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Improving the Surface Quality using Combined Ultrasonic Vibration and Magnetic Abrasive Finishing Method

In this paper, a new non-contact ultrasonic abrasive finishing mechanism is designed and fabricated. This mechanism combines the function of ultrasonic vibrations and the magnetic abrasive finishing (MAF) process. A permanent magnet which is mounted on a horn has been used as the processing tool. This polishing tool is vibrated at an ultrasonic frequency with piezo-electric actuators. Ultrasonic energy and the relative motion between magnet and the workpiece are the stimulus of the steel grit abrasives for improving the surface quality. In order to take advantage of the cavitation collapse pressure, the components is immersed in water. The present work also studies the effect of parameters, i.e., finishing time and working gap on the surface roughness (Ra).

Keywords: magnetic abrasive finishing, ultrasonic vibration, cavitation collapse, surface quality

1 Introduction

The rapid development of modern industries has increased the importance of geometrical precision and part surface quality. Hence, numerous finishing techniques have been applied for finishing specimens to obtain parts with high quality. Traditional methods involving a single process cannot meet the current demands for both high quality and accuracy simultaneously. In order to satisfy the present demands in the advanced industries, a combination of machining and finishing process may be presented.

Requirements of high surface finish, accuracy, and minimal surface defects, such as micro-cracks have necessitated the development of an alternate finishing technology, namely,

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magnetic abrasive finishing [1]. In the MAF process, the material is removed from the surface of workpiece, by the circulation of the abrasive particles in the magnetic field. The working

gap between workpiece and magnet is filled with mixture of ferromagnetic particles and abrasive powder popularly known as magnetic abrasive particles (MAPs). These particles form a flexible magnetic abrasive brush (FMAB) which does not require dressing. MAPs are either bonded (fabricated by compacting and sintering of the mixture) or unbounded (mechanical mixture of ferromagnetic and abrasive particles). In this process the workpiece surface is smoothened by removing the material in the form of microchips by abrasive particles [2, 3].

One of the ‘non-traditional’ machining techniques is ultrasonic machining which is part of a family of relatively modern material finishing and shaping processes described as ‘chipless machining’. Using this technique controlled material removal can be achieved. In this process, the workpiece material is removed by the high frequency hammering of abrasive particles, in the form of water based slurry, into the workpiece surface. These processes do not use cutting tools and do not create residual stresses in the workpiece. Ultrasonic machining is often used in combination with other chipless machining techniques, such as electro discharge machining, in the manufacture of precision components. As the name implies, the process operates at ultrasonic frequencies and typical frequencies used in the ultrasonic machining process range between 20 and 40 kHz [4, 5].

In recent years, many studies have focused on ultrasonically assisted polishing. For example, Suzuki et al. [6] studied ultrasonic, two-axis, vibration-assisted polishing with five-axis, piezoelectric actuators developed in order to finish molds used to fabricate lenses with high numerical aperture. Kobayashi et al. [7] introduced an ultrasonically assisted polishing technique for silicon wafer edge treatment and developed a corresponding experimental apparatus with an ultrasonic, elliptic vibration pad holder. The surface roughness of wafer edges polished by the presented method improved by over 31.7% relative to a wafer without ultrasonically assisted polishing [6]. Manas et al. reported the experimental findings about the improvement in out-of-roundness (OOR) of stainless steel tubes finished by Rotational–Magnetorheological abrasive flow finishing (R-MRAFF) process. In this process, a rotating motion is provided to the magnetorheological polishing (MRP) medium by means of a rotating magnetic field, and simultaneously, a reciprocating motion is provided to the polishing medium by a hydraulic unit. By controlling these two motions, nano level uniform smooth mirror like finished surface has been achieved and simultaneously OOR of internal surface of tube is reduced. Experiments are planned according to the central composite rotatable design of response surface methodology based on the selected range of process parameters obtained from the preliminary experiments. In this article, analysis of variance (ANOVA) is conducted and contribution of each model term affecting OOR improvement is calculated. It has been found that R-MRAFF process potentially reduces roundness error of axisymmetric parts (maximum improvement in OOR = 2.04_m) improving their reliability and wear resistance. This study shows that, OOR improves with an increase in the rotational speed of the magnet up to an optimum value beyond which the improvement in OOR reduces. From the scanning electron micrographs and atomic force micrographs it has been found that the abrasive cutting marks in R-MRAFF process generate cross-hatch pattern which helps in oil retention in cylindrical workpieces to reduce friction [8].

