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Design and fabrication of an ultrasonic waveguide for nano-scale surface reformation

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Abstract
In this research, a 20 kHz Titanium (Ti) ultrasonic waveguide for nano-surface reformation was designed and fabricated. When designing the system, finite element analysis using ANSYS software was performed to find optimal dimensions of the waveguide, which can raise energy efficiency. The obtained anti-resonance frequency for a Ti waveguide with a piezoelectric actuator was 20.6 kHz, which agreed well with the experimentally obtained value of 20.1 kHz. Chromium molybdenum steel (SCM) 435 specimens were tested for the system assessment. As a result, the reformed thickness was 30.0 µm. In addition, hardness tests were performed and the hardness before the process was 14.0 Rockwell Hardness-C scale (HRC) and after the process was 21.0 HRC, which means 50% increase. At last, friction coefficient was measured and the value was 0.02. Considering these result, the developed Ti ultrasonic machining equipment is thought to be effective in the nano-surface reformation.

Keywords: Ultrasonic waveguide; Finite element method (FEM); Nano-surface reformation

1. Introduction

Ultrasonic machining systems for enhancing hardness of material and reducing surface friction have been studied and developed, elsewhere [1-2]. Ultrasonic can help the surface reformation effect and the surface roughness is reduced with the decrease of the friction coefficient [1]. As a consequence, the durability of rolling parts such as bearings and so on, can be increased by adapting this process. Previous study was mainly focused on analysis of effect and conditions in the ultrasonic processes. To develop ultrasonic system, optimal design process is necessary and several papers were published by us regarding ultrasonic cleaning system design [3-5]. Until now, there is no work about developing optimal design and fabrication of an ultrasonic equipment for nano-surface reformation considering a waveguide structure.

In this article, a 20 kHz ultrasonic system for nano-surface reformation was designed and fabricated. The design process of the lead zirconate titanate (PZT) actuator and the Titanium (Ti) waveguide using the finite element method (FEM) software ANSYS is described. The fabrication process of the system is explained. And the electrical characteristics of the system are measured and compared with the analysis results. To assess the performance of the proposed system, surface hardness and friction coefficient are measured and compared with untreated specimens.

2. Ultrasonic waveguide for surface reformation

2.1. System configuration

The 20 kHz Ti ultrasonic waveguide system is mainly composed of two parts, the ultrasonic unit and the electric generator. The ultrasonic waveguide is shown in Fig 1. The ultrasonic waveguide has a cylindrically shaped Ti waveguide with a PZT actuator attached on top. When power is supplied to the PZT actuator, the actuator vibrates and the displacement is transferred through the waveguide to the end part.

To do a surface treatment, the ultrasonic unit is placed on a 3-axis servo system, which can control the waveguide system with 10 µm accuracy. Then it is placed on the surface of substrates and its physical vibration is transferred to the substrate through the waveguide by hitting the surface with 20 kHz frequency. And it can help the rearrangement of the nano-scale structures of the substrate with reducing the friction coefficient.

Figure 1. Ultrasonic waveguide for surface reformation

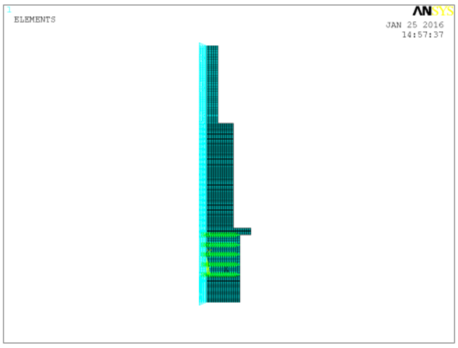
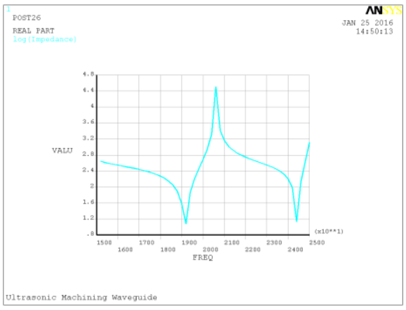
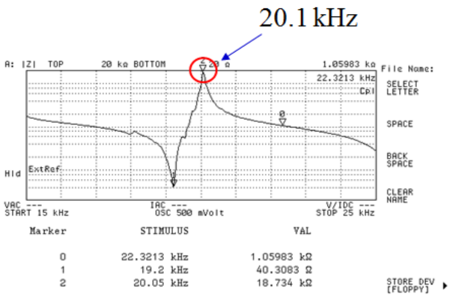


