MICRO-MILLING WORK-HOLDING DEVICES EMPLOYING ADHESIVE FORCES

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ABSTRACT

Micro-parts are often very fragile rendering conventional, mechanical work-holding fixtures unsuitable for them since they exert large straining forces. Furthermore, macro-workholding devices occupy a large space which impedes high precision required in micro-milling. Although some micro-clamping fixtures exist, they are limited to specific part shapes and in most cases expensive to manufacture. Hence this paper focuses on the application of adhesive forces namely electrostatic, surface tension and van-der-Waals forces; in work-holding strategies for micro-milling operations. An analysis is given as to their applicability with reference to micro-milling cutting forces.

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1. INTRODUCTION

The demand for micro products is steadily increasing (Gill et al [3]). The production cycle times of these products have to be reduced so as to meet this demand. Currently micro clamping systems are widely used. These are down scaled macro-sized mechanical clamps which have several limitations in micro-milling application. They take a lot of work-space, and in most cases are larger than the machined micro-part obscuring vision of the operator as shown in Figure 1. They make it difficult to effectively integrate sensors and other machining monitoring devices. When it comes to the securing of the micro parts on such clamps, a lot of time is required to engage and disengage them, thus increasing production cycle times. These clamps, inclusive of vacuum clamps, also impose mechanical strain on the micro-part which can result in cracking of brittle micro parts. Mechanical clamping might also impose scratches, wear and bending on the micro-parts (Kalkowski et al [6]). On the other hand magnetic and electromagnetic clamps are limited to ferrous materials. Given such a scenario, this paper focuses on promising alternatives which include physical solidification bonds, surface tension clamping, electrostatic force clamping and van-der-Waals force actuated clamps.

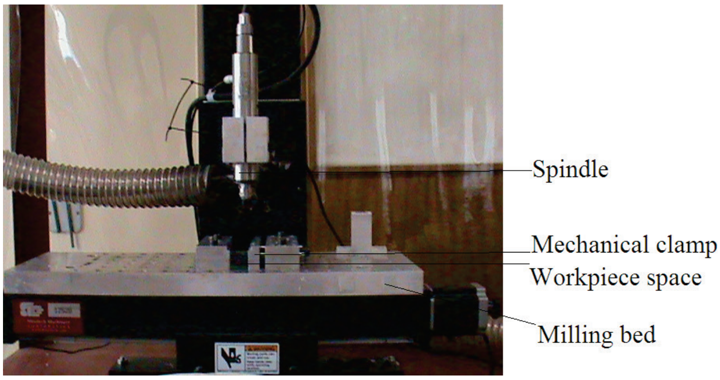

Figure 1: Micro-milling machine with mechanical clamps

2. PHYSICAL SOLIDIFICATION BONDS

Physical solidification bonds refer to clamping performed by the freezing of a liquid. A good example is a cryogenic clamp. It employs the freezing of water as the clamping principle (Walle et al [19]). A work-piece is placed on a substrate and water is frozen around it, clamping the micro-part. When unclamping, heat is supplied to melt the ice.
However, there are several limitations to the employment of a cryogenic gripper. It is time consuming to freeze and de-freeze the water which inevitably increases the production cycle time of the micro-product. It also requires an efficient heat exchanging system since water has a relatively high specific heat capacity. It is very inefficient with hydrophobic substances. Since water is involved, it is unsuitable for corrosive material. In cases of porous hydrophilic materials, it may lead to thwarting or weakening of the material.

An alternative would be a wax clamp which works on the same principle as the cryogen clamp. Clamping is achieved when the wax solidifies. The wax is better in clamping than water because it has a higher solidification temperature such that it solidifies easily even at ambient temperature. This removes the need of a sophisticated heat exchange system required for the cryogenic clamp. However, when unclamping, fracture may result especially with brittle micro-parts. Hence heat to melt the wax is required.

3. SURFACE TENSION CLAMPING

Surface tension clamping employs the use of a fluid between interacting surfaces. The liquid induces an adhesive force between the interacting surfaces. Hydrophilic substances work well with this kind of clamping (Lambert [8]). However, in the case of ferrous materials, corrosion is a problem. Hence, the choice of material combinations should be designed such that this phenomenon is avoided. It also has to be noted that hydrophobic substances, for example Teflon, cannot be clamped by surface tension involving water.

The surface tension force between two plates of same material with a very small separation distance compared to their length is given by Equation 1 (Lambert [8]).

$$F_s = \frac{2\pi\gamma}{D} R^2 \cos\theta \qquad \text{Equation 1}$$

Where F_s - Surface tension force, γ- surface tension constant, R - radius of the meniscus from the centre of the plates, and D - separation distance and θ is the contact angle of a given liquid.

