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An innovative approach to monitor the chip formation effect on tool state using acoustic emission in turning

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A B S T R A C T

Chip formation in metal cutting is inevitable and has a remarkable effect on tool state and therefore on the tool life. The work presented here introduces a new technique to independently monitor the chip formation effect on the tool state. This has been done by separating the chip formation events from the rest of the frequencies of occurrences. A customized tool holder and sensor setup are designed and integrated with the conventional tool holder to capture the signals from chip formation independently during turning. The signals taken by acoustic emission (AE) sensor represent the effect of chip formation on the tool state. The frequencies remaining below the transient offset signal are mostly coming from the tool wear and plastic deformation of the workmaterial. It has been observed that the acoustic emission is more susceptible to entire occurrences in turning. The time domain signal and corresponding frequency response can predict the tool state effectively. From raw AE signals and their RMS values, the tool wear and plastic deformation are observed to increase with the increase of cutting speed, feed rate and depth of cut. However, the tool wear has been found to decrease with chip breakage even at higher cutting speed and feed rate, and this has been verified by measuring the tool wear. The chip formation frequency has been found to vary between 68.3 kHz and 634.83 kHz while the maximum intensity was observed at 97.7 kHz.

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1. Introduction

A machining process includes a number of occurrences like tool wear, tool chipping, tool breakage, tool failure, chip formation, chip breakage, process interruption and some other irregularities and so on. The entire phenomena have their particular effect on the process and also on the tool state. The different occurrences during metal cutting affect the cutting tool condition and disturb the process stability. In conventional turning, the chip formation is the only way to remove material from the workpiece to shape the workmaterial into a desired dimension. The chip formation has a significant influence on the cutting tool condition depending on the formation mechanism and its geometry. The mechanism of chip formation, the types of chips, the separation and rate of removal of chips, the energy content and temperature of chips and the rubbing action of chips with the tool face determine the tool wear. Dolinsek and Kopac [1] have pointed out that the heat generation and the chip formation force during metal cutting dominate the tool wear. The chip formation not only produces the tool wear, in some cases it causes breakdown of the cutting tool. Tool wear increases power consumption and tool breakdown interrupts the operation and affects the product's quality. To avoid the difficulties and uncertainties associated with the chip formation in machining, effective monitoring system is necessary.

2. Chip formation in metal cutting and monitoring

2.1. Chip formation in metal cutting

The chip formation is a certain happening in metal cutting to remove material from the workpiece. Therefore, its effect on the cutting tool is unavoidable. This is associated with a complicated interaction of plastic and elastic deformation of the workmaterial within a small region known as shear zone. Jared and Dow [2] have pointed out that the interaction in shear zone ultimately defines both the geometry and motion of the generated chips in metal cutting. However, the cutting speed affects the shape and dimensions of the chip formation zone, and therefore controls the chip formation types and also the chip geometry. Kim and Kweun [3] observed that as the cutting speed increases, chips become thinner. The reason has been explained by Tsai [4] as in high cutting speed the controlled chip region decreases and consequently the chip thickness is reduced. Depending on the cutting

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conditions, both the steady state and the cyclic types of chips are generated in turning. It is reported from Astakhov [5] that the steady state type chips generate from the blunt tool-tip and are continuous in nature. In continuous chip formation, Dolinsek and Kopac [1] have found that at slow cutting speeds, adhesion and abrasion are the main tool wear mechanisms whereas abrasion and chemical wear are most likely at high cutting speeds. The cyclic types of chips are discontinuous, wavy and saw toothed in shape and are caused by built-up-edge (BUE). Kishawy and Wilcox [6] have pointed out that the saw-toothed chip formation is caused from the periodic cracking, and not from the adiabatic shear. On the other hand, the adiabatic shear is involved with the micro-crack region and it has a specific effect on the chip flow. Shaw and Vyas [7] observed that, with the thinning of micro-crack region, the chip moves up the tool face and changes the types of tool wear. Davies et al. [8] have observed that among the entire chip types, the segmented chip is typically produced from conventional turning and its effect on the cutting tool is the most. Besides, Chen et al. [9] have empirically established that the segmented chip formation force is less whereas the generated heat is more than the continuous chip formation. From the observation of Balaji and Ghosh [10], for a particular tool geometry, the cutting speed typically controls the onset of strain localization and thus the segmented chip formation. Depending on the cutting conditions and tool geometry, the generated chips flow in different direction to dispose. According to Jared and Dow [11], the chip flow direction or the flow angle only defines its initial direction of motion however, that might be changed by the external force in later stage. With the change of chip flow angle the stress concentration in chip as well as its geometry are reportedly altered. According to Shamoto and Aoki [12], the chip flow in a grooved tool basically consists of side-flow and back-flow, whereas the chip curl consists of up-curl and side-curl.

