Dependency of Machining Forces on Process Parameters During Sustainable MQL-Based Micro-milling of D2 Steel

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1 Introduction

Machining is one type of subtractive manufacturing process, where material is gradually sheared-off from the workpiece in the form of chips using a well-defined cutting tool in order to impart pre-defined shape, size, and finish. End milling is one type of machining process, where the workpiece is fed in a pre-defined trajectory against a rotating cylindrical cutter. Based on the diameter of the cutter, end milling can be categorized as macro-scale, meso-scale, and micro-scale operation. Micro-end milling cutters typically have diameter 1.0 mm or below, with a minimum of 0.03 mm diameter cutter fabricated till now [1]. Although various researchers attempted to fabricate three and four flute cutters [2], commercial micro-mills usually come in the diameter range of 100–1000 μm, mostly two-flutes and coated. Mechanical micro-milling process can productively fabricate micro-features like slots, pockets, pillars, fins, webs, dimples, etc., on a large variety of base material requiring minimum effort.

In micro-milling, the uncut chip thickness remains very low, typically in the order of 0.5–6.0 μm (maximum values, theoretically same with the feed per flute). The curvature radius at the principal cutting edge (called edge radius, r_e) also remains in the similar range, typically within 1.0–4.0 μm. Thus, the material removal is essentially accomplished by the rounded cutting edge, rather than a perfectly sharp

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B. Bhattacharyya et al. (eds.), *Advances in Micro and Nano Manufacturing and Surface Engineering*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-19-4571-7_11

edge. As a conventional machining process, material removal in micro-milling is accomplished by deforming the workpiece material by expending mechanical energy. Cutting forces thus arise across all possible directions owing to the existence of relative velocities under solid-to-solid tool-workpiece contact. Force magnitude in different directions depends on the workpiece material, cutter geometry, process parameters, lubrication, cutting zone temperature, tribological condition, etc.

AISI D2 steel offers high abrasion and wear resistant owing to the presence of high chromium and carbon, and thus, it is used for making micro-die, micro-punch, etc. [3]. However, high chromium and carbon content reduce the machinability of this particular steel. In macro-scale cutting, Sharma and Sidhu [4] highlighted that application of small quantity lubricant (near-dry machining) can reasonably overcome difficulty in machining of the D2 steel. Sharma et al. [5] also highlighted that application of nanofluids in minimum quantity lubrication (MQL) helps improving machinability by controlling cutting temperature.

Micro-milling performances of D2 steel, particularly cutting force related aspects, are not been explored in details. During micro-milling of AISI D2 steel using two-flute 200 μm diameter helical cutters, Jin et al. [6] observed an increasing tendency of forces with the increase in feed per flute. Babu et al. [7] highlighted that dead metal zone formation ahead of the cutting edge can significantly increase the cutting forces, and a higher feed of the order of 5 μm/flute was suggested during micro-milling of D2 steel.

Objective of this article is to analyze the measured cutting forces to understand their dependency on the process parameters during minimum quantity lubrication (MQL)-based sustainable micro-milling of AISI D2 steel using 0.5 mm diameter micro-end milling cutters.

2 Experimental Details

As-procured AISI D2 steel samples of size $20 \times 20 \times 10$ mm^3 are first made flat by end milling using a 6.0 mm diameter end milling cutter. Flatness of the top surface is essential in order to achieve a constant depth of cut for further micro-scale operation on this sample. An island of 5.0 mm wide, 2 mm height, and 20 mm long is also made by removing material from sides using the same end milling operation (Fig. 1). Without altering the gripping, full-immersion straight slots are micro-milled on this island in transverse direction. Thus, each micro-slot is of 5.0 mm long with width equals to micro-mill diameter (0.5 mm). Entire micro-milling operation is carried out on a high-precision CNC micro-machining centre (Kern-Evo, KERN microtechnik, Germany).

