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Development of a Ultrasonic System for Nano-Surface Reformation Process

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ABSTRACT

In this article, a 20 kHz Titanium (Ti) ultrasonic waveguide system for a nano-surface reformation process was designed and fabricated. First, finite element analysis using ANSYS software was performed to find the optimal dimensions. The obtained anti-resonance frequency for the Ti transducer with the piezoelectric device was 20.0 kHz, which value agreed well with the experiment result of 20.1 kHz (0.5% error). To test the system, chromium molybdenum steel (SCM) 435 was chosen as a test-piece. The result proved that the reformed depth was 36 µm. In addition, hardness was measured before and after the process. The value was changed from 14 HRC to 21 HRC, which is 50% increasing rate. Finally, the friction coefficient test result showed that the surface coefficient was reduced from 0.14 to 0.10 (28.6% reduction). Based on the results, the Ti ultrasonic equipment is regarded as a useful device for nano-scale surface reformation.

1. Introduction

Surface treatment technologies have been adapted for enhancing metal surface characteristics. Traditionally, well-known technologies have been roughly categorized according to the reformation processes, such as heat treatment and physical force quenching. Heat treatments are processed by heating the metal to a high temperature and cooling with water. The metal surface then becomes denser, subsequently improving the hardness of the metal. In the physical process, a structure is changed by the given forces or pressures, such as forging. This process involves beating the metal and forming the desired shape. Another method is shot peening, which mainly involves beating the surface with round metallic or ceramic particles using physical force. Subsequently, the surface is hardened and durability is enhanced.

Ultrasound is widely used in industrial areas and scientific researches. Research was conducted to apply the ultrasonic energy in welding[1], bonding process for micro systems[2], and hole machining[3]. Regarding the surface treatment process, in contrast to traditional methods, the ultrasonic surface reformation process uses rapid ultrasonic impact up to 20,000 times per a second[4,5]. This is a direct impact method which differs from the tapping method of shot peening. The energy efficiency is therefore better than that for the shot peening, and the ultrasonic surface reformation process is thus being actively researched.

However, previous research mainly deals with experiments on surface reformation[4-7], burnishing[8-10], and polishing[11,12] using a previously fabricated ultrasonic waveguide. Therefore, the research topic is limited to explorations of the ultrasonic process conditions for the improvement of mechanical

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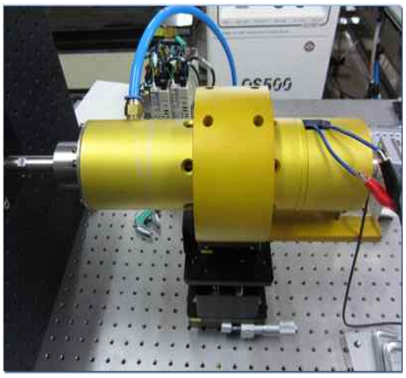
characteristics. Ali Zahedi et al. developed ultrasonic device, but the application was for grinding processes[13]. While we have previously presented several papers regarding the development of ultrasonic waveguides for cleaning applications[14,15], in this research an ultrasonic waveguide for surface reformation was designed and fabricated.

Finite element analysis using ANSYS software was performed to design the waveguide. Modeling and analysis processes using finite element method (FEM) are explained. The predicted anti-resonance frequency for a 20 kHz piezo-electric actuator was assessed with the experimental result. After manufacturing the system, chromium molybdenum steel (SCM) 435 specimens were tested for the system assessment. In addition, hardness tests were performed and the hardnesses before the process were compared. Finally, the friction coefficient was measured. The ability of the developed Titanium (Ti) ultrasonic machining equipment was then appropriately discussed.

(a) Fabricated ultrasonic system



(b) Installed picture for experiments

Fig. 1 Ultrasonic system for nano-surface reformation

2. Design of an Ultrasonic Waveguide

2.1 Working Principle

The ultrasonic waveguide consisted of a lead zirconate titanate (PZT) actuator, a Ti waveguide, and a tail mass. The fabricated ultrasonic waveguide operated simultaneously at an operating power of 20 kHz is shown in Fig. 1(a) (The waveguide 1 and 2). We selected 20 kHz as the operating frequency due to high displacement at the tip (as frequency increases, displacement decreases in reverse). Inside the cover, four PZT actuators are attached to the top of the Ti waveguide. The role of the waveguide is to magnify and transfer displacements from the actuators to a substrate surface. The resonance frequency for the PZT actuators is 20 kHz. The PZT actuator has a ring type structure. The four PZTs are placed layer by layer and are fastened to the top of the waveguide with their centers aligned, and they were connected mechanically in series, and electrically in parallel.

