Finite Element Analysis of Cutting Forces and Temperatures on Microtools in the Micromachining of Aluminum Alloys

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Abstract

Micromachining is increasingly continuing to have very significant impacts on national security, defense, energy, healthcare and domestic manufacturing base. Micro-parts are being utilized in the electronic and drive systems for small unmanned reconnaissance planes, for high precision parts used in missile guided systems, for medical devices to deliver medicines in tumors located in fragile internal organs, and many other significant applications. Tooling in micromachining involves endmills and drills with dimensions that make them usually invisible to the human eye. It is therefore difficult to detect tool wear, let alone tool failure or breakage. This problem is also compounded by the lack of machinability data that could be used to select optimum cutting conditions that minimize possibility of failure in addition to lowering the amount of wear on the tool. This paper presents a finite element analysis of the machining of aluminum T6061 alloys. The cutting forces and temperatures are predicted using AdvantagEdge™ software. The results are used to guide machining operators to select machining conditions that produce favorable stresses on the tools, thus avoiding tool breakage.

Introduction

The increased need for miniaturization of parts has continued to play a major role in developing micro-manufacturing technologies. Micro-manufacturing focuses on technologies used to produce parts in the sub-millimeter range, and essentially bridges the gap between nano-scale manufacturing and macro-manufacturing. According to the World Technology Evaluation Center’s (WTEC) commission report [1], micro-manufacturing has and will continue to have very significant impacts on national security, defense, energy, healthcare and domestic manufacturing base. Micro-parts are being utilized in the electronic and drive systems for small unmanned reconnaissance planes, for high precision parts used in missile guided systems, for medical devices to deliver medicines in tumors located in fragile internal organs, and many other significant applications.

Although micromachining has a very lucrative future, key aspects such as chip formation and the mechanics of machining are still not well researched. Current research on micro-machining has focused mainly on developing the actual machine tools. In the U.S., micro-machining centers have been developed successfully at several institutions, including the University of Illinois Urbana-Champaign [1, 2], at the Florida International University [3, 4], and Georgia Institute of Technology [5, 6]. Although these machines, and those developed elsewhere nationally and globally, have been proven to work, complete commercialization has not been realized due to several factors. Firstly, micromachining applications dictate high precision, often in the sub-micron range. Inspection for tolerance and tool condition in this regime requires the use of expensive optical equipment that would not be economically feasible to incorporate into a micro-machine tool for practical applications. Moreover, tool wear monitoring continues to be a challenging issue as there is no reported method that can be adapted to perform this task in a practical way. Most researchers [1, 3, 7] have found that in micro-machining, premature tool breakage and chipping is more is a common occurrence than tool wear. This has a significant influence on the resulting precision of the final product. In addition to tool condition, another factor that affects machinability and precision is vibration. Vibration and chatter leads to poor surface finish. Increased vibration has been shown to increase chip load, thus significantly increasing cutting forces [2,8]. In micro-machining, this may be a major cause for tool failure. Vibration modeling is essential to support chatter avoidance [8]. Research shows that with careful design of a rigid micro-machine, vibration can be predicted and isolation can be achieved [2, 8, 9]. However the influences of material properties at the micro-structure level and cutting conditions are still uncertain [2, 9].

Secondly, the mechanics of micro-cutting is still a relatively new area, not well understood by many researchers. At macro-scale, the chip formation process is well researched and is known to depend on several factors such as material properties and flow stress characteristics. There is a wide variety of literature that explains this process. However, the same does not apply in micromachining. For example, the tangential cutting force in conventional milling using Tlusty and MacNeil's model [10] is assumed to be proportional to the cutting area, and the radial force is proportional to the tangential force. In micro-milling, the actual chip thickness is very different from conventional milling, and hence the Tlusty-Macneil model must be modified to accommodate this difference [3]. In micro-cutting, there is no formal explanation of scaling effects (also referred to as "size effects"), for example, in the relationship between material removal rate and the specific cutting energy [5]. Size effects are not only an issue in micro-machining but also in other micro-manufacturing processes. In micro-forming, it has been observed that decreasing the specimen size causes a decrease in the flow stress [11, 12]. It is clear that manufacturing techniques used at the macro-level cannot be scaled down simply and used in micro-manufacturing.

