Fundamental study of ultrasonic polishing of mold steel

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Abstract

Ultrasonic Machining (USM) is conventionally used for machining hard and brittle materials. As polishing of steel mold has been a serious concern in the industry, an innovative cost-effective ultrasonic polishing system is developed for this purpose. The ultrasonic tool moves in a patterned path to cover the entire surface to be polished. Microcutting, plowing and indentation by abrasives are observed on the polished surface. The experiment was conducted on typical mold steel with the emphasis on the effects of the abrasive size and the static load on the surface finish. The optimal abrasive size depending on the surface roughness prior to polishing is identified. Large static loads possess an advantage in that the abrasives are more effectively activated for polishing. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Since the discovery of ultrasonic machining (USM) [1], various applications of ultrasonics have been successfully developed, such as ultrasonic welding, ultrasonic cleansing, and ultrasonic inspection. USM is among the most effective methods for machining hard and brittle materials, such as glass and ceramics. Concerning the machining of hard mold steels, the potential for USM is highly assessed in the polishing stage. Mold steels are widely used in injection molding and sheet metal forming, where polishing is a vital process in the mold manufacturing. The primary machining of a mold is mostly carried out by electrical discharge machining (EDM) and traditional metal cutting, beyond that a secondary polishing is required for mold applications. However, the molds are often polished by skillful handwork. As a result, the process is time-consuming and not well accepted concerning the reliability of the polished surface. An effective automated polishing process is desired. The purpose of this research is to provide the fundamental knowledge of a patented ultrasonic polishing process for further development of an industrial polishing system for molds.

With regard to the material removal mechanism of USM, Shaw considered direct hammering to be the major cause for material removal [2]. Rozenburg proposed that the material removal mechanisms involved in USM included three actions: (a) direct hammering of the abrasive particles on the workpiece; (b) impact of the free-moving abrasive particles on the workpiece; and (c) erosion on the work surface due to cavitations effect of the abrasive slurry [3,4]. Kremer showed that the cavitations effect played an important role in material removal in USM [5,6]. Though the mechanisms of USM have been discussed, there have been few studies on material removal in ultrasonic polishing. There were considerable references about the conventional polishing mechanism. Aghan and Samuels provided the visual evidence, which was in favor of an abrasive mechanism for polishing instead of the molecular removal concept [7]. Rabinouicz found that neither fine-scale abrasion nor melting could entirely explain polishing [8]. In this research, the mechanism of ultrasonic polishing is observed. The effect of ultrasonic polishing on the surface finish of mold steel is also investigated experimentally.

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2. Experiment method

2.1. Experimental set-up

Fig. 1 shows the ultrasonic polishing system for the present work. The system includes an USM set, a moving table, and a PC-based controller. The transducer of the machining set is used to generate the ultrasonic vibration needed. A horn is connected to the transducer to magnify the vibration. A tool made of copper is fixed at the bottom of the horn to transmit the vibration energy to the machining area. During the process, the vibrating tool energizes the abrasive slurry, such that the material of the work surface is removed by the mechanisms mentioned in Section 1. The vibration is generated at high frequency and small amplitude, which favors the polishing effect. Motions of three degrees of freedom (linear motion in two directions and a rotation at the base) are controlled simultaneously by the PC-based controller. The polishing path can be automatically generated in either a loop or zigzag manner, as shown in Fig. 2, to cover the entire surface to be polished. There is no significant difference in ultrasonic polishing between the loop and zigzag path when polishing a plane surface, while the zigzag path feeding parallel to the cylinder axis shows better effect when polishing a cylindrical surface. It can be attributed to less thinning of abrasive slurry on the surface by gravitation in use of zigzag path.

The static load of the tool applied on the surface of the mold steel is determined by the weight difference between the counterweights and the transducer and the horn. The weight of the transducer and the horn acts on one end of the lever assembly via an arm and a wheel, while several counterweights are placed on the other end of the lever assembly. By changing the counterweights, one can adjust the static load of the tool. The arrangement is shown in Fig. 3.

2.2. Experimental procedure

The dimensions of the work sample are 90 mm by 90 mm divided into four zones, each 30 mm by 30 mm, and 8 mm in thickness. It takes 9 min and 14 s to polish. The material of the specimen is SKD61 with HRC 52, which is typical mold steel for injection molding. The average surface roughness ($R_a$) of the samples after EDM before ultrasonic polishing is 3.9–4.4 µm. Abrasives of...
diamond powder, SiC, Al₂O₃, B₄C, and TiC, are used in USM. In this study, the abrasives of SiC at 40% volume concentration is mixed with dishwasher cleaner as slurry. The output frequency is automatically adjusted by the generator to match the resonant frequency of the horn and the tool, maintained at 25.6 KHz in this study. The resonant frequency varies with the shape and the material of the horn [9]. The horn is made of a steel rod of exponential shape, and the polishing tool is brazed on to it, as shown in Fig. 4. The tool is a straight cylinder of 3 mm in diameter.