Commercial micro-end milling cutters (AXIS-Microtools, India) of 500 μm diameter with flat-end are employed for cutting micro-slots. Such micro-mills consist of two helical flutes located at 180° apart with a helix angle of 30°. The tools are made of tungsten carbide with TiAlN coating. As shown in Fig. 1, average edge radius of the tool is 1.3 μm. As summarized in Table 1, cutting speed is varied in four levels,

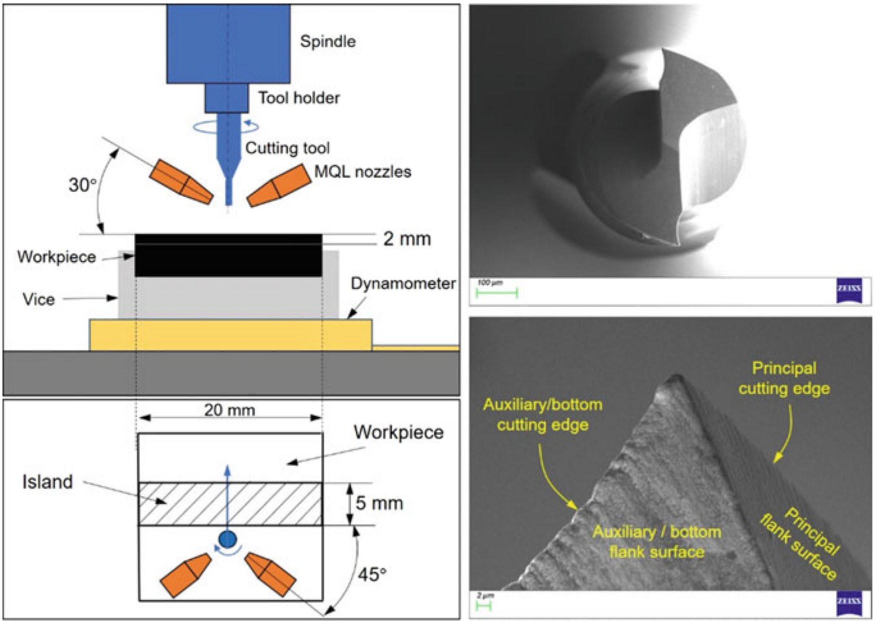

Fig. 1 Experimental setup and SEM images of the micro-milling tool employed for experimentation

from 15,000 rpm to 45,000 rpm with 10,000 rpm interval. The corresponding cutting velocity lies in the range of 24–71 m/min. Feed per flute is also varied from 0.5 to 1.5 μm/flute. Depth of cut is, however, kept constant at 50 μm. An eco-friendly (biodegradable) cutting fluid UNILUBE 2032 is also supplied at the cutting zone at a very low-flow rate (6 mL/h) using two nozzles following a sustainable cutting fluid delivery technique called minimum quantity lubrication (MQL) [8].

During the micro-milling operation, instantaneous cutting forces in three mutually perpendicular directions are measured using a piezoelectric dynamometer (Kistler

Table 1 Micro-milling operating summery

Workpiece material	D2 stainless steel
Micro-milling tool material	TiAlN-coated tungsten carbide
Micro-milled feature	Full-immersion straight slot
Tool features	500 μm diameter two-flutes flat-end
Edge radius	1.3 μm
Spindle speed	15 k, 25 k, 35 k, and 45 k rpm
Feed per flute	0.5, 1.0, 1.5 μm/flute
Axial depth of cut	50 μm
Lubrication	Sustainable MQL at 6 mL/h

9254) set under the work holding device. Force data are gathered through three separate charge amplifiers and one oscilloscope, and the same are further processed through MATLAB software to retrieve average maximum and RMS force values. Generated micro-chips are also collected using carbon tapes, and the same are observed a scanning electron microscope (SEM) (EVO 18, ZEISS, Germany).