This paper reports some results of on-going research efforts between Northern Illinois University and EIGERLabs in Rockford, Illinois. These efforts have resulted in the development of several micromachine tools. Of interest is the low cost micromachine designed and built at Northern Illinois University♣. Simulation results for micromilling of aluminum T6061 are presented. These results can be used to predict factors that affect machinability such as cutting forces and temperature.

♣ See NIU news release at http://www.niu.edu/PubAffairs/RELEASES/2008/july/micromachine.shtml

Finite Element Simulations

The study of machining processes (macro or micro) involves analyzing the chip formation process. Years of research has conclusively shown that it a process involving plastic deformation in which large strains and strain rates are developed by localized shear deformation of work material immediately ahead of tool [13, 14]. Heat is generated during the chip formation process as a result of plastic deformation and friction. The heat generated influences chip shape, tool wear, surface finish and cutting forces. These effects have been well studied in macro machining but barely research in the case of micro machining.

The finite element method (FEM) has been applied extensively to study various aspects of the chip formation process. The generalized FEM model is represented by the equation [15]:

$$[K]\{u\} = [F] \quad \text{……………………………………………………………………….(1)}$$

where [K] is the overall stiffness matrix, {u} the displacement vector and {F} the force vector in the direction of displacement. In order to estimate forces, first the relationship between stress and strain is analyzed. The generalized equation for stress rate $\dot{\sigma}$ is given as [16]:

$$\left\{\dot{\sigma}\right\} = [D]\left\{\dot{\varepsilon}\right\} \quad \text{……………………………………………………………………….(2)}$$

$\dot{\varepsilon}$ is the strain rate and the matrix [D] accounts for the elastic and plastic constitutive relations between stress and strain rates. Given that the strain rate is related to the deformation according to the equation:

$$\left\{\dot{\varepsilon}\right\} = [B]\left\{\dot{u}\right\} \quad \text{…………………………………………………………………………(3)}$$

$\left\{\dot{u}\right\}$ represents the nodal velocity vector and the matrix [B] is derived from the polynomial displacement function for the element chosen. Combining equations (2) and (3) yields:

$$\left\{\dot{\sigma}\right\} = [D][B]\left\{\dot{u}\right\} \quad \text{……………………………………………………………………..(4)}$$

The nodal force vector $\{p\}$ is computed by the following equation:

$$\{p\} = A[B]^T\{\sigma\} \quad \text{……………………………………………………………………...(5)}$$

A represents the area of the element. Differentiating equation (5) to get the force rate:

$$\left\{\dot{p}\right\} = \dot{A}[B]^T\{\sigma\} + A\left[\dot{B}\right]^T\{\sigma\} + A[B]^T\left\{\dot{\sigma}\right\} \text{ .... (6)}$$

Substituting for $\dot{\sigma}$, it can be seen that equation (6) is in the form:

$$\left\{\dot{p}\right\} = ([k_1] + [k_2] + [k_3])\left\{\dot{u}\right\} \text{ .... (7)}$$

or simply as:

$$\left\{\dot{p}\right\} = [k]\left\{\dot{u}\right\} \text{ .... (8)}$$

$[k_1]$ and $[k_2]$ account for volumetric and shape change while $[k_3]$ is the stiffness term with respect to strain rate. The latter also accounts for rotation. For micromachining, the first two may be insignificant due to size effects.

Considering equilibrium of forces, the sum of all nodal forces at any given node, say i, in a given direction, say x, , $\sum p_{xi}$ must balance with the external forces, F_{xi}, acting at node i. Given this condition, the element stiffness equation simplifies to:

$$\left\{\dot{F}\right\} = [k]\left\{\dot{u}\right\} \text{ .... (9)}$$

The size of the stiffness matrix, [*k*] depends on the shape of the element. For instance, for a three-node triangular element, it is a 6 by 6 array.