To study the effect of grit size on ultrasonic polishing, five sizes of 100 mesh, 400 mesh, 800 mesh, 1500 mesh and 2000 mesh were selected for the experiment with the static load maintained at 841 KPa. The effect of static load, on the other hand, was varied from 591 to 1291 KPa with a fixed abrasive size of 400 mesh. In both cases of the experiment, the horn was inclined and maintained at 30° with respect to the normal of the surface (Fig. 5) to provide a horizontal force for polishing. The surface roughness was measured by a digital surface profile tester (Mitsutoyo 210). The capacity of the profile tester used is from 0.05–40 µm. The cut-off length of the measurement was 1.5 mm.

3. Results and discussion

3.1. Surface morphology

As mentioned above, the work samples are prepared by EDM before the experiment. Fig. 6(a) shows the micrograph of the cross section of the workpiece before polishing, and Fig. 6(b) shows the top view of the EDMed surface. The surface alteration (called white layer), craters, pockmarks, globules and cracks are found on the EDMed surface. The white layer has been known to be a re-hardened layer with microstructure change. For the majority of mold applications, the polishing is conducted on the white layer to improve the surface integrity. A cross-section micrograph of the workpiece after the proposed ultrasonic polishing is shown in Fig. 7. The rough and uneven surface produced by EDM is significantly improved by ultrasonic polishing. The average thickness of the white layer is about 20 µm in the current study. Although the white layer is unable to be removed in most cases, the remaining hardened surface can be advantageous during service of a steel mold.

Two major events are observed on the processed surface. The first is the microcutting done by grits on the work surface and the associated plowed ridge along the microcut. The second is the plastic deformation caused by indentation of grits on surface. Based on the fact that the amplitude of the horizontal vibration of the tool parallel to surface is 35 µm and the abrasive particles are activated by the tool, numerous abrasive cutting traces of 10–30 µm in length in all directions are observed on polished surface, as seen in Fig. 8. This is considered the major mechanism of ultrasonic polishing, with which the finish is achieved by the numerous isotropic microscopic cuts on surface. While the ultrasonic kinematic energy is transmitted from the polishing tool to the numerous abrasives in slurry, the suspended small abrasives (tens of microns in diameter) naturally collide with each other and move in various directions in the slurry. They leave the traces of micro-cutting in an isotropic manner on the surface. Each trace shows large length-to-width ratio. The length is about 10 to 30 µm produced by the amplitude of tool vibration. The width is less than a few microns determined by the small indentation of abrasives on the surface, which is produced by the tool pressure shared among numerous abrasive particles. The polishing is achieved by these numerous repetitive microcuts occur at very high frequency via a great deal of abrasives. Indentation marks reflecting the size and shape of abrasive particles are also observed (Fig. 9). It indicates that in some cases the work surface layer is locally plastically deformed by individual abrasive particles, like the aerolites hit on earth. Furthermore, some abrasive particles are even found trapped at the end of stroke of the tool vibration, as shown in Fig. 10. The spectrometer analysis shows that the trapped fractured piece in Fig. 10 is rich in silicon, which implies it is the abrasive particle of silicon carbide. The irregular indentation mark can worsen the surface finish obtained by microcutting. Fig. 11(a) shows the magnified view of an abrasive particle and the chip material. Fig. 11(b) indicates that the major element of the chip is Fe. This figure
Fig. 5. Ultrasonic polishing showing 30° inclination with respect to the vertical direction.

Fig. 6. Micrograph of EDMed workpiece before polishing: (a) cross-section view (b) top view.

Fig. 7. Micrograph workpiece cross-section after ultrasonic polishing.

Fig. 8. Numerous abrasive cutting traces on workpiece surface.
implies that chip removal by microcutting is indeed involved in the polishing process. Since the work surface layer is hard and brittle, the chip size of 1–5 µm, as shown in Fig. 11(a), is considered reasonable with the grit size of 37 µm in average (400 mesh). Note that the micrograph is taken after cleansing the slurry by pure water for several times with precipitation, while the slurry collected after polishing is kept away from any possible contamination. Therefore nothing else but the abrasive particles and the chips are left on the specimen after the cleansing. One can reason that smaller abrasive particles provide more frequent and uniform plowing and microcutting at the same volume concentration of slurry, while the polishing rate is slower. It is conceivable that both plowing and microcutting take place in a smaller scale than in use of the large abrasives, thus a longer time for polishing is needed. When the static load is increased, on the other hand, the pressure exerted on the work surface by the abrasives through the vibrating tool also increases. Higher degree of local stress, deformation and material removal rate are expected.

