

Simulation of thin features machining by micro end-milling using finite element modelling

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Abstract

High aspect ratio manufacturing in the micro dimensional range by the micro milling process represents some difficulties for diverse applications such as micro moulds, micro channels, micro gears, miniaturized surgical instruments, etc. This study investigates the thin wall machining with different machining approaches and applies 3D finite element modelling (FEM) for the minimum machinable wall thickness to improve the experimental machining and enhance the quality of the machined features. The high stress distribution during machining the thin features are presented and the smallest machined wall is investigated. Finally, the FEM prediction results are compared against the experimental tests.

Keywords: Micromilling; Finite Element Modelling; Precision Milling; Thinwall Machining.

1. Introduction

Miniature scale parts demand is increasing due to many applications of micro features in several industries. High precision micro milling is a widely used, cost effective and efficient method for manufacturing thin features. Micro milling has been studied intensively, by the means of experiments and modeling. Defects such as wall bending and burrs, stability problem of the tools, and the lack of systematic control of feature quality are the main challenges in micro milling of thin walls.

In this study finite element (FE) model of micro end milling operations were applied in order to predict the behavior of the thin wall machining process and to control different wall thicknesses in diverse cutting conditions. This study explores the cutting conditions prior to experimental tests to obtain high aspect ratio features in the micro milling range.

2. Numerical procedure

2.1. FE Model

The FE model for high precision milling was simulated using an explicit time integration method by employing a Lagrangian formulation to perform coupled thermo-mechanical transient analysis (AdvantEdge® by Third Wave Systems). Fig. 1 represents the setup for the thin wall corner milling. The modelling strategy was selected to machine one side of the wall. The tool was modeled with a detailed geometry and its CAD model was used for the FE analysis. The detail of the tool measurement and modeling with cloud of points can be found in the previous work [1]. The continuous remeshing was applied in the simulation in order to remove the deformation induced the element distortion [2]. The tool and workpiece were meshed with four node tetrahedral elements, for a total number of 61879 while 60916 elements were used for the corner milling process.

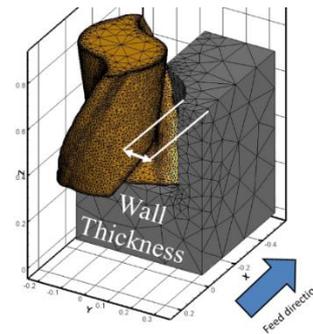


Fig. 1. FE model setup, workpiece and tool meshing

The Johnson-Cook (JC) constitutive material model was applied (Eq. 1).

$$\sigma = (A + B(\varepsilon)^n) [1 + C \ln(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0})] [1 - (\frac{T - T_a}{T_m - T_a})^m] \quad (1)$$

Where: σ is the material flow stress, ε is the plastic strain, $\dot{\varepsilon}$ is the strain rate, $\dot{\varepsilon}_0$ is the reference strain rate. T is the material temperature, T_m is the melting point and T_a is the room temperature. The JC constants are as follows: A is the yield stress, B is the pre-exponential factor, C is the strain rate factor, n is the work hardening exponent and m is the thermal softening exponent. The thermo-mechanical properties of the workpiece and the material constants selected from previous study [3] with the same material. Table 1 shows material constants for modelling the plastic behaviour of Al6082-T6. Coulomb friction, (Eq. 2) applied in the cutting area. A constant value of friction coefficient used is assigned in this study, as $\mu = 0.7$.

$$\tau = \mu \sigma_n \quad (2)$$

Table 1 Coefficients of the JC model for Al6082-T6 [3]

A (MPa)	B (MPa)	C	m	n	T _m (°C)	T _a (°C)
214.25	327.7	0.00747	1.31	0.504	582	21

3. Experimental details and machining strategy

Table 2 shows the cutting condition employed in the experiments. A five-axis milling machine (MIKRON HSM 400U LP equipped with a Heidenhain iTNC 530 HSCI control unit) was used to conduct the experiments. The 500 μm micro end-mill NS tool was used for the experiments with a downmilling approach.

Table 2 Micro end-milling parameters employed

Parameter	Value
Spindle speed, (rpm)	40000
Feed per tooth (μm tooth/rev)	8
Axial depth of cut (μm)	10, 20, 40
Radial depth of cut (μm)	20

The workpiece was designed in a way to machine two different wall thicknesses (50 and 100 μm) both with a 500 μm height. Fig. 2(a) and Fig.2(b) present the experimental setup and correct machining strategy applied for the thin wall experiments. The machining was carried out in dry condition. All the conditions were replicated two times for the consistency of the results. Different machining strategies were investigated to find the optimized machining approach. Fig. 2(c) and Fig.2(d) show another machining strategy which caused the failure of the walls in all machining conditions. The Alicona 3D optical microscope was used for the inspection of the wall quality.

