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Fabrication and metrology of micro-scale sinusoidal surfaces in polymer workpiece materials

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Introduction

This study investigates the fabrication of precision, micro-scale sinusoidal surfaces in polymer workpiece materials and discusses methods to quantitatively characterize these surfaces. These precision sinusoidal surfaces are an important feature in a meso-scale assembly that will be used as part of a physics experiment. The experiment will study the formation of Rayleigh Taylor instabilities and requires a sinusoidal surface with an amplitude of 2.5 μm and a wavelength of 70.7 μm in both the x- and y-directions. The sinusoids must have sub-μm form accuracy with a surface finish on the order of 100 nm, and they must be produced in a workpiece consisting of adjacent pieces of polyimide and iodine-doped polystyrene, a portion of which is illustrated in Figure 1.

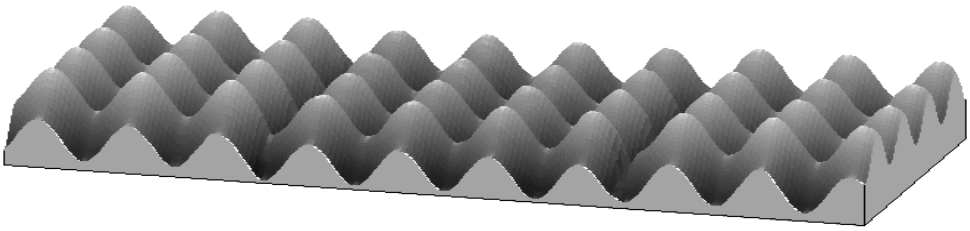

Figure 1. Machined sinusoidal surface

The fabrication of micro-scale sinusoidal surfaces is a recurrent problem relevant to many different scientific applications. The most common use for precision sinusoidal surfaces is the optics field, for which sinusoidal optical components are commonly produced using lithography processes. However, lithography can only be used with limited types of workpiece materials, and they cannot be used to make precision parts from iodine-doped polystyrene or polyimide. Other applications for micro-scale sinusoidal surfaces involve more traditional engineering materials, such as metals [1,2].

In the current study, sinusoidal surfaces are machined using a single point diamond tool with a commercial fast tool servo on a diamond turning machine. Producing acceptable surfaces requires the programming of the fast tool servo, the selection of the proper diamond tool geometry, and the selection of appropriate cutting conditions.

Fabrication Method

Machining is performed with a Precitech Nanoform 200 diamond turning machine. The workpiece is mounted on the spindle of the machine tool and rotates clockwise with a constant angular velocity, as shown in Figure 2. A Precitech Fast Tool Servo Ultra Precision Machining System with a stroke of 35 μm is mounted on the tool slide and is oriented so that its stroke is parallel to the z-axis, perpendicular to the face of the workpiece. The stroke of this fast tool servo is driven by a piezoelectric actuator, and a capacitance probe in-line with the stroke provides closed-loop control. A single point diamond cutting tool is mounted in the fast tool servo, and the height of the cutting edge is carefully set so that it cuts to the center of the workpiece. To machine the face of the workpiece, the machine spindle (the C-axis) rotates the workpiece clockwise, and the motion of the x-axis moves the workpiece relative to the diamond tool such that the tool travels from right to left relative to the workpiece, from the outer edge toward the center of rotation. The stroke of the fast tool servo is slaved to the C-axis and the x-axis, both of which contain high resolution encoders that constantly read the angular orientation of the machine spindle, θ, and the distance of the diamond tool tip from the axis of rotation of the machine spindle, r. In other words, the fast tool servo is programmed so that its stroke is a function of the encoder readings, θ and r.

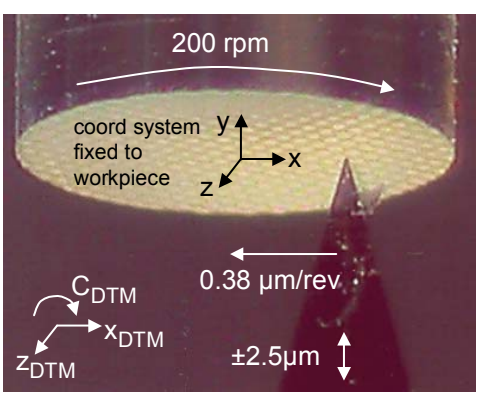

Figure 2. Machining setup

Programming the Fast Tool Servo

The desired form of the surface machined by the fast tool servo is given by Eq. (1), where the amplitude, A, is 2.5 µm, and the wavelength, λ, is 70.7 µm. In Eq. (1), x and y lie in the workpiece coordinate system. r and θ lie in the machine tool coordinate system, where r corresponds to the x-axis of the machine tool and θ corresponds to the C-axis of the machine tool.

