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Measurement of the contact area of a dovetail milling cutter using an ultrasonic method

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ABSTRACT

Since there is no reliable mathematical model to analyze a multi-points contact simultaneously, the most effective way to know the contact area is to use experimental method directly. This study measures the contact area between a dovetail milling cutter and a steel plate by using ultrasound for regional scanning. This is a novel application for milling cutters and has not been applied before. The transducer emits an ultrasonic pulse to detect the contact surface. If contact occurs, the pulse is partially transmitted into the specimen. Therefore, the signal reflected back to the pulse receiver is reduced. The amount by which the signal amplitude is reduced is a measure of the degree of contact.

The contact area between a dovetail milling cutter and specimen is calculated using an image analysis software package. The range of contact areas varies from 4 mm^2 to 50 mm^2, depending on the contact force and the definition of the contrast ratio. The distribution map shows that the most common range of contact area is 10–40 mm^2.

1. Introduction

One of the most common machining operations in manufacturing processes is a milling operation, which usually involves the machining of flat or curved surfaces by feeding the workpiece against a rotating cutter that contains a number of cutting edges. The most common tools in milling operations are end-mill cutters, especially for vertical milling machines. When development and improvements of the milling machine and components continue, it results in the manufacturing of high speed steel and carbide cutters. These components allow the operator to remove metal faster, and with more accuracy, than previous machines. Variations of milling machines are also developed to perform special milling operations. During this era, computerized machines have been developed to alleviate errors and provide better quality in the finished product.

Many studies of milling operations have only considered cutting force because cutting force is an important factor related to the surface of the workpiece and tool wear. It has also been used for simulations to study the cutter stability, the effect of roughness, to estimate tool wear and to, predict machining accuracy. Kline et al. [1] proposed a model and performed some experiments to predict the surface error in end milling process. Choudhury and Subhashree [2] studied the relationship between frank wear and the average tangential cutting force coefficient to estimate tool wear. Thevenot et al. [3] studied the dynamical behaviour variation of the tool position to determine optimal cutting conditions during the machining process. Sarhan et al. [4] used computer simulation to investigate tool wear by a cutting force based model. Wan et al. [5,6] developed a systematic procedure and a numerical method to study the peripheral milling process of thin-walled workpiece. Wan et al. [7] also developed a new ternary-mechanism cutting force model to predict cutting forces in flat end milling by analyzing chip removal, flank rubbing and bottom cutting effects. Based on the study, a calibration approach was presented to identify the cutting force

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coefficients together with the cutter runout parameters for general end mills [8]. However, there is no research found for measuring the contact area between the dovetail milling cutter and the workpiece, even though it is a significant parameter in the study of the cutting force used in dovetail milling operations.

The milling machine removes metal with a revolving cutting tool called a milling cutter. With various attachments, milling machines can be used for boring, slotting, circular milling dividing, and drilling. This machine can also be used for cutting keyways, racks and gears and for fluting taps and reamers. Therefore, the contact between a cutter and a workpiece is an important area of study. There are a number of theoretical models that predict the contact area between any two objects. The study by Hertz [9] presented the first reliable mathematical solution of this problem. Later, Greenwood and Williamson [10] proposed a solution for multiple junctions and showed that the relationship between the contact area and the contact resistance depends not only on the size, number etc. of the asperity junctions, but also on their spatial distribution. Antoine [11] used approximations of elliptical functions and proposed an empirical explicit formulation through a mathematical study of Hertz's results. All of these models assume an elastic contact. However, there are few experimental methods [12,13] available to measure contact area directly. This study utilizes ultrasound to detect the contact interface between a dovetail milling cutter and a steel plate, in the laboratory.

Plain milling, also called surface milling, is milling flat surfaces with the milling cutter axis parallel to the surface being milled. Generally, plain milling is accomplished with the workpiece surface mounted to the milling machine table and the milling cutter mounted on a standard milling machine arbor. Angular milling, or angle milling, is milling flat surfaces which are neither parallel nor perpendicular to the axis of the milling cutter. A single-angle milling cutter is used for this operation. Milling dovetails is a typical example of angular milling. When milling dovetails, the usual angles of the dovetail cutter are 45°, 50°, 55°, or 60°, based on common dovetail designs.

In contrast to the single contact area between two common objects, dovetail milling cutters commonly have more than two contact points between the cutter and the workpiece. The design of the cutter profile also has an effect on the contact patches. It is difficult to theoretically predict the contact area between the cutter and the workpiece. A convenient way to study the contact and to measure the area directly is to use ultrasonic detection. A single ultrasonic transducer can perform a point measurement of reflection. There are some studies using the ultrasonic method to investigate various contact situations between two objects. Dwyer-Joyce and Drinkwater [14] utilized the phenomenon of the ultrasonic reflection to measure the contact area and pressure distribution in machine elements. Marshall et al. [15] used the ultrasonic technique to quantify the contact pressure distribution in a bolted connection. Lewis et al. [16] studied the pressure distribution of an interference fit interface by using ultrasonic method. Pau et al. [17] applied an ultrasonic technique for investigating contact problems between the wheel and rail and the size and shape of the contact area were determined.

In the contact zone, the contact area of a dovetail milling cutter will be increasing during its historical cutting process due to the tool wear. There is no technical standard for operators to know the correct timing to change a new cutter. In the factory production, the timing for changing a tool is important because it affects the machining efficiency. The decision is usually made by experienced technicians according to their visual inspection or the observation of the chip flow type. Thus, this study intended to propose a method to detect the contact interface of a dovetail milling cutter. Also, this method can be applied to measure the contact area of any retired cutter and then the area size can be considered as a reference standard of tool life. The future objective is to set up a helpful database for various machining cutters and provide useful information for users to know the correct timing of changing a cutter.

2. Background

2.1. Ultrasonic detection

An ultrasonic wave is partially transmitted and partially reflected when it reaches an interface between two objects. The proportion of the wave reflected, known as the reflection coefficient, R, depends on the acoustic impedance between the two objects, according to Eq. (1). The ratio of the amplitude of the reflected pulse to the amplitude of the incident pulse, known as the reflection coefficient, R, is determined by [18]:

$$R = \frac{z_1 - z_2}{z_1 + z_2} \tag{1}$$

where z is the acoustic impedance (the product of density and wave speed) of the media and the subscripts refer to the two sides of the interface.

The impedance of air and steel are 0.004 and 46.02 kg/m^2 μs, respectively, so when a pulse strikes a steel–air interface ($z1 \gg z2$) it is almost totally reflected and $R = 1$. If the wave strikes a steel–steel interface and there is perfect contact, it is fully transmitted ($z1 = z2$) and $R = 0$.

The surfaces of a dovetail milling cutter and a specimen are rough and when they are pressed together only a proportion of the geometrical contact area is actually in real contact. The rough surface is composed of individual asperity junctions and air gaps. This method uses the fact that ultrasound is transmitted through a rough surface interface, where there is asperity-to-asperity contact, and reflected where there are small air gaps, so it is possible to perform a scan of the reflected ultrasound across an interface and R is always less than one. The detail of the relationship between the reflection coefficient and the rough surface contact conditions can be found in the studies by Baltazar et al. [19] and Dwyer-Joyce et al. [20].

An ultrasonic ray has a finite beam width and Eq. (1) is only valid if all of the pulse strikes the interface normally. If some of the pulse misses the contact, then the signal is partially reflected, so, in practice, the reflection coefficient varies from $0 < R < 1$, depending on whether the ray strikes