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Fiber Bragg grating sensor for cutting speed optimization and burr reduction in micro-nano scratching

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Abstract

Patterning a surface by scratching at micro-nano scale requires precise instrumentation strategies for generation of accurate patterns which are used in variety of surfaces ranging from bacteria resistant surfaces to water repellent ones. The scratching action leads to temperature rise of tool tip causing expansion of tool and work surface. This results in positioning inaccuracies and surface defects of the machined work. In this work a fiber Bragg grating sensor (FBG) is used to record the temperature rise at the tool tip under different scratching/cutting speeds. The surface integrity of the patterned work was evaluated after machining using a profilometer. The optimized value of cutting speed for minimum inaccuracy and minimum burr was found using Lagrangian multiplier based technique. This work thus ensures real time control of scratching speed based on tool tip temperature variations only, which finally results in better surface integrity of patterned profile.

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Keywords: micro-nano scratching; fiber Bragg grating; machine control; optimization; surface integrity; Lagrangian multiplier.

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1. Introduction

Patterning a surface at micro-nano scale renders a number of interesting properties of the surface such as water repellant nature, anti-microbial nature, algae generating nature and so on, which are used in a myriad of industries

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ranging from consumer products to biodiesel generation firms [1, 2]. Imparting the properties mentioned above requires controlled and accurate patterning of the surface at micro-nano scale [3]. Among number of methods for surface patterning, scratching based strategy is emerging in research and industry due to its low production cost, high productivity, good longevity and its exceptional capability to generate surface patterns over larger area. The scratching based patterning strategy involves scribing of a cutting tool with nose radius in micro-nano meter range over a work sample where pattern is to be generated. For scratching over softer materials such as plastics or ceramics usually AFM (atomic force microscope) based scratching is used whereas for hard to machine surfaces or metals metallic tool and a variant of AFM set up with higher machine stiffness is applicable [4]. Fig. 1. shows the schematic of scratching based pattern generation method.

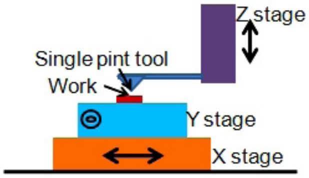

Fig. 1. Schematic for micro-nano scratching process.

In scratching based method, an X-Y stage is used to move the work on which patterns are to be generated and the tool is fixed to the Z axis actuator which may be a single motion stage or a piezoactuator for accurate tool positioning. The X-Y stages move during the scratching process and the Z axis actuator moves intermittently only during tool positioning. Due to continuous frictional contact between the tool and the work, rise in temperature occurs at the tool-work interface. The rise in temperature leads to thermal expansion of the tool and the work which results in interfacial deformation and changes in the material removal mechanism [5]. The effect of temperature is even higher in hard to machine materials due to higher rate of heat generation and difficulty in chip removal. This in turn leads to inaccuracy in machining and poor surface integrity of the machined work. At micro-nano scale inaccurate dimensions of the scratched patterns renders the work surface to be useless as, a slight variation in the patterned topology does not render the surface properties as envisaged.

It thus becomes essential to optimize the machining parameters during micro-nano scratching process, so that the deterioration of the surface integrity and machining errors due to temperature rise is alleviated and the machining accuracy is enhanced. In real time, checking the surface profile is a difficult task whereas recording the temperature is easy. Nevertheless, surface integrity is related to tool tip temperature which is related to machining parameter. So a correlation between machining parameter and tool tip temperature is a vital tool for controlling the surface integrity in real time. The relation between surface integrity vs. tool tip temperature and machining parameter vs. tool tip temperature is calibrated offline in this work. These two calibrations lead to establishment of relation between surface integrity and machining parameter online which can promote dynamic and real time control. In this work we use a strain compensated fiber Bragg grating sensor embedded at the cutting edge of the tool tip to record the temperature variations during scratching and establish a relation with the surface integrity of the patterned surface using a profilometer. FBG sensor was used in order to combat the problem of limited footprint of the cutting tool as none other sensors could be accommodated in micro-nano scale dimensions. Recently similar approach to measure temperature in machine tool condition monitoring application is presented in Mandal et al [6] and Liu et al [7] for micro face turning and temperature measurement of a rotating spindle respectively. A Lagrangian multiplier based optimization was carried out in order to find the optimum value of scratching speed (machining parameter) based on tool tip temperature and surface integrity correlation.