Finite element (FEM) simulations were carried using Third Wave Systems' AdvantEGDE FEM software. The cutting conditions were modeled as a downmilling process with a two-fluted end mill. In 2-D analysis, the milling process was simulated as a single point cutting process shown in figure 1 below. The cutting conditions were selected as follows:

- Tool : 0.02 inch diameter carbide two fluted end mill (manufactured by Performance Micro Tool company);
- Spindle speed: 20000 and 80000 rpm
- Feed: 0.01 – 0.025 mm/tooth
- Depth of cut: 0.01 – 0.03 mm
- Work material: Aluminum 6061
    - E = 70 GPa, ν = 0.33
- Tool material : K10 Carbide

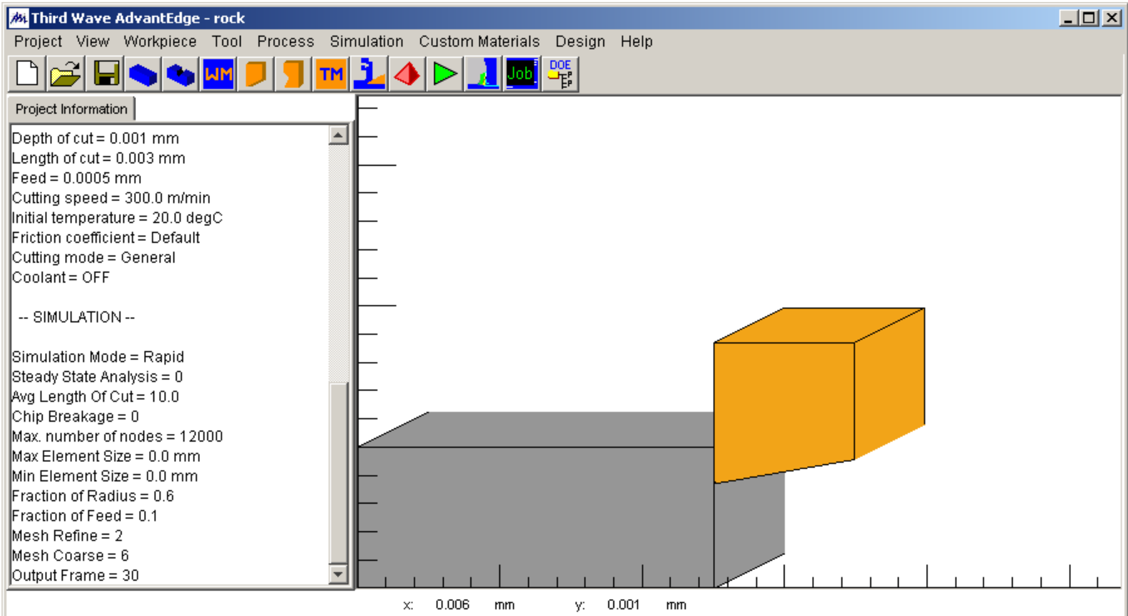

Figure 1. 2-D single point cutting simulation.

To obtain results from the AdvantEdge simulation, a third party software known as Tecplot is utilized. The initial force and temperature data contain a lot of "noise" and it is difficult to determine steady state results. Tecplot has an additional feature that was used to extract results. This is a filter that was applied to smooth the force and temperature curves. A probe tool was then used to determine the maximum steady state value (of the force or temperature). Figure 2 illustrates the details of the chip formed after steady state conditions have been reached, and the force and temperature data. In the interest of CPU usage and computation time, the length of cut was chosen as 20 times the feed in each case. In these simulations, each run lasted approximately 3 hours running on a Windows XP™ environment, on a desktop with 2 Gb of RAM and 2.6MHz processor.

