Design and Fabrication of a Longitudinal Vibration Transmitter for Ultrasonic-Vibration Assisted Milling

Hossein Jalali Asbforoshani[1], Hamid Soleimanimehr[1*], Shahram Etemadi Haghighi[1]
[1]Department of Mechanical Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran
[*]Email of Corresponding Author: Soleimanimehr@srbiau.ac.ir
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Abstract
The increase in materials with high mechanical capabilities has increased the number of advanced production methods. One of these methods is the merging of ultrasonic vibrations with conventional machining methods. The milling process is flexible in making different geometric shapes of the workpiece. In this paper, the longitudinal vibrations assisted milling process is studied. The main problem with this process is the transmission of ultrasonic vibrations to the cutting area. Therefore, different transfer methods were studied and analyzed and the most efficient method was presented. Longitudinal vibration equations for the horn were analyzed and different types of horns were designed. The best horn was identified and fabricated in terms of increased vibration amplitude and less stress. It was shown that the 5-element horn is the best option for vibration transmission. In order to transfer electrical energy to the rotary ultrasonic converter, a new tool was designed and manufactured. By machining thin-walled parts, it was shown that the fabricated tool can create appropriate dimensional accuracy in the workpiece.

Keywords
Longitudinal Vibrations, Ultrasonic, Milling

1. Introduction

Advances in technology have increased the need for workpieces with specific applications. Therefore, new production methods must be developed to produce these materials. Some of these methods include magnetic field-assisted EDM, Biomachining, and ultrasonic vibration assisted turning. Milling is one of the most widely used processes for making special parts. However, machining special alloys and high-hardness composites result in high cutting forces as well as heat generation 0and workpieces dimensional error, thereby imposing huge costs on organizations. The decrease of cutting forces in a milling process has various benefits, including increasing the tool life and improving the surface quality of the workpiece. The cutting ratio has the most important effect on reducing the cutting forces in the ultrasonic-vibration-assisted machining process. Zarachi et al. 0evaluated the effect of machining and vibration parameters on cutting force along with vibration cutting of 7022 aluminum alloy. Also, they assessed the effect of the parameters of cutting velocity, feed rate, radial depth of cut, and vibration amplitude on three components of cutting force and compared this impact in two processes of conventional machining and ultrasonic-assisted milling. Zarachi, et al. 0modeled the forces in ultrasonic-assisted milling. They calculated the undeformed chip thickness in the one-dimensional ultrasonic-assisted milling process. They applied ultrasonic vibration to the workpieces. In another study, Shen et al. 0investigated the effect of vibration frequency on surface roughness and dimensional accuracy of aluminum parts in the ultrasonic milling process. Results showed applying vibrations led to improving workpiece surface, increasing dimensional accuracy, and separating the burr from the workpiece properly. Besides, the intermittent separation and contact cycle of tools and workpieces prevented the thermal concentration in tools and workpieces, thereby increasing tool life and eliminating the negative thermal impacts on workpieces. In another study, Tao et al. 0 carried out a test series to evaluate cutting forces. Cutting forces in tangential, radial, and axial directions were calculated, and the established model of cutting forces demonstrated that all forces of the three directions were affected by the feed speed, vibration amplitude, and the ratio of vibration frequency and rotation speed. Due to the cutting forces in the milling process, the thin parts are deformed, which causes a dimensional error. In another research, Teymoori et al. 0 modeled the deformation of a one-millimeter-thick workpiece drilled by ultrasonic-assisted drilling. The workpiece deformation was tested experimentally in both conventional and ultrasonic-assisted drilling processes. It was shown the average prediction error was less than 20% in the worst case. Also, there was a considerable decrease in workpiece deformation in both experimental and theoretical approaches through ultrasonic vibration-assisted drilling. Sereda et al. 0conducted experimental research to evaluate the effect of milling parameters on the distortion of the thin-wall workpiece. They also investigated the effect of cutting force and cutting area temperature on workpiece distortion using finite element analysis. Designing a vibration device for the milling process is very complicated. Many researchers work on this subject. Zheng et al. 0designed and controlled a two-dimensional tool for vibration-assisted micro-milling.

The present study aims to design and manufacture a set for applying ultrasonic vibrations to the milling tool. Due to the stability of the ultrasonic-vibration-assisted milling process and the reduction of cutting force in it, this process is suitable for machining thin-walled parts.