3 Results and Discussion

Micro-milling is characteristically an intermittent type cutting process where a particular edge repeatedly engages and disengages with the workpiece in every tool rotation. In full-immersion straight slot micro-milling, each edge remains in physical contact with workpiece for only half of the rotation. During this 180° contact duration, uncut chip thickness gradually increases from zero (at the beginning of engagement) to maximum (after 90° rotation) leading to the generation of the up-milling (conventional milling) phase. Down-milling (climb milling) begins with the maximum uncut chip thickness; however, the same gradually reduces to zero within a quarter-cycle. The maximum uncut chip thickness is, however, same with the set feed per flute in absence of tool deflection or run-out.

As the chip load changes with the engagement angle, the cutting forces also vary. It is thus pertinent to consider both root means square (RMS) and maximum values of the developed forces. The maximum value of the force components determines the cutting power requirement. The cutting power, in turn, controls the limiting values of the process parameters based on machine capability. On the other hand, the RMS value of the cutting force components is useful in designing the cutter, or selecting an appropriate cutter in a defined condition. However, in micro-milling, forces usually remain very low (typically below 1.0 N) owing to very low-uncut chip thickness and depth of cut [9]. In this study, three different force components, namely the longitudinal force (P_X) that acts along the feed direction, the radial thrust force (P_Y) that acts perpendicular to the feed direction, and the vertical thrust force (P_Z) that acts along the tool axis, are considered separately. Average maximum and RMS values are retrieved and used for further analysis. When speed is varied, feed per flute is kept constant to 1.5 μm/flute. When feed per flute is varied, speed is kept unchanged to 25,000 rpm to ensure adequate lubricant supply [8].

3.1 Dependency of Cutting Forces on the Spindle Speed

As shown in Fig. 2, all three measured components of the cutting force reduce with the increase in spindle speed. Although considerable reduction can be noticed for P_X and P_Y components, P_Z force reduces marginally. Reduction of cutting forces with the increase in tool rotation speed can be attributed to two distinct factors—(i) increased plastic nature of the chip and (ii) reduced minimum uncut chip thickness.

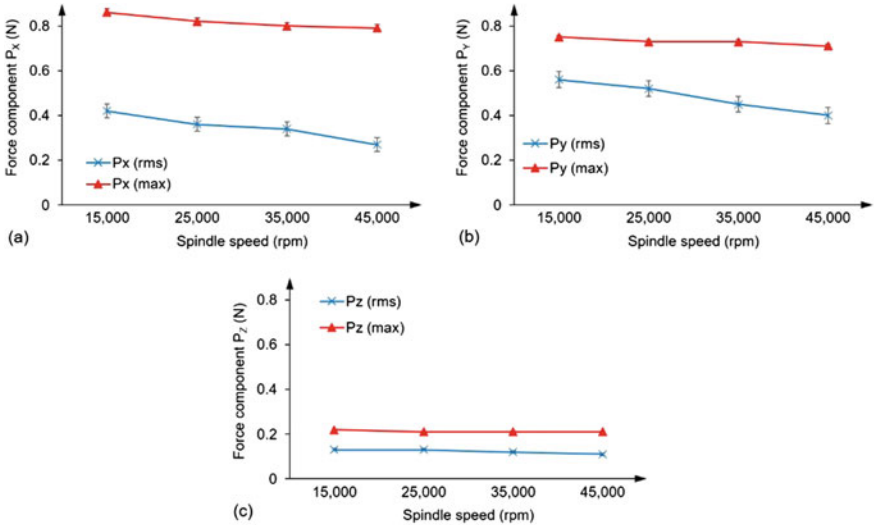

Fig. 2 Variation of RMS and maximum force components with the spindle speed

As the rotation speed of the tool increases, the tribological contact duration between the workpiece and edge for a particular engagement reduces [8]. Thus, each layer of uncut material is removed in a relatively shorter duration. In other words, the relative velocity between the tool and chip increases as spindle speed is increased. At higher velocity, the flow of the chip becomes more plastic [10], and thus, the contact friction drops. As shown in Fig. 3, the shining surface (underside) of the chips indicates such changes in frictional characteristic [11]. Chips obtained through low-speed micro-milling are characterized by the presence of scratch marks and adherence deposits. These are the indications of higher friction at the chip-tool interface. On the other hand, chips obtained at the highest speed are almost free from scratch marks and adhered deposits. Accordingly, relatively lesser energy is required to remove the same amount of material at higher speed that ultimately leads to the generation of lower forces.