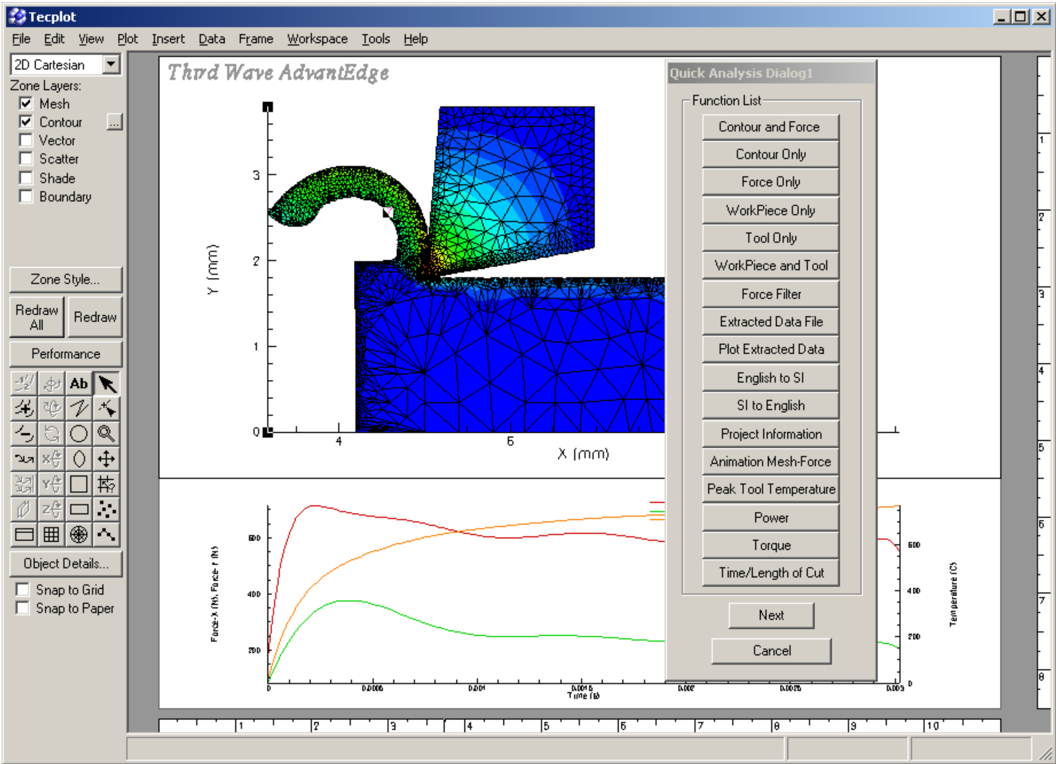

Figure 2. Steady state cutting forces and temperatures.

Results and discussion

a) Effect of spindle speed on cutting forces and temperatures

Figures 3 and 4 illustrate the effects of cutting speed on feed and temperature at a feed and depth of cut of 0.02mm. It is a general tendency that at constant feeds and depths of cut, an increase in spindle speed does not necessarily increase the material removal rate (MMR). In fact it reduces the MMR, thus resulting in reduced tool forces. At higher cutting speeds, due to the reduced MMR, the heat flow into the chip is reduced. A greater proportion of the heat generated flows through the tool and workpiece. This results in an increase in the maximum tool temperature with speed.

b) Effects of feed and feed.

As the feed rate is increased, the amount of material engaging each tooth of the tool increases – this implies an increased tool-work contact length. Due to this, tool forces also increase. The same effect occurs as the depth of cut is increased. In addition to increased contact length, the force resisting deflection is high because of the amount of material engaging the tool. This also contributes to an increase in the tool forces. These results can be seen in figures 5, 6 and 7.