In the present research, in order to enhance finishing performance such as improving surface roughness and reducing finishing time, a new micro finishing process is proposed. This technique is combination of the processes of magnetic abrasive finishing and ultrasonic vibration. In this case, the abrasive grains could be energized ultrasonically and magnetically. These abrasive particles act as cutting tools and produce a process capable of finishing and polishing surfaces. In this study the novelty arises from the use of magnetic tool which is immersed in water and vibrate ultrasonically in the presence of ferromagnetic abrasive powders. The whole experiments indicate the success of the method for polishing the inner surface of cylindrical specimens.

2 Principle of material removal

2.1 Ultrasonic machining

Ultrasonic machining is an ideal manufacturing process for shaping hard and brittle materials irrespective of their electrical conductivity. The material removal rate obtained by this process is often acceptable for super-hard and brittle materials. Though the process is commercially used for many years, the details of the material removal mechanism is yet to be fully understood. Application of loose abrasive particles in machining makes this process a stochastic one [9]. However, the earlier works done to understand the process parameters, have thrown light on the possible mechanism of material removal in ultrasonic machining.

The ultrasonic machining process begins with the conversion of low frequency electrical energy to a high-frequency electrical signal, which is then fed to a transducer [10]. The transducer converts high-frequency electrical energy into mechanical vibrations, which are then transmitted through an energy-focusing device, i.e. horn [11]. This causes the tool to vibrate along its longitudinal axis at high frequency. The benefits of ultrasonic machining method include considerably increased material removal rate, decreased cutting force, reduced tool wear, and improved surface finish [12].

Rozenburg et al. [9] 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 cavitation effect of the abrasive slurry. Ichida et al. [13] showed that the cavitation effect played an important role in material removal in ultrasonic machining process (see "Figure 1").

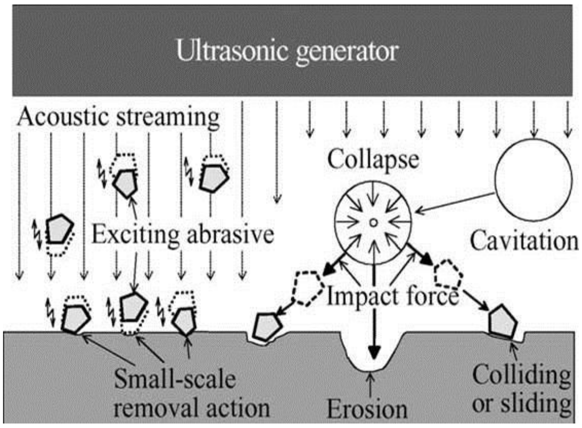

Figure 1 Schematic illustration of the modes of material removal in noncontact ultrasonic abrasive machining [13]

2.2 Magnetic abrasive finishing

Magnetic abrasive finishing (MAF) process has been recently developed for efficient and precision finishing of cylindrical and flat surfaces. MAF is a fine finishing technique which can be employed to produce optical, mechanical, and electronic components with micrometer or submicrometer form accuracy and surface roughness within nanometer range with hardly any surface defects [14]. Finishing of bearings, precision automotive components, shafts, and artificial hip joints made of oxide ceramic and cobalt alloy are some of the products for which this process can be applied. Figure (2) shows a diagram of the abrasive behavior during the magnetic abrasive finishing process using a pole rotation system for a nonferromagnetic workpiece. In this process, magnetic abrasives introduced into the workpiece are attracted by the magnetic field. The magnetic poles N and S are positioned side by side and the grains of magnetic abrasive particles then tend to get attracted towards the magnetic poles. The rotation of magnetic poles causes the grains to move outward under the action of centrifugal forces (see "Figure 2"), and with linear feed motion of the workpiece the peaks (high points) of the surface topography are removed [15].

