Ultrasonic Abrasive μ-Machining with Thermoplastic Tooling

A. Curodeau1, J.Guay1, D. Rodrigue2,
L. Brault3, D. Gagné3, L.-P. Beaudoin3,
1- Department of Mechanical Engineering, Laval University, Québec, QC, G1K 7P4, Canada
2- Department of Chemical Engineering, Laval University, Québec, QC, G1K 7P4, Canada
3- Department of Applied Research, Surfasys inc, 2750 rue Einstein, Québec, QC, G1P 4R1, Canada

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Abstract
Ultrasonic machining generally involves the use of high hardness tooling material such as tungsten carbide, monel or else in order to provide efficient energy transmission to abrasive particles and minimize tool wear. In this paper, an alternative tooling material is proposed whereas viscoelastic thermoplastic composite material is used as tooling to conduct ultrasonic micromachining operations. Such tooling is used within the UAμM (Ultrasonic Abrasive μMachining) process in which a polymer composite tool is initially formed by compression molding, against the very same workpiece to be finished, before being used as ultrasonic μmachining tool. To demonstrate the feasibility and applications of the process, basic micro-machining experiments were conducted with acetal and uhmwpe composite polymer tooling. In test #1, a uniform micron scale layer of material was removed in hammering mode from a flat P20 tool steel sample, while in test #2, a similar P20 tool steel sample with initial EDMed surface finish was μpolished in contactless machining mode. Analysis of μmachined sample surface profile and progression of surface finish in time are presented along with SEM pictures of surface details allowing to establish the occurrence of various material removal mechanisms.

Keywords:
Ultrasonic machining, Micro-machining, micro-finishing, polishing, surface finish, thermoplastics, viscoelastic, abrasive

1 BACKGROUND

Ultrasonic machining is primarily known for applications requiring the machining of through holes or cavities in hard and brittle materials of HRC 40 hardness and above, whether or not the material is an electrical conductor or insulator [1]. The fundamental mechanisms of ultrasonic machining are dominant on very brittle material, like glass and ceramics, where the main material removal mechanism relies on the propagation of minute cracks that are inherently present in such material [2,3,4]. For other material that exhibit minor plastic deformation prior to fracture (i.e. carburised or nitrided steel), ultrasonic machining can also be used to some extent. Otherwise in case of ductile material with larger elastic region, like most annealed metals, ultrasonic machining mechanisms should not occur in principle [2]. Nevertheless, it was showed that ultrasonic machining can work as well in ductile mode [5,6], in which case, abrasive particles can generate micro-cut and plow into the material to produce indentations [5,6,7]. In such instances, the workpiece material is not necessarily removed but can simply be displaced as it was observed for some fine polishing operations [8,9]. As a result, refinements of ultrasonic machining were proposed to conduct polishing operations [5,7,10,11,12]. Some ultrasonic polishing processes were limited to flat 2D surfaces while others proposed ultrasonic polishing of 3D freeform surfaces using small tool tip 1 to 3 mm in diameter [5,11] or even smaller with 5 to 300 µm tool diameter [10]. However, even though such processes are meant to promote polishing operations up to an automated level, they are considered as serial processes which require complex, time consuming tool path programming with challenging tool wear compensation schemes [13].

In this research, we propose the use of a new parallel ultrasonic abrasive µmachining (UAµM) process which acts over the entire surface to be polished by the use of a conformal geometry polymer composite tool. The novelty arises from the use of a thermoplastic composite tool that is molded in the very same mold cavity to be µmachined or µpolished [14]. Thus, since the tooling geometry precisely match freeform surfaces and require simpler tool path programming, UAµM can be foreseen as a fully automated finishing and polishing process for closed die and mould workpieces.

The process is described in more details in the next section, followed by an assessment of the use of thermoplastic material as ultrasonic tooling and two material removal experiments demonstrating micro-finishing and micro-polishing feasibility to conclude.

2 PROCESS DESCRIPTION

UAµM refers to a process which can control the removal of very small amount of material as part of the finishing process of closed dies, injection or blow molding production molds. In this framework, micro-machining implies essentially three different material removal operations that target different surface feature topologies, namely:

1- removal of heat affected or cold worked zone which consists in a 10 to 50 µm layer of hard brittle material,

2- removal of surface waviness features (low frequency surface pattern) left as tool marks or chatter on either hard brittle or ductile material condition and,

3- removal of surface roughness (or high frequency surface pattern) down to mirror finish on either hard brittle or ductile material condition.

Since more material is removed in the first two material removal procedures, we will refer to these procedures as µmachining while the surface roughness removal is better defined as µpolishing. A complete UAµM sequence does not necessarily involve the use of all three material removal operations since the heat affected zone, for example, is useful in some applications.

2.1 Description of UAµM with thermoplastic tool

UAµM is a variation of regular ultrasonic machining with the difference that; 1) the tool is made of a thermoplastic material instead of hard metal and 2) this latter polymeric tool is molded directly in or on the workpiece to be polished. The following process flow chart summarizes the main sequences:

