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Investigation on cutting mechanism of vibration assisted micro-milling

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Abstract
Size effect in micro milling has been identified as one of the critical factors in defining the process performance. Significant size effect can be found in vibration-assisted milling process due to the changed uncut chip thickness induced by vibration of cutting tool. In this paper, the vibration assisted micro milling is investigated in terms of size effect and compared with the conventional micro milling. A finite element model of vibration assisted micro milling process is established for pure magnisium with the Johnson-Cook material model. The simulation model is verified by the experimental results.

Keywords: Vibration assisted machining; size effect; micro milling; finite element simulation

1. Introduction

The world is experiencing a growing demand for miniaturised products in various applications. Micro milling is believed to be the most flexible micro machining process with the capability to generate a wide variety of complex micro components and microstructures due to its wide range of materials processing ability, which enables complex geometric features to be machined and simple set-up. During the machining process, the so called size effect which is associated with tool edge radius, workpiece non-homogeneity with respect to the tool/cut size, negative rake angles and workpiece material minimum chip thickness effects has been identified as a critical factor in defining the process performance. The size effect is reported to increase the burr formation and exacerbate the tool wear. The low ratio of undeformed chip thickness to tool edge radius leads to ploughing, poor edge definition and burrs, this impedes the attainment of good finishing surface and hinders functional compliance. Post processing of micro components is extremely difficult or on higher cost. The application of conventional deburring techniques may introduce dimensional errors and residual stresses in the components. Therefore, suppression of burr formation requires investigation into how burr formation correlates with cutting conditions and material properties.

Vibration-assisted machining is an external energy assisted machining method in which high frequency and small amplitude vibration superimposing to the tool or workpiece to improve the material removal process. It has been applied to a number of cutting processes such as turning, drilling and milling. In this paper, the influence of the vibration assisted machining on the size effect in micro milling is investigated by finite element modelling, and model validation was conducted by comparing with experimental data.

2. Materials removal mechanism in micro milling

Fig.1 illustrates the material removal mechanism in micro milling process. It can be noted that in the region that the cutter engaging with workpiece, the uncut chip thickness is smaller than a certain critical value h_c. The value of h_c which is known as minimum chip thicknesses is found to be around 0.15~0.4 of the edge radius for most of the metals [1]. During machining process, the cutting force, tool wear, surface roughness, burr formation could be reduced by employing the uncut chip thickness which is larger than minimum chip thickness, while simultaneously improve process stability. However, the minimum chip thickness cannot be avoided in the whole machining path, e.g. in region highlighted in Fig.1.

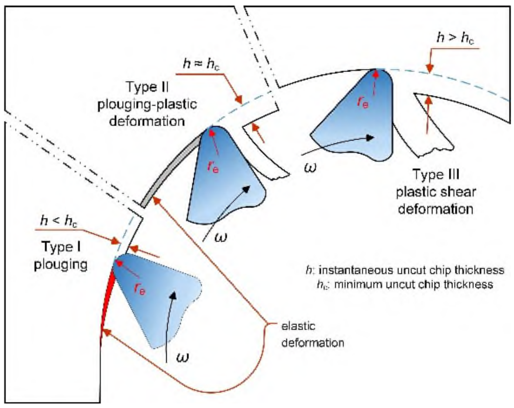

Figure 1. Material removal mechanisms in micro milling

By applying the elliptical vibration in micro milling process, the instantaneous cutting thickness is changed siginificantly compared with the conventional micro milling, especially in the cutting in and cutting out area. Therefore, the ploughing effect can be reduced.

3. Simulation results

The finite element cutting simulations in ploughing region shown in Fig.1 are carried out for the conventional micro milling and vibration assisted milling process. The machining parameters used in the simulation are as follows, the cutting speed is 2.9m/s; cutting depth is 0.1μm; the cutting edge radius is 1μm. The vibrations are applied in the feed and cross-feed directions on the workpiece with the frequencies of 40kHz and the amplitude of 0.5 µm, the phase angle between the two vibration signals is $\pi/2$, which forms an elliptical vibration in micro milling process.

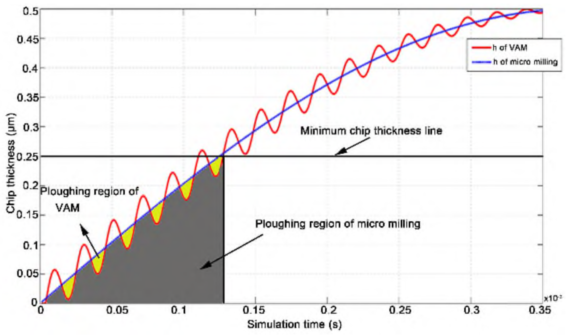

Figure 2. Comparision of the chip thickness between conventional and vibration assisted machining

Fig.2 illustrate the uncut chip thickness of the cutting path as shown in Fig.1, assuming that the h_c is around 0.25 of the edge radius, it can be found that with the given vibration parameters, the ploughing region is siginifcantly reduced comparing with the conventional micro milling.

