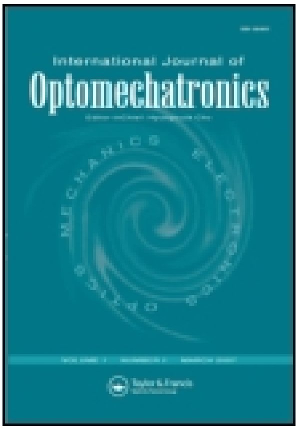

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Technical Note

FIBER BRAGG GRATING SENSOR FOR TEMPERATURE MEASUREMENT IN MICRO TURNING OF OPTICAL SURFACES WITH HIGH SURFACE INTEGRITY

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This article presents the use of Fiber Bragg Grating (FBG) sensor to measure the temperature induced at the tip of the tool, while micro-face turning of optical surfaces. FBG sensor of 120μm diameter was mounted near the tip of the tool and the shift in Bragg wavelength due to induced temperature was acquired with the help of an interrogator. The experiments were conducted on a Taylor Hobson DT-250 SPDT machine, over three different optical grade alloys namely Aluminum 6061, OFHC (Oxygen free highly conducting) copper and stainless steel. It was observed that while machining stainless steel, temperature at tool tip was highest and in case of OFHC copper it was lowest. The roughness and waviness of machined optical surfaces were measured using PGI 400 Profilometer. The results confirm that temperature induced in micro cutting and the rate of heat dissipation of work material contributes significantly to optical surface integrity.

Keywords: fiber bragg grating, machining temperature, micro turning, optical surface, surface integrity

1. INTRODUCTION

Optical parts fabrication demands more complex surfaces such as aspheres of sub-nanometers accuracy, micro-structured (micro patterned) surfaces and freeform surfaces. The major issue is achieving desired surface integrity, which is defined as the topographical, mechanical, chemical and metallurgical state of optical surfaces that alters functional performance. Compared to the conventional lapping/polishing processes and the modern processes such as lithography, ultra precision diamond turning is widely practiced in optical industry.

The Diamond turning is a single point metal cutting process done by removing a thin chip or layer material from the work very accurately to produce

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NOMENCLATURE

C_s	Coefficient of strain	λ_B	Nominal Bragg's wavelength
C_T	Coefficient of temperature	ΔT	Change in temperature
$\Delta\lambda_B$	Shift in Bragg's wavelength	ε	Induced strain

finished optical surfaces. It is generally applicable to ductile materials that machine well rather than to hard brittle materials. But at a very small effective depth of cut, brittle materials behave in an apparently ductile manner. This allows diamond turning of optical surfaces over a wide range of materials. In diamond turning, other than work materials characteristics such as grain size, inclusion size, etc, optical surface integrity is largely determined by the machine, tool and the cutting process. The tool has to be very accurately moved with respect to the optical element to generate a good optical surface, and the edge of the diamond tool has to be extremely sharp and free of defects. High fracture strength and hardness of diamond have made turning of hardened steel possible. However, in turning of highly machinable materials such as copper which is much softer than hardened steel as stated by Tanaka et al. (2005), chipping of cutting edge of diamond tool sometimes takes place due to some thermo-chemical reactions. Therefore, it is apparent that monitoring and controlling the temperature at cutting zone and its dynamic assessment ensures high surface integrity of the optical surfaces being machined. This is because, this temperature not only depicts tool performance but also influences cutting mechanism by affecting the yield point of material, phase transformations and other metallurgical properties that might attribute to change in optical performance.

In literature, evidence of conversion of mechanical energy involved in metal cutting into thermal energy and its contribution to rise in temperature at cutting zone is highly established (Komanduri and Hou 2001a; Abukhshim et al. 2006). However, measurement of temperature at the cutting edge of tool is a daunting task, and very limited progress has been made in this direction. Earlier, in one such study by Shin (1984), electromagnetic radiation from the heated work and the tool were made to fall on special Infrared (IR) detector and the intensity of that IR radiation was processed to compute the temperature rise in turning using synthetic diamond tool. Similar approach has been adopted to measure the temperature at the rake face of a single crystal diamond tool while turning Aluminum and Copper in Udea et al. (1998). Authors have used two-color IR detector and an optical fiber to transmit the temperature related infrared light. The measured maximum temperature was 190°C for aluminum and 220°C for copper at a cutting speed of 620 m/min as in the reference paper. This thermally induced problem attributes to rapid tool wear as stated by Zhou et al. (2003) and dimensional changes over the machined surface as in Ikawa et al. (1991) and Rakuff and Beaudet (2007). Thermography based method for tool temperature measurement is stated in Nedic and Eric (2013). Though it is a non contact based method, it is difficult to be implemented for micro cutting operations because the measurement relies on knowledge of emission coefficient of the surface as stated in the reference paper, whose exact value is difficult to be determined. Further due to miniature size of the tool, the set up for thermography would be very expensive and bulky as it would employ magnifying devices. It thus becomes essential to propose a method for temperature determination at cutting edge of the tool tip for micro scale machining operations possessing good accuracy, miniature footprint and quick response time.