During the chip removal, the friction occurs at the sticking and the sliding region of the tool–chip interface. According to Kilic and Raman [13], the uniform shear stress in the sticking region decreases with a power law in the sliding zone. The cutting tool is thereby affected from the sticking and sliding of chips during formation. Balaji and Ghosh [10] have investigated that the sticking regions are the most heat-affected regions due to the intense friction between the underside of the chip and the tool's groove. They have found an increase in cutting force and contact length with the decrease of chip curvature. On the other hand, Arcona and Dow [14] have reported that the change in the cutting force indicates a change in cutting tool geometry and workpiece surface finish. Besides, the change in cutting force indicates different types of chip generation in machining. The various types chip formation and disposal affects the tool in different way and to different extent depending on their types, geometry and flow angle.

2.2. Chip formation monitoring

Although, monitoring of metal cutting process is common, independent monitoring of a particular occurrence, i.e., chip formation is hardly reported. In metal cutting, a number of researchers have reported monitoring of the chip formation during tool state investigation. Both the direct and indirect sensing methods have been used to make the monitoring possible. Direct methods consist of laser, optical, and ultra-sonic sensors which provide a direct measurement. These methods are still very expensive and difficult to apply in the machining process environment. In contrast, indirect methods are more economical, and are based on sensors which represent the machining state by sensing cutting forces, vibrations, temperatures, current consumption, etc. Basically, four sensors: dynamometers, accelerometers, AE sensors and current sensors have been widely used to monitor machining systems and the associated occurrences [15].

Gandarias et al. [16] have used laser sensor to investigate the tool breakage in monitoring the cutting tool state in milling. Tool condition was monitored by focusing a laser beam with a spot size of 50 μm constantly on the cutter, and at the same time directing the beam reflection towards a receiver. As the laser beam is required to reflect back from the object to be monitored; therefore application of laser sensor in monitoring chip formation like transient occurrences in a clumsy machining environment is really very difficult, and therefore not being used yet. Barry and Byrne [17] have monitored chip formation with AE sensor in turning. They have investigated the nature of AE signal corresponding to the continuous and saw tooth chip formation at various depths of cut. The observation result revealed that, during continuous chip formation the AE_{RMS} varied between 0.05 V and 0.1 V; and during saw tooth chip formation, AE_{RMS} contained at least one order of magnitude greater. Pawade and Joshi [18] have used AE signal to determine the quality of machined surface in high-speed turning of Inconel 718. The energy, number of counts, and mean frequency amplitude of the AE signals were used to evaluate the dependence of the machining deformation on the surface generation mechanism. From their observation, the AE signal variations is found to be useful to correlate abnormal events during machining, such as higher thrust forces, chip form variation, and surface anomalies produced in machining. Teti et al. [19] have measured different force components to investigate the chip formation types in metal cutting. The measured cutting forces were demonstrated with six different variables (feed force, radial force, cutting force, resultant force and the force ratio between the axial and radial force). The different variables and Partial Least Squares (PLS) method have been used to correlate the signals of three cutting force components with the corresponding chip types. The experiment showed that at low feed rates, the force ratio became more effective than the other variables considered, and at relatively larger feeds the resultant force was more significant. Somkiat [20] have used dynamic cutting force to investigate the chip formation types in turning. From their observation, the dynamic cutting force has its own characteristic pattern in each cutting situation of continuous chip formation, broken chip formation, and the chatter. When the chips were continuous, the dynamic feed force was relatively small in amplitude and the power spectrum density (PSD) was relatively large at low frequency range, typically less than 50 Hz. On the other hand, the dynamic component of the feed force, among the three force components, was relatively large in amplitude when the chips were broken into pieces, and the relatively large PSD appeared in the frequency range, which corresponded to the chip breaking frequency. Tanhjitsitcharoen and Moriwaki [21] have used various cutting force signals to identify the chip forms, especially the favorable and unfavorable chip types. From their observation, the dynamic components of three cutting forces were small in amplitude when the chips were continuous. However, when the chips were broken, the dynamic feed force component becomes larger. Hence x, y, and z components of cutting force were larger in broken chips than in the continuous chips. From the literature, the force dynamometer is an extensively used sensor in chip formation monitoring. Despite, the force dynamometer can effectively senses the continuous chip formation; it has limitation in sensing segmented chip formation. As the frequency of segmented chip formation is greater than 10 kHz, it is beyond the response of conventional dynamometers [17]. On the other hand, the strain energy released during saw tooth chip formation is the dominant source of AE signal. Therefore, chip formation monitoring using AE sensor is more effective.

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