2. Analysis and Design

In general, the tool or workpiece is vibrated with a specific frequency and amplitude of vibration during the process. Therefore, the set should be designed in a way that the ultrasonic transducer is in line with the horn and rotational tools. To reach this purpose, the main body of the set should be able to include the transducer, horn, and cutting tools along with the ability to rotate. To simplify the use of the tool, the set of tool holder was designed and manufactured, inspired by existing collets. Generally, the ultrasonic system has three kinds of vibration modes that each one has special usage. In longitudinal mode, the ultrasonic horn vibrates along the axis of the horn, in torsional mode, the ultrasonic horn vibrates around the axis of the horn, and in bending mode, and the horn vibrates transversely. In this paper, longitudinal vibration has been used.

The design of the ultrasonic horn was carried out by using the wave equation, which is extremely complicated. A horn with random cross-section is shown in Figure 1. u is longitudinal displacement, A is the area of the horn section, σ is stress, L is the length of the horn, A_0 and A_L are the areas of the first and end section of the rod respectively.

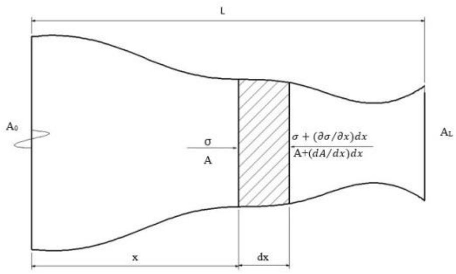

Figure 1. A vibratory rod with a random cross-section

One element of the rod was considered. Newton's second law for this element is in the form of Equation (1).

$$\left(\sigma+\frac{\partial\sigma}{\partial x}dx\right)\left(A+\frac{\partial A}{\partial x}dx\right)-\sigma A=\rho A dx\frac{\partial^2 u}{\partial t^2} \quad (1)$$

Hooke's law assumes that the relationship between stress and strain is linear. It is mean:

$$\sigma = E\frac{\partial u}{\partial x} \quad (2)$$

By replacing Equation (2) in (1), the longitudinal vibration equation of the horn is obtained according to equation 3.

$$\frac{\partial^2 u}{\partial x^2}+\frac{1}{A}\frac{\partial u}{\partial x}\frac{dA}{dx}+(\frac{2\pi}{\lambda})^2 u=0 \quad (3)$$

Where λ is the wavelength. Also, the vibration amplitude (u_0) equation was obtained by solving Equation (4).

$$\frac{d^2 u_0}{dx^2}+\frac{1}{A}\frac{dA}{dx}\frac{du_0}{dx}+(\frac{2\pi}{\lambda})^2 u_0=0 \quad (4)$$

Ultrasonic horns are generally made of aluminum, steel, and titanium due to mechanical properties such as yield stress and fatigue resistance, as well as acoustic properties (e.g., high speed of sound and low vibration damping). In this study, aluminum 7075 horns were applied. Equation (5) is the wave velocity in an infinite rod. E is the modulus of elasticity and ρ is the density of rod material which their amounts for aluminum 7075 were given in Equation (5).

$$c=\sqrt{\frac{E}{\rho}}=\sqrt{\frac{68.9\times10^9\ (Pa)}{2700(^{kg}/_{m^3})}}=5051.58\ ^{m}/_{s} \quad (5)$$

The wavelength was also obtained from Equation (6) by dividing the wave velocity by the ultrasonic frequency f.

$$\lambda = \frac{c}{f} = \frac{5051.58\ ^{m}/_{s}}{20000\ Hz} = 0.252\ m = 252mm \qquad (6)$$

In order to reach the standing wave condition, the horn length must be an exact factor of half the wavelength. Also, it should be noted that the largest diameter of the horn should be smaller than or equal to a quarter of the wavelength in the horn.

$$\frac{\lambda}{4} = \frac{252\ mm}{4} = 63\ \ mm \qquad (7)$$

Ultrasonic horn transmits mechanical waves to the cutting tool. These vibrations were generated by piezoelectric transducers. Step type horn was considered in this paper and the numerical technique was applied for solving wave equations. Therefore, the ultrasonic horn was designed and manufactured according to the range specified. Figure 2 shows a five-element horn.