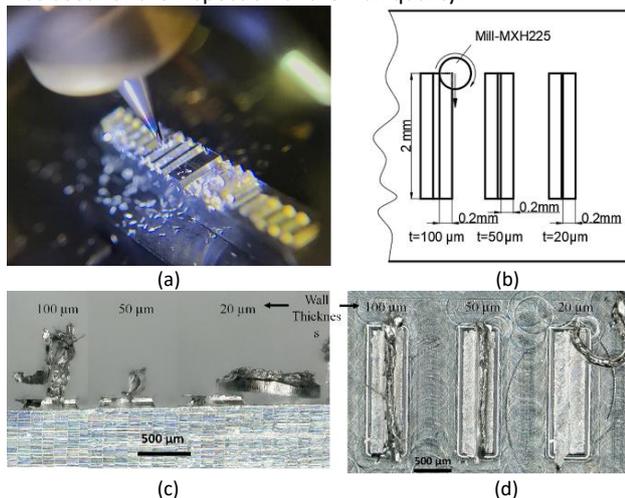


Fig. 2. (a) Machining setup; (b) optimized machining strategy; (c) and (d) experiments with incorrect machining strategy.

4. Results

Fig. 4 shows the experimental and simulated side view of the stress distribution during micro end milling simulation of thin wall and the experimental machining for three different wall thicknesses and axial depth of cut. The thin wall quality was evaluated by inspection of the wall with a 3D microscope. The simulated conditions presented a lower initial axial depth of cut however, in the experiments it was continued till machining the full wall. The maximum stress distributed in the wall area was in the range of 200 MPa, which increased near the cutting zone.

A high stress distribution was detected in a condition with higher axial depth of cut of 40 μm mainly along the thin wall in the contact region of the cutting edge. In the low cutting condition (depth of cut of 10 μm) the high stress distribution was observed in the 20 μm wall and started to deform the wall. However, in the thicker wall, it was localized in the cutting area. The wall deformation is visible in the thinner walls with thickness of 20 and 50 μm . The failure of the 20 μm thick wall was visible in both simulations and experiments. The maximum stress generated in the wall area was in the range of 500 MPa, which

increased with the tool movement in the cutting zone. Moreover, burr formation is a significant phenomenon which is noticeable in micro milling process for instance, in optical functionality of the features [4]. This is a predictable phenomenon with numerical modeling as top and entrance burr formation are visible in the machined area (see Fig. 3). The nominal angle of the wall was considered 90° and the measurements were applied at the top of the wall. The optimal value to the nominal angle of the wall was observed with a 10 μm axial depth of cut for 50 and 100 μm wall thickness. The maximum error at the top of wall angle was about 8.5% and most of the conditions were comparable with experimental results with well matching variations trends.

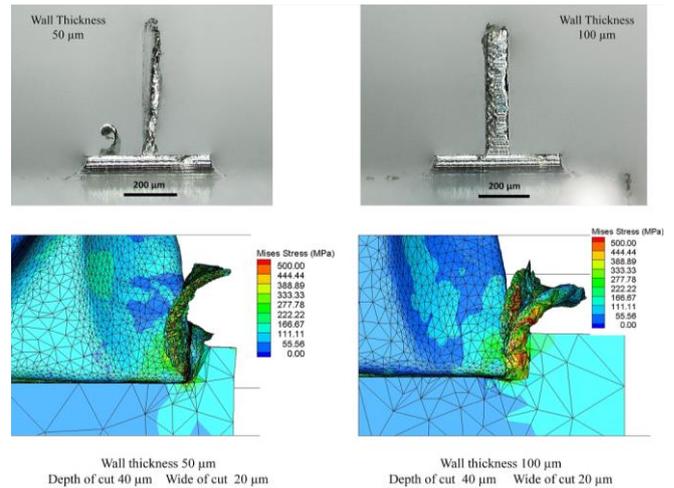


Fig. 3 Von Mises stress distributions along the machined wall

5. Conclusion

In this study, a FE model used to investigate the process of thin wall machining. The simulated conditions are verified against experimental tests. The wall quality and uniformity during milling process has been evaluated. In a lower cutting condition (10 and 20 μm), wall condition enhanced with a lower wall angle error. Concerning the stress distribution along the machined wall larger stress spread in the cutting zone in higher cutting conditions. Regarding wall angle error with cutting conditions a linear trend of deformation recognized in higher condition. A comparable error~8.5% at the top of the wall angel between experiment and simulation were calculated.

Acknowledgements

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