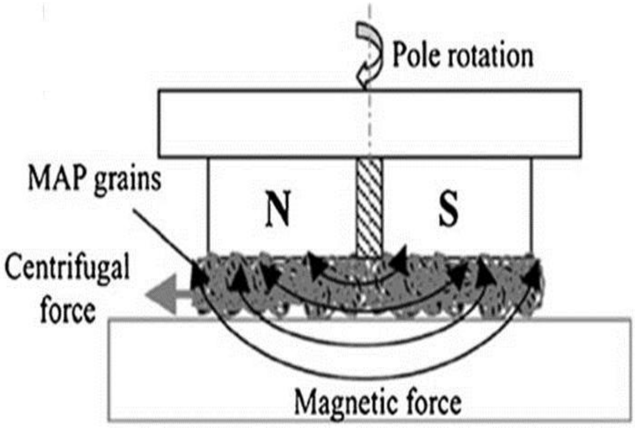

Figure 2 Mechanics of material removal in MAF on flat surfaces [15]

Figure (3) shows a two-dimensional (2-D) schematic of the abrasive behavior during the internal magnetic abrasive finishing process using a pole rotation system for a nonferromagnetic workpiece. In the process, magnetic abrasives introduced into the workpiece are attracted by the magnetic field and bear on the inner surface of the workpiece. The rotation of the poles, which consist of small permanent magnets, around the workpiece causes the rotation of the magnetic field at the finishing area [16].

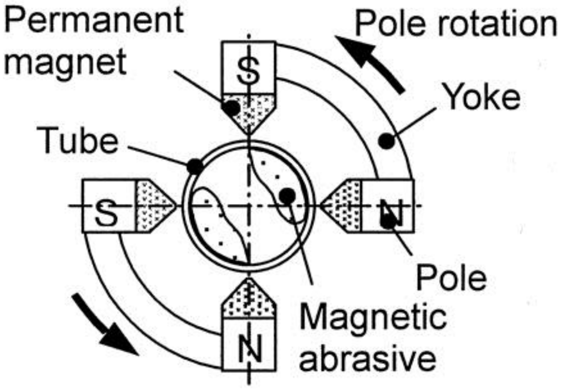

Figure 3 Two-dimensional schematic of abrasive behavior during the process [16]

The abrasive behavior is primarily determined by the relative strengths of two opposing forces: the magnetic force and the friction force acting on the abrasive against the inner surface of the tube. When the magnetic force is greater than the friction force, the abrasive follows the magnetic field. This generates relative motion of the abrasive against the surface, removing material from the workpiece. The applied force on the abrasive is the predominant component of finishing force, which is the result of the magnetic and centrifugal forces experienced by the rotating magnetic abrasive [15]. The mechanism of finishing in MAF process, either for cylindrical specimens or for plates is micro-cutting and scratching [17, 18].

3 Experimental setup

Based on abrasion behavior of the abrasive in a combination with ultrasonic vibration, a finishing experimental device was designed and fabricated. The experimental apparatus for the non-contact ultrasonic abrasive machining used in this research is shown in Figure (4) and Figure (5). The entire setup is mounted on the table of lathe machine. The rare earth permanent magnet is fixed on the horn and the components are immersed in water. The magnet tool moves inward the cylindrical workpiece while it is surrounded by steel grits as abrasives. In this process the workpiece is not in direct contact with the magnets. Magnetic poles form a flexible brush of magnetic abrasive particles. In addition to the rotational motion of the flexible magnetic abrasive brush, ultrasonic vibrations induce the abrasives. Ultrasonic vibration of magnet and rotational movement of workpiece are the stimulus of this process for improving the surface quality.

The finishing setup consists of an ultrasonic vibration generator unit and a specially designed magnetic tool. The ultrasonic vibration generator unit consists of a power supply, piezoelectric transducer, and concentrator or horn. The ultrasonic power supply generates high-frequency electrical signals, which are supplied to the piezoelectric crystals within the transducer.

The high-frequency electrical signals of 20KHz are converted to mechanical vibrations by the transducer. The amplitude achievable from the transducer does not exceed 3 to 5µm. Hence, the amplitude is amplified by the concentrator or horn and then transmitted to the magnets, which is connected to the horn. The small longitudinal movement may promote the relative motion of abrasives against the peaks of the workpiece surface needed for the finishing operation in addition to rotary motion of the specimen. The amplitude of the ultrasonic vibration can be adjusted by changing the input power to the transducer through the power supply.

