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A new method based on Fiber Bragg grating sensor for the milling force measurement

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ABSTRACT

Milling force is an important parameter to describe the mechanical processing chip removal process, and it has a direct influence on generation of heat, tool wear or failure, quality of machined surface and accuracy of the work piece. Its accurate measurement is a significant basis for judging process state and improving the reliability of machining system. In this study, through analyzing the variation rule of ring diameter, a new method that using Fiber Bragg grating sensors and variation rule of ring diameter to measure the milling force has been proposed, and the basic structure of annulus has also been designed. A dynamometer has also been constructed, and the preliminary verification test was done. Through the analysis of experimental data, the dynamometer based on annulus elastic body can be used in milling force test, and it owns high sensitivity.

1. Introduction

Metal cutting is one of the most momentous manufacturing processes and is used widely in various industries such as automotive, watercraft and project machine. During metal cutting, in order to prolong machine tool service life and prevent tool breakage, mechanical properties of the milling tool should be known and therefore care should be taken to prevent this [1]. Knowledge of cutting forces is important in metal cutting, which should not deform the machine tools, milling tools and tool holders. Milling force measurement is very important in metal cutting field as they are used to determine the processing state of machine tool, achieve the process intelligently and machining process controllable, improve the reliability of machining system. Beside this, the milling force has direct impact on the generation of cutting heat, tool wear, quality of machined surface and accuracy of the work piece [2,3].

The current study on the cutting force is divided into two directions, one of which is the prediction of cutting forces, and the other is the measurement of cutting force. Prediction of the cutting force has significant meaning in choosing appropriate machining parameters and suitable processing conditions; it also can be used in process planning [4,5]. Due to the complex tool configuration/cutting condition of metal cutting operations and some unknown factors and stresses, theoretical cutting force calculations failed to produce accurate results [6]. Therefore, measurement of cutting forces is necessary. In order to obtain accurate cutting force during the machine processing, many scholars have conducted long-term research [7], and studies on cutting force measurement mainly focus on direct measurement of cutting force and indirect measurement of cutting force. Indirect measurement of cutting force is mainly by the way of measuring the spindle motor power or motor current to reflect the change of cutting force [8,9], or measuring the driving motor power or motor current to reflect the change of cutting force [10,11]. The indirect measurement has the advantages of simple structure, convenient installation and required technologies mature, but the interference factors, like mechanical structure, transmission, temperature and others, easily affect the stability of power or current signal, so it is hard to reflect the cutting force precisely. Direct measurement of cutting force usually uses elastic body to convert the cutting force into the strain of elastic body, then utilizing the sensing element to detect the strain. The sensing element commonly used is concentrated in resistance strain gage [1,6,12,13] and piezoelectric element [14–16]. Resistance strain gage possesses high sensitivity, small volume, easy installation, low cost and other merits, however, it also has the characteristics of complex line, wiring difficulty and easily being affected by environment, etc. Besides, the elastic body adopted in the dynamometer based on resistance strain gage is octagonal ring or similar structure of octagonal ring whose measurement accuracy is lower than needed. The main advantage of piezoelectric element is of good rigidity, small volume and quick

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response, but it is very sensitive to temperature changes, humidity and electromagnetic disturbance, and the piezoelectric element itself has hysteresis characteristics, which cannot meet the cutting force test environment. In order to adapt to the complex environment requirements and measure the cutting force accurately, other methods on the cutting force measurement are also explored. Ref. [17] uses Fiber Bragg Grating (FBG) sensors to measure cutting force; however the FBG sensors were directly pasted on the tool bar of turning tool which is easily influenced by temperature.

Compared with traditional sensors, FBG sensors are light in weight, small in volume, high in precision, immune to electromagnetic, resistant to corrosion and easy to conduct distributer dynamic measurement. The research group studied the theory of strain measurement of FBG sensor, and developed a dynamometer based on FBG sensor and octagonal ring [18]. Owing to the limitation of measurement sensitivity of octagonal ring, a dynamometer based on FBG sensor failed to meet the requirements. At the same time, influenced by pasting skill, there is adhesive layer between sensor and the surface of octagonal ring, and the thickness of adhesive layer is uneven [19]. What's more, the elastic modulus of adhesive layer and the bare optical fiber generally varies greatly, and this resulting in the strain measured by sensor and the real strain of the surface of the octagonal ring are different. It has a great effect on the measurement precision of the dynamometer. Because of the poor reproducibility of pasting skills, multiple measurement points' strain transfer ratios, which are the ratio of measured strain of FBG sensor to the real strain of measured point, are different from each other, so it is difficult to distinguish the reliability of measured data. Because the sensor itself has a certain size, like length and width, and the contact between the sensor and the octagonal ring is an area, rather than a point, all of which lead to the strain of sensor perception is the average strain of the contact surface not equal to the strain nodes. Beside the strain nodes, all other points of strain are caused by multiple direction forces, so it is quite difficult to work out the external applied loads when the measured strain is not the strain of strain nodes.

