000    | Material | 37.94  | 0.000   |
|   | Strategy           | 46.55   | 0.000    | Strategy | 10.29  | 0.002   |

Table 4. F-values and P-values for \( F_c \) and \( F_z \)
Based on the statistical analysis, the use of up milling strategy results in smaller forces. This result is similar to that found in our previous study when AISI 1045 steel was micro-milled [7]. Smaller forces result in smaller deflection of the tool, which could provide more accurate geometry. Moreover, it could be a positive effect on tool life, too. The burr formation is not part of the present study, but according to many researches, the top burr is smaller on the up milling side than on the down milling side [7, 27, 28]. Considering the results as well as other considerations, the use of up milling strategy is recommended when milling with a half-diameter of the tool.

The effect of the materials is also noteworthy in the half-diameter milling strategies. In the case of the AISI H13 was machined, the $F_z$ forces were 21% higher at the up milling strategy and 8% higher at the down milling than in the case of the Böhler M303 was cut while the $F_z$ forces were 21% and 24% higher, respectively.

4. Conclusions
Micromachining experiments were conducted on a VHTC 130M 5-axis machining centre using commercially available, 500 μm diameter, two fluted, coated carbide micro-milling tools. A Böhler M303 martensitic stainless steel and AISI H13 hot-work tool steel with 50±1 HRC hardness were micro-milled. Based on the present research work, the following conclusions can be drawn:

- It was observed that the feed per tooth and the depth of cut increase the cutting forces, due to the increasing chip cross-section.
- ANOVA results show that the effect of all of the examined factor is statistically significant at a confidence level of $p=0.05$.
- Experimental results show that the material type has a significant influence on the cutting forces. The Böhler M303 martensitic stainless steel can be micro-milled on average 30% smaller forces than the AISI H13. Thus, the demand from the industry for the corrosion resistance may result in more favourable cutting conditions in terms of cutting forces during micro-milling.
- It was found that the effect of the corner radius is significant in micro sizes due to the size reduction. It increases the $F_z$ force component at a small depth of cut values.
- The $F_z/F_x$ ratio decreases with the increase of the feed per tooth and the depth of cut. An exception was observed where the depth of cut is equal to the corner radius when the half-diameter strategies were applied. The ratio is on average 11% higher at down milling than at up milling in the case of AISI H13. In contrast, the ratio of $F_z/F_x$ is up to 5.5% smaller at down milling than at up milling in the case of Böhler M303. In terms of the force ratio, differences can be seen in the trends when the depth of cut is the same as the corner radius.
- The milling strategies were compared based on the characteristics of cutting forces. It is recommended the use of the up milling strategy in the case of milling with a radial depth of cut of the half-diameter of the cutting tool.

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