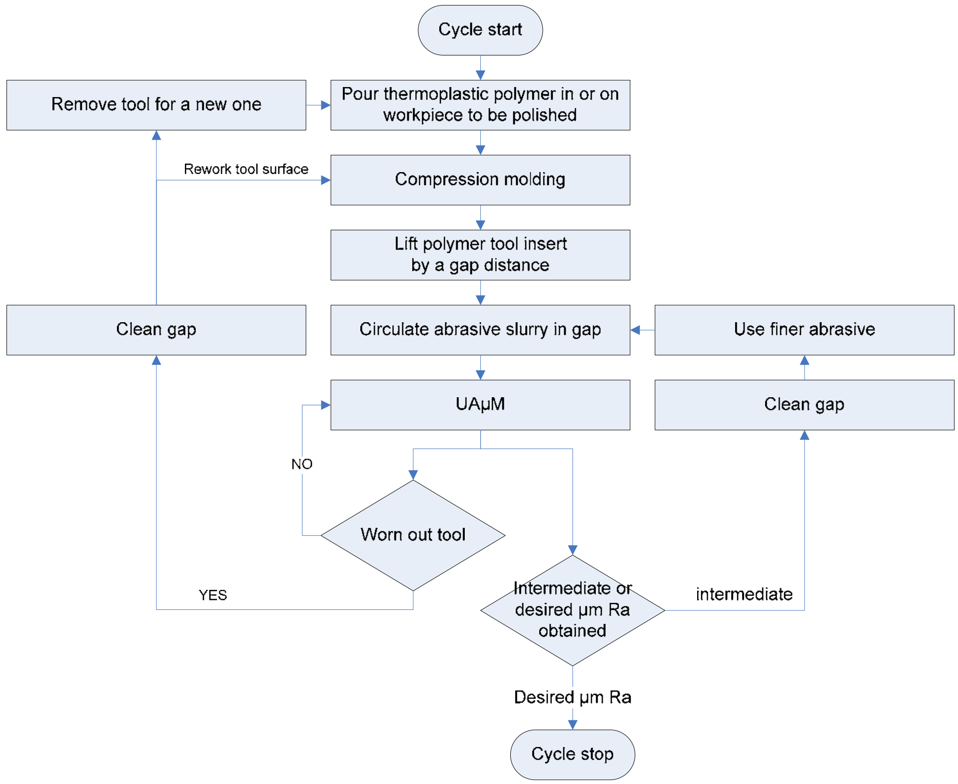

Figure 1: UAμM simplified process flow chart

The process starts by pouring polymer composite in or on the workpiece to be polished. Then, the piezoactuator horn tip is used as a ram to compression mold the polymer composite to the desired pressure level (1000 to 1500psi), as temperature is controlled slightly above the polymer melt point. After cool down, a polymer composite tool insert is firmly attached to the horn which can be disengaged from the workpiece (see figure 2).

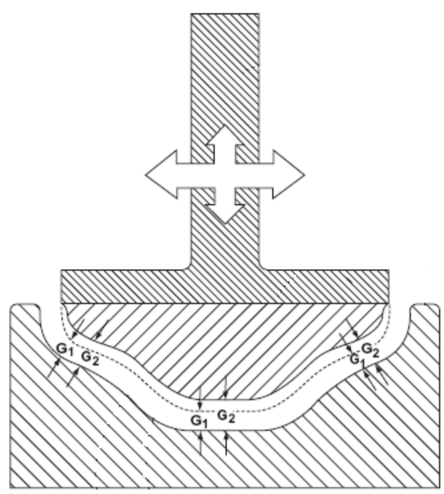

Figure 2: Polymer tool and gap control

As showed in figure 2, thermal contraction (G_2-G_1) of the composite polymer material leaves a smaller tool with predictable dimensions, adjustable to some extent via proper compression molding control parameters. An undersized tool allows the application of small orbital motion which can be used to vary the tool-workpiece gap G_2 in all directions. The surface finish of the molded tool exhibits a comparable or even better surface finish than the mold in which it was made. This principle follows the relationship between the minimum radius of a liquid meniscus with the applied molding pressure as described in the following equation:

$$\Delta p = \sigma \cos(\beta)\left(\frac{1}{R_1}+\frac{1}{R_2}\right) \qquad \text{for } \beta = 180° - \theta \tag{1}$$

where: R_1 and R_2 are the meniscus orthogonal radius
θ : wetting angle between molten polymer and workpiece material
σ : surface tension of molten polymer (N/m)

In a word, the equation reveals that a molten polymer will not fill completely the surface roughness fine details. Instead, it will create tiny hemispherical humps of orthogonal radius R_1 and R_2 overhung between the surface roughness peaks without making it to the bottom of the valleys as a function of the molding pressure and temperature. For example, a trial validation was obtained by measuring the surface finish of the following mold cavity used in a standard injection molding process (see figure 3).

Figure 3: P20 mold cavity of truck alarm casing

Five surface finish measurements were made at five different locations on the mold and at the same five positions on 2 matching molded parts. The results showed that as the mold cavity average surface finish was measured at 1.28 μm Ra surface finish, the average surface finish of the molded parts was 0.89 μm Ra for a 30% surface finish improvement.

Once the tool is separated from the workpiece, abrasive slurry is injected in the tool-workpiece gap either in a continuous or discontinuous manner. Depending on the μmachining method used, the polymer tool can either apply a static load on the workpiece in hammering mode or leave a controlled tool-workpiece gap distance to μmachine or μpolish in non-contact or impact mode[15]. Once the UAμM process is engaged, the gap can be cleaned at any time in order to replace abrasive slurry for a finer grade as the process becomes less efficient at improving the surface finish. Furthermore, as the polymer tool wears out, it can either be replaced automatically or else since the material is thermoplastic, simply reprocessed through the compression molding cycle to only rework its surfaces.

In ultrasonic machining, a broad range of material removal mechanisms can be achieved depending on the process conditions. Here is a summary of the main material removal mechanisms which could be done:

1- Mechanical abrasion or indentation by direct hammering of the abrasive particles against the workpiece surface[6],
2- Micro chipping by ballistic impact of free moving, or sliding abrasive particles driven by cavitation collapse[6],
3- Cavitation collapse erosion[7],
4- Lapping & grinding action [15],
5- Chemical action associated with the fluid employed [6],
6- Rolling action [16],
7- Small-scale removal action by exciting abrasive[7],

As a result, several options are available for UAμM, whether a μmachining or μpolishing operation is desired. Hence, in order to assess the full potential of UAμM with polymer tool, a series of test should be conducted with different ultrasonic conditions already described in the litterature. For example, in hammering mode, the static load is controlled by allowing the piezo-electric actuator to apply between 0.1 to 30N force on the workpiece[4]. As mentioned in [5,17], optimum polishing occurs for the larger values of static loads, with abrasive particles selected to approximately three time the R_{max} feature height of the surface prior to polish. On the other hand, larger abrasive grain size combined with larger tool amplitude would lead to larger MRR[5] more tailored to heat treated zone removal applications. In addition, impact mode[18] is also an option where optimum value of surface finish is obtained for:

$$a_{crit} \approx \frac{h_0 + d_{moy}}{4} \qquad \text{and} \qquad (\mathrm{h}_0)_{crit} \approx a + d_{moy} \tag{2}$$

where

a_{crit} : Tool amplitude for optimum surface finish

$(\mathrm{h}_0)_{crit}$: Tool workpiece gap for optimum surface finish

h_0 : Initial tool workpiece gap

d_{moy} : Average abrasive particle diameter

When solving for $(ho)_{crit} - a_{crit}$ this expression confirms that optimum surface finish should be obtained when the minimum gap width is equal to d_{moy} which means a theoretical zero interference between the tool in full extension and abrasive particles.