In this paper, by analyzing the variation rule of ring diameter, a new method that using FBG and variation rule of ring diameter to measure the milling force has been proposed, and the basic structure of annulus elastic body and pre-tightening device has also been designed. Owing to the grating part of FBG sensor does not need to be pasted on the surface of elastic body, so annulus elastic body is capable of measuring strain without being limited by the pasted skill and pasted area. Besides, the strength of annulus elastic body has been checked, and the static frequency of annulus elastic body which is a clear limitation threshold for the useful has also been studied. For the sake of obtaining the basic properties of annulus elastic body, several tests have also been done.

2. The principle of measuring milling force

2.1. Measurement theory of FBG

Fiber Bragg grating sensor uses photosensitive properties of fiber materials, thus only certain wavelengths of light will be reflected back when broadband spectra via grating, the rest of the light will pass through the grating, as is shown in Fig. 1. The reflected light wavelength of grating λ_B mainly relies on the fiber grating period Λ and effective refractive index n_{eff} , it can be calculated by the following equations:

$$\lambda_B = 2n_{eff}\Lambda \tag{1}$$

Under the influence of stress strain or temperature, effective refractive index of fiber grating and the fiber grating period will change. The wavelength of light that being reflected by grating will change from λ_{B_0} to λ_B , so it can be considered as a function of strain σ and temperature T, and its change can be calculated as follows:

$$\Delta\lambda_B = \lambda_B(\sigma, T) - \lambda_{B_0}(\sigma_0, T_0) \tag{2}$$

Make the formula (1) as a Taylor expansion and take the first order approximation, and pull in Young's modulus of Fiber Y_F , thermal expansion coefficient α_Λ , thermo-optic coefficient α_n and photo elasticity coefficient P_e , then the wavelength shift can be expressed in the following equation:

$$\Delta\lambda_B = \lambda_B[(1 - P_e)\Delta\varepsilon + (\alpha_\Lambda + \alpha_n)\Delta T] \tag{3}$$

where $\Delta\varepsilon$ represents the variation of axial strain of Optical fiber; ΔT represents the change of temperature, which is equal to $\Delta\sigma/Y_F$; $\Delta\sigma$ represents the change of axial stress of Optical fiber.

The wavelength of fiber and temperature changes can be measured by test, then utilizing the formula (3) can get the strain of corresponding measured point.

2.2. The principle of measuring milling force

When the radius of the ring far outweighs the thickness of it, for the sake of simplifying the calculation, it can be simplified into a thin ring. Deformation of ring under external loads is shown in Fig. 2.

Under the action of vertical force F_t, points C and D are the largest strain points, however, the strain of E, F, G and H points is zero. Under the action of horizontal force F_c, the strain of C and D points is zero, however, the strain of E, F, G and H points is the largest strain points. Under the action of external force, these special points on ring are called strain nodes. According to the knowledge of Mechanics material, the relative displacement between two points located on the same diameter of one ring can be figured out. A method that using FBG and variation rule of ring diameter to measure the milling force has been proposed. The diameter of bare Fiber is only 0.125 mm, so both ends of FBG can be fixed in the two strain nodes located at one diameter of ring. The FBG is respectively arranged between C and D points, E and F points and G and H points, the magnitude and direction of external loads can be obtained through measuring the strain of FBG when it is stretched or compressed.

3. The variation rule of ring diameter

3.1. The deformation analysis of ring under the action of vertical force

The deformation of ring under the action of vertical force F_t is shown in the Fig. 3.

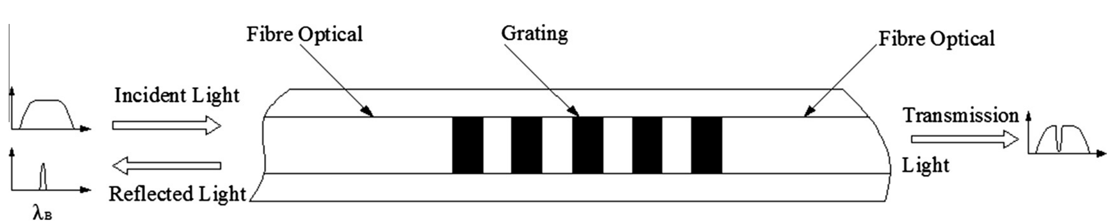

Fig. 1. Fiber Bragg Grating sensor.