3.2. Effect of grit size on surface finish

Fig. 12 shows the surface roughness cannot be improved when the large 100 mesh abrasive grits are
used. The measurement shows that the surface becomes even rougher after ultrasonic polishing. Similar results are obtained after being polished for more passes. The reason is as follows. The vertical (perpendicular to surface) magnitude of the tool vibration is identified around 60 µm. The average size of the 100 mesh abrasive particle is around 149 µm. Under this situation, the abrasive particles have little chance entering the opening between the tool and the work surface during ultrasonic polishing. The fact remains true even the additional tolerance is considered, namely the peak-to-valley feature height of surface profile. This additional space is approximately 20 µm (4-6 times of $R_a$) in average, which does not yet allow the 149 µm grits to enter the working gap between tool and specimen.

Fig. 12 also shows more passes of polishing are conducted in use of other grit size. The average surface roughness is measured after each polishing process. The grit size of 800 mesh and above shows similar results, while different behavior is found when 400 mesh grit is used. The result actually indicates a strong relationship between the surface roughness and the vibration amplitude of the tool ($a$), the average grit size ($s$) and the surface feature height ($h$) prior to polishing. The average dimension of the 400 mesh abrasive particles is around 37 µm, and the gap between the tool and the work surface is 60–80 µm. Therefore the abrasive particles are able to enter into the gap to be activated by the tool for ultrasonic polishing. When the grit is changed to even smaller, e.g. 8 µm for 2000 mesh, it becomes much easier for these particles to enter into the polishing zone. As the figure shows, 400 mesh appears to be better for the first several passes of polishing, but might not keep the effectiveness after the fifth pass. On the other hand, for grits of smaller sizes (mesh 800, 1500 and 2000), the effect of polishing is not as effective as the first four passes, but the same level of finish is reached after the fifth polishing pass. These facts tell that the ratio $s/a$ should be less than 1.

An additional fact must be examined here. Since the feature height of the work surface is around 20 µm, considerable amount of abrasive particles will be idle in the valley and not participate the polishing process. When the feature height becomes smaller by polishing, i.e. $s/h$ changes from less than 1 to larger than 1, the polishing becomes more effective. The above discussion suggests that the grit size used for polishing should be chosen according to the vibration amplitude of the tool as well as the surface roughness of the work surface prior to polishing. There should be an optimal size of grit for effective polishing.

Fig. 13 illustrates the optimal grit size for effective ultrasonic polishing. The improvement of surface finish ($\eta$) is defined by

$$\eta = \frac{h_1 - h_2}{h_1}$$

where $h_1$ is the maximum surface roughness ($R_{max}$) before polishing pass, $h_2$ is $R_{max}$ after polishing pass. $s/h_1$ describes the use of grit size. The experimental results show when the grit size is selected approximately three times of the feature height of the surface prior to polishing, the surface finish improvement is maximized. When the grit size is smaller or comparable to the surface feature height, the abrasives are often not active. Beyond the optimal ratio, the large grit removes material by cutting in rough manner; fine surface finish is thus less accomplishable. In summary, the mesh number of abrasives should be continuously updated to larger one as the polished surface becomes finer and finer.

### 3.3. Effect of static load on surface finish

The effect of static load on the surface roughness is shown in Fig. 14. Smoother surface is obtained when larger static load is applied. Large static load can confine the abrasives in the polishing gap for more effective kinetic activation. Within the range of tested static load, an approximately linear relationship between the static load and surface roughness is found. However, higher static load also causes faster tool wear. A trade off should be made between the targeted polishing performance and tool wear.
4. Conclusion

Based on the above experimental results, the following remarks can be drawn:

1. A cost-effective PC-based ultrasonic polishing system has been successfully applied to improve the surface finish of mold steel after EDM. The moving tool can cover the entire surface to be polished.

2. The size of abrasive particles should be properly selected according to the vertical vibration magnitude of the tool and the surface roughness prior to ultrasonic polishing. The polishing abrasive should be: (a) smaller than the vibration amplitude of tool; and (b) three to four times larger than the maximum surface roughness of workpiece.

3. For a specific size of abrasive particle, there is a limit of the accomplishable surface finish. Multiple polishing passes improve the surface roughness until the limit is reached.

4. There is a linear relation between the acquired surface finish and the static load. The larger the static load is, the smoother the surface will be produced.

Thanks to the automated tool path generation and tool motion, the surface can be effectively covered for polishing. The dependence on hand polishing is significantly reduced, particularly when polishing large-area simple-shape mold surface. The mold surface can also be divided into several zones of different shape complexity and polished by individual automatic schemes for minimum cycle time.

References