Nomenclature

ξ	inaccuracy in the depth of cut (μm)
β	burr height (μm)
ΔT	change in temperature at tool-work interface (°C)
f	cutting speed (mm/sec)

2. Methodology

The scratching process to generate the patterns was conducted using X-Y stage based system on which the work material was placed rigidly. The single point tool used had a nose radius of 50 microns and was composed of HSS (High speed steel). The experimental set up involved and the experiments conducted are stated in the following sections.

2.1. Experimental set up

Fig. 2. shows the experimental set up employed for micro-nano scratching. It consists of an X-Y stage for workpiece platform and a Z axis stage for positioning the tool and adjusting the depth of cut. The stages and the motion controllers were supplied by Holmarc company, India. The X-Y stages had a resolution of 10 micron whereas the Z axis stage had a resolution of 1 micron. A strain compensated FBG temperature sensor supplied by Micron optics (os4210) was attached rigidly to the cutting edge of the tool. NI-PXIe4844 FBG sensor interrogator system was used as interrogation element. Copper (ASTM B1 grade) was used as work material on which patterns were generated.

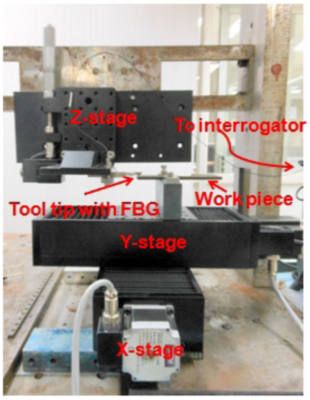

Fig. 2. Experimental set up.

2.2. Experiments conducted

Micro-nano scratching was conducted using the stated set up with 9 different scratching speeds and the temperature profile at the tool tip was recorded. The depth of the cut was set to 1 micron for all of these 9 cases. Scratches of 1 m length were conducted under each of these 9 machining conditions. The temperature rise and surface quality assessment was conducted at the end of the stated scratch length. These 9 samples were tested for their cutting depth and side burr using a stylus type profilometer supplied by Taylor Hobson (PGI400). The depth of cut and burr were calculated from the P (Primary)-profile. An illustration for the side view cross section showing the depth of cut and burr height for P-profile is shown in Fig. 3.

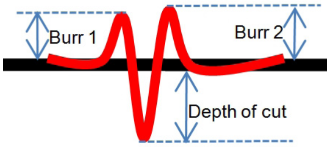

Fig. 3. Cross section for the machined pattern demonstrating depth of cut and the burrs on its sides. (The burr height was calculated as the mean of burr 1 and burr2).

A correlation between the maximum temperature vs. maximum error in depth and maximum temperature vs. maximum burr was established. The correlation equations may be considered as objective functions. In this case the scratching speed is to be selected in such a way that minimum burrs and minimum inaccuracy persists. Thus it becomes a problem of optimization under constraints. The scratching speed optimization was carried out using these objective functions by the method of Lagrangian multiplier.

3. Results

The values of cutting speed, measured temperature, depth of cut and side burr is presented in Table 1. The temperature at the start of machining operations was 25.6°C for each experimental case.

Table 1. Variations of inaccuracy in depth of cut and burr height with cutting speed and change in temperature at tool tip.

S. No	Speed (mm/sec) f	ΔT (°C)	Inaccuracy (μm) ξ	Burr (μm) β
1	0.04	1.8	0.023	0.41
2	0.2	2.7	0.027	0.34
3	1	4	0.033	0.30
4	5	8.9	0.051	0.27
5	10	11.5	0.07	0.21
6	15	16.1	0.079	0.19
7	20	19.3	0.081	0.17
8	25	22.5	0.083	0.12
9	30	28.6	0.087	0.09

The best fit equations for temperature vs. depth of cut and temperature vs. side burr was obtained (Equation 1 and 2).

$$\xi = 0.1263(\Delta T)^{0.1511} - 0.1186 \tag{1}$$

$$\beta = 0.3757e^{-0.04585\Delta T} + 6.033e^{-2.524\Delta T} \tag{2}$$

The curve fitting plot is presented in Fig. 4.

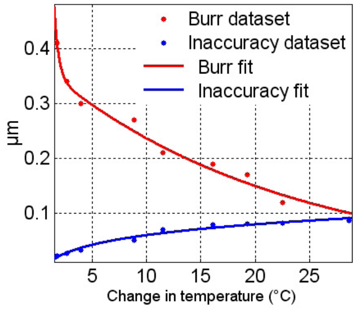

Fig. 4. Curve fitting plots for inaccuracy and burr heights with change in tool tip temperature.