The cutting edges of the abrasives may scratch the workpiece material in many directions in the intermittent cutting mode. Hence, the small longitudinal movement of the magnetic tool is important to obtain the effect of ultrasonic vibrations in ultrasonic-assisted magnetic abrasive finishing to improve the workpiece surface effectively. In this case, a special magnetic tool is needed so that the magnets can be excited using ultrasonic vibrations.

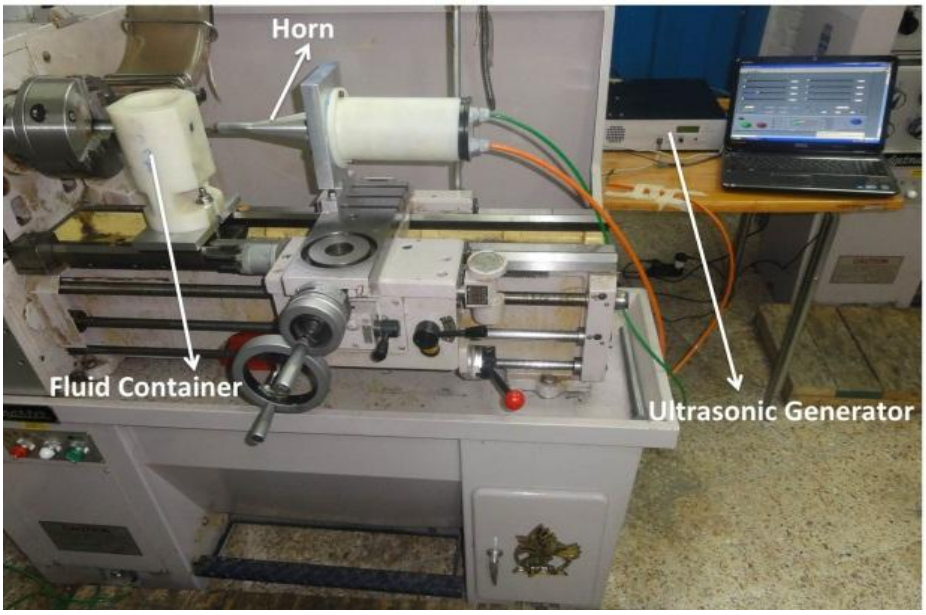

Figure 4 External view of experimental setup

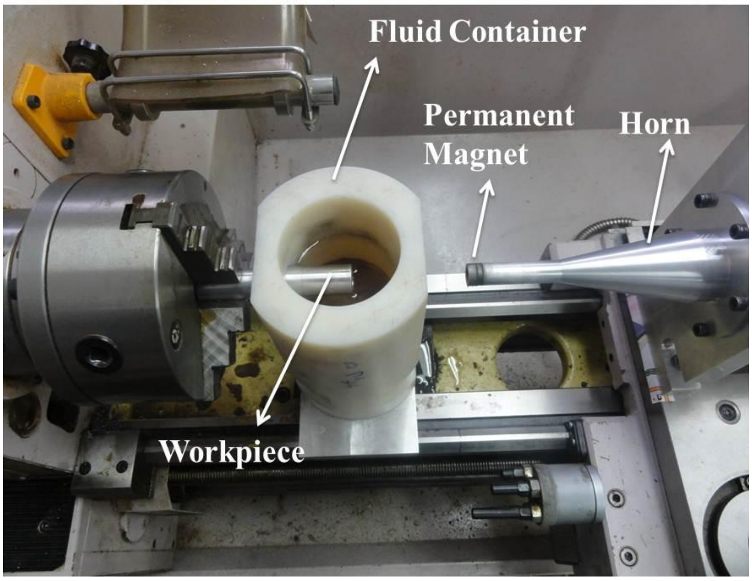

Figure 5 External view of finishing components

3.1 Finite element analysis

Finite element analysis has been used to design horn suitable for oscillating the magnet tool with piezo-ceramics, as well as to locate the vibrating node for fastening the horn to the lathe machine. In this case the finite element software has been used for the three-dimensional modeling of the horn and the embedded tool (see "Figure 6"). Based on this analysis the horn, made of 7075 aluminum alloy, was fabricated and attached to an ultrasonic generator. The resonance frequency of the horn is 19 kHz. In polishing with magnetic powder, head of the horn is connected to the vibrating transducer with the help of ultrasonic waves, while its end is in contact magnets. Therefore, there are no boundary conditions or fixing force at the head and end of the horn. The only place where clamping force is applied is the node point in which clamping has no effect on the intended result of the finite element, due to the lack of vibration. Therefore, boundary conditions are considered to be free-free.