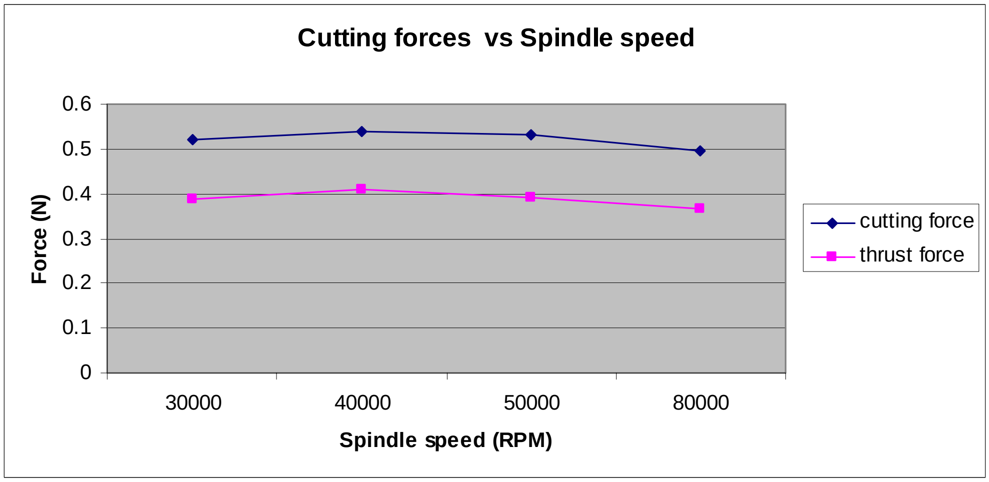

Figure 3. Effects of spindle speed on the cutting forces at feed of 0.02 mm/tooth

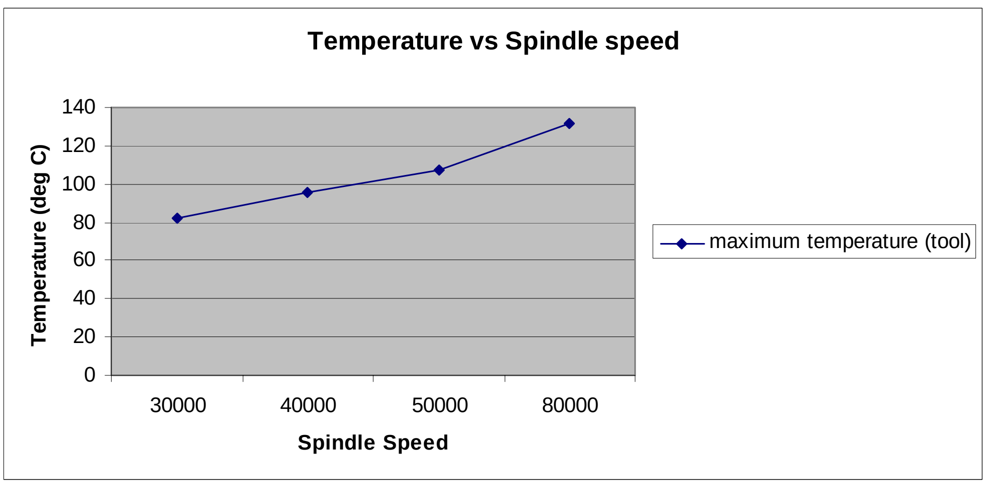

Figure 4. Effects spindle speed on maximum tool temperature.