For electrical power supply, the megasonic waveguide needs an electric generator connected through an electric wire. The manufactured electric generator is shown in Fig. 1(b). In the front panel, a main power switch appears on the left side, which can turn the system on and off. On the right side of the front panel, a power control part is provided, which can regulate power levels. The input power of the electric generator is 220 V and the generator can transmit power with tuned frequencies for 20 kHz PZT actuators.

For the operation of the surface treatment process, the Ti ultrasonic waveguide is placed on a 3-axis servo stage. At the left side of the stage, the metal plate that needs to be processed is firmly installed. The ultrasonic waveguide moves precisely with 5 μm resolutions. The end of the waveguide is pressed by an air-compressor at 5 psi. When starting the process, ultrasonic power is supplied by the electric generator.

2.2 Finite Element Analysis

For the design of the ultrasonic megasonic waveguide, FEM analysis was performed. The 20 kHz piezoelectric actuator was first modeled and analyzed, as shown in Fig. 2. It was modeled as a 2-axis and symmetrically. The four PZTs were bonded together for electrical connections. The predicted anti-resonance frequency for the 20.0 kHz piezoelectric actuator was 20.0 kHz, which coincided with the experimental result.

Subsequently, the Ti waveguide with the PZT actuator was modeled and analyzed. Following the same procedures as those in the previous analysis, anti-resonance frequency of the 20 kHz PZT operation was obtained. As a result, calculated

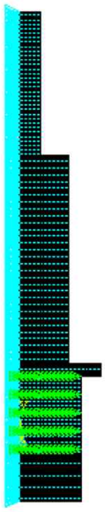


Fig. 2 Finite element analysis model

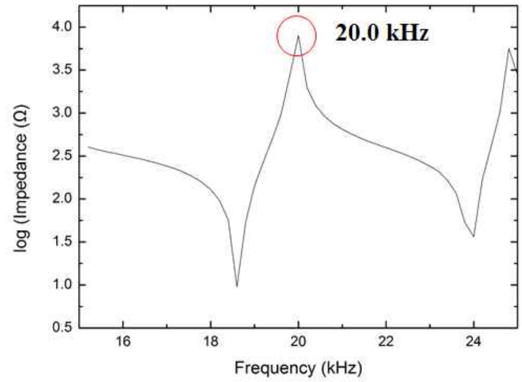
anti-resonance frequency was 20.0 kHz, that agreed with the experimental result of 20.1 kHz (same for No. 1 and No. 2 waveguide), as shown in Figs. 3(a), 3(b) of No. 1 waveguide and 3(c) of No. 2 waveguide.

In addition, displacement was predicted and the result is shown in Fig. 4. In this figure, the red area refers to a higher displacement area, whereas the blue area refers to a lower displacement area. This figure also explains the deformed displacement. By observing the lines of the deformed shape, the displacement at a given node can be determined, where a large area refers to a higher displacement and a smaller area refers to a lower displacement. We chose the optimal dimension, the result of which shows the best displacements at the tip, while the lower displacement appears at the flange.

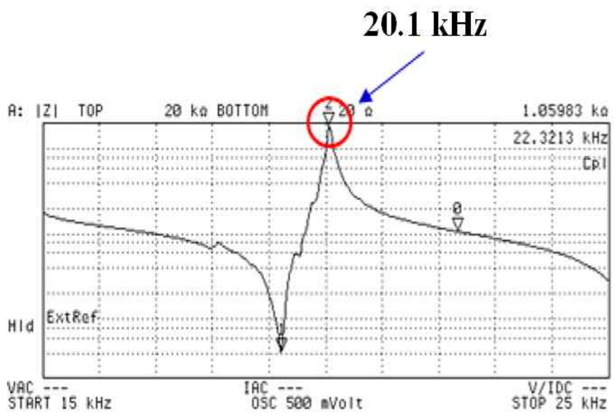
Based on the FEM analysis results, the ultrasonic waveguide was fabricated. Ti was chosen as the material for the waveguide part due to its good hardness characteristic. For the operation, the ultrasonic waveguide was tuned with the electric generator for effective working. The power frequency was adjusted precisely to the resonance frequency of the waveguide by using a power meter, which is connected to the electric generator.