Figure 2. FEM analysis model



(a)



(b)

Figure 3. (a) FEM analysis result and (b) experimental result of the impedance graph

2.2. System design

The ultrasonic was designed by FEM analysis using Ansys, which is commercial FEM software. At first, the PZT actuator was modeled with the analysis tool. The analysis model was axis-symmetric and the nodes of the top and bottom electrodes were coupled to apply voltages, as shown in Fig. 2. And a series of calculations were performed from 15.0 kHz through 25.0 kHz. As a consequence, the highest impedance value was 20.0 kHz, which was decided as a design frequency.

The obtained peak frequency value of impedance was 20.6 kHz, which agreed well with experimentally measured value of 20.1 kHz, as shown in Fig. 3 (a) and (b), respectively.

Next, displacement analysis was performed. Firstly, the PZT actuator and the waveguide were modeled. Modal analysis was performed and structural motion could be predicted. The FEM displacement analysis result at the operating frequency of 20.6 kHz is shown in Fig. 4. We could obtain the maximum displacement at the end of the waveguide.

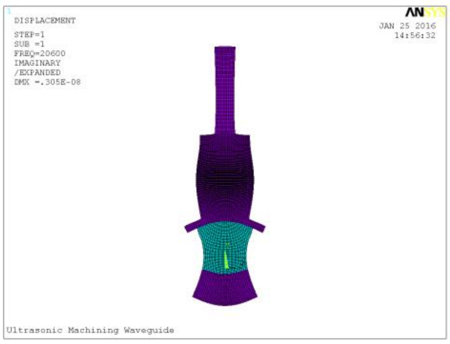


Figure 4. FEM analysis result

3. Experiments

For the system performance assessment, chromium molybdenum steel (SCM) 435 alloy specimens were tested. Cross-sectional microscopies of before and after ultrasonic treatment were measured and compared. As a result, the treated thickness was proved to be 30.0 µm.

Secondly, hardness tests were performed. So the hardness before the process was 14.0 Rockwell Hardness—C scale (HRC) and after the process was 21.0 HRC, which means 50.0% increase.

Lastly, friction coefficient tests were processed. In Fig. 5 (a), an experimental set up for friction tests is shown and a specimen jig is shown in Fig 5. (b). The vertical force for the test was 50.0 N and the movement distance for measurement was 10.0 mm. And the measurement frequency was 1 Hz with lubricated surface condition. When measuring, the probe moves back and forth with the desired distance and the measurement numbers. The result showed that the surface coefficient was 0.02.

(a) (b)

Figure 5. Experimental set up for friction tests: (a) overall system and (b) a specimen jig.

4. Conclusions

In this research, a 20 kHz Titanium (Ti) ultrasonic waveguide for nano-surface reformation was designed and fabricated. When designing the system, finite element analysis using ANSYS software was performed to find optimal dimensions of the waveguide, which can raise energy efficiency. The obtained anti-resonance frequency for a Ti waveguide with a piezoelectric actuator was 20.6 kHz, which agreed well with the experimentally obtained value of 20.1 kHz. Chromium molybdenum steel (SCM) 435 specimens were tested for the system assessment. As a result, the reformed thickness was 30.0 µm. In addition, hardness tests were performed and the hardness before the process was 14.0 Rockwell Hardness-C scale (HRC) and after the process was 21.0 HRC, which means 50% increase. At last, friction coefficient was measured and the value was 0.02. Considering these result, the developed Ti ultrasonic machining equipment is thought to be effective in the nano-surface reformation.

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