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On reliable measurement of micro drilling forces and identification of different phases

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A R T I C L E I N F O

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A B S T R A C T

Mechanical micro-drilling process is often used in the manufacture of miniature components and molds. Frequent breakage of micro-drill is a major problem necessitating a thorough investigation into the process. One of the important responses measured during micro-drilling process is variation of thrust force and torque. Since the values of thrust force and torque are very low in micro-drilling, reliable measurements have to be carried out using high-resolution dynamometer. In the present work, micro-drilling is carried out using 0.5 mm diameter drill on Al 6061-T6 sheet of 3 mm thickness. The measurement results obtained from multi-component dynamometer are discussed first. Subsequently, a torque sensor mounted on the multi-component dynamometer is used to measure the torque, while the thrust force is acquired from latter. Since it is practically impossible to start acquiring the signals at a given time instant, the signals have to be synchronized in time domain using a novel signal processing technique. Different phases in micro-drilling, namely entry, full penetration and dwell are identified uniquely.

1. Introduction

In the manufacture of engineering components, different metal cutting operations such as end-milling and drilling are widely used. In order to understand the process behavior, different responses have to be measured and monitored [1,2]. One of the important responses is the forces generated during metal cutting operations. In end-milling operation, a rotating multi-point tool is set to certain axial depth of cut and moved in a specified path. This machining operation generates forces in *X*, *Y* and *Z* directions. Three-component milling dynamometers are available to measure *Fx*, *Fy* and *Fz*. In case of drilling, rotating drill is axially fed and hence thrust force and torque are developed. Drilling dynamometers are also available to measure thrust force (*Fz*) and torque (*Mz*). Studies have been carried out to understand the effect of tool wear on cutting forces and quality of features produced [3–6]. In general, size of features and/or tools used is above 3 mm in conventional macro machining.

With miniaturization of products, micro-machining operations have started playing a major role in the manufacture of such products. In general, machining of features that have sizes below 1 mm is referred to as micro-machining. More conservatively, machining of features with 0.5 mm and below size and use of micro-tools of size 0.5 mm and below are taken to fall under regime of micro-machining. The meso-machining regime between 0.5 mm and 3 mm is sometimes taken under micro-machining. It is also more important in micro-machining operations to study the cutting forces, as breakage of micro-tools leads to downtime of expensive machine tools. Replacement of micro-tools is also expensive since these micro-tools are costly [7,8]. The cutting forces are quite low in micro-machining operations. Special types of dynamometer, with responding threshold

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much lower than that of macro-machining dynamometer, have been developed. In order to extend the applicability of dynamometer to all machining operations, multi-component dynamometers have been developed for measuring *Fx*, *Fy*, *Fz*, *Mx* and *Mz*. Researchers are encouraged to measure the forces in micro-endmilling as well as micro-drilling using high-resolution multi-component dynamometers. Unfortunately one can come across instances where *Fz* and *Mz* have been measured in micro-endmilling and *Fx*, *Fy*, *Fz* have been measured in micro-drilling.

Micro-endmilling forces have been successfully measured by Srinivasa and Shunmugam using high-resolution multi-component dynamometer [9]. Since the milling is carried out with translation of micro-endmill in a specified direction, measurement of three components of the cutting force is necessary. Measurement of *Fx*, *Fy* and *Fz* are more reliable, as these signals are acquired simultaneously in multi-component dynamometer. It is important to note these force components exhibit phase-shifts that are inherent in the endmilling process. Study of forces in micro-drilling has been the focus in the recent times [10–15]. The multi-component dynamometer used for the measurement of endmilling forces [9] has been used to measure the thrust force and torque in micro-drilling of plastics and fiber reinforced plastics. The thrust forces show much consistent behavior in the above micro-drilling process. In contrast, the torque values show wider scatter, but the values of torque are in order [12–14]. The large scatter is presumed to be due to the presence of fibers in the polymer matrix. While carrying out micro-drilling of metals, certain difficulties are experienced as the forces are higher.

In this paper, the difficulties experienced in the measurement of thrust force and torque in micro-drilling of metals using the multi-component dynamometer are discussed. A method to measure micro-drilling forces using a combination of multi-component and torque sensor is presented. The measurements done using two systems pose a different kind of problem. This paper proposes a novel technique based on cross-correlation function to synchronize the signals. The results are presented and discussed in this paper.

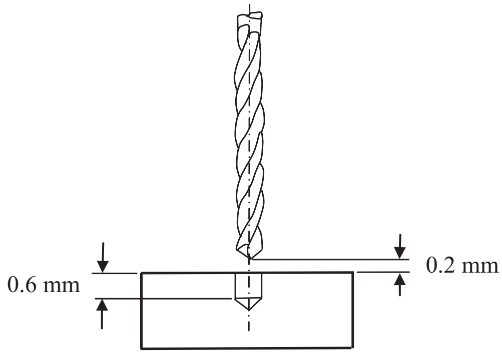

Fig. 1. Micro-drilling details.

2. Experimental setup

Approach and depth details in micro-drilling as relevant to the present work are shown in Fig. 1 schematically. Also shown in Fig. 2 is a schematic representation of the experimental setup for the present investigation. A 0.5 mm diameter solid carbide drill of Mitsubishi Make is used in the micro-drilling experiments. The workmaterial is Aluminum 6061-T6 alloy sheet of 3 mm thickness having a size of 45 mm × 30 mm. Micro-drilling is carried out on a high-speed high-precision 5-axis CNC machining center, KERN Evo, Germany, having spindle speeds in the range of 500–50,000 and 50,000–160,000 rpm. Initial experiments are carried out after holding the sheet in a special fixture mounted on a multi-component dynamometer. This is a 5-component, Kistler piezo-electric type '*MiniDyn*' 9256C2 dynamometer which has a responding threshold <0.002 N and a measuring range of ±250 N for *Fx*, *Fy* and *Fz*. The dynamometer also indicates *Mx* and *Mz* values. The signals from the dynamometer are fed to a charge amplifier and data acquisition is done using Dynoware software with a sampling interval of 0.125 ms. Fig. 3 shows thrust and torque signals obtained during micro-drilling carried out for a typical drilling condition. It can be seen from the plot that the torque values are of the order of N-m which is quite high. The dynamometer readings are checked again after calibration for the forces, namely *Fx*, *Fy* and *Fz*. However, the moments could not be calibrated, as these are derived from the forces acting on the piezo-stacks located at four corners of the dynamometer body.

In the next step, a torque sensor (Kistler model 9339A) is used for sensing *Mz* and it is mounted at the center of the multi-component dynamometer. A unique advantage of the torque sensor is that it can be calibrated directly. The torque sensor has two calibrated ranges of ±1.0 N-m and ±10 N-m with a responding threshold < 0.18 mN-m. An important requirement of the torque sensor is that it must be centered properly and it is done in the present work using a touch probe available in KERN Evo machining center. The torque sensor has a dedicated charge amplifier and data acquisition is done using Dynoware software loaded in another computer. Fig. 4 shows thrust and torque signals acquired using multi-component dynamometer and torque sensor combination for the same conditions as in Fig. 3. Further details of thrust force and torque measurements are elaborated in Section 4.

From Fig. 4, initial time difference between both signals can be seen distinctly, as it is very difficult to start acquiring the signals at a given instant. Any further analysis of micro-drilling process will be meaningful only when the synchronization between the signals is achieved. In next section, a novel technique is proposed for overcoming this practical difficulty.

3. Proposed technique

The technique proposed in this work is based on cross-correlation coefficients [16,17]. The values are computed using the following equations: