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Effect of polymer relaxation in automated micro polishing

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Abstract. Micro polishing is a process used when a fine surface quality is desired. In optics, it represents the key process to achieve low surface roughness and form error required for optics application. Automated micro polishing with polymer-based tools requires a better understanding of the interaction between tool and workpiece than conventional polishing, and an important phenomenon that has to be taken into account is polymer relaxation. Stress relaxation is due to the non-linear viscoelastic behaviour of polymers. This relaxation is a time-dependent phenomenon that causes a decrease in stress, although the strain is kept constant. In this work, the effect of polymer stress relaxation on polishing is studied. While this effect can be neglected in conventional polishing, it becomes an essential and dominant factor in micro polishing. Characterization tests are conducted on a very common extruded polyurethane (LP-66) used in polishing. Subsequently, bonnet polishing using a spherical tool with a diameter of 1 mm is performed for 8 minutes on a nickel sample. Due to relaxation, the induced stress on the tool decreases during polishing, causing a reduction in the polishing pressure. This implies a reduction in the material removal rate in accordance with Preston's law. Experimental results are in accordance with the physical phenomenon. The polymer relaxation characteristics can be used to compensate the tool path to achieve uniform removal along the polished surface.

Keywords: Stress relaxation, Micro polishing, Polymer.

INTRODUCTION

Polishing is an essential manufacturing process used when a fine surface quality, together with sub-micron form tolerance, are needed [1]. Micro polishing tools offer several advantages when used for deterministic polishing. Among others, accessibility issues can be overcome, and small features can be polished. Besides, as the tool contact area is smaller than in conventional polishing, a more uniform material removal can be achieved.

On the other hand, the process requires careful control of the contact conditions. Preston's equation (eq.1) describes the factors affecting material removal in polishing. The equation states that the MRR is directly proportional to the applied pressure p and the relative velocity v between the workpiece and the polishing tool. A constant K (Preston coefficient) comprises all mechanical and chemical interactions not directly linked through pressure and velocity, e.g., grain size, lubrication, abrasive concentration and properties of the workpiece/tool [2].

$$MRR = \frac{dz}{dt} = K \cdot p(\vec{x}, t) \cdot v(\vec{x}, t) \tag{1}$$

According to Preston's equation, when the pressure decreases, so does the material removal. This implies that when the real contact pressure departs from its nominal value, form error on the polished surface may occur. It is, therefore, crucial to understand which factors can potentially change during polishing, and if needed, compensate them. Since polishing tools are usually made from a polymeric material, a stress relaxation phenomenon is inevitable. This relaxation is due to the non-linear viscoelastic behaviour of polymers. Stress relaxation is defined as a decrease in stress in response to a nominal constant strain [3], [4]. This phenomenon is a time-dependent problem. Contact stress can be related to the contact pressure, as shown in [5]. This implies that if the contact stress decreases while polishing, then the pressure and consequently, the material removal would have a similar trend. It is for these reasons that understanding and quantifying this effect can minimise form error in polishing and provide a more deterministic approach towards ultra-precision polishing. As a general trend in polymeric materials, the higher the strain, the higher

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the stress relaxation. In this work, the effect of polymer relaxation is characterised, and its effect on the rate of polishing material removal is studied.

METHODOLOGY

The following methodology is adopted to prove that the material removal rate is strongly affected by polymer stress relaxation, and provide quantification of this effect.

The tool used in all polishing experiments is made with a common extruded polyurethane (Universal Photonics LP-66) used for polishing applications, which was dressed to a spherical shape with radius 0.5 mm. The polished sample is a nickel disk of radius 2.5 mm. The experimental activities are divided into three stages: relaxation tests, tool wear, and temperature variation during polishing. Four hypotheses are stated and proven through the polishing experiments. The hypotheses are listed as follows:

- Stress relaxation is one of the main contributors to form error in polishing
- Wear of the polishing tool is negligible over the typical run time
- Temperature variations during polishing are negligible
- The temperature reached during polishing influences neither the relaxation behavior nor the elastic modulus

Polishing tool relaxation test

First, a relaxation test is performed to quantify the relaxation of the polymer under study. The experiment is conducted by pressing the tool against the sample for a fixed amount of time and a prescribed offset. Beneath the sample, a highly sensitive 3-axis dynamometer (Kistler 9027C) measures the contact forces (see Fig.1). The tool stays in contact with the sample with a tool offset of 100 µm. This tool offset is the same as used for the polishing experiments. Due to drift behaviour of the charge amplifier of the dynamometer, only the ten first and last seconds of the experiments are sampled and acquired. This is done because acquiring data for a long period of time generates thermal drift on the charge amplifier that cannot be adequately compensated. By doing so, the trend of the relaxation test cannot be observed, but the absolute value between the start and the end of the experiment can give a useful quantification on the total relaxation as a function of time (see Fig.2). To quantify and subsequently use the results of these relaxation tests, we define, in this work, the total relaxation Re at time t* as follows in equation 2.

$$\mathrm{Re}(t^*) = \frac{F(T_{in}) - F(t^*)}{F(T_{in})} \times 100 \tag{2}$$

Where $F(T_{in})$ is the force at initial contact condition and $F(t^*)$ the force at the time the relaxation is calculated. This simple metric has the objective to quantify the effect of relaxation on material removal. Relaxation tests are repeated five times to assess measurement repeatability. At time t*=8 min the relaxation corresponds to 43.2 ±1.81%

It has to be noted that a relaxation test is usually conducted while maintaining a constant real strain. In this experiment, this cannot be assured.

Nevertheless, the nominal strain is constant due to the nominal tool offset value. This makes these results valid only to this particular configuration. The methodology is, however, of a more general nature.

Tool wear in polishing

Tool wear hypothesis is tested by profiling the spherical tool with a beam laser interruption system before and after polishing. If the tool profile does not change, within a given tolerance after polishing, then it can be concluded that tool wear does not affect the material removal rate. Polishing tests were conducted using the parameters reported in table 1 to asses whether the tool wear can be neglected or not. Tests are repeated five times. The tool wear observed was 1 µm. Being that the tool offset is 100 µm, tool wear represents only 1% of the total offset.

Moreover, from the relaxation test, the residual deformation immediately after interrupting the load is approximately 45 µm, which is considerably higher than the measured wear. The residual deformation is obtained as a subtraction between the measured profiles, before and after the relaxation test. The measurement is also performed with a beam laser interruption system. Based on these observations, it is safe to conclude that the tool wear does not affect the material removal, and it can be neglected as a source of error.

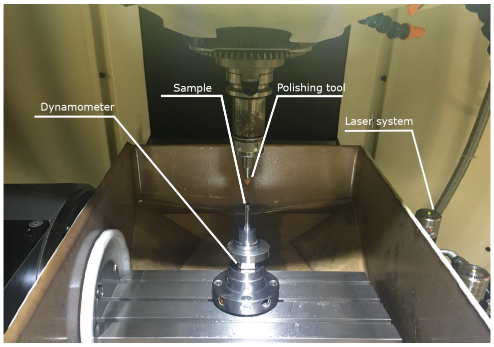

FIGURE 1. Relaxation setup

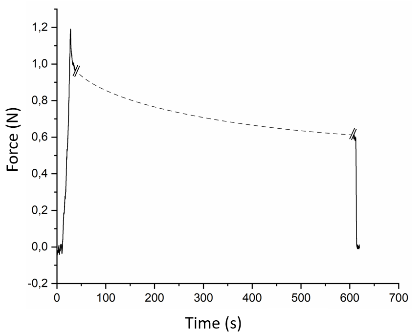

FIGURE 2. Tool relaxation behaviour

TABLE 1. Polishing parameters and associated tool wear on the right.

Process parameters	Values	Units	Tool wear
Feed velocity	50	mm/min	1±0,7 µm
Spindle speed	2000	rpm	
Precess angle	30	deg	
Tool radius	500	µm	
Abrasives	Alumina	/	
Abrasives size	200	nm	
Concentration	40	g/l	

Temperature variation in polishing

Lastly, the temperatures reached during polishing were experimentally characterised. Temperature affects the Young modulus of the material. The Young modulus decreases with increasing temperature, and ultimately, the contact pressure follows the elastic modulus. A reduction in contact pressure results in a lower material removal rate, according to Preston's law. Temperature also affects the relaxation of the polishing tool material, making it more severe. For these reasons, if the temperature during polishing does not increase considerably, then the hypothesis of stress relaxation being the main contributor to form error can be accepted.

To characterise the temperature during polishing both a thermal camera and thermocouple are used. Measuring the temperature is a challenging problem in micro polishing. Due to the small contact areas and accessibility issues, the required resolution of a thermal camera must be small enough to sense small variations. Thermocouples have to be placed as close as possible to the heat source, and inevitable convective heat flow causes losses before reaching the thermocouple. In this paper, a method that overcomes these issues is presented that is suitable for polishing setups.

Polishing is performed directly on the thermocouple's junction (see Fig.3). This is possible because of the small size of the tool and because of the low material removal rate in polishing. Some crucial assumptions are made in this experiment. First, the heat flow produced during polishing is considered to be nearly completely transferred to the thermocouple. This is equivalent to neglecting convective heat flow losses. Secondly, the cross-sectional dimension of the thermocouple is considerably larger than the material removed during polishing. The thermocouple's junction has a cross-section of 0.4x0.4 mm², which is lower than the spot size (approximately 0.2x0.2 mm²). Moreover, the material removed is in the order of 100 nm for the duration of the experiments and therefore, negligible material removal from the thermocouple is expected. Thus, it is safe to accept this assumption. The thermocouple is a type K with a sensitivity of 41µV/°C, chosen to match the material of the sample to be polished. Type K thermocouples are made of two different alloys, Chromel and Alumel, both of which have a minimum content of nickel higher than 90%. With these choices and assumptions, a reasonable temperature during polishing can be inferred.

The spindle speed of 2000 rpm with a tool offset of 100 µm was tested. These parameters are chosen to be consistent with the ones used for the polishing experiments in the next section. The test is conducted with the same polishing tool as previously used, and a tool influence function (removal footprint) is generated with the tool being stationary (feed = 0) for 1 minute. A tool influence function represents the material removal produced by the polishing tool in a unit of time. Tests are performed with polishing slurry to replicate the real polishing conditions. In Fig.4, it is possible to see the results of the temperature characterisation. The temperature during polishing increases by about 2 °C when polishing starts, stabilises, and then gradually decreases when polishing ends. It has to be noted that the local maximum temperature could potentially be higher in some points. However, the temperature in the bulk material is the main factor affecting both the stress relaxation and Young modulus. The Young modulus decreases by less than 0.5% respect to the one at room temperature. Because of this observation, it can be concluded that, with the used parameters, the temperature variation due to polishing does not influence the stress relaxation nor the Young modulus significantly.

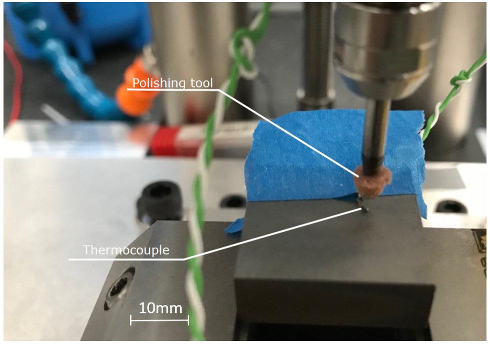

FIGURE 3. Setup for polishing on thermocouple

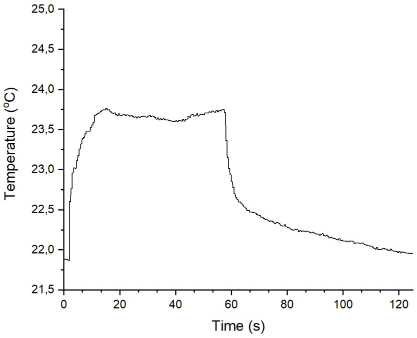

FIGURE 4. Temperature variation on thermocouple

Uniform polishing experiments

Having tested the above-listed hypotheses, polishing was conducted on a flat nickel disk of radius 2.5. Polishing experiments are performed on a CNC machine adapted for polishing purposes. The tool is a polyurethane sphere of radius 500 µm. The workpiece used for the polishing experiments is a diamond-turned nickel disk presenting an initial surface roughness of 4.1 nm Sa. The used abrasives are alumina particles dispersed in a slurry with low viscosity to improve the slurry flow and promote a uniform distribution of abrasives in the polishing area. The slurry is then continuously pumped towards the polishing area assuring constant and uniform distribution of abrasives. The CAM program is generated using the ZephyrCam software developed by Zeeko Ltd. The parameters used for these tests are listed in table 2.

TABLE 2. Polishing parameters.

Process parameters	Column Header Goes Here	Units
Feed velocity	50	mm/min
Spindle speed	2000	rpm
Precess angle	30	deg
Tool radius	500	µm
Abrasives	Alumina	/
Abrasives size	200	nm
Concentration	40	g/l

Again, the polishing tool profile was measured with a beam laser interruption system before and after polishing to assess tool wear. The form of the sample is measured with a Fizeau laser interferometer from Veeco before and after polishing. The two surfaces are then subtracted to obtain the material removal distribution. This experiment is repeated three times to assess results repeatability and consistency.

RESULTS AND DISCUSSION

Figure 5 shows the material removed after 8 minutes of polishing and the raster path direction. It is possible to see how the material removal decreases in the cross feed direction. This is associated with the previously described relaxation behaviour. It can be seen that the relaxation starts immediately and that at the end of the polishing, it accounts for ΔRe=38.59% of the material removal. This demonstrates the importance of quantifying and consequentially compensate for this behaviour. By extrapolating the relaxation behaviour from the relaxation tests at t^*= 8 minutes, a total relaxation of 43.2 ±1.81% was obtained. This result is in accordance with the conducted polishing tests.

It has to be observed that for long polishing runs, the material removal rate becomes more stable in relation to the stress relaxation. Moreover, it is common to polish a surface multiple times, with different scan directions, in order to minimize the effect of polymer relaxation. Besides, when dealing with conventional size polishing tools, this effect is more averaged on the surface area than in micro polishing, where the spot size and tool offset are considerably smaller than the micro-domain process. Moreover, due to the very low material removal rate in micro polishing, it becomes essential to take the relaxation effect into account. The results are also biased by the stationary condition of the relaxation tests.

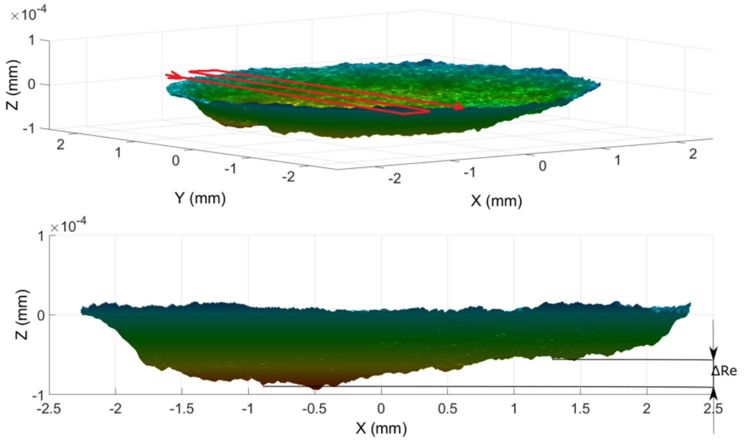

FIGURE 5. The material removal decreases along the direction of the polishing path. The trend and the final material removal are coherent and consistent with the relaxation test.

CONCLUSION

Polymer stress relaxation has been observed to be an important factor in high precision polishing. If this factor if not taken into account, form errors may occur that are not negligible any longer when tight tolerances are required. Experimental tests were conducted to isolate the effect of stress relaxation. The paper presents an innovative approach to quantify and measure polishing process temperatures by performing the polishing on the thermocouple itself. The hypothesis of negligible tool wear and temperature variation were proven to be robust and non-refutable. As a main result, the effect of temperature variation on the bulk material during polishing was seen to be insignificant on both the Young modulus and the relaxation behaviour of the material. Tests were finally conducted to prove the main hypothesis retained in this paper, i.e. relaxation as primary contributors to form error. Relaxation behaviour is critical to achieving uniform material removal rate.

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