Apart from lower friction, reduced minimum uncut chip thickness also contributes towards the reduction of cutting forces with speed. In micro-milling, the uncut chip thickness remains close to the edge radius owing to very small feed per feed. Accordingly, workpiece material experiences highly negative rake angle when the edge tends to compress it. Unless the uncut chip thickness exceeds a minimum uncut chip thickness (h_{min}) value, chip formation does not initiate. Rather, the material undergoes elastic–plastic deformation or ploughing (plowing) leading to lateral flow of the material mostly in the form of burr that can also be removed through separate post-milling deburring operation [12]. Even when the uncut chip thickness is higher than h_{min}, a thin layer of material having thickness h_{min} undergoes ploughing, and rest of the part undergoes shearing to produce chip. For a tool with given edge radius, the h_{min} value depends on the apparent coefficient of friction at the chip-tool interface.

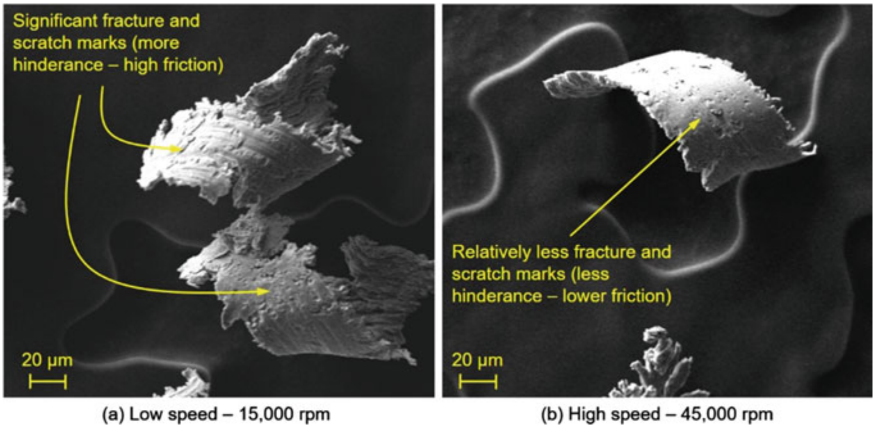

Fig. 3 Underside of the chips showing the frictional characteristics during micro-milling at the lowest and highest speed investigated here

As established by Malekian et al. [13], the $h_{\min}$ can be expressed as a function of apparent coefficient of friction (η) and edge radius (r_e) in the form of Eq. (1).

$$h_{\min} = r_e\{1 - \cos\eta\} \tag{1}$$

Thus, the $h_{\min}$ is proportional to the apparent coefficient of friction between the chip and rake face. As explained through Fig. 3, contact friction drops with the increase in speed. Accordingly, a lower $h_{\min}$ is expected at higher spindle speed. As $h_{\min}$ reduces, volume fraction of the material undergoing ploughing reduces (Fig. 4). In other words, majority fraction of the uncut chip experiences shear deformation to produce chips (instead of ploughing). It is well known that the ploughing requires significantly larger specific energy as compared to shearing [14]. As a result, relatively lower forces develop at higher spindle speeds. Whilst force components P_X and P_Y strongly depend on the frictional characteristics and minimum uncut chip thickness [11], the $\mathrm{P_Z}$ component is less dependent on such factors. For micro-milling with a constant depth of cut, the P_Z force mainly changes with nose radius, chip clogging, and tool wear. Accordingly, P_Z force does not change significantly with speed even though P_X and P_Y components decrease considerably.