In cases where the $\gamma = 0.037$ N/m (Hryniewicz et al [5]) and $R = 5\text{x}10^{-3}$ m (half the size of the micro-part), $\theta = 60^o$ (which approximates to an average value, since cos 60^o is 0.5) and $D = 1\text{x}10^{-5}$ m (almost a hundredth of the thickness of the micro-part), it is observed that $F_s = 0.290$ N. These figures were assumed for the elements in the micro-milling operation. This surface tension force was experimentally proven to be capable to withstand the micro-milling forces as in the following paragraphs.

Experimentation on the use of surface tension as a clamping force was executed as illustrated in the Figures 2 to 5. The experiments were done under ambient atmospheric conditions. The materials included an aluminium micro-part (10 mm x 10 mm x 1 mm), a drop of a coolant (as a clamping liquid), Perspex as the work-piece support. As for the micro-milling operation a 12.7 µm ultra-fine grain carbide hard metal, 2-flute end-milling tool was used. The milling feed rate was 19 mm/min and the spindle speed was 60 000 rpm.

Figure 2 shows a Perspex micro-part holder with a 100-150 µm deep square cavity. Blind holes (B) were drilled to allow the flat micro-part (C) in Figure 3 to fit in snugly. Dry milling of the micro-part was attempted, but failed. However, when a drop of a coolant liquid was applied into the cavity of the micro-part, milling was achieved proving that the surface tension of the fluid helped in securing the micro-part. Two parallel grooves of 5 mm length, approximately 13 µm width and 10 µm apart were milled as shown in Figures 4 and 5 without any detectable movement of the work piece. The maximum depth of cut was slightly less than 10 micron.