In non-contact mode, less empirical expressions were developed, nonetheless in [7] it was found that a 0.3 mm gap or less is suggested for 6 wt.% of 1 μm Al_2O_3 abrasive size particles to optimize the polishing process which translates in a gap/abrasive diameter ratio of 300 or less. Finally, other process variation of UAμM could be possible such as a combination of μEDM and UAμM [19]. In this particular case, the composite polymer has to be made electrically conductive[20] and both processes can either be used in sequence or in tandem as described in patent[14]. From these results, it was decided to investigate primarily two modes; first the hammering mode and second the non-contact mode.

2.2 Thermoplastic polymer as ultrasonic tool

According to [4], an ultrasonic tool should have the following properties to perform well in an ultrasonic machining process: high wear resistance, good elastic and fatigue strength properties, and optimum value of toughness and hardness. Thus, tungsten carbide, silver steel, monel, polycrystalline diamond and silicon nitride material are a good match according to these specifications. However, a polymer composite such as uhmwpe (ultra high molecular weight poly ethylene)-alumina can also serve several of these specifications as well. Indeed, uhmwpe has one of the highest abrasion resistance and impact strength of all thermoplastic polymer[21] which are key properties in ultrasonic machining. Nonetheless, hardness and elastic properties are far behind any metals with shore D hardness of 60-66 and elastic modulus of about 1 GPa compared to 40 to 60 HRC hardness and 200 GPa for steel. Besides, shore D and HRC can not be compared directly, but hardness can be empirically related to the material tensile strength and in such a case the hardness of P20 tool steel would be comparably more than 20 times harder than uhmwpe for example.

However, some polymer properties might change significantly with strain and rate of deformation. Since uhmwpe is a viscoelastic material which can be mathematically expressed with the Kelvin-Voight model [21,22]:

$$\tau = G'\gamma + \eta\frac{d\gamma}{dt} = G'\gamma + \frac{G''}{\omega}\frac{d\gamma}{dt} \tag{3}$$

where

η : viscous coefficient

ω : frequency (rad/s)

γ : shear deformation with phase lag δ

we know that viscoelastic material have a stiffening behaviour relative to the strain and rate of deformation of the material. In addition, the dynamic shear modulus G* ,which is a combination of the shear storage modulus G' and shear loss modulus G";

$$\left|G^*\right| = \sqrt{(G')^2 + (G'')^2} \tag{4}$$

where phase angle: $\delta = \arctan\left(\frac{G''}{G'}\right)$

evolves with excitation frequency. A rheology test was made on uhmwpe sample to evaluate the variation of the dynamic modulus G* of the polymer in its solid state, with increasing frequencies at constant temperature (i.e. 23°C). The test provided us with the storage shear modulus G' and the loss shear modulus G" which can be directly related to G*and then E* through the following equation:

$$E = 2(1+\nu)G \tag{5}$$

where ν is the poisson ratio which can be estimated at 0.34 for UHMWPE

However, our equipment allowed us to go only up to 400 rad/s (about 60 Hz) at a constant temperature of 23°C, when 125 000 rad/s were necessary to reach ultrasonic range. Nevertheless, even at low frequency the results revealed a decreasing trend of the loss modulus by a factor of 4 while the phase angle decreased by a factor of 6 and storage modulus increased by a factor of 1.5. An analysis of these figures reveals that:

1- The viscoelastic nature of the material evolves toward a pure elastic mode for higher frequencies considering constant bulk temperature and small deformation,
2- A rough estimate of E* for 125 000 rad/s (20 kHz) would give a value of ≈1.6 GPa considering a linear behaviour at constant temperature and small deformation.

Therefore, we can presume that the dynamic elastic modulus E* of uhmwpe does not increase significantly enough to make a difference with respect to steel which stands 2 orders of magnitude higher. However, strain hardening effect could partly explain the stiffening phenomenon but further experiments would be needed to evaluate the strain deformation of the polymer tool material under µmachining conditions.

On the other hand, based on the following equation for the speed of sound in a material [1]:

$$V_s = \sqrt{\frac{E}{\rho}} \text{ m/s} \qquad \text{where } \rho_{\text{UHMWPE}} = 930 kg/m^3 \tag{6}$$

we can estimate that for E*=1.6 GPa, speed of sound V_s would have increased by a factor 3 relative to DC, up to about 1200 m/s in the polymer which is beneficial since more acoustic energy can be transmitted through the tool[23].

Finally, a recent study[24] has demonstrated that storage modulus E' is about an order of magnitude higher (≈10 GPa) than the bulk properties of uhmwpe on a thin 40 nm range outer region of the material at 200 Hz excitation frequency. In addition, since the rheology test results were obtained for a frequency up to 200 Hz only, this latter value of E' has to be even larger in the ultrasonic range but it is not quantified yet. This significant increase in storage modulus is probably due to the polymer surface enrichment by the crystalline phase that varies according to the molding pressure level. It is certainly possible that abrasive particle would indent the polymer tool surface within the specified 40 nm range and see a much higher modulus than originally expected but the answer as to why a polymer tool can perform ultrasonic machining is probably a combination of the themes discussed above.

3 EXPERIMENTAL METHOD

Two UAµM approaches were conducted in order to:

1- test the hammering mode in an attempt to remove a thin uniform layer of tool steel material,
2- test the non-contact µpolishing mode in an attempt to improve the surface finish of a workpiece with initial EDM surface.

A schematic drawing of the experimental apparatus is showed in figure 4.

