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Dynamic shear stress evaluation on micro-turning tool using photoelasticity

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Abstract. The paper presents an experimental methodology for evaluation of shear stress induced on a micro-turning tool during micro-turning operation. A micro-turning tool manufactured by Sandvik Coromant was used for micro- turning of a brass spindle. The front face of the tool was cleaned, polished and coated with a thin layer of Ethylene-Vinyl Acetate (EVA), a birefringent material. Subsequently, reflection photoelastic experiments were conducted to find the shear stresses induced on the micro-tool. A custom designed grey field poledioscope was used for this purpose which was pre-calibrated and verified using disk under compression test. The tool was subjected to turning operation and dynamic images of the tool were captured using Casio ELIXIM ZR-200 camera in high speed movie mode at 1000 fps (frames per second) for four different orientations of the analyzer simultaneously. These images were processed using a code developed in MATLAB software to generate a shear stress map of the tool dynamically at different time instants of the machining process.

Introduction

Micro machining industry and its related applications have undergone significant progress in today's world of miniaturization due to its outstanding performance in generating miracles ranging from tiny micro holes to 3- D complex micro features. Lot of efforts have been focused to maintain reliability, accuracy, precision machining characteristics and efficacy of micro machining process by various researchers [1, 2]. However, research pertaining to health monitoring of cutting tool to prevent breakage during dynamic operation is limited in literature. Tool breakage may occur due to various reasons like increase in temperature, shearing, plowing, spindle vibration, high feed etc. It is a well established fact that shear stress on any material results in material fatigue. The same is applicable on machining tools during operation and hence is a prevalent cause for tool failure [3]. It becomes mandatory to evaluate the shear stress induced on the micro tool during cutting operations so that desired performance and tool life can be achieved. In this paper authors have proposed a process for shear stress measurement on micro-turning tool using photoelasticity. Photoelasticity is a well known and established phenomenon to evaluate stress on a material experimentally. The phenomenon is based on the property of birefringence, an unique property exhibited by few materials like calcite, plastics, glass, sapphire etc, showing double indices of refraction when stress is induced on the material. In order to visualize photoelasticity and correlate it mathematically to find desired stress parameters a polariscope is used. We have used a grey field polariscope for our application. A grey field polariscope works on detection of distribution of intensity (grey levels) on the image which is simple to acquire and process. Further it uses a very simple set of mathematical equations to evaluate stress parameters. Due to its simplicity of implementation and mathematical calculations authors use a grey field polariscope which was modified and customized into a grey field poledioscope for the purpose.

Experimental set up

Micro machining center

In order to conduct micro-turning process a micro machining center manufactured by Mikrotools DT 110, Singapore was used. Fig. 1 shows the set up of the center with tool mounted on tool holder, a brass spindle for micro-turning fixed on work piece holder along with the custom designed grey field poledioscope.

Processing the micro-turning tool

For photoelastic experiment it is mandatory that the sample under investigation must be birefringent. The tool used here manufactured by Sandvik Coromant (MAFL3010 1025) is a metallic micro tool and hence was devoid of such property. The front plane of the tool was coated with a thin layer of ethylene-vinyl-acetate, a photoelastic material.

Development of Grey field polariscope and poledioscope

A grey Field Polariscope (GFP) is combination of both plane and circular polariscope. It uses a linear and a circular polarizing plate as its polarizer but only a linear polarizing plate as its analyzer. Further, the analyzer rotates and a camera synchronized with it captures images at specified orientations. In literature commonly GFP camera captures 3 or more images for every half circle rotation of the analyzer. These images are processed mathematically to find stress parameters present in the sample [4]. A poledioscope is a combination of a polariscope and a kaleidoscope. From design point of view, the polarizer section of a poledioscope is same as a polariscope but in the analyzer part, a multi image lens (beam splitter) or a kaleidoscope is used. Thus 4 different images can be captured for 4 different orientations of linearly polarizing plates of analyzer in a single shot. Fig. 2 shows the schematic of a typical polariscope along with the modifications. The designed poledioscope can be visualized from Fig. 1.

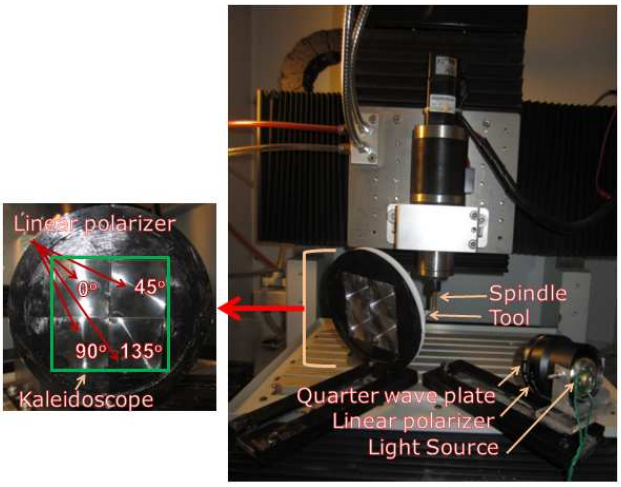

Fig. 1 Experimental set up

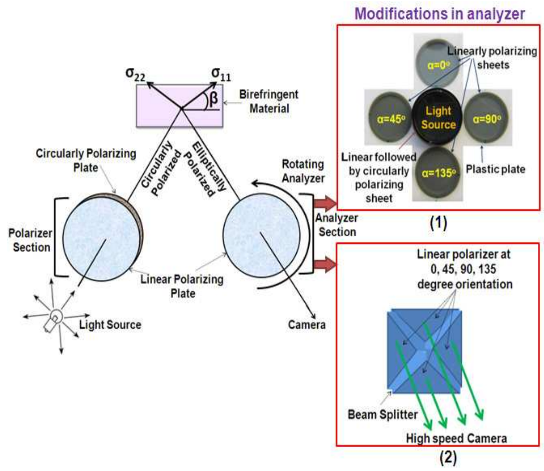

Fig. 2 A polariscope and modifications

Experimental procedure

Before we describe the procedure, we present here a brief overview of the mathematics used to determine quantitative values of stress from images captured using poledioscope which would be used recursively in each step of the experimental process. The equations and procedure used here can be found in detail in [5].