$$z = A\sin\left(\frac{2\pi x}{\lambda}\right)\sin\left(\frac{2\pi y}{\lambda}\right) = A\sin\left(\frac{2\pi r\cos\theta}{\lambda}\right)\sin\left(\frac{2\pi r\sin\theta}{\lambda}\right) \tag{1}$$

To produce the desired form of the machined workpiece surface, the fast tool servo must be programmed to account for the finite nose radius of the cutting tool. Note that because the cutting edge of the tool always lies along the x-axis, compensation for the tool nose radius must only be performed in the radial direction. The importance of this compensation is apparent from Figure 3. This figure illustrates a radial trace of the workpiece surface at some angle $\theta=\theta_0$, and it shows that to machine the surface correctly, the stroke of the fast tool servo must be such that when the center of the tool is at $r=r_0$, the nose of the tool is tangent to the desired workpiece surface.

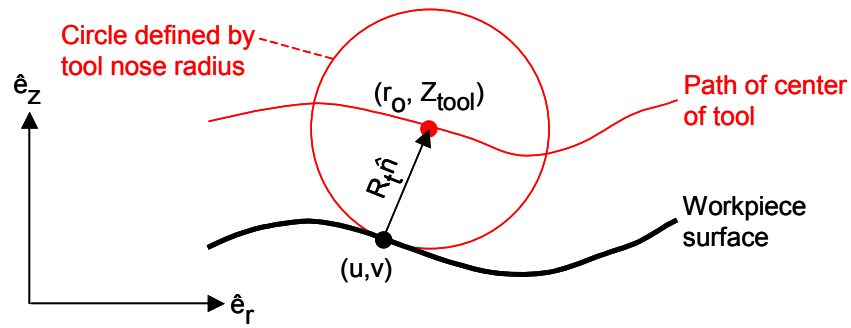

Figure 3. Tool nose radius compensation for a tool of nose radius R_t

The problem is to find the z-coordinate of the center of the tool, z_{tool}, at which the tool is tangent to this radial trace of the workpiece surface. The point of tangency is denoted as ($r = u$, $z = v$). Thus, the problem reduces to finding the value of u that satisfies the relation in Eq. (2).

$$u + \left(R_t\hat{n}\right)\bullet\hat{e}_r = r_o \tag{2}$$

R_t is the nose radius of the tool. $\hat{n}$ is the unit vector that is normal to the trace of the workpiece surface in the plane $\theta=\theta_0$, and it can be found by taking the gradient of the equation of the machined workpiece surface. To facilitate calculating the gradient, a function $m(r, \theta_0, z)$ is defined in Eq. (3).

$$m(r,\phi_0,z) = 0 = z - A\sin\left(\frac{2\pi r\cos\theta_0}{\lambda}\right)\sin\left(\frac{2\pi r\sin\theta_0}{\lambda}\right) \tag{3}$$

The unit normal vector to the trace of the workpiece surface is simply the normalized gradient, which is given by Eq. (4).

$$\hat{n} = \frac{\vec{\nabla} m}{\left|\vec{\nabla} m\right|} = \frac{\frac{\partial m}{\partial r}\hat{e}_r + \frac{\partial m}{\partial z}\hat{e}_z}{\sqrt{\left(\frac{\partial m}{\partial r}\right)^2 + \left(\frac{\partial m}{\partial z}\right)^2}} = \frac{\frac{\partial m}{\partial r}\hat{e}_r + \hat{e}_z}{\sqrt{\left(\frac{\partial m}{\partial r}\right)^2 + 1}} \tag{4}$$

Eq. (4) can be substituted into Eq. (2) to solve for the value of u. After finding u, the value of v can be calculated from Eq. (5).

$$v = A\sin\left(\frac{2\pi\cdot u\cos\theta_0}{\lambda}\right)\sin\left(\frac{2\pi\cdot u\sin\theta_0}{\lambda}\right) \tag{5}$$

The z-coordinate of the center of the tool can now be calculated from Eq. (6) and can be used to calculate the stroke of the fast tool servo for the point ($r=r_0$, $\theta=\theta_0$).

$$z_{tool} = v + R_t\hat{n}\bullet\hat{e}_z \tag{6}$$

This algorithm for calculating the stroke of the fast tool servo for every point ($r=r_0$, $\theta=\theta_0$) on the surface of the workpiece is programmed into the controller of the fast tool servo.