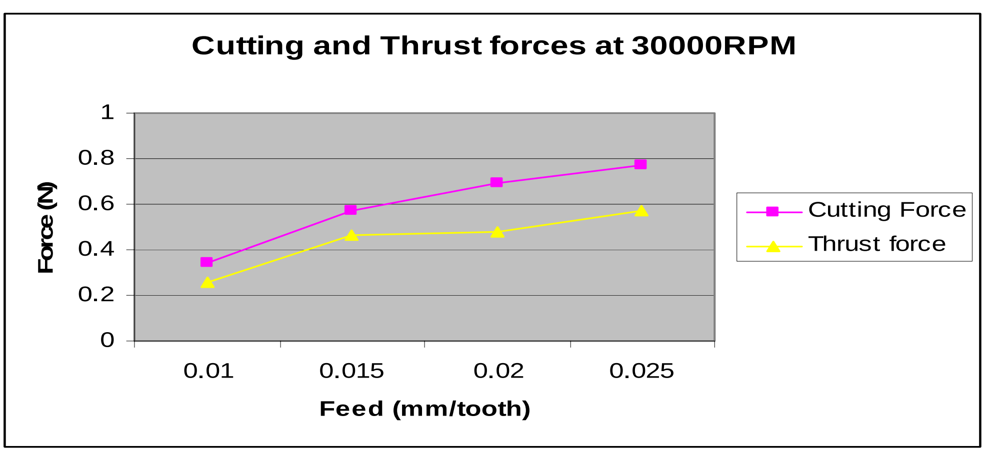

Figure 5 - Effects of feed on cutting forces at spindle speed of 30000 rpm

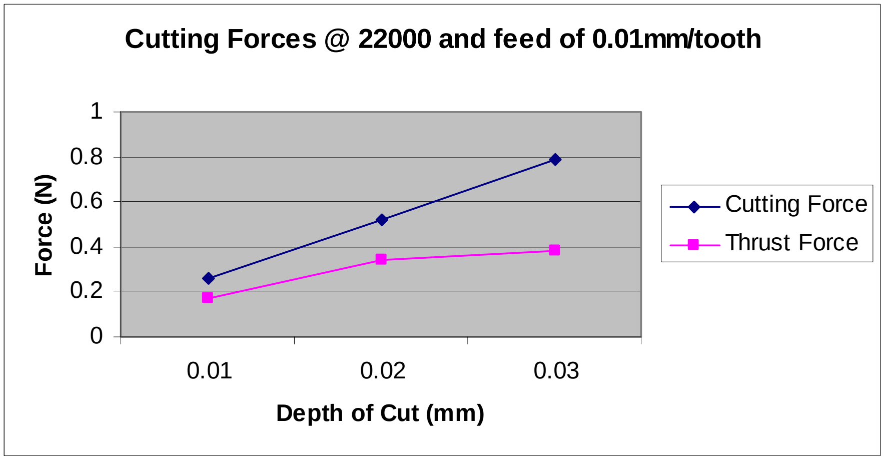

Figure 6. Effects of feed on cutting forces at spindle speed of 22000 rpm

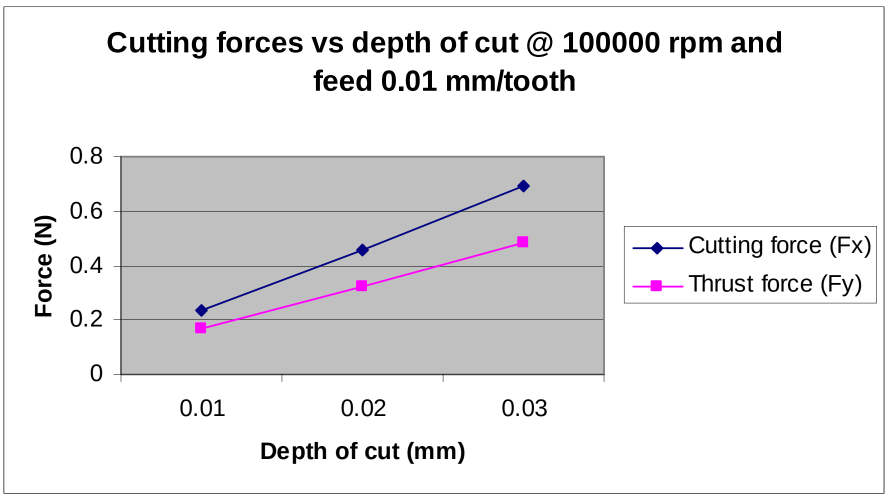

Figure 7 - Effects of depth of cut at 100000 rpm

Conclusions

Micromachining is a fairly complex phenomenon, not easily studied by the scaling of the macromachining process. From the results of this study, it can be seen that increasing cutting speed reduces cutting forces. Higher cutting speeds are suitable for micromachining applications. However, depth of cut has the most significant influence on the machinability of a material in micromachining applications. When the depth of cut is tripled, the cutting forces increase on the average 3.5 to 4 times. On the other hand, when the feed is tripled the cutting forces increase by 2.5 – 3 times. The preliminary results from this study can be used in an optimization process to determine optimum cutting conditions. Moreover, by studying the stresses in the tool material, it is possible to determine what the maximum recommended feeds and depths of cut should be for given cutting speeds.

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Biographical information

Andrew Otieno is an associate professor in the Department of Technology at NIU. He has done extensive research in experimental and theoretical analysis of machining problems, including environmentally friendly manufacturing processes. His research and teaching interests include materials and manufacturing processes, finite element analysis, and manufacturing automation.

Clifford Mirman received his Ph.D. degree from the University of Illinois at Chicago in 1991. From 1991 until 1999, he was a faculty member in the Mechanical Engineering Department at Wilkes University's. He is currently the Chair of the Department of Technology at NIU. His research areas are CAD, finite-element-analysis, and kinematics, both securing grants and writing publications. Dr. Mirman is actively involved in ASEE and SME.