3.2 Dependency of Cutting Forces on the Feed Per Flute

The frictional properties do not change considerably with the change in feed per flute. Therefore, the minimum uncut chip thickness remains more-or-less constant when feed per flute is increased. However, for a given edge radius, the fraction of

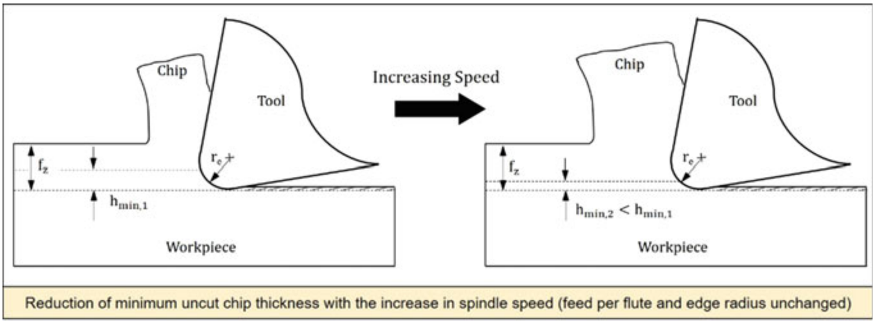

Fig. 4 Schematic representation on the changes in shear-able and plough-able material when $h_{\min}$ reduces owing to the increase in speed

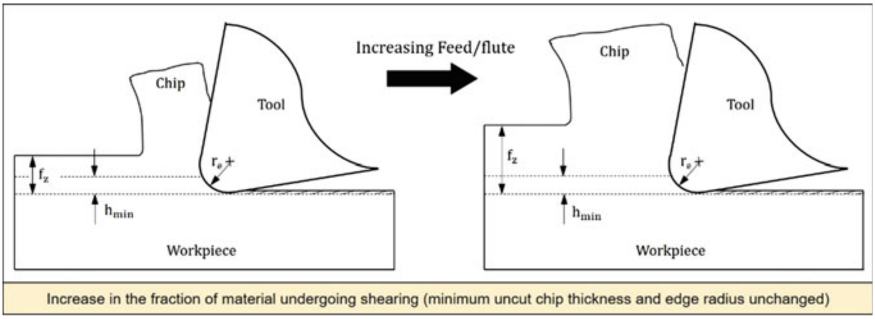

Fig. 5 Schematic representation on the increase in shear-able material when feed per flute is increased (plough-able material remains unchanged)

workpiece material undergoing shearing increases when feed per flute is increased. This scenario is schematically shown in Fig. 5.

As the chip load per cutting edge increases, more energy is required for removing the material, and hence, high-cutting forces are expected at higher feed per flute. As shown in Fig. 6, an increasing tendency amongst force components P_X and P_Y can be observed with the increase in feed per flute. P_Z component also increases, however, only marginally. For all of the feeds per flute investigated here, the maximum value of the P_X component is somewhat higher than that of the P_Y component. However, an opposite scenario can be observed for the RMS values of the force components. An increasing nature of the micro-milling forces with the increase in feed per flute was also observed by Yadav et al. [15].

To identify the parameter (amongst speed and feed) that has relatively more influence on cutting forces, percentage change can be calculated. In this regard, three-fold increase in response valuable is considered only. When speed is increased three-fold (from 15,000 rpm to 45,000 rpm), RMS value of the P_X component changes (actually reduces, but only magnitude is considered) as much as 36% (Fig. 7a). On the other hand, for three-fold increase in feed per flute (from 0.5 μm/flute to 1.5 μm/flute),