Machining Parameters

The stroke of the fast tool servo controls the motion of the diamond tool to produce the desired surface form. However, it is important that the single point diamond cutting tool have an appropriate geometry, so that there is adequate clearance between the clearance surface of the tool and the machined workpiece surface. The sinusoidal surfaces machined on the workpiece have a maximum slope of 13º. This large slope complicates the machining process, because the cutting tool must have a relatively large primary conical clearance. The single point diamond cutting tool selected for this study has a primary conical clearance of 15º. In addition, the large slope of the sinusoids means that the effective cutting rake angle varies from -13º to +13º. The large variation in the rake angle causes very different cutting mechanics to occur on the opposite sides on the sinusoidal features.

The other important geometrical feature of a single point diamond tool is the nose radius, which affects the surface finish and the mechanics of chip formation. Normally, to achieve a good surface finish, the tool should have the largest possible nose radius. For the current workpiece surface, the minimum radius of curvature of the machined surface is 50 μm, which would be an acceptable nose radius when machining a simple workpiece, such as a solid piece of copper. However, because the workpiece in this study consists of two dissimilar polymer materials, other factors must be considered.

The two polymer materials that make up the workpiece have different rheological properties, so their machining characteristics differ. The machinability, cutting forces, and degree of material deflection and recovery differ for the two materials. The result of these differences is that after the cutting tool passes across the surface of the workpiece, the two materials spring back to different heights, so a step discontinuity forms at the interface of the dissimilar workpiece materials. The magnitude of the step discontinuity is known to vary with the nose radius of the tool, with a smaller nose radius causing a smaller step discontinuity. Note that there is a tradeoff between surface finish and the step discontinuity at the interface between dissimilar workpiece materials. To achieve a reasonable balance, this study uses a single point diamond tool with a nose radius of 4 μm.

Characterization of Machined Sinusoids

The workpiece into which the sinusoids are machined consists of a rod of polyimide with a diameter of 1.25 mm. A strip of iodine-doped polystyrene with a width of 200 μm and a depth of 100 μm runs through the center of the rod. Pictures of the machined sinusoidal surface taken with a scanning electron microscope (SEM) appear in Figure 4. Because the polymer workpiece materials are not electrically conductive, the sample must be coated with a thin layer of carbon dust prior to placing it in the SEM.

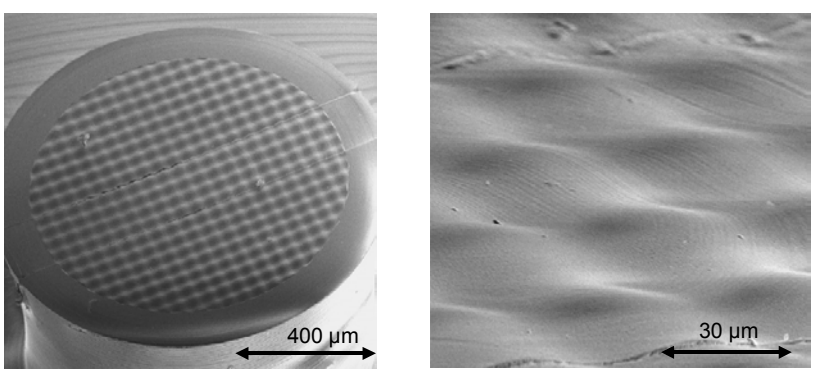

Figure 4. SEM pictures of machined sinusoids

These SEM pictures reveal that the sinusoids have the correct general form, but there are some roughness features on the machined surface. SEM pictures such as these provide a qualitative assessment of the machined sinusoids, but a different method of surface metrology must be performed to obtain quantitative information.