3.1. Feed velocity optimization using the method of Lagrangian multiplier

In order to optimize the value of feed velocity, a maximum permissible inaccuracy level (5% of the stage resolution) was fixed. This value may depend and vary on applications however to establish the proof of concept we selected this particular value. Inaccuracy was thus fixed to 0.05 micron for the Z-axis (depth of cut axis). Thus we have to minimize the burr such that the inaccuracy in depth of cut is 0.05 micron. Use of Lagrangian multiplier based optimization thus leads to equation [8]

$$\Lambda(\Delta T, \lambda) = (0.3757e^{-0.04585\Delta T} + 6.033e^{-2.524\Delta T}) + \lambda(0.1263(\Delta T)^{0.1511} - 0.1186 - 0.05)$$

Partially differentiating Λ with respect to ΔT and λ and by equating them to zero we get ΔT=7.467 °C.

3.2. Calibration of ΔT and feed velocity

We could thus find the change in temperature for which there will be minimum burr with the stated inaccuracy (0.05 micron). The change in temperature is related with the feed velocity and is found using curve fitting from the data values of Table 1. The relation between change in temperature and feed velocity is shown in equation 3.

$$f = -0.00201\Delta T^3 + 0.09587\Delta T^2 - 0.03634\Delta T - 0.2761 \tag{3}$$

The optimized feed for the stated accuracy and minimum burr is found to be 3.95 mm/sec. Thus a correlation is obtained between the temperature rise and feed velocity which could be controlled in real time. This eventually ensures the accuracy and minimization of burr height of the machined work.

In order to verify the optimum value of feed, scratching operation was carried out at same conditions with cutting speed of 3.95 mm/sec. It could be found that the temperature rise at the tool tip was 7.34 °C and the inaccuracy after the machining operation was 0.058 microns with a burr height of 0.26 microns which shows good concordance with the calibration values.

4. Discussions and inferences

It could be seen from the experiments that increase in cutting speed during micro-nanoscratching enhances the temperature of the tool workpiece interface. This changes the interface geometry due to thermal expansion and material deformation which leads to inaccuracies in scratching depths. On the contrary higher cutting speed minimizes burr heights. This could be justified from the fact that higher cutting speed causes the tool and the part of workpiece undergoing scratching to be in contact for lesser duration. The interaction duration is hence reduced which may be a factor for lesser burr height. The observation recorded here follows a similar tendency like other material removal processes at micro scale like micro-milling, micro-turning etc [9].

The relationship between inaccuracies in cutting depth with temperature follows a power law equation with ΔT. This indicates that inaccuracy in the depth of cut is highly dependent on interfacial temperature of tool-workpiece contact in micro-nano scratching. The power law curve may be justified from the temperature dependant thermal conductivity of the tool-tip work interface [10]. Due to material removal, the thermal conductivity of the surface varies with time (due to change in surface area) which is dependent on heat generated and dissipated governed by cutting mechanics.

On the other hand the burr height has exponential dependence on change in temperature for micro nano scratching. Though in other material removal processes (viz. grinding) the burr height is not very much influenced on temperature of the interface, however in this case the dependence may be justified due to plowing action of the tool tip leading to plastic deformation of the metal at micro-nano meter scale. At lower cutting speed, the duration (contact time) of cutting forces acting on a part of the workpiece is more, leading to higher exponential creep like phenomenon [11] causing more material to flow out. This results in higher burr height at lower feeds/ lower temperatures which increases at an exponential rate.

5. Conclusions

It could thus be understood that the relationship between the change in temperature during micro-nano scratching varies in some of the aspects when compared to other micro machining techniques. In this work the relationship between scratching (cutting) speed and temperature variations are correlated with depth of scratch and burr height. Evaluating the surface integrity in real time is a difficult task and needs complex instrumentation strategies and is also time consuming in nature. A correlation between rise in temperature at tool tip vs. inaccuracy in depth of cut and rise in temperature at tool tip vs. burr height thus ensures real time control of the process as the temperature can be correlated with the cutting speed in real time. Fiber Bragg grating sensor to map the tool tip temperature has been used to cope up the limited footprint of the tool for the very first time ever in micro-nano scratching process. The relationships and the technique presented here is thus a boon to the production industries requiring control strategies for accuracy and surface integrity enhancement in precision machining.

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