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Tool wear monitoring of micro-milling operations

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ABSTRACT

The mechanical removal of materials using miniature tools, known as micro-mechanical milling processes, has unique advantages in creating miniature 3D components using a variety of engineering materials, when compared with photolithographic processes. Since the diameter of miniature tools is very small, excessive forces and vibrations significantly affect the overall quality of the part. In order to improve the part quality and longevity of tools, the monitoring of micro-milling processes is imperative. This paper examines factors affecting tool wear and a tool wear monitoring method using various sensors, such as accelerometers, force and acoustic emission sensors in micro-milling. The signals are fused through the neuro-fuzzy method, which then determines whether the tool is in good shape or is worn. An optical microscope is used to observe the actual tool condition, based upon the edge radius of the tool, during the experiment without disengaging the tool from the machine. The effectiveness of tool wear monitoring, based on a number of different sensors, is also investigated. Several cutting tests are performed to verify the monitoring scheme for the miniature micro-end mills.

1. Introduction

The miniaturization of components has become increasingly important for various modern technologies, in order to meet the demands for shrinking component size and high accuracy. Miniature systems can provide portability, disposability, lower material and power consumption, lower sample requirements, higher heat transfer, and the capability of better process integration and automation. Several researchers (Hesselbach et al., 2004; Masuzawa, 2000) have reached the consensus that the fabrication of 3D structures with high aspect ratios and complex geometry, utilizing a variety of materials, is important. Hence, micro-mechanical machining is gaining greater importance, due to the ability of fabricating complex 3D structures, the high material removal rate, and the capability of machining a variety of engineering materials, especially metallic alloys.

There are several critical issues associated with micro-mechanical milling operations that arise mainly from the miniaturization of the components, tools and processes. Miniature tools are more likely to experience relatively large vibrations and forces, due to size, reduced stiffness, and the size effect. Because of the miniature size of the end mills, these vibrations can be detrimental to the longevity of tools and part tolerances. Also, it is very difficult to detect wear, damage to cutting edges, or even tool breakage due to sensor limitations at the micro-scale. As a result, the monitoring of micro-milling operations is critical to avoid excessive tool wear and to maintain part tolerances and surface quality.

Several researchers have conducted investigations into monitoring of machining processes, especially in the macro-realm, using various variables and sensors. Matsushima et al. (1982) and Deyuan et al. (1994) have used motor current and power for detecting tool wear and breakage. Altintas (1992) and Kim et al. (1999) presented the use of current drawn by feed drive motors for milling process monitoring. Youn et al. (1994) and Dornfeld et al. (2006) investigated the feasibility of using acoustic emission (AE) and cutting force signals for the detection of tool breakages, small fractures and wear of the cutting tools in turning. Others, like Saglam and Unuvar (2003), Kuljanic and Sortino (2005) and Tlusty (1978), have used force signals to detect tool failure and breakage in milling. Among these sensing methods, the accurate measurement of cutting forces provides the most effective method for monitoring tool conditions, since it yields higher signal-to-noise ratios and best represents the state of the machine tools and machining operations (Chae and Park, 2007).

The most common method of measuring cutting forces in machining operations is through the utilization of table dynamometers or piezoelectric load cells. Tansel et al. (2000), Tansel et al. (1993, 2000) have used a neural-network-based usage estimation method for monitoring end mills with a diameter bigger than 1 mm. They have used force signals with different features, such as root mean square, mean, maximum, segmental average

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based and wavelet transformation-based values. Ghosh et al. (2007) fused several signals (i.e. cutting forces, spindle vibration, and spindle current) via a neural network to estimate the average flank wear of the main cutting edge in a milling operation. However, the majority of the machine tool monitoring research work has been directed at the macro-domain. Despite years of research, reliable, versatile and practical methods are not yet available for the monitoring and controlling of high-speed machining processes, especially for micro-machining operations. Moreover, the use of a neuro-fuzzy algorithm, such as the adaptive neuro-fuzzy inference system, for monitoring micro-milling processes has not been thoroughly investigated.

This study examines a tool wear monitoring method using various sensors, such as force and AE sensors and accelerometers, for micro-milling operations. In order to monitor tool conditions effectively in the micro-realm, where the rotational speed is high and the cutting mechanism is complex, sensor fusion is needed to overcome the difficulties associated with the low-frequency bandwidth of the sensors and the complexity of micro-machining processes (Vogler et al., 2003). Sensor fusion through an adaptive algorithm can provide a higher frequency bandwidth and redundancy of various sensor signals. A high-power optical microscope was used to measure the actual tool conditions during the experimental machining tests. The sensor signals were collected and then fused through the neuro-fuzzy algorithm, which had been previously trained using a set of carefully gathered training data, to determine the tool condition and the amount of wear for different cutting conditions, such as different feed rates and spindle speeds. To verify the effectiveness of the sensor fusion and monitoring scheme, different combinations of sensor signals were tested for various experimental micro-milling tests. The methodology has also been extended to estimate high-frequency bandwidth cutting forces.