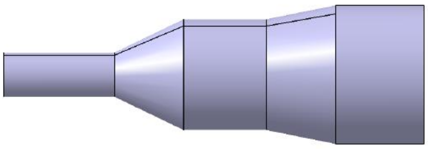

Figure 2. Five-element ultrasonic horn

3. Experiment

The milling tool was connected to the three separate ultrasonic horns with three different methods. Figure 3 shows the exploded view of the mention horns and Figure 4 shows the horns which have been made. In the first method, the milling tool was fastened with one screw on the surface of the horn (Figure 3A). Unbalancing of machining process was the main problem of this mechanism (Figure 4). Then the tool has been clamped by using three screws (Figure 3B), during the machining tests, the horn was cracked between the connecting screws. Then the milling tools were placed in the machined horn using a cone collet (Figure 3 C).

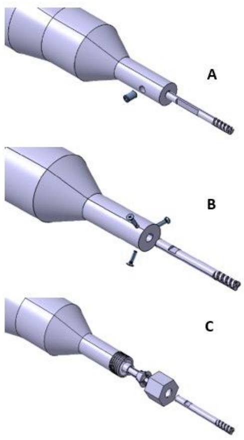

Figure 3. Connection mechanism of cutting tool by using A) a screw B) three screw C) cone collet

Figure 4. Three separate ultrasonic horns

The most important challenge was how to deliver the electric power to the transducer from the ultrasonic generator. The transducer must get positive and negative voltage separately. Besides, it is impossible to connect the wire from the generator to a rotary tool. Therefore, a set was designed with the ability of the slip ring. Two copper rings with a specific diameter were designed to connect to the outer body of the tool holder. Since the entire set was conductive, the rings were installed in a way that they did not contact with conductive materials. According to Figure 5, a Teflon mold was created and the copper rings were placed in the mold. Afterward, the mold was placed in the desired position and electrical insulation resin was poured into the mold chamber and the ducts were electrically insulated.

Figure 5. The transducer, copper rings, and tool holder of the vibration setting

In order to keep the horn fixed to the rotating shell, a fixture was designed and built. A horn vibration node is a place where the amplitude of the vibration is zero over time. The location of the vibrating node was obtained from the static wave relationships. Inside the fixture, a wall was created to clamp the point of this node (Figure 6). The fixed fixture was attached to the rotating shell using three screws.

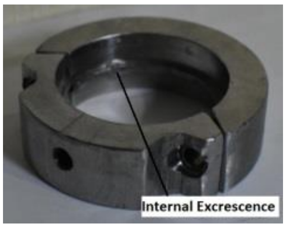

Figure 6. The fixture for clamping the horn

Holes were created in the distance between the copper rings for electricity transmission so that the wires connected to the transducer could pass through the chambers. The whole of parts has been montaged as Figure (7).

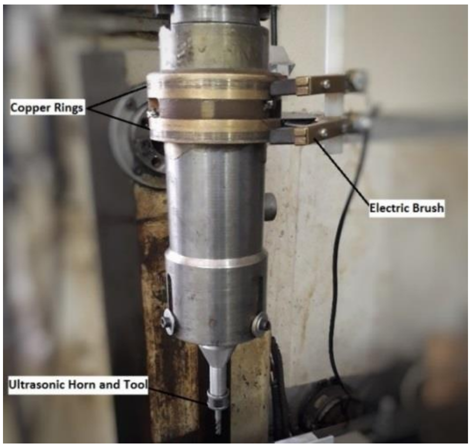

Figure 7. Ultrasonic Vibration assisted end milling

A 3 kW ultrasonic device with a vibrational frequency of 20 ± 0.5 kHz was used. The diameter of the end-mill tool was 5 mm and its model was Din 844. The mentioned set was designed and manufactured with the goal of research in the field of ultrasonic vibration-assisted milling of specific workpieces. The process was applied for machining some workpieces with different materials (figure (8)). According to the experimental results, the balance error reached an acceptable level of 0.02 mm and the milling operation of the thin-wall workpiece was successfully carried out. The dimensional error wasn't made on the workpiece during the process.

Figure 8. Machining of the Aluminum Workpiece

4. Conclusion

Ultrasonic vibration-assisted machining is a new process in cutting hard and brittle materials. Meanwhile, the ultrasonic vibration milling process has been less studied due to the limited transfer of electrical energy to rotating tools. Unbalance of the vibrating tool due to the presence of a chain of parts, reduces the dimensional accuracy of machined workpieces in this process. In this paper, various methods of vibration transmission were studied and analyzed, and after testing, it was shown that the 5-element horn is the best vibration transmitter in this process. A new tool was also introduced to transmit this vibration from the horn to the cutting tool.

5. Acknowledgment

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6. References

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