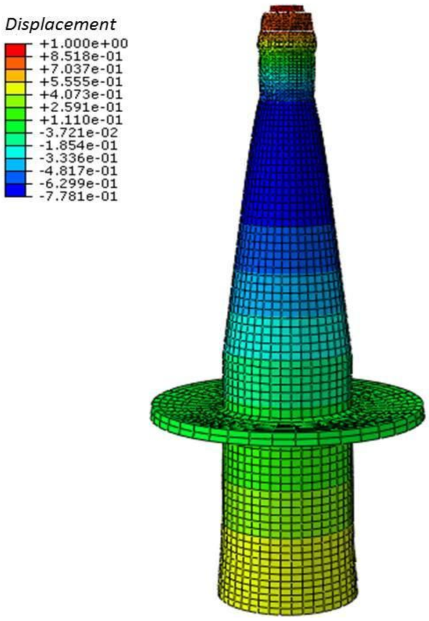

Figure 6 Three-dimensional modeling of the horn and the embedded tool

3.2 Workpiece material

In recent years, aluminum alloys have attracted attention of engineers, researchers and designers due to their growing range of usage in the automotive industries and aerospace applications. Particularly, 6xxx aluminum alloys that have advantages such as corrosion resistance, medium strength and low cost, comparing to other aluminum alloys. The material used in this study was 6062 aluminum alloy.

4 Results and Discussion

In order to identify the capability of the proposed method and study the effective parameters, some experiments have been conducted. Figure (7) shows the relationship between the magnetic abrasive finishing processing time and the surface roughness (Ra). It is clear that adding ultrasonic source causes better quality of surface. It is shown that by using the ultrasonic vibration the surface roughness of 0.16 micrometers has been obtained, while the surface roughness does not become better than 0.92 micrometers without using this vibration. It is indicated in Figure (7) that the slope of improvement slows by passing time. The reason that the roughness did not improve after about 8 minutes is the large size of the abrasives which can not produce better surface roughness.

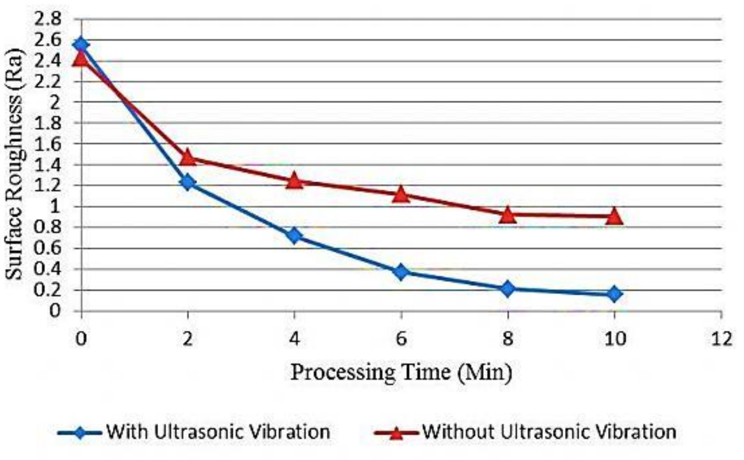

Figure 7 Variations of surface roughness vs. processing time
(working gap: 0.7 mm, abrasive mesh size: 120)

Figure (8) shows the relationship between the working gap (air gap between the magnet pole and the inner surface of the workpiece) and the surface roughness. This relationship is attributed to the fact that there is an optimum gap in order to have the best surface quality in this method. Decreasing the gap consumedly causes the surface to be plowed by the abrasives and it makes the surface rough. On the other hand by increasing the working gap the force of abrasives which is applied on the surface decrease so the abrasives lose their effect.