3. Experiments

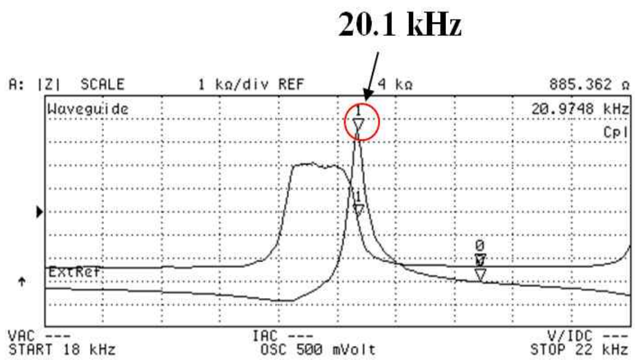
To assess the system performance, chromium molybdenum steel (SCM) 435 specimens were tested using No. 1 waveguide, that anti-resonance frequency was nearer to 20 kHz. The size of the specimen was 50.0 mm by 50.0 mm. The test was performed using the developed waveguide, with the pressure of 5 psi. The tip of the waveguide moved in a zigzag pattern, and was controlled using a personal computer (PC). The size of the treated area was 10.0 mm by 10.0 mm, and the path step was 100 μm. After treatment, the specimen was cut in the center and the cross-sectional area was polished for observation with scanning electron microscopy (SEM). The treated surface of the specimen is shown in Fig. 5.



(a) FEM impedance analysis result



(b) Measured impedance graph of No. 1 waveguide



(c) No. 2 waveguide

Fig. 3 FEM impedance analysis result and measured impedance graphs

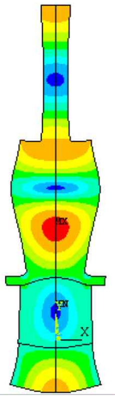


Fig. 4 FEM displacement analysis result

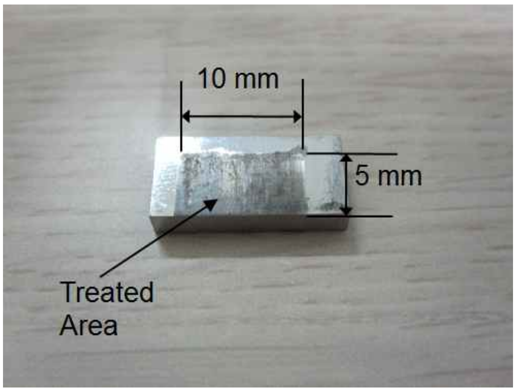


Fig. 5 Treated surface of the SCM specimen

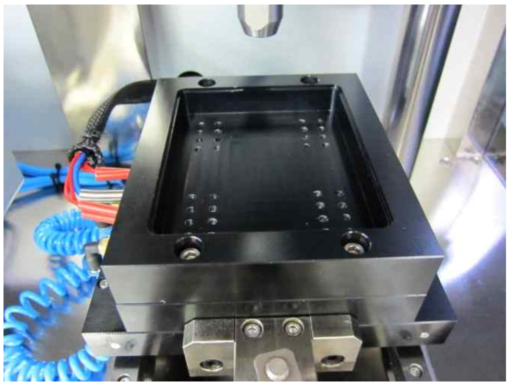
The hardness tests were then carried out. The preparation of the specimen was similar to that for the SEM test. The specimens underwent the same process of surface treatment with the ultrasonic waveguide. The hardnesses before the process and after the process were then measured and compared.

Lastly, friction coefficient tests were performed. An experimental set up for friction tests is shown in Fig. 6(a), and a specimen jig is shown in Fig 6(b). The vertical force for the test was 50.0 N and the movement distance for measurement was 10.0 mm. In addition, the measurement frequency was 1 Hz with a lubricated surface condition. When measuring, the probe moves back and forth with the desired distance and the measurement numbers.