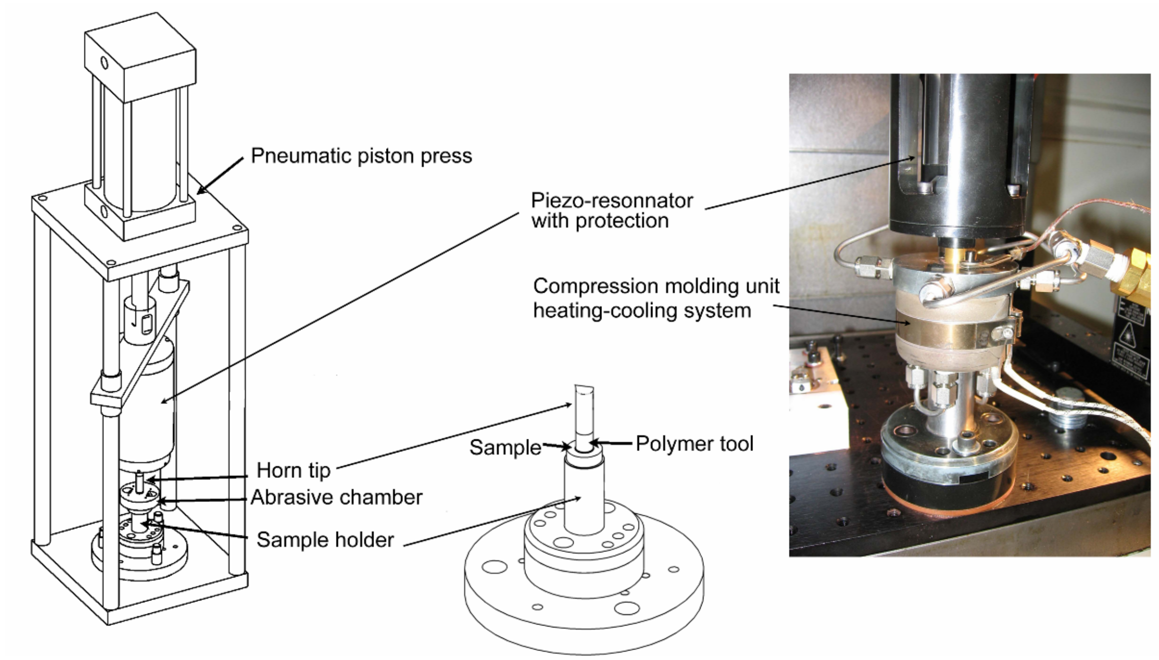

Figure 4: Schematic view of the UAμM experimental apparatus

All the surface finish measurements were made with the surface profiler Mitutoyo SV2000. The surface profiler probe diamond tip has a 5 μm radius which allows surface finish readings down to 0.05 μm Ra with a standard cut-off length of 0.8 mm or 0.25 mm for finish finer than 0.1 μm Ra.

3.1 Experimental set-up and procedure

Test #1: μmachining in hammering mode

The horn used for μmachining was made of 6061-T6 aluminum alloy with a ϕ18 mm horn tip diameter. The resonance frequency of the horn tip is 20 kHz with 8 μm Peak-to-Peak amplitude at the horn tip (without the polymer tool). The piezo driver was not self tuning during the μmachining process and resonance had to be adjusted manually. The 18 mm diameter x 8 mm thick test sample is made of P20 tool steel 32 HRC with a test surface turned on a lathe with coarse surface finish above 2 μm Ra. P20 was chosen as our sample material since it is regularly used for the fabrication of injection molds. No apparent heat affected zone could be seen on the sample surface to be μmachined. A $\approx$30N static load was applied on the workpiece by letting the entire piezo actuator assembly hover on its own weight (3,16 kg) with 0 mm gap. The polymer tool was fabricated by compression molding uhmwpe-alumina over the sample at 200°C with an approximate 6000 N compression force provided by a CNC machine tool. The tool had a 10 mm working width x 18 mm long in order to μmachine a trench of similar dimension on the sample. Abrasive slurry was inserted into the gap every 5s by lifting the piezo-actuator assembly and pumping fresh abrasive in the open gap. The abrasive was a 20% vol. SiC abrasive 100 grit suspended in Parlap oil. The sample was cooled down by a $\approx$10°C cold plate located underneath the sample. The experimental conditions are listed in Table 1.

Table 1: Experimental conditions for test #1: micro-machining

Ultrasonic actuator	**1000 W**
Resonant frequency	20 kHz
Amplitude of horn tip	8 µm peak to peak
Tooling material	90% UHMWPE + 10% Alumina
Tooling surface rework	5 times @ 200˚C (every 10 or 20 minutes)
Abrasive material	20 %vol. SiC suspension in Parlap oil
Grain size	122 µm (100 grit size)
Temperature	ambiant, 10°C cold plate underneath sample
Process conditions	
Average Gap width	0 µm
Static load	30 N
Machining time between abrasive refresh	5 sec
Duration	90 minutes
Workpiece material	P20 tool steel 32 HRC hardness
Initial surface finish	over 2 µm Ra (turn on a lathe)
Dimensions	Φ18 mm flat disk

Test #2: µpolishing non contact mode

The horn used to µpolish was made of 6061-T6 aluminum alloy with a ϕ20 mm horn tip diameter over which a ϕ10.9 brass tool holder extension was bolted tightly. The resonance frequency of the horn tip is 30 kHz with about 10 µm Peak-to-Peak amplitude at the horn tip (without the polymer tool). The piezo driver was not self tuning during the µmachining process and resonance could not be adjusted while µpolishing. The 12.7 mm diameter x 3.2 mm thick test sample is made of P20 tool steel 32 HRC with 0.48 µm Ra wire EDM surface finish (2 finishing paths) with no measurable white layer thickness. A 470 µm gap was maintained between the polymer tool and workpiece. To simplify the experiments, the polymer tool was machined from acetal bar stock instead of being compression molded. The tool had a ϕ10.9 mm diameter covering part of the sample section. Abrasive slurry was changed over periodically every 2 minutes by cleaning and applying new abrasive into the gap with a syringe. The abrasive was about 20% vol. SiC 180 grit abrasive suspended in oil. The sample was left at ambient temperature with no temperature monitoring. The experimental conditions are listed in Table 2.