The paper is organized as follows: in Section 2, micro-milling operations and their uniquely associated aspects, which can significantly affect tool wear, are described. In Section 3, the experimental setup used for performing the cutting test, measuring and gathering data, and observing the actual tool condition is explained. Section 4 discusses the methodology that is used to construct the monitoring scheme. In Section 5, the results of the proposed monitoring method for different signals and conditions are presented. Several challenges and limitations of the method are discussed. Lastly, Section 6 provides a summary of our findings.

2. Micro-milling

Micro-machining operations are different from conventional machining in several aspects, making the monitoring of the process even more important. In macro-machining, the feed per tooth is generally much larger than the tool edge radius; and, the cutting models are based on the assumption of a sharp tool that completely removes the surface of the workpiece without any elastic recovery or plowing. In micro-machining, due to the small edge radius of the tool and very low feed rates, this assumption is no longer valid. The edge radius of the tool in micro-milling is comparable to the chip thickness and causes a large negative rake angle. This negative rake angle then causes plowing and elastic recovery of the surface, as shown in Fig. 1(a) . If the depth of cut is less than a certain value, called the minimum chip thickness, the material is just squeezed underneath the tool. After the tool passes the material, the material is plowed with no chip formation and part of the plowed material recovered elastically. Fig. 1(b) depicts micro-milling operations where each flute goes through both shearing and plowing during machining, resulting in fluctuations of and increases in cutting forces (Malekian et al., 2008a,b) and accelerated tool wear, since increases in the cutting forces significantly affect tool wear. Other aspects of the micro-machining operations that can be attributed to severe tool wear are elastic recovery of the workpiece, dynamic deflections and runout of the tool, and low feed instability.

The elastic recovery of the material in micro-scale affects the tool wear in two ways: the cutting forces, and an increase in the contact area between the tool and workpiece at the flank face of the tool, as can be observed in Fig. 1(a). This increased area causes more friction and rubbing and consequently more flank wear of the micro-tools.

Elastic recovery of a workpiece can be obtained through either indentation or scratching tests using hardness indenters and measuring the elastic recovery of the workpiece using either a profilometer or interferometer (Malekian et al., 2008b). We found the average elastic recovery of the studied aluminum workpiece was approximately 10% by using a scratch test and measuring the scratch with a profilometer (Mitutoyo Surf-test 201). Knowledge about the elastic recovery of the workpiece can be helpful in understanding and estimating the flank wear in micro-scale.

Since micro-tools are very small in diameter, the tool deflection due to cutting forces can be quite significant. Furthermore, even a very small spindle or tool runout can affect the tool engagement and cutting forces considerably. Finding the dynamics of the tool tip in micro-scale, however, is challenging. Unlike macro-scale machine tools, performing the impact hammer test in micro-mills is not possible due to the fragility of the miniature tools. One of the methods to identify the dynamics at the tool tip is through the receptance coupling (RC) method (Mascardelli et al., 2008), which mathematically couples substructure dynamics as shown in Fig. 2. In the RC method, the dynamics of the machine, spindle and tool holder are measured through experimental modal analysis; and, the dynamics of the tool are obtained with finite element analysis. The frequency response functions are then assembled based on the compatibility and equilibrium conditions. The tool tip dynamics can be

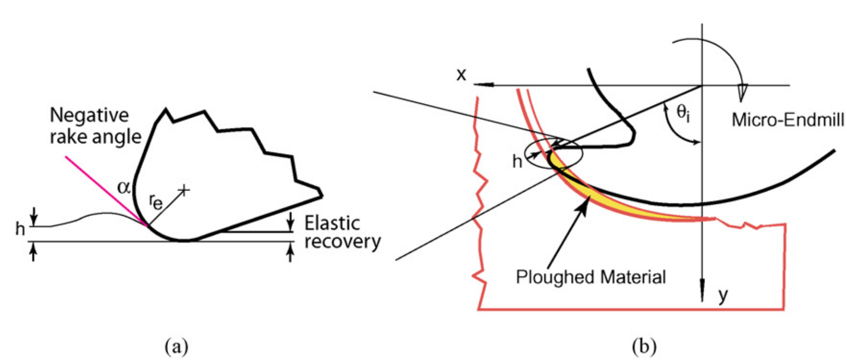

Fig. 1. Micro-end milling operations: (a) tool and workpiece and (b) top view.