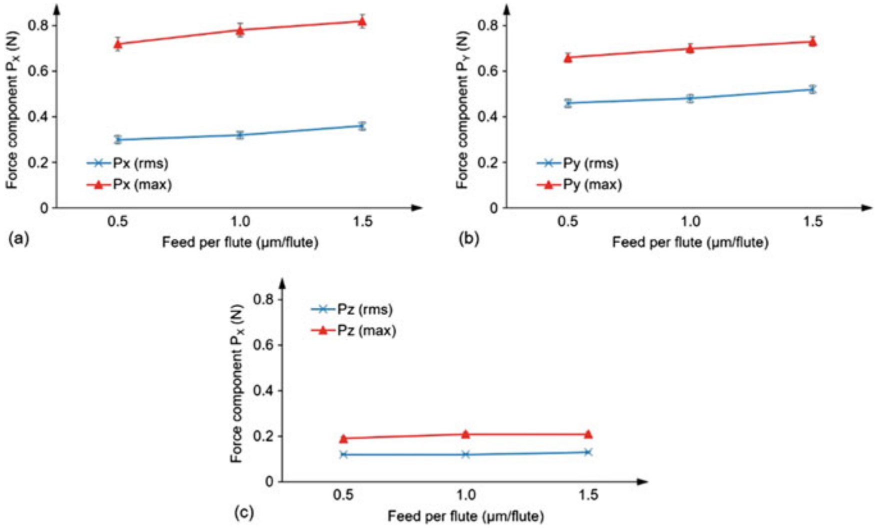

Fig. 6 Variation of RMS and maximum force components with the feed per flute

the RMS value of the P_X component changes (increases) only 20%. Similar pattern of variation can be observed for RMS values of all other force components. Thus, RMS values of the force components are more sensitive towards cutting forces as compared to feed per flute. However, a reverse situation occurs when maximum values of the force components are considered. As shown in Fig. 7b, relatively less change in the force components occur as speed is increased three-fold as compared to the same when for three-fold increase in per flute.

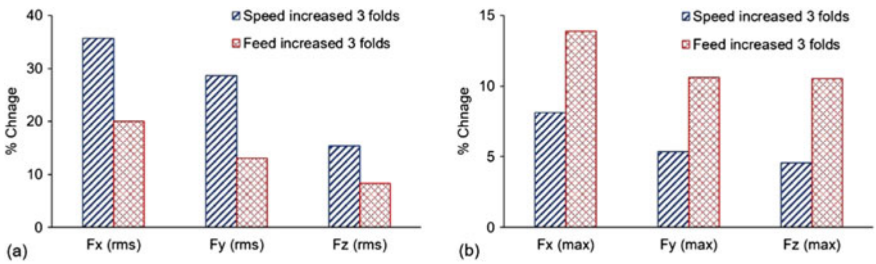

Fig. 7 Sensitivity of speed and feed per flute on the **a** RMS values and **b** maximum values of the cutting force components

4 Conclusions

This article analyzed the variation of cutting forces with spindle speed and feed per flute during sustainable minimum quantity lubrication (MQL)-based micro-milling of full-immersion straight slots on AISI D2 steel samples using 500 μm diameter two-flute micro-mills. Based on the analysis of the results, the following conclusions can be drawn.

- At higher cutting speed, the chips flow over the rake surface with lesser tribological hindrances. Volume fraction of the plough-able material also drops with the increase in speed. These two factors, together, lead to the reduction in cutting forces with the increase in spindle speed.
- The higher the feed per flute, the more is the chip load for each cutting edge in every rotation of the tool. The volume of plough-able material remains unchanged with the increase in feed per flute; however, the volume of the shear-able material increases leading to the growth of cutting forces. Accordingly, cutting forces increase with the increase in feed per flute.
- The RMS values of the cutting force components are more sensitive towards the spindle speed (as compared to the feed per flute). On the contrary, the maximum values of the cutting force components are more sensitive towards the feed per flute (as compared to the spindle speed).
- Vertical thrust force (along the tool axis) is least influenced by the variation of the spindle speed and feed per flute.

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