Table 2: Experimental conditions for test #2: micro-polishing

Ultrasonic actuator	**400 W**
Resonant frequency	≈30 kHz
Amplitude of horn tip	10 µm peak to peak
Tooling material	100% acetal
Abrasive material	≈20% SiC suspension in oil
Grain size	76 µm (180 grit size)
Temperature	ambient
Process conditions	
Average Gap width	470 µm
Static load	0 N
Machining time between abrasive refresh	2 minutes
µpolishing time	90 min
Workpiece material	P20 tool steel 32 HRC hardness
Initial surface finish	0,48 µm Ra, Wire EDM finish
Dimension	Φ12,7 mm

4 µMACHINING RESULTS AND DISCUSSION

4.1 µMachining:hammering mode

Figure 5 illustrates the P20 tool steel sample and the composite uhmwpe polymer tool which was compression molded over it. Flash lines can be seen on both sides of the tool. Those flash lines do not interfere with the process since they are located on the outer edge of the sample. After 90 minutes of µmachining operation and 5 tool remolding operations, an average 22 µm deep trench was effectively cut in the sample(see figure 7). In figure 6a, two ridges can be seen on top and bottom of picture, beyond which no µmachining was performed. In figure 6a and 6b, several sparsely spaced large indentations can be seen on the sample surface. These large indentations coincide with abrasive grains which have been embedded in the polymer tool by the hammering action. Constant hammering of the same abrasive particle at the same spot probably caused the relatively large indentations marks. In figure 6b a close up view of the ridge shows that surface finish is relatively smooth but waviness pattern have appeared.

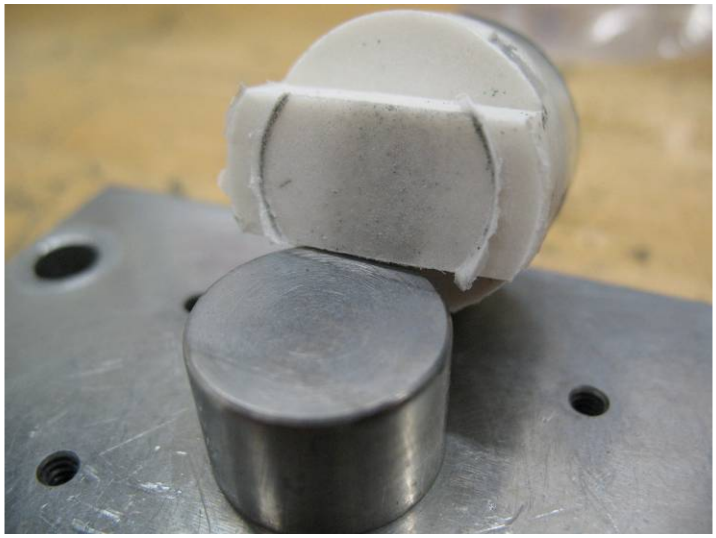

Figure 5: Polymer tool showing molding flash line and matching µmachined sample

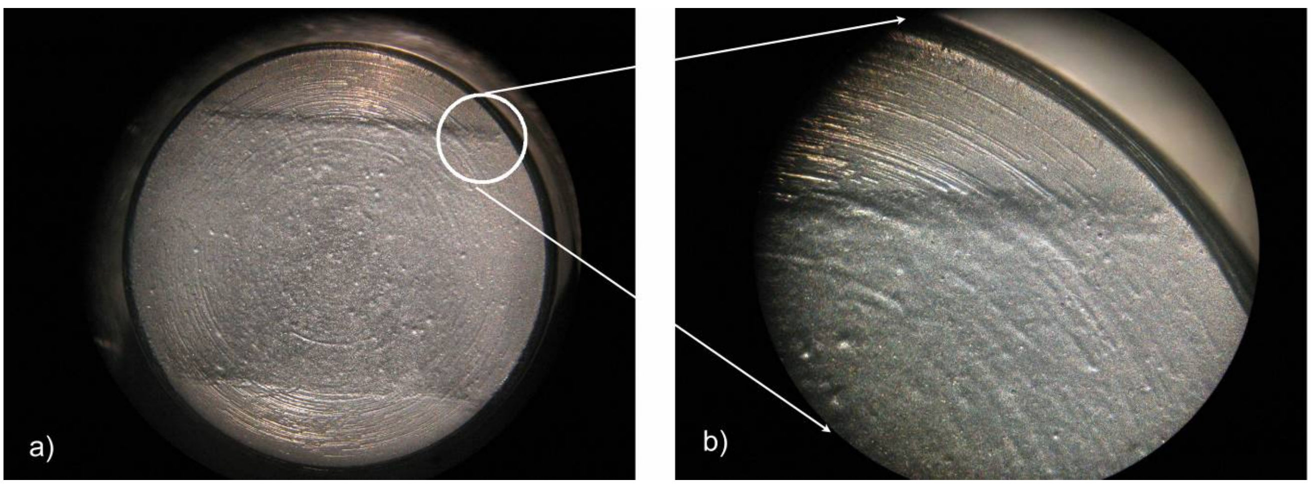

Figure 6: a) Top view of P20 steel sample after micro-machining, b) detail of the ridge region

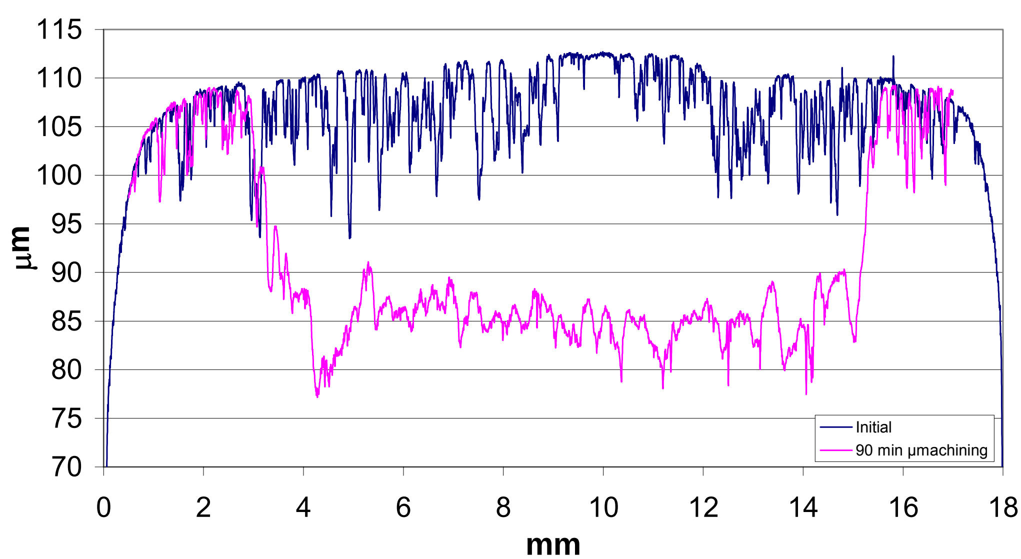

Figure 7: Mitutoyo SV2000 measurement of surface profile prior to and after µmachining

Several specific surface topologies helped determined the material removal mechanisms which probably occurred in the µmachining process, namely:

I. Indentation processing marks with plastically deformed piled up material on the side,
II. Sequence of decreasing size indentations processing marks and plastically deformed piled up material,
III. Irregular shape elongated processing marks.