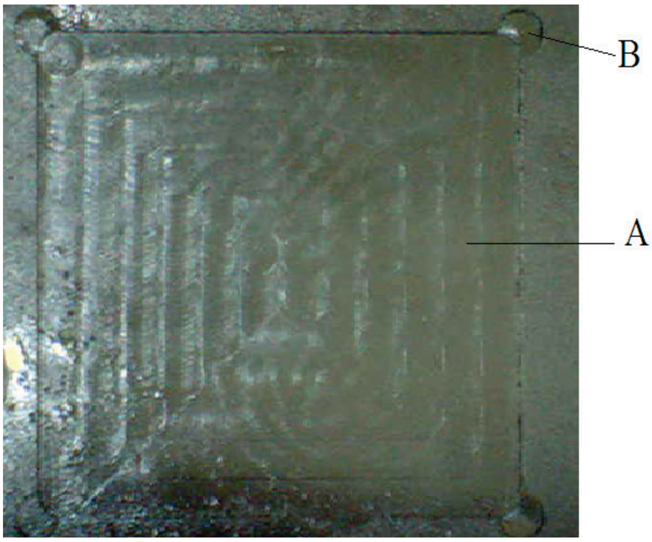

Figure 2: Milled space for micro-part holding

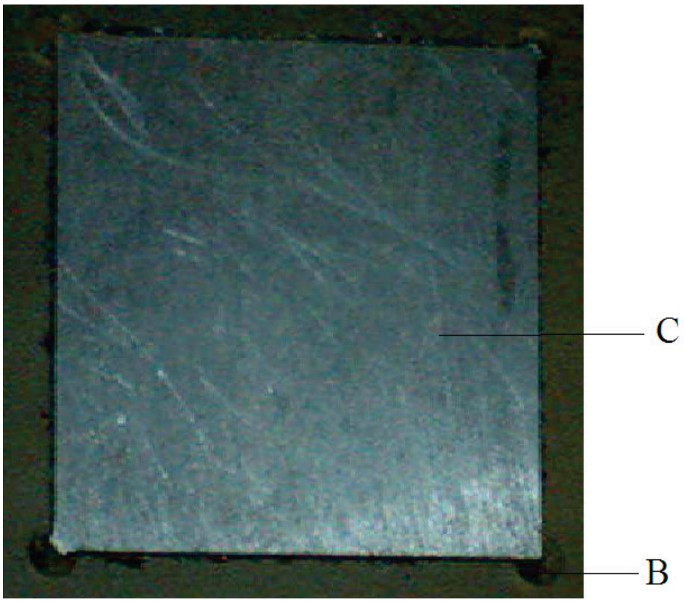

Figure 3: Micro-part positioned in the cavity

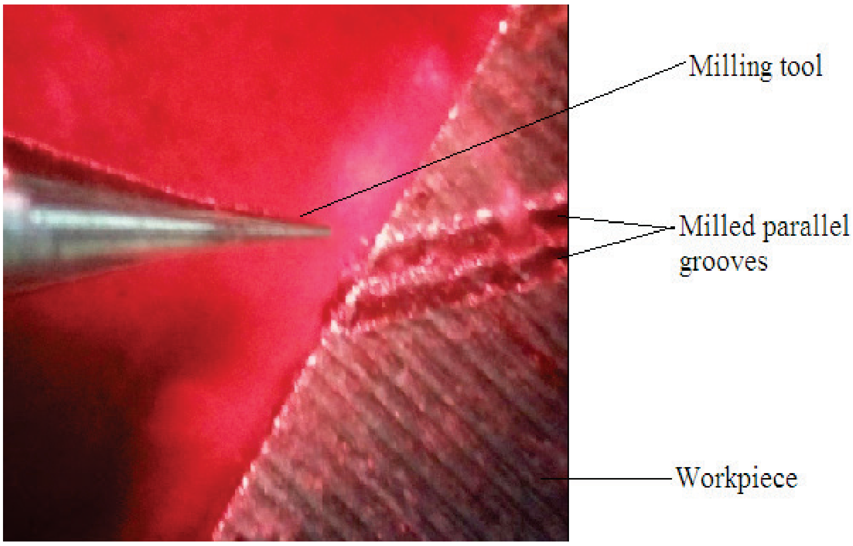

Figure 4: Milling tool and micro-part

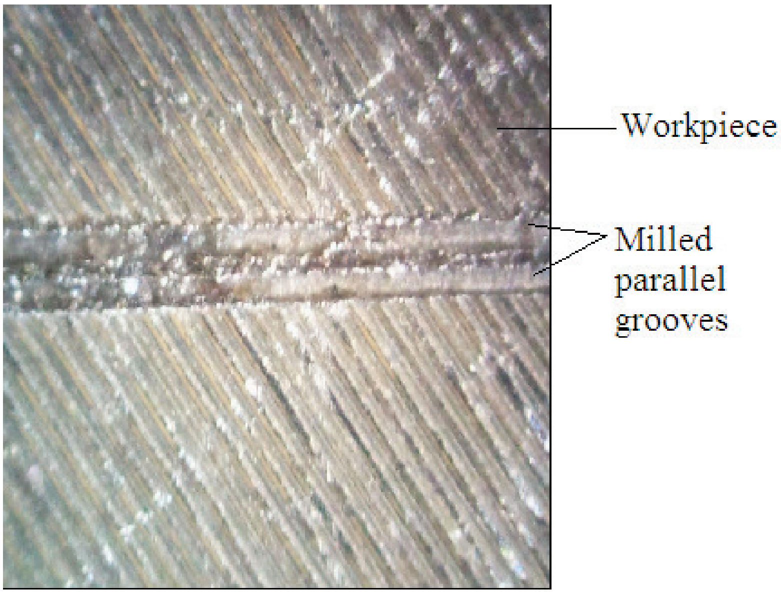

Figure 5: Milled parallel grooves

Cutting forces for micro machining do not follow the conventional formulas, due to size effects and vibration. Therefore, the cutting forces are estimated using the steel-milling experimental data produced by Schmidt & Tritschler [17]. They experimented on heat-treated steel of hardness ranging between 42 and 56 HRC; and obtained a maximum radial force of 2 N, maximum feed force of 0.7 N, chip thickness of 4 µm, depth of cut of 20 µm, and the shearing strength of steel was 82 GPa. From their findings Equation 2 is developed to estimate the maximum cutting forces involved in the milling of another material, which in this case is aluminium with the following data: average chip thickness of 0.16 µm, depth of cut of 10 µm, and shearing strength of steel of 28 GPa .

$$F_r = \frac{F_{max} t_s d_s \tau_s}{t_a d_a \tau_a} \qquad \text{Equation 2}$$

With F_r being the radial milling force for aluminium, F_{max} being maximum radial force for steel milling, t_s being chip thickness of steel, d_s being depth of cut of steel, and τ_s being shear strength of steel. In the formula aluminium has corresponding values t_a, d_a and τ_a.

A similar calculation can be done for the force in the feed direction. Using Equation 2 the force in the radial direction was approximately 0.014 N and the force in the feeding direction 0.005 N. These forces are far below the clamping forces exerted by a surface tension gripper as calculated earlier. This explains why the micro-part did not slip when machined as described in the experiment.

4. ELECTROSTATIC FORCE CLAMPING

The electrostatic force clamping principle exploits the attraction between oppositely charged substances. A simple electrostatic clamping employs the use of polymers and any other materials which do not conduct away electric charge easily. When a polymer is mechanically rubbed by a wool material, an electrostatic charge is induced which may be used in clamping micro-parts. The charge is maintained either by continuous or intermittent rubbing. An electrically operated rotational rubbing tool may be used to generate a uniform charge between the clamped surfaces.

