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Short Communication

Dynamic ultrasonic contact detection using acoustic emissions

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ABSTRACT

For a non-contact ultrasonic material removal process, the control of the standoff position can be crucial to process performance; particularly where the requirement is for a standoff of the order of <20 μm. The standoff distance relative to the surface to be machined can be set by first contacting the ultrasonic tool tip with the surface and then withdrawing the tool to the required position. Determination of this contact point in a dynamic system at ultrasonic frequencies (>20 kHz) is achieved by force measurement or by detection of acoustic emissions (AE). However, where detection of distance from a surface must be determined without contact taking place, an alternative method must be sought.

In this paper, the effect of distance from contact of an ultrasonic tool is measured by detection of AE through the workpiece. At the point of contact, the amplitude of the signal at the fundamental frequency increases significantly, but the strength of the 2nd and 3rd harmonic signals increases more markedly. Closer examination of these harmonics shows that an increase in their intensities can be observed in the 10 μm prior to contact, providing a mechanism to detect near contact (<10 μm) without the need to first contact the surface in order to set a standoff.

1. Introduction

Ultrasonic machining (USM) is long established as a manufacturing technique having been suggested as long ago as 1927 in a paper by RW Wood and Loomis [1]. The process essentially involves the conversion of high frequency (>20 kHz) electrical energy to a mechanical displacement by a transducer. This transducer can be either magnetostrictive or piezoelectric in operation and is connected via a focusing horn to a tool or end effector. The design of this horn/tool assembly in terms of step down geometry and length is critical to achieve maximum displacement at the tip. The sound waves generated by the transducer will have a characteristic wavelength dependent upon the materials and geometry used and an anti-node in the wavelength of the transmitted longitudinal wave should occur at the tip of the tool to generate maximum amplitude.

Ultrasonic transducers are also employed in conjunction with other machining techniques to ultrasonically assist with material removal rates and surface finish. Techniques include the application of ultrasonic vibration to tooling in physical contact with the workpiece surface in processes such as turning [3] and drilling [4]; this category of processes is well-known and does not represent the scope of the present investigation.

Conventional USM uses an ultrasonically vibrated tool shaped with the contours of the recess form required in the final machined part. A static load is applied to the tool and an abrasive slurry containing particles such as boron carbide, alumina or diamond suspended in a carrier fluid is introduced into the interface. This is therefore a contact process, the feedback control for which is provided by a load cell measuring the force applied. The dominant mechanism for material removal in this process is direct hammering of the abrasive particles onto the workpiece causing micro-chipping. Ultrasonic activation of an abrasive has been acknowledged to have a number of material removal mechanisms, summarised by Thoe et al. [2]: abrasion by direct hammering of abrasive particles against the workpiece; micro-chipping by the impact of free-flowing particles in the turbulence caused by ultrasonic displacement; cavitation effects as air bubbles form and subsequently collapse carrying abrasive particles to the work surface and chemical action caused by reaction with abrasive fluid used.

A non-contact material removal process has been developed which uses the focussed ultrasonic vibration of a tool to agitate abrasive slurry. This process is less aggressive than conventional USM as there is no direct hammering of the abrasive particles on the surface as a result of controlling the stand-off distance of the oscillation with respect to the abrasive particle size. Due to the non-contact nature of the process, there is no force feedback mechanism available. Therefore other methods must be sought to accurately determine the standoff distance of the tool with respect to the workpiece surface. Recently, work by Huang et al. on

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the modelling of the sound wave from a tool tip and subsequent non-contact material removal has been performed [5] and agreement with the model has been demonstrated.

The technique of acoustic emission (AE) monitoring uses sensors to capture events that occur in solid bodies in response to stimuli. The resultant disruption to a solid body releases energy in the form of heat and also a characteristic elastic wave. Dependent upon the speed of the release of energy, the waves generated are generally in the range 20 kHz–1 MHz, and will result from any significant perturbation of the atomic structure.

AE monitoring has been developed for non-destructive testing and evaluation. It can be employed in a number of different applications, from bridge [6] and pipe monitoring to the monitoring of processes during precision manufacturing [7,8]. The construction of an AE sensor generally consists of an electromagnetically shielded piezoelectric sensor element contained within a metal cylinder. The frequency response of the sensor used can be tailored to the range of signals generated by the process at the specification stage; this is done by doping the piezoelectric material to shift the resonant frequency to the area of interest and thus generate the largest response in a particular band of frequencies.

The uses of AE for tool contact detection in rotary machining processes have been explored [9] with particular consideration of the surface damage caused during the detection process. AE systems are successfully used in industrial applications for contact detection of grinding wheels and other machining tools, allowing faster identification of initial contact and thereby increasing duty cycles. Gap control systems are also commercially available but rely upon touch-on before the gap can be set. The scope of this paper is to address the needs of non-contact ultrasonic machining/polishing to develop a new technique for dynamic determination of near contact (<10 μm); this is of critical importance to the effectiveness of the process.