Evidence of indentation marks and plastically deformed piles of material was observed on the workpiece (see figure 8a, 9a & 9b). In addition, a spectrometer analysis has even detected SiC abrasive particles embedded in the tool steel workpiece. At first glance, these observations confirm that powerfull ultrasonic energy can be transmitted through a viscoelastic polymer tool.

Besides, as stated in [16], the superposition effect of multiple indentations marks, caused by random abrasive particle impacts with different incident angle and position, is linear in time. In other words, even though each indentation deforms the workpiece material, the overall summation of multiple impacts will reduce the surface variance into a smoother surface. This phenomenon can be observed in graph of figure 7, where the variance of the surface finish, after µmachining, is lower than the surface prior to µmachining with reduced average feature height as well. In addition, as seen in figure 8a, 9a and 9b, several indentation marks can be seen but dents evidence can be hardly noticed since other material removal are probably at work.

On the other hand, since the ratio grain size to feature height (s/h) is largely over 1 at $\approx$10, µmachining becomes more effective[5]. In addition, since mobility of the abrasive particles is restrained because of a ratio grain size / tool amplitude (s/a) much larger than 1 at 12.5, the tool must regularly be lifted in order to refresh the gap with new abrasive particles[5] and maintain µmachining effectiveness. Finally, one should notice, that a groove was formed on the lower left portion of the µmachined trench (see graph figure7). Deformation of the polymer tool tip under ultrasonic and hydrostatic loads could provide an explanation for this phenomenon. As mentioned in [5], it is suggested that soft materials such as copper and brass are unsuitable as tooling material since they develop burrs at large oscillatory amplitudes. For polymer tool, burrs did not occur, however pressure gradient along the tool interface might deform periodically the polymer tool tip and create a dynamic burr. FEM analysis of the polymer matrix with ultrasonic and fluid dynamic modelling should be performed to investigate this phenomenon more in depth. Nevertheless, the undesired groove topology occurred only on one side off the trench.

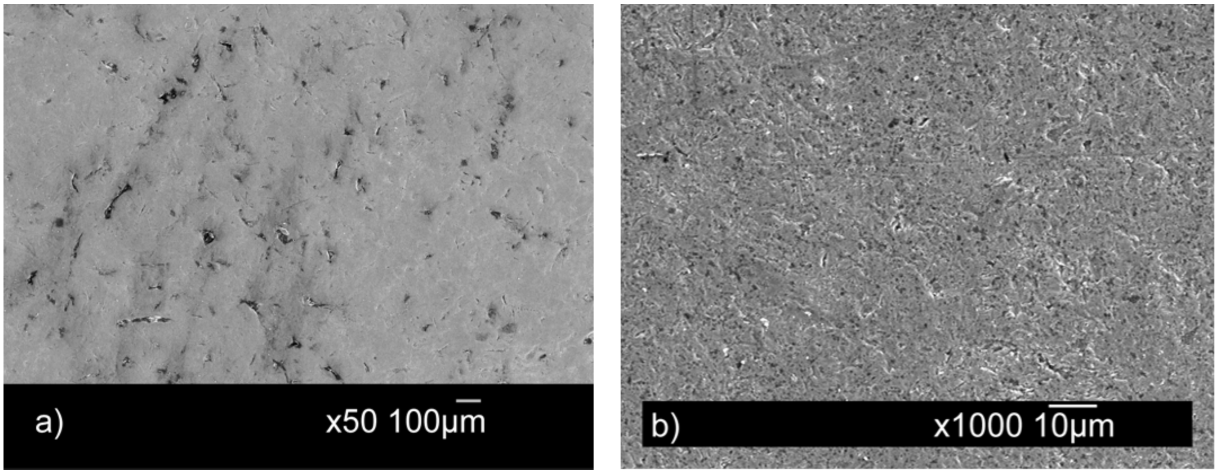

Figure 8: a) SEM picture of μmachined surface X50, b) SEM picture of μmachined surface X1000

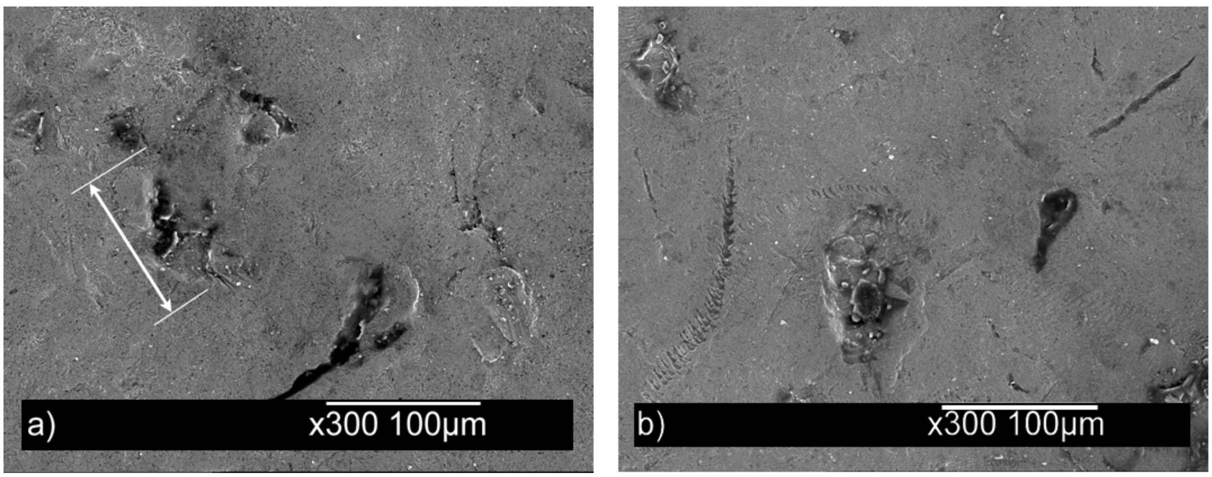

Figure 9: SEM pictures of a) X300 rolling indentations marks, b) X300 indentation and sliding marks

Signs of another material removal mode related to abrasive particle rolling action could be observed on the workpiece surface (See figure 9a). In fact, processing marks with characteristic dent topology following the simple relation[16]:

$$W_0 + W_1 \approx L \tag{7}$$

could be observed on the surface as showed by the ≈100 μm arrow which represents the width of the initial indentation W_0 plus the width of the first heap W_1 followed by a second indentation mark which are typical rolling action evidence of an abrasive particle of size L [16]. The effect of multiple abrasive rolling actions in random direction follows the same uniformity rule as for direct indentation with no angular movement where smoother surface should be obtained in relation with the superposition effect.