The most common method of characterizing sinusoidal surfaces such as this has historically been white light interferometry, which works well for surfaces with a small slope and good surface finish. However, this particular workpiece surface contains slopes as large as 13º and does not return enough light for an optical profiler to make a reliable measurement. Therefore, the form of the machined sinusoids is determined by measuring the surface with a Panasonic UA-3P coordinate measuring machine (CMM). This CMM uses a diamond-tipped touch

probe with a radius of 2 μm to measure the specimen surface with an accuracy of 0.1 μm in the displacement direction and a lateral accuracy of 50 nm. A dataset collected by this device with a lateral point spacing of 2 μm is plotted in Figure 5.

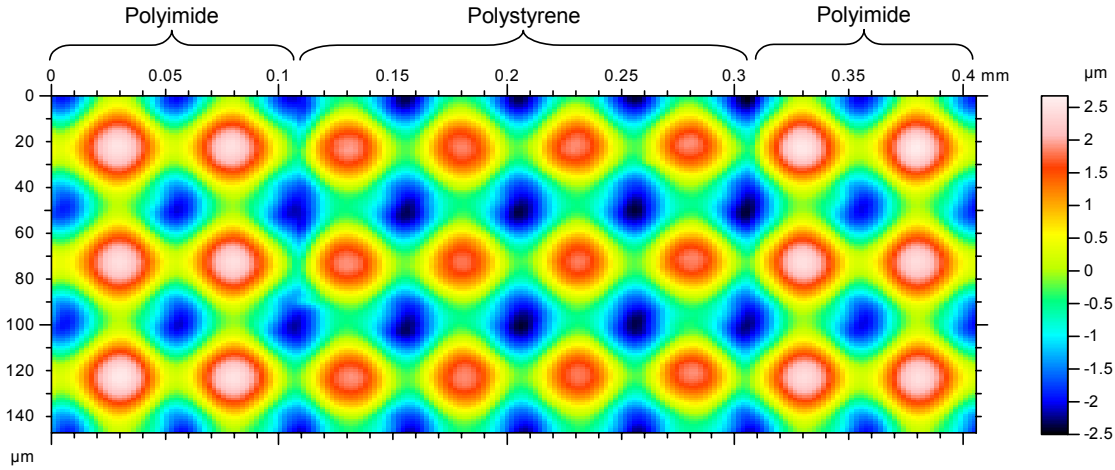

Figure 5. Surface profile data measured by the CMM

The data clearly shows the interfaces between the polyimide and the 200 μm wide strip of iodine-doped polystyrene. Several profile traces were taken through this dataset to measure the magnitude of the step discontinuity at the interface between the dissimilar materials, and the measured values ranged from 0.3 to 0.6 μm.

The form of the machined surfaces can also be determined from this dataset. Profile traces of the dataset in the iodine-doped polystyrene region reveal sinusoids with an amplitude of 2.5 μm and a wavelength of 70.7 μm. Profile traces in the polyimide material reveal an amplitude of 2.4 μm and a wavelength of 70.7 μm. The 0.1 μm error in the magnitude of the sinusoids in the polyimide could be a result of the poor machining characteristics of this material [3]. The depth of cut of only 1.25 μm combined with a rake angle that varies from +13º to -13º may result in significant ploughing or workpiece deflection that cause an error in amplitude. Conversely, the iodine-doped polystyrene is known to machine well with this type of depth of cut when using a diamond tool.

To determine the surface finish of the machined sinusoids, the specimen is measured in several places using an atomic force microscope (AFM). The AFM measures a 65 μm × 65 μm area with a lateral point spacing of 0.13 μm, and the environment is estimated to cause a noise floor in the displacement direction of approximately 2 nm. To separate the form of the surface from the roughness profile, the dataset collected with the AFM is filtered with a 10 μm Gaussian filter to reveal an RMS roughness of $S_q = 50$ nm.

Conclusions

This study investigates the fabrication of precision, micro-scale sinusoidal surfaces in a workpiece consisting of adjacent pieces of polyimide and iodine-doped polystyrene. A diamond tool in a commercial fast tool servo machines a sinusoidal surface with an amplitude of 2.5 μm and a wavelength of 70.7 μm. Because of the large slope of the machined surface and the optical properties of the workpiece material, the surface cannot be adequately characterized with a white light interferometer. Measurements with a precision touch-probe CMM indicate that the sinusoids have sub-μm form accuracy, and AFM measurements indicate a surface finish on the order of $S_q = 50$ nm.

Acknowledgement

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