4. Results and Discussion

First, in the SCM435 thickness test, the specimens were cut and the cross-sectional surface was observed. The microscopies and electron backscatter diffraction (EBSD) result revealed that treated thickness was up to 36 μm as

(a) Overall system



(b) Specimen jig

Fig. 6 Experimental set up for friction tests

shown in Figs. 7(a), 7(b). By observing EBSD figures, grains before the surface reformation process were changed into flatter grains after the process. This process was performed by maximized tip displacement of the waveguide, that was designed by FEM analysis. Secondly, the hardness before the process was 14 Rockwell Hardness−C scale (HRC) and after the process was 21 HRC, which means a 50.0% increase. This result was caused by finer structures with change of grains. Lastly, the friction coefficient test result revealed that the surface coefficient was reduced from 0.14 to 0.10 (28.6% reduction). The measured data are shown in Fig. 8 (after surface treatment), where the positive and negative refer to the measuring directions. As seen in Fig. 5, the polished glassy surface was changed into coarse after the process. This phenomenon involved an increase in surface roughness. In contrast, the test result revealed decrease of the friction coefficient. So, additional scientific research is needed.

5. Conclusion

For a conclusion, a Ti transducer using ultrasonic range of

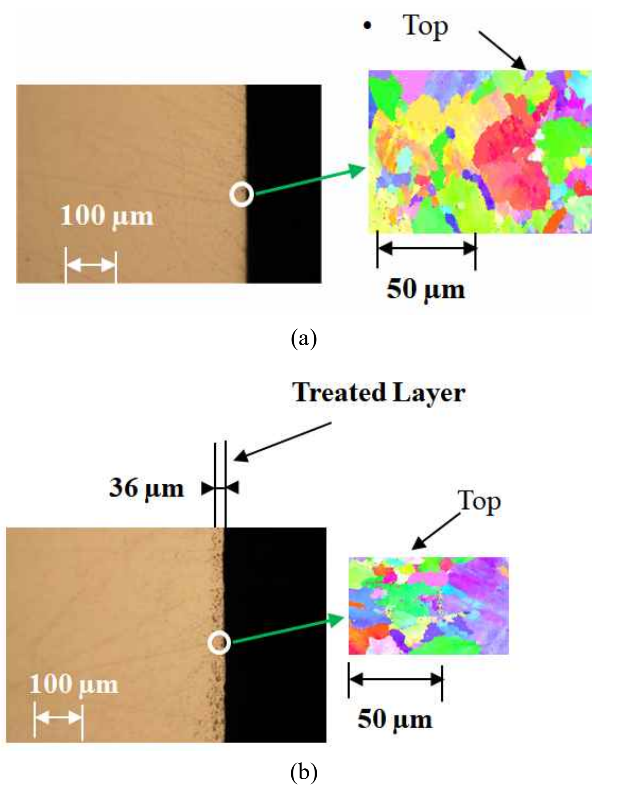


Fig. 7 SCM specimen microscopies and EBSD result of (a) before and (b) after the process

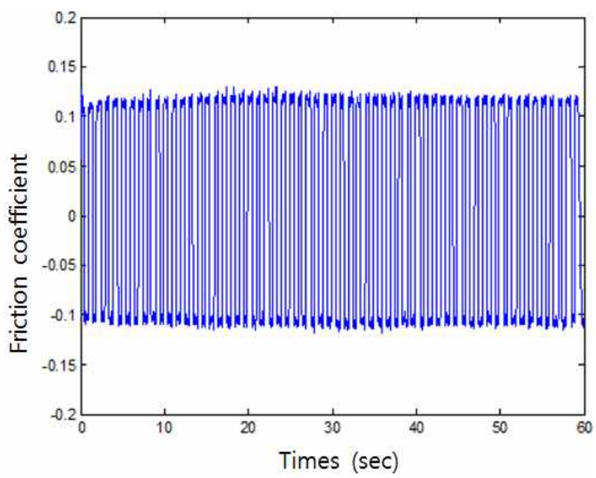


Fig. 8 Measured result

20 kHz frequency, was fabricated for nano-scale surface reformation. In the design stage, FEM using ANSYS tool, was processed to investigate the optimized waveguide structure that is capable of increasing electrical power conversion efficiency. The obtained anti-resonance frequency for the Ti transducer attached with the piezoelectric device was 20.0 kHz, which value agreed well with the experiment result of 20.1 kHz. SCM435 specimens were tested for the system assessment. The result proved that the reformed depth was 36 ㎛. In addition, hardness were measured and compared before and after the process. In advance of the process, the value was 14 HRC and at the end of the process, the hardness was 21 HRC. So an increasing rate was calculated as 50%. Finally, the friction coefficient test result showed that the surface coefficient was reduced from 0.14 to 0.10 (28.6% reduction). Based on the results, the fabricated Ti ultrasonic machining equipment is regarded as a useful device for nano-scale surface reformation.

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