In recent years, as the demand is continuously growing to produce optical surfaces with nano-metric scale accuracy, the need arises to replace the conventional diamond tools of $\sim 700\,\mu m$ nose radius with micro tools having few nanometer nose radii to produce aspheric surfaces of this scale. This makes the temperature measurement further complex with smaller chip thickness, high cutting speed and micro scale cutting edge that produce smaller intensity of IR radiation. On the other hand, temperature rise attributes to chip-off of micro cutting edge due to thermo-chemical reactions unless the temperature at cutting zone is dynamically monitored and controlled through appropriate compensation in machining parameters.

In this work, a uniform fiber Bragg grating (UFBG) sensor of $120\,\mu m$ diameter which possesses enhanced sensing capabilities has been used to measure the temperature at micro cutting edge of turning tool. Fiber Bragg grating sensor works on the principle of Fresnel's diffraction and is widely used in many applications for temperature and strain sensing as stated in Kuncha et al. (2008). It consists of an optical fiber with spatial modulation of refractive index. This modulation causes a specific wavelength of broadband light incident on the gratings to get reflected back. Variations in cutting temperature results in the shift in wavelength of reflected light. With the help of interrogation circuitry, this shift in wavelength was detected and the corresponding change in temperature near the cutting edge was assessed. As FBG sensors have a miniature footprint (i.e. 120 μm diameter) and additionally the interrogator circuits commercially available are accurate, reliable and possess a quick response; measurement of temperature at cutting edge of tool tip during micro face turning using FBG sensor is appropriate and bears promising utility from machining industry point of view.

2. MATERIALS AND METHODS

The micro-face turning operation was conducted on a machine DT-250 of Taylor Hobson (West Chicago, IL, USA). The cutting tool used was a turning insert of whiskered type Silicon carbide material, manufactured by Sandvik Coromant (Pune, India, Part number MAFL 3010). A fiber Bragg grating sensor fabricated in-house was mounted on the tool using a thin tape and was connected to an interrogator of Micron Optics (Atlanta, GA, USA) make. Subsequently, machining was carried on three different optical grade materials viz. Aluminum-6061, OFHC copper and stainless steel. Details of the materials used in the experiment along with their properties as specified by the manufacturer are as in Table 1.

Table 1. Specifications of materials used in the experiment

Material	Supplier	Hardness (Vickers)	Thermal Conductivity (W/m-K)
Alumunium-6061	Glemco Inc.	107	167
Oxygen Free Highly Conducting Copper	Morgan Technical Ceramics	122	398
Stainless Steel- 316	Sandmeyer Steel Company	155	16

2.1. Procedure to Mount FBG Sensor on Micro-Tool

Fiber Bragg grating sensors possess cross sensitivity effect to strain and temperature i.e. the response of FBG (shift in wavelength) is affected by both strain and temperature. The shift in wavelength is given by Eq. (1) as in Yin et al. (2008):

$$\left[\frac{\Delta\lambda_B}{\lambda_B}\right] = C_s\varepsilon + C_T\Delta T \tag{1}$$

where $\Delta\lambda_B$ is the shift in Bragg's wavelength, λ_B is the nominal Bragg's wavelength, C_s is the coefficient of strain, C_T is the coefficient of temperature, ε is the induced strain and ΔT is the change in temperature. Techniques like dual fiber method, use of rocking filters, long period grating based method, etc, are suggested in literature to separate strain and temperature as in Yin et al. (2008) and Hao et al. (2008). However, with miniaturized tool tip, mounting of these sensors becomes difficult, hence in order to eradicate cross sensitivity issue a single FBG was mounted near tool tip by attaching it using a tape. The method of placing a sensor on the tool surface using adhesive, mounts, tape etc is a standard method to find surface temperature of the tool surface as in Komanduri and Hou (2001b). In the reference paper, the authors have shown that merely placing a probe type thermocouple on the tool surface in macro-scale machining operations could yield reliable surface temperature measurement data. Authors in this work used similar strategy to place the FBG sensor on the surface of the micro-tool. During this attachment, it was ensured that the FBG sensor can not move away from the attached position.