At last, 50μm to 200μm long sliding and micro-cuttings marks can be seen in figure 9a and 9 b. Such processing marks bear the less efficient material removal rate as compared to vertically generated indentations[25] or rolling action of abrasive particles. In figure 9a and 9b, it can be noticed that all the work hardened dents have been shaved away from the surface either by brittle fracture or shear force, leaving a levelled surface with indentations. Finally, no observation of irregular shape micron size holes typical to cavitation collapse erosion has been noted.

4.2 µPolishing: non contact mode

First, by comparing the surface topology of a µmachined surface (figure 8b) with a µpolished one (figure 12a), one can notice a much higher number of indentation marks on the µmachined surface as compared to the µpolished one. This observation leads to the interpretation that material indentation is more dominant in the hammering mode than in non-contact mode in which case parallel movement such as sliding and micro-cutting seems to be the main material removal and displacement mechanism. This latter assertion confirms that direct hammering of a particle creates more vertical force or damage to a surface than non-contact mode where a fluid medium acts on the abrasive particle instead of a more direct mechanical contact.

Besides, as the initial 0.48 µm Ra wire EDM surface (see figure 11) was µpolished, the operation was regularly stopped every 6 minutes in order to take surface finish measurements. The collected data are represented in graph of figure 10 which shows a surface finish gradually reducing from a 0.48 µm Ra surface finish down to a 0.15 µm Ra surface finish for a 3.3 reduction factor. After 90 minutes of operation, the µpolishing process was slowing its progression rate from a high 0,03 µm Ra/min down to ≈0 µm/min, at which point the surface finish was even starting to degrade in some cases.

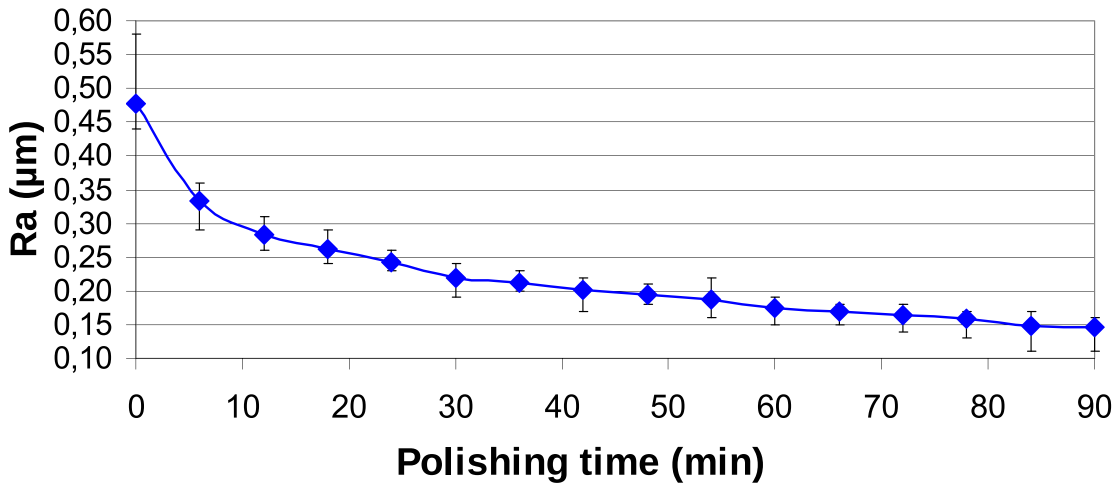

Figure 10: Graph of surface finish improvement over µpolishing time

After 90 minutes, a surface finish typical of non-contact ultrasonic machining is obtained (see figure 12a, 12b, 13a & 13b). The size of indentations and wedge-shape pits processing marks are ranging from 0.5 to 0.75 µm width by 2 to 3 µm long (see figure 12b). The wedge-shape pits have no specific directionality which means that the processing marks may have been formed by collision and by sliding of hard abrasive grains accelerated by impact force triggered by cavitation collapse on the workpiece surface [7].

