MODELING OF CUTTING FORCES AND CYCLE TIMES FOR MICRO-MACHINED COMPONENTS

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ABSTRACT
Micro-machining employs specialized machine tools and cutters to achieve micro-scale (<1 mm) features with uncut chip thicknesses and surface finish requirements ranging from a few microns to several hundred nanometers. Machining in this regime is often dominated by ploughing and rubbing phenomena over shearing at the cutting edge and requires micro-structural effects to be taken into consideration. The ability of a micro-machining process to achieve geometry and surface finish requirements depends on several factors including workpiece material microstructure, tool geometry, tool integrity during the cutting process, and the machine tool. Although important in conventional machining, these effects have a much more dramatic effect on micro-machining process productivity. Process productivity is further affected by the ability of the machine tool to follow rapid changes in the micro-machining toolpath. Any attempts to improve machining productivity must demonstrate a reduction in on-machine cycle times without deteriorating tool life or integrity. Current understanding of issues unique to micro-machining must be improved before stable, uniform processes can be implemented by industry. Specifically, understanding the cutting behavior of workpiece materials in this regime and developing an ability to predict, analyze, and improve machining cycles times present two opportunities for improving the stability and productivity of micro-machining processes. Although feed rate optimization is an effective approach to reduce cycle times, the transient characteristics of the machine tool controller plays a much more pronounced role on the on-machine cycle times in micro-machining than in conventional machining. Similarly, tool failure and tool wear behavior must be better understood while accounting for the micro-structural machining behavior of the workpiece. It is necessary to capture these two aspects within any process improvement effort.

This paper presents a physics-based modeling approach to understanding and predicting the micro-machining behavior of the Al6061 alloy and corresponding machining processes. Al6061 was chosen for this study due to its frequent application in medical device industries owing to its high availability, low weight, ease of manufacturing, and low costs. Due to its optical properties, Al6061 is also used in defense optics applications. A physics-based finite element model was developed to model the cutting behavior of Al6061 in the micro-machining regime. This model was validated by comparing cutting force predictions against measurements obtained from experimental machining tests performed on a three-axis milling machine. Experiments encompass multiple tool diameters, uncut chip thicknesses, and depths of cut. New advancements aimed at the accurate prediction of cycle times for micro-machining processes within a physics-based toolpath-level analysis framework are also presented. The model takes into account acceleration, deceleration, and jerk characteristics of the machine tool controller to improve overall cycle time predictions. Model predictions are compared against on-machine cycle times for micro-machined features. Finally, the significance of the results for process improvement efforts of micro-machined components is discussed. Although this paper focuses on Al6061 alloy, the underlying modeling techniques and components are applicable to a large variety of materials and processes.