2. Approach for detection of tool standoff distance

Unlike conventional USM, a contact process where measurement by a load cell can provide the feedback required for initial positioning, the ultrasonic machining/polishing process under development is a non-contact process for which AE feedback is to be employed to determine *z*-axis location. The axial ultrasonic displacement at the tool tip is in the range 10–25 μm and the end of travel of the tool must approach no closer than 5–10 μm in order that efficient material removal be achieved; preliminary ultrasonic machining trials (not presented here) have identified significant differences in material removal rates with a variation in standoff as small as 5 μm; it follows that it is critical for this operation that the distance between the end of the travel of the reciprocating tool and the workpiece be accurately determined, therefore any measurement of the contact point should be performed under dynamic tool conditions. To set this distance, a process was initially devised for detection of the point at which contact occurs and subsequent standoff from this datum.

Detecting the contact position of an oscillating tool with a workpiece is also critical for another reason. If one were to contact a surface too heavily there is a great potential for damage, particularly given the frequency of the impact; it is not only damage to the workpiece surface that is to be avoided, but also damage to the tool tip. Greater amplitude at the tip can be achieved using a titanium alloy sonotrode, but this material has low wear resistance in an abrasive environment, whereas a hard material such as tungsten carbide provides less amplitude but greater wear resistance. Both types of material can be damaged by surface impact, ductile tool tips may be deformed whereas brittle tool tips may fracture under these conditions, particularly given the form and diameter (∼500 μm) of the tool tip (see Fig. 1); this damage can have repercussions for the process such as a decrease in the maximum amplitude obtainable at the tool tip or a change in the influence function (i.e. the shape of the abraded footprint) upon the target surface.

AE signals from the high frequency tool tip can be detected through an air gap providing there is sufficient perturbation of workpiece surface resulting from the transmission of these sound waves. Monitoring the signals received through the workpiece in both the time and frequency domain as the reciprocating tool approaches the surface can provide very precise determination of the exact position at which initial contact occurs; with little encroachment upon the surface.

3. Experimental

The ultrasonic tool, supplied by Sonic Systems Ltd., is mounted on the *z*-axis of a 3-axis system capable of micron precision in position; the axes are software controlled and positional feedback data can be polled from the motor controller which has been calibrated using a dial test indicator. The direction of oscillation of the tool is normal to the workpiece surface. Direct feedback of the peak-to-peak displacement at the tooltip is not possible; instead displacement readings are taken from the transducer face. The amplitude of this displacement is subsequently mechanically amplified using an ultrasonic horn; the magnitude of this amplification is determined by the geometry of the horn [10]. Finite element analysis was used by the supplier in the design of the horn to calculate a theoretical gain from the horn but laser vibrometer measurements using a Polytec Laser Vibrometry system were used to accurately determine the real peak-to-peak displacement at the tool tip with respect to transducer displacement. The resultant relationship is linear over a working range as described by the following equation:

$$a_2 = 3.42\ a_1 + 0.98 \tag{1}$$

where a_1 is the amplitude at transducer in the working range 2–4 μm and a_2 is the intensified amplitude at the tool tip. This equation is for a particular Titanium 6–4 horn geometry with a theoretical gain of 3.5 and a measured gain of 3.7–3.9 over the working range.

The workpiece was clamped below the tool along with the AE sensor, a Physical Acoustics R6d differential sensor. The response of the sensor is highly dependent on the clamping force with which it is attached to the workpiece and also dependent to a lesser extent upon the distance from the origin of the signal. Whilst a

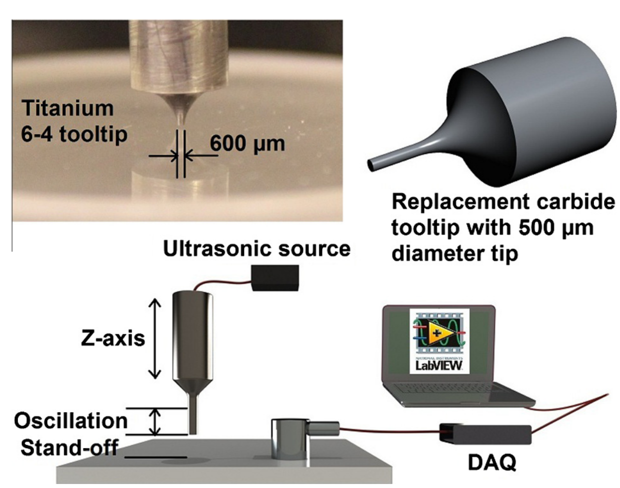

Fig. 1. Schematic of experimental setup with tooltip detail.