Stress is defined as the internal forces that the neighboring particles of a continuous material exert on each other. As the FBG sensor rests on the tool and is not embedded inside it, the strain induced in the tool due to machining forces does not affect the measurement due to lack of continuity between the sensor and the tool. Thus the effect of temperature could be sensed but strain on the tool during machining process merely comes to the measurement as both tool and sensor are separate bodies.

The tool vibrations does not come into measurement as the interrogator circuit used (Micron Optics sm225-500) has a maximum scan frequency of 1 Hz. In SPDT machine (Taylor Hobson DT 250), the low frequency (less than 10 Hz) machine vibrations are dampened by damping system inherently present in the machine as in TMC website (2013). Further in typical micro machining process the spindle vibrations lie in the range of 60-70 Hz as stated in Ali et al. (2013). As the maximum scan rate of the interrogator is 1 Hz which is much lesser than the frequency of vibrations, the effect of high frequency tool vibration gets ignored in the measurement process.

2.2. Experimental Study

The tool mounted with FBG sensor was used for machining alloys of Al 6061, OFHC copper and Stainless steel on a micro-face turning at a tool feed rate of 1 μm/second, the depth of cut 100 μm and spindle speed 1000 rpm. The experiments were conducted inside the temperature controlled chamber at an

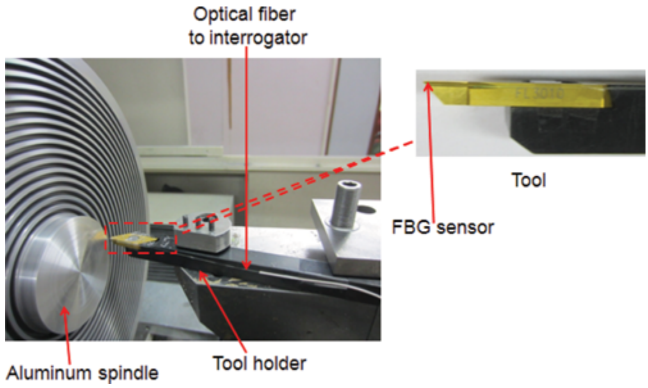

Figure 1. Micro face turning experimental set up with FBG mounted turning tool.

ambient temperature of 27.2°C. The induced temperature on the tool tip was recorded for 20 minutes for each of these operations using FBG interrogator. The set up is as shown in Figure 1.The UFBG sensor used in the experiment has a temperature sensitivity of 10.6 pm/°C in the measurement range of 20 to 40°C. The temperature sensitivity curve is shown in Figure 2.

2.3. Measurement of Surface Integrity of Machined Surface

Each of these machined optical surface profile is measured using a contact type profilometer (model number PGI 400) manufactured by Taylor Hobson. A diamond stylus traverses over the desired surface and records the profile which is called primary profile. Surface roughness and waviness are key factors in ensuring surface integrity. These are extracted from primary profile by passing the profile plot through software based signal filters as recommended by DIN EN ISO 4288, ASME B46.1 standards as in ISO (1996). Talysurf software (Taylor Hobson) that was compatible with the profilometer was used for the purpose.

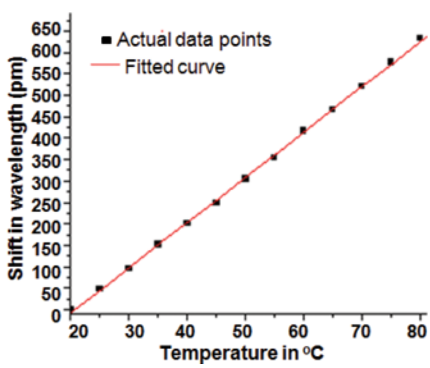

Figure 2. Temperature sensitivity curve for the UFBG used in the experiment.