Pure magnesium is used as workpiece material in the finite element model. Johnson-Cook material model and JC damage model are used to describe the workpiece material behavior. The details of the material parameters can be found in [2].

Fig.3 (a-c) illustrate the simulated conventional machining. It can be observed that as the cutting depth is smaller than the minimum chip thickness, the cutter squeezes the material forward during the cutting process with elastic deformation occurring in the workpiece. The deformed material fully recovers to its original position after the tool pass without chip formation.

Fig.3 (d-f) illustrate the simulated cutting process with an elliptical vibration applied on the cutter. Within this process, the machining parameters are same as the conventional machining process, except the assisted vibrations. Based on the observation of Fig.3 (d), it can be found that due to the vibration applied on the cutter, the instantaneous cutting thickness is found to be greater than the minimum cutting thickness although the initial cutting depth is less than the minimum cutting thickness. Thus, the material directly comes into the shearing removal mode instead of ploughing.

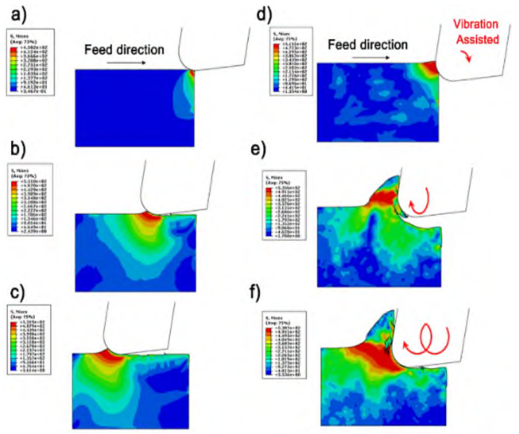

Figure 3. A comparision between conventional and vibration assisted machining

Specific cutting force is calculated by dividing the resultant cutting force by the section area of cutting area. Based on observation of Fig.4, the specific cutting force obtained from vibration assisted cutting process (3.02 GPa) which is smaller than that obtained from non-vibration one (4.47 GPa). It can be said that the vibration added within cutting process exhibits a better capability to reduce size effect at small uncut chip thickness, which is conducive to reduce the tool wear rate.

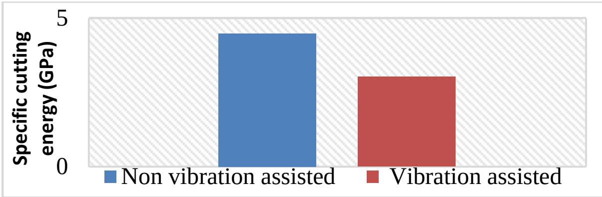

Figure 4. Specific cutting force obtained in conventional machining and vibration assisted machining process

4. Machining experiments

The comparison between the conventional micro milling and vibration assisted micro milling is conducted with the following machining parameters: cutting depth is 50 µm, spindle speed is 40,000rpm, feed per tooth is 0.1 µm. After cutting 20 x 20mm long slots of magnesium alloy, it is found that the tool wear rate obtained from vibration assisted micro milling is significantly reduced compared with the that obtained from conventional micro milling, as shown in Fig.5a,b). From Fig.5c,d) it also can be found that the machined surface of the conventional micro milling surface is worse than that of the vibration assisted micro milling.

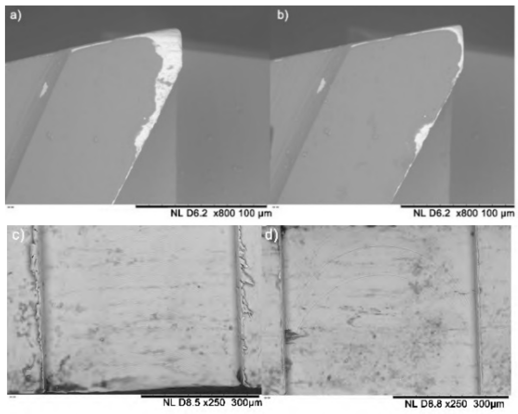

Figure 5. Tool wear and machined surface test results. a,b) tool wear in conventional and vibration assisted micro milling; c,d) machined surface in conventional and vibration assisted micro milling.

5. Conclusion

This paper investigated the cutting mechanism of the vibration assisted micro-milling. In conventional micro milling, the ploughing cutting process occurs at the cutting in or cutting out area, the size effect exacerbates tool wear. It is found that by introducing the elliptical vibration in the micro milling process, the vibration assisted can overcome the restriction of the minimum cutting thickness, which is conducive to reduce the tool wear and improve the machined surface quality.

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