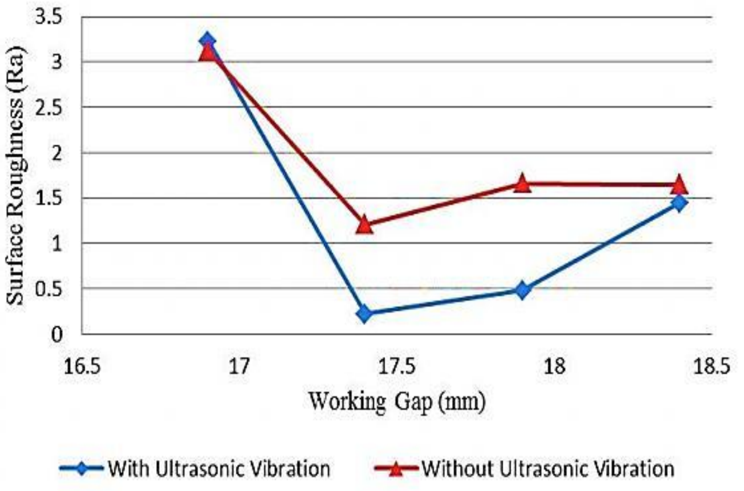

Figure 8 Variations of surface roughness vs. working gap
(Finishing time: 10 Min, abrasive mesh size: 120)

Using the Hommel Werk Turbo Wave V7.2 roughness tester, the surface roughness profiles was obtained (see "Figure 9"). It can be seen that after finishing using combination of ultrasonic vibration and magnetic abrasive finishing method the average height of peaks-to-valleys has been reduced.

Figure (9a) shows peaks and valleys for the ground surface which range from −3 to +6.4µm. These peaks and valleys are finished to less than 0.2µm valley height, giving surface roughness of 0.16 µm as shown in Figure (9b). There is a significant reduction in surface roughness value within 10 minutes using non-contact ultrasonic magnetic abrasive finishing for the 6062 aluminum alloy specimen.

Along with the rotational motion of the flexible magnetic abrasive brush, the abrasive particles in the flexible magnetic abrasive brush make impacts on the machined surface at different places under the influence of ultrasonic vibrations. Fine scratches produced by the relative motion of abrasives against the workpiece surface appear on the surface finished by ultrasonic-assisted magnetic abrasive finishing. The cutting process is discontinuous or intermittent in the ultrasonic-assisted magnetic abrasive finishing due to ultrasonic vibrations. Although the cutting torque in ultrasonic-assisted magnetic abrasive finishing is variable compared to magnetic abrasive finishing and it does not damage the surface of the workpiece. Rather, increased torque helps in cutting the peaks of the workpiece surface more effectively to give a surface of better quality in terms of surface finish. Surface profiles obtained during grinding appear to be sheared off and the new surface profiles containing fine scratch marks were produced during the ultrasonic-assisted magnetic abrasive finishing process. These fine scratches are due to high energy impacts of abrasives on the workpiece surface striking in various directions under the influence of ultrasonic vibrations.

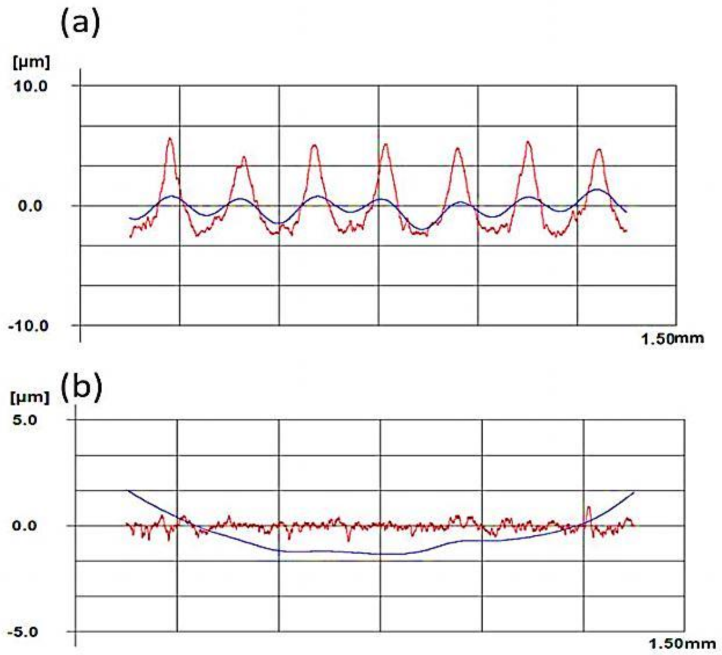

Figure 9 Surface roughness profiles: (a) before finishing, (b) after finishing using combination of ultrasonic vibration and magnetic abrasive finishing process

The surface morphologies of specimens before and after treating are displayed in Figure (9) .These microscopic pictures demonstrate the effect of finishing by the proposed method on the surfaces. Figure (9) and Figure (10) display the elimination of machining marks and pits after the finishing process using ultrasonic vibration.