3. RESULTS AND DISCUSSIONS

The temperature variation on tool tip for the materials machined is shown in Figure 3. Exponential fit generated best fit for Al-6061 and OFHC copper whereas Gaussian fit was suitable for stainless steel. In generic form, the equations for softer materials like Aluminum and OFHC copper can be represented as Eq. (2) whereas for harder material like steel can be represented by the generic Eq. (3).

$$T(t)_{Soft} = a_1 e^{-b_1 t} - a_2 e^{-b_2 t} \tag{2}$$

$$T(t)_{Hard} = \sum_{n=1}^{m} a_n e^{-((t-b_n)/c_n)^2} \tag{3}$$

where a, b and c are constants. For Eq. (3), the value of 'm' is taken as the number of Gaussian terms with which the best fit (minimum fit error) is obtained. The constants a, b and c for aluminum, copper and steel obtained while curve fitting in Figure 3 are presented in Table 2.

The surface roughness and waviness of machined surface are shown in Figure 4 (a, b, c) and Figure 4 (d, e, and f) respectively. It was found that the surface roughness approximately doubles and the waviness gets approximately tripled on 10 degree rise in temperature on tool tip under similar machining conditions.

Creation of micro-nano scale geometries such as optical surfaces, demands reduction of relative surface roughness by a factor of five to ten. Therefore, rapid rise in cutting temperature becomes a significant concern in micro machining of optical materials. In micro machining, temperature rise at the tool-work contact interface occurs due to three reasons (Liu et al. 2006), namely: (a) the mechanical energy involved in shearing to form the chip (b) the friction of the chip moving over the tool rake face and (c) ploughing/rubbing in the vicinity of the dead metal cap due to finite tool edge radius. Further, the temperature is dissipated due to three factors: (a) conductivity of cutting tool (b) conductivity of work piece and (c) thermal energy carried out by the chip. Moreover, chip geometry plays a critical

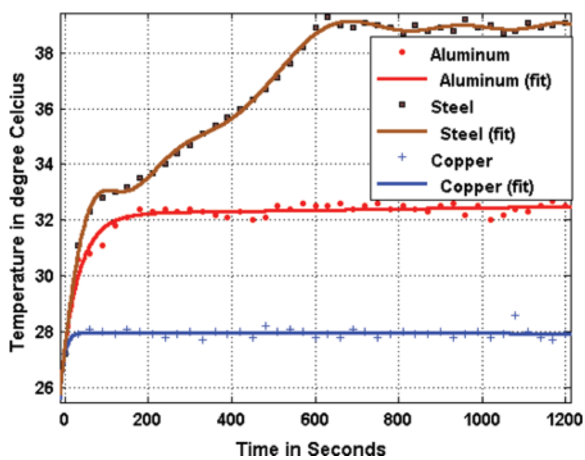

Figure 3. Variation of temperature on tool tip with machining time for three different alloys.

Table 2. Constants a, b and c for aluminum, copper and steel

	Materials		
Coefficients	Al-6061 (Eq. (2))	OFHC Copper (Eq. (2))	Stainless steel (Eq. (3))
a_1	32.22	27.96	35.88
a_2	4.809	0.7634	35.03
a_3			2.088
a_4			20.39
a_5			9.175
b_1	6.616×10^{-6}	9.733×10^{-7}	624.30
b_2	0.023	0.094	1291
b_3			951.80
b_4			151.10
b_5			24.99
c_1			423.80
c_2			401.40
c_3			146.70
c_4			262.20
c_5			107.80

role as it attributes to rise in temperature and abrasion over machined surface. In turning, C-type broken chips and shorter helical broken chips are more desired over longer unbroken chips as they enhance heat dissipation from the chip-tool-work surface interface. In this experimental study, it is observed in Figure 3, that the temperature plot vs. time for Aluminum and Copper bears an exponential relationship whereas the relationship is Gaussian for stainless steel. These effects are attributed to mechanism of chip formation, heat dissipation and the material properties explained next.