Eq. 1, 2 and 3 were used for processing the images.

$$\Delta = \frac{1}{2I_a}\left(\left(I_3 - I_1\right)^2 + \left(I_4 - I_2\right)^2\right)^{1/2} \tag{1}$$

$$\beta = \frac{1}{2}\tan^{-1}\left(\frac{I_1 - I_3}{I_4 - I_2}\right) \tag{2}$$

$$\Delta = \frac{2\pi C(2t)}{\lambda}\left(\sigma_{11} - \sigma_{22}\right) \tag{3}$$

C is the stress optic coefficient, t is the specimen thickness (2t is used as light travels through the coating twice in reflection photoelasticity), σ_{11} and σ_{22} are the principal stresses, λ is the wavelength of light used, I_1, I_2, I_3 and I_4 are the intensity of each image pixel captured by the camera.. From equation 3, we can find the value of difference of principal stresses (σ_{11}- σ_{22}) provided that C, t and λ are known. The specimen thickness (t) and wavelength of light (λ) are already known parameters from experimental set up. The value of stress optic coefficient (C) can be found by calibrating the polariscope with standard known stressed specimen.
From Mohr circle the shear stress Γ_{12} is given by Eq. 4.

$$\tau_{12} = \frac{(\sigma_{11} - \sigma_{22})}{2}\tan 2\beta \tag{4}$$

Calibration and testing of the instrument

A circular disk with diameter 9.1 cm and thickness 1.69 mm, coated with EVA layer of thickness 1.29 mm was subjected to compressive loading under load of 4.68 N. A schematic is presented in Fig. 3.
From theory of linear elasticity [6], the solutions for the normal stresses are given by Eq. 5, 6 and 7.

$$\sigma_x = \sigma_{11} = \frac{2P}{\pi h D}\left(\frac{D^2 - 4x^2}{D^2 + 4x^2}\right)^2 \tag{5}$$

$$\sigma_y = \sigma_{22} = -\frac{2P}{\pi h D}\left(\frac{4D^4}{\left(D^2 + 4x^2\right)^2} - 1\right) \tag{6}$$

$$\sigma_{11} - \sigma_{22} = \frac{8P}{\pi h D}\left(\frac{D^4 - 4D^2x^2}{\left(D^2 + 4x^2\right)^2}\right) \tag{7}$$

Where, P is the applied load, h and D are the sample thickness and diameter respectively. The values of Δ (phase lag) on X axis of the disk were scanned with respect to position of the point on the axis and a smooth and continuous curve was obtained by fitting these data points in MATLAB.
The calculated stress using the continuous curve so obtained was linked with the stress values obtained using mathematical equations and the stress optic coefficient for the material was determined. The calculated value for stress optic coefficient is 1.96 X 10^{-10} Pa^{-1}. Verification for the determined value of stress optic coefficient was conducted by the same set up, under loading condition of P= 9.12 N. Good agreement was found between theoretical and experimental values.

Recording images during dynamic conditions

Tool images were recorded under dynamic conditions during micro-turning process in a continuous manner. Turning process was carried out with depth of cut being 100 micron, the feed velocity being 0.5 mm/min while the spindle was rotating at 2500 rpm. Casio EXILIM ZR-200 camera was used in high speed movie mode at 1000 fps (frames per second) and images were captured during dynamic operation. These images include the tool and also a number of other components like tool holder, work piece, work piece holder and other materials adjoining the tool. These unnecessary objects were cropped out, so that proper analysis could be performed. The processed images captured for an instant t= 1 second are presented in Fig. 4.

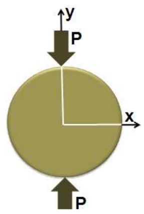

Fig.3 Schematic of disk under compression.

Fig. 4 Polariscope images for 0, 45, 90 and 135 degree of analyzer.

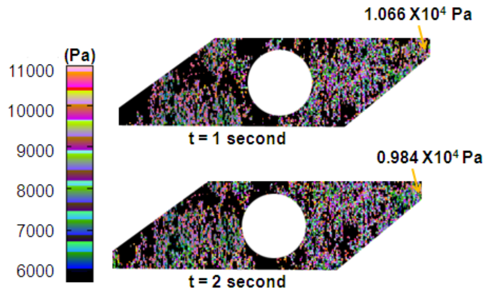

Fig. 5 Shear stress maps of the tool at time t=1 and 2 seconds.

Experimental results

The captured images were processed using the mathematical equations 11 to 13. For this purpose a MATLAB code was developed and 4 images for 4 orientations were fed in the program as input at a particular instant of time. Thus at any instant of time authors were able to assess the shear stress values at any point of the tool face. Complete shear stress map at time instants t=1 and 2 seconds along with variation of stress at a particular point at these time instants is shown in Fig. 5.

Conclusion

It is very well understood that due to process complexity and miniature tool size of turning process at micro scale, mapping stresses during dynamic operating conditions is a difficult task. The difficulty is conciliated here using a very simple but robust photoelastic coating methodology. The methodology can effectively check tool breakage and inconveniences caused due to the same as complete shear stress map at every instant of dynamic operation is available to the user.

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