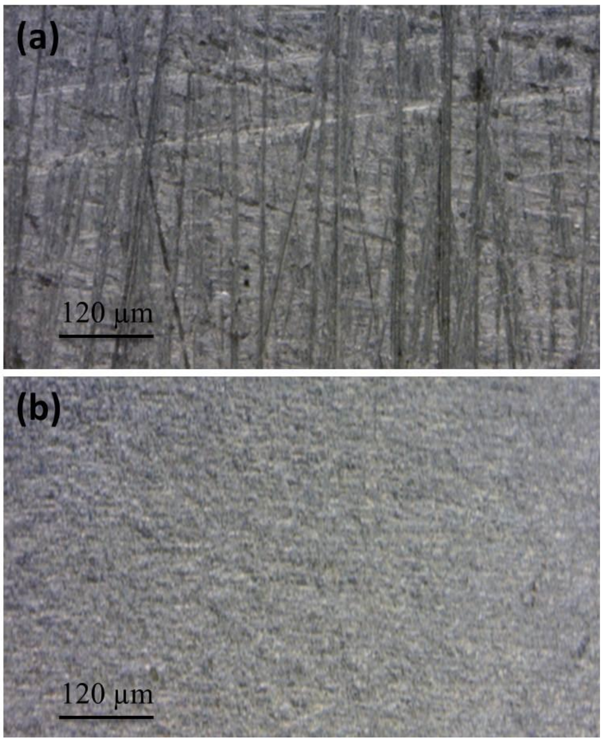

Figure 10 Surface morphologies: (a) before finishing, (b) after finishing using combination of ultrasonic vibration and magnetic abrasive finishing process

5 Conclusions

In this paper a new method of finishing, using combination of ultrasonic vibration and magnetic abrasive finishing process is proposed. The main results obtained in this study are summarized as follows:

1) Using ultrasonic energy in the magnetic abrasive finishing method has significant effect on improving the surface qualities of specimens.

2) The best quality of surface occurs after 10 minutes ultrasonic assisted magnetic abrasive finishing, in which the surface roughness reduced from its initial value, 2.545 µm Ra, to the final value of 0.16 µm Ra. Without using the ultrasonic vibration the surface roughness does not become better than 0.92 µm Ra.

3) By increasing the finishing time, the surface microchipping increases and it improves the surface roughness by removing the recast layer. However, increscent chips which are removed from the surface mix with abrasive particles and reduce their efficiency. So passing time would not have its primary effect on surface improvement and the size of abrasive powders has determinative effect on the final surface roughness.

4) Decreasing the gap consumedly causes the surface to be plowed by the abrasives and it makes the surface rough, although increasing the gap more than enough decreases the pressure force which is applied on the surface. Hence there is an optimum working gap in this method of finishing for obtaining the best surface roughness.

5) Microscopic photos and the surface roughness profiles confirmed the improvement of surface quality using combination of ultrasonic vibration and magnetic abrasive finishing process.

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چکیده

در این پژوهش یک مکانیزم نوین پرداخت به کمک امواج آلتراسونیک طراحی و ساخته شده است. این مکانیزم ارتعاشات آلتراسونیک را با روش پرداختکاری سایشی به کمک میدان مغناطیسی تلفیق نموده‌است. یک آهنربای دائم که بر روی هورن آلومینیومی نصب شده است نقش ابزار را ایفا می‌کند. این ابزار پرداخت به کمک نوسانگرهای پیزوالکتریک با ارتعاش آلتراسونیک شروع به نوسان می‌کند. انرژی آلتراسونیک و حرکت نسبی ابزار و قطعه‌کار محرک‌های ذرات ساینده فولادی برای بهبود کیفیت سطح هستند. به منظور بهره‌گیری از اثرات کاویتاسیون عمل پرداخت به صورت غوطه‌ور در آب انجام می‌شود.

همچنین در این پژوهش اثرات زمان پرداخت و فاصله هوایی ابزار و قطعه‌کار مورد مطالعه قرار گرفته است.