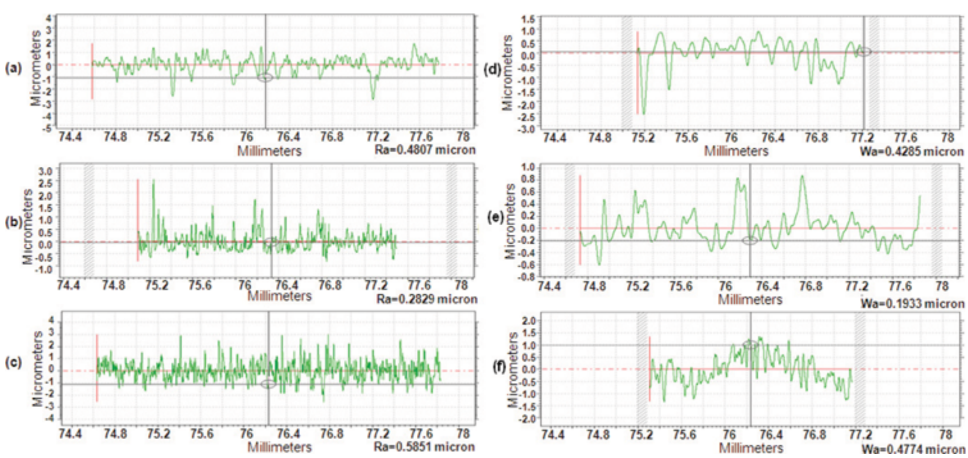

Figure 4. Surface roughness profiles: (*a*) aluminum 6061, (*b*) OFHC copper, (*c*) stainless steel. Waviness profiles: (*d*) aluminum 6061, (*e*) OFHC copper, (*f*) stainless steel.

In case of stainless steel machining, higher hardness increases the heat generation and the longer unbroken chips coupled with lower thermal conductivity delays the heat dissipation from the cutting zone, resulting in 13°C–14°C rise in temperature. It is also observed that the temperature profile for the steel is irregular; it reaches equilibrium in the range of 38°C to 39°C after a time interval of 600 seconds. The initial rise in temperature can be attributed to the heat generated due to abrasion of tool at lower speed over harder surface. This is followed by slow heat dissipation by relatively longer unbroken chips sliding over the rake surface of turning insert that results in temperature gradients fluctuating at tool-work interfaces. This is also reflected on to poor surface roughness and waviness measurements illustrated in Figure 4(*c*) and 4(*f*).

On the contrary, Aluminum and OFHC copper that are relatively softer material induce lesser abrasion/ploughing effects and generates low heat. These temperature profiles reach the transient thermal equilibrium quickly owing to rapid heat dissipation due to high thermal conductivity. Thus, it could be clearly observed that OHFC which possess good machinability, produced smaller curled chips. This factor coupled with higher thermal conductivity dissipates the heat rapidly and temperature profile reaches equilibrium state much faster. Similarly, both Aluminum and OFHC copper shows improved surface finish and smaller waviness (Figure 4) compared to that of stainless steel machined surface. The comparative analysis of the temperature profile and surface characteristics of these three optical materials machined at same conditions thus strongly establishes the underlying relations that exist between machining attributes viz. hardness, thermal conductivity and the chip geometry in micro cutting.

4. CONCLUSION

In this article the use of FBG sensor of 120μm diameter with interrogators has been proposed to acquire the shift in wavelength as a result of rise in the temperature at cutting edge of micro turning tool. The method is used to assess real time temperature variation on tool tip which would be very difficult if done by conventional methods due to micron size tool tip, thin layer of chip removal and low intensity of IR radiation. Further, the surface profile obtained is related to temperature at the tool tip which can effectively preserve surface integrity. The FBG sensor based method for temperature determination at cutting edge of the tool in micro material removal process is real time in nature. FBG based sensing accuracy is well established which adds to the fidelity of this method in temperature determination at cutting edge of tool tip in micro machining process. Following points can be concluded from this study regarding increase in temperature at the tool tip and surface integrity of the work:

- From experimental study, it has been found that the increase in temperature on tool tip is dependent on hardness of material being machined. The temperature rise is highest for stainless steel which is harder than other optical materials under consideration (As in Figure 3 and Table 1).
- The rise in temperature also depends on thermal conductivity and rate of heat dissipation of material being machined. In OFHC copper, due to its high

conductivity, the rise of temperature during machining process is less than that of Aluminum (As in Figure 3 and Table 1).

While use of FBG for temperature measurement in micro turning is a new approach, it assists in maintaining the micro cutting dynamics, resulting in the enhancement of the surface integrity of machined optical surface as required in the fabrication of ultra-smooth optical mirrors, reflectors, etc.

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