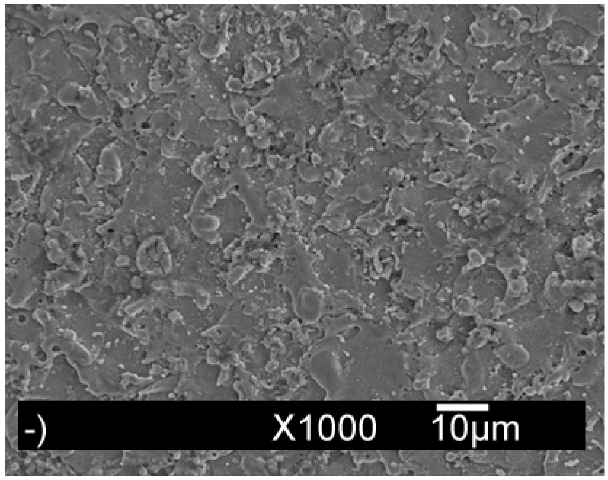

Figure 11: Initial wire EDM 0.48 μm Ra surface finish

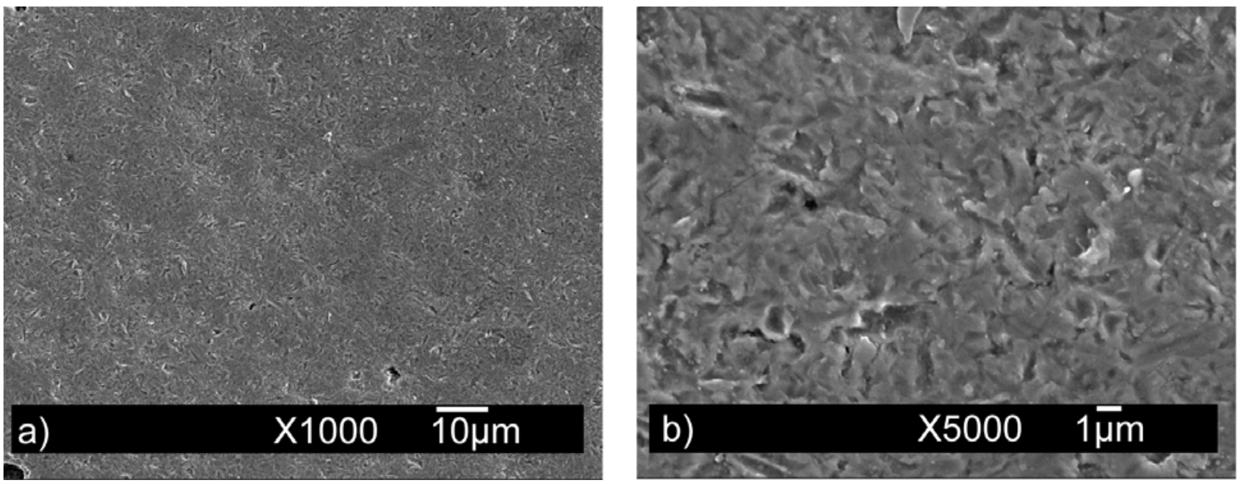

Figure 12: SEM picture of indentations and micro-scratch marks

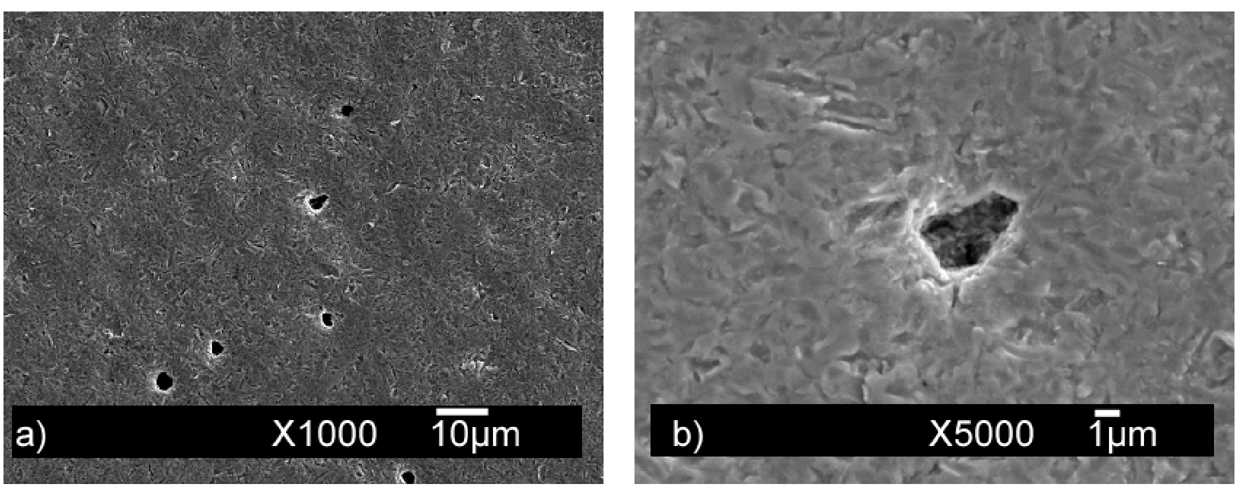

Figure 13: SEM pictures showing erosion pits cavities

In addition, other surface features were observed such as irregular 3 to 4 μm diameter pin hole sparsely spaced over the entire surface (see figure 13a & 13b). These processing marks (holes or erosion pits) are a typical consequence of cavitation erosion effect[7]. Although relatively small, such surface features are undesirable side-effect for a μpolishing process since it does not have uniform behaviour and since it would be a perfect site of stress concentration enhancing failure mode for several applications involving thermal or stress cycling.

Figure 14: Preliminary results of 3D cavities (part in backgroung was wire EDM cut, (part forfront) was µpolished with polymer tool

Finally, successful preliminary investigations were conducted on 3D surfaces in order to asses the feasibility of the UAµM process on freeform geometry. As seen in figure 14, the cylindrical mold shape was effectively polished but further research should be done to understand the various material removal mechanism involved.

5 CONCLUSION

In this paper, we have described a new µmachining process, namely the (UAµM) Ultrasonic abrasive µmachining process, involving the use of a moldable and reworkable thermoplastic tooling material. A rationalization of the use of visco-elastic polymer, such as uhmwpe or acetal, as ultrasonic machining tooling material was proposed. Two different µmachining modes were investigated, that is the hammering mode for µmachining application and non-contact ultrasonic machining mode for µpolishing application. The main results obtained in this study are summarised as follows:

1- A 22 µm uniform surface layer was removed from a P20 32HRC hardness sample. Three material removal mechanisms were observed: simple indentation enforced by perpendicular motion of the tool, abrasive particle rolling along a tangential direction, and sliding or micro-cutting mechanisms along multiple tangential directions.

2- A µpolishing operation successfully improved a wire EDM sample having a 0.48 µm Ra initial surface finish down to 0.15 µm Ra. Three main material removal mechanisms were observed: simple indentation caused by normal direction motion of abrasive particles driven by cavitation collapse forces, wedge-shape pits caused by oblique motion driven by cavitation collapse forces and sparsely spaced erosion pits caused by cavitation erosion effect.

3- Proof of concept that UAμM can be efficiently used to μmachine a tool steel surface with a thermoplastic tool.

4- Proof of concept that UAμM can be efficiently used to μpolish a tool steel surface with a thermoplastic tool.

Future work:

1- Develop understanding of viscoelastic behaviour of polymer tool and surface interface under ultrasonic and fluid dynamic constraints with respective FEM model,

2- Refine UAμM experimentation to remove waviness or long wavelength pattern on 2D and 3D geometry.

3- Refine UAμM experimentation to improve final surface finish up to mirror finish or 0,01 μm Ra on 2D and 3D geometry.

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