An alternative to the rubbing technique is the parallel-plate-capacitor which electrostatically clamps a micro-part by induction when an electric current is supplied. This electrostatic clamp is positioned as a fixture on the bed of the micro-milling machine (Kalkowski et al [6]). The force per unit area is given by Equation 3 (Kalkowski et al [7]).

$$F_e = \frac{\varepsilon V^2}{2D^2} A \qquad \text{Equation 3}$$

With F_e being the electrostatic force, V being the voltage across the parallel plates of the gripper, A being the cross-sectional area of the micro-part in contact with the dielectric material, D being the thickness of the dielectric material between the micro-part and the metal electrode, ε being the permittivity of the dielectric material.

Neugebauer et al [13] and Neugebauer et al [14] used electrostatic force to grip piezoceramic materials. They simulated the electrostatic forces with ANSYS Multiphysics (Electrostatic) and observed that the gripper could exert forces ranging from 56 μN to 600 μN. They then experimentally gripped elements of 56 μN weight in the assembling of piezoceramic sensors. The simulated range is well over the milling forces mentioned earlier proving that electrostatic forces are a viable alternative for micro-milling clamping.

The advantage of an electrostatic clamp over a mechanical one is that its force is distributed homogeneously all over the micro-part's surface, and can be easily switched on or off by a simple turn of a knob (Kalkowski et al [7], Neugebauer et al [14]).

5. VAN-DER-WAALS FORCES

The clamping of micro-materials can also be achieved by van-der-Waals forces. The virtue of these forces lies in the fact that they work in both aqueous and vacuum conditions. They are active in almost all materials. Polyurethane polymers have been found to exert a relatively high intensity of van-der-Waals clamping force on micro-parts. Unclamping is easily achieved by peeling off the micro-part (Murphy et al [2011]).For a firmer clamping to be realized, the contact area should be relatively large. The van-der-Waals force equation for ideal flat surfaces is given by equation 4 (Parsegian [15]).

$$F_{vdW} = -\frac{A_H}{6\pi D^3} A \qquad \text{Equation 4}$$

With F_{vdW} being the van-der-Waals force, A_H being the Hamaker coefficient , D being the separation distance, A being cross-sectional area of the micro-part.

Although surface roughness at times adversely affect the van-der-Waals clamping force; if interacting surfaces are uniformly rough such that they match (making contact along their profiles), then the contact surface area increases significantly leading to a better clamping force (Matope & Van der Merwe [9]). Such surfaces have the additional advantage that they allow surfaces to interlock preventing slippage during machining. They also help in the self-alignment of clamped micro-parts.

The emergence of polyurethane gecko-setae-like micro- and nano-structures has enhanced van-der-Waals force clamping of micro-parts (Glassmaker et al [4], Geim et al [2]). These are directional, hierarchical and high aspect ratio micro-structures with nano-fibres at the end (Murphy et al [11]). They can firmly clamp both micro- and macro-workparts (Murphy et al [2011]) whose root-mean-square surface roughness values can be as high as 35µm. These numerous nano-fibres have the advantage that they can increase the surface's contact area by being in touch with the whole profile of a rough surface. Another advantage is that they are anisotropic allowing a relatively easy clamping and unclamping operation (Menon et al [10], Murphy et al [11], Sitti & Fearing [17], Murphy & Sitti [12]). Van-der-Waals forces were experimental proven by Murphy & Sitti [12] and Murphy et al [11] to hold (in a fixed position) micro-robot masses of at least 0.1 kg on vertical walls. This corresponds to shearing forces of 0.981 N magnitude. Hence the van-der-Waals forces exerted by polyurethane are capable to withstand the micro-milling forces previous presented.

6. CONCLUSION

Conclusively, micro-milling clamping of micro-parts can be achieved by employing physical solidification bonds, surface tension, electrostatic or van-der-Waals forces. However, solidification bonds are inefficient in that they go through a heat exchanging cycle during the clamping and unclamping operation. On the other hand clamps of adhesive forces need less production times. Adhesive forces are capable to securely clamp an aluminium micro-part milled with a radial force of 0.014 N and a feeding force of 0.005 N, and they can even withstand greater forces. Surface tension clamps tend to have most limitations because they are susceptible to corrosion, cannot work in a vacuum and in aqueous environments, and are ineffective in the case of hydrophobic substances; but they are advantageous because they have self-centering capabilities. Electrostatic force clamps cannot work in aqueous conditions and at times they leave some residual charges after operation. The van-der-Waals clamps are versatile since they can work in almost all environments, including vacuum and aqueous, but they lack the self-centring capability. The merits of employing clamps actuated by adhesive forces for micro-milling operations are as follows: an efficient grip-and-release mechanism is realised, ample work space is availed, production cycle times are reduced, and high micro-milling precision of micro-parts is achievable.

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