An Experimental Study on Cutting Forces in Ultrasonic Assisted Drilling

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Abstract

This paper presents the effect of imposing ultrasonic vibration on conventional drilling. The cutting force was compared between conventional drilling (CD) and ultrasonic assisted drilling (UAD). With numerical calculations and analytical software (Ansys), the test structure and the horn were designed and also the vibratory behavior of the parts was predicted to have vibrations with longitudinal mode and in the direction of the tool feed, reaching to the peak at the tip of the tool. The results show a considerable improvement in drilling process due to transformation of cutting process and chip removal mechanism: In ultrasonic assisted drilling the average of the drilling thrust force along the axis of the tool decreased noticeably.

Keywords: Ultrasonic assisted drilling; Vibration; Machining; Drilling thrust force, Hybrid processes

1. Introduction

Applying ultrasonic vibration could be the origin of many more advances in cutting processes of hard and brittle materials. The principle of this method is adding high frequency (16-40 kHz), low amplitude vibration (2-40 μm) to the tool or workpiece. The outcome is transformation of the material’s elastic-plastic characteristic into that of a visco-plastic material. The dry friction present also appears to transform into viscous friction by exciting high frequency (ultrasonic) vibration at the tool’s cutting edge [1]. It is shown that the vibro-impact process plays a crucial role and is the most efficient process when present in the cutting zone. In order to achieve the maximum effect from the vibration that is superimposed on to the cutting process, the vibration system needs to be tuned to resonance.

Some authors studied the formation of the chip while drilling in absence and presence of the ultrasonic vibration. Kumabe [2] studied on the application of vibration cutting. Chang and Bone [3] showed that when the vibration in ultrasonic assisted drilling (UAD) was above a certain threshold, chip segmentation happened. This results in discontinuous chips, increasing the tool life. Neugebauer and Stoll [4] had some experiments in UAD of Aluminum alloys and demonstrated that reduction of axial and radial forces is possible and this would lead to an increase in tool life, 20 times more than conventional cutting. Y. S. Liao et al [5] carried out some experiments on UAD of Inconel 718. They reported that applying vibration up to 12μm would reduce the chip size and the thrust force while increasing tool life. Azarhoushang and Akbari [6] have also carried out some experimental studies and have shown that discontinuous chips and better tool life were achievable in UAD. They also found that geometrical properties of the holes can be improved. Baghlani et al [7] used ultrasonic vibration for deep hole drilling of super alloys. The effect of vibration method on Burr Size Reduction in Drilling of Al/SiC Metal Matrix has been investigated by Kadivar et al [8]. Furthermore, in some previous studies by the authors, the effect of ultrasonic vibration on burr size and force reduction on ultrasonic assisted drilling of metal matrix composite were investigated and the results clearly showed that the ultrasonic vibration has superior effect on burr size and force reduction [9,10]. A review published by Kumar et al. pointed out that the
2. Experimental setup and test procedure

To perform this experimental study, some bar-shaped samples were used from high alloyed steel X20Cr13, with 60 mm diameter and 30 mm length. Since the tests were designed to run on different samples, repeatability of the tests had high importance. The resemblance of the samples had been guaranteed using accurate CNC turning and grinding machines. The grinding operation had been performed simultaneously for all the samples to guarantee the similar height and surface condition. 7 holes were drilled on each specimen. HSS drill tools were used with 8mm diameter and the drillings were operated under dry condition. The UAD and CD were carried out at speeds of 10 and 12 m/min were selected.

The effectiveness of UAD has gained many proofs by both academia and industry. In this study, the authors intended to evaluate the effect of UAD through an experimental study and extract the thrust force directly through a dynamometer.

2.1. The machine and the fixture design

A universal milling machine (Tabriz-FP4M) used to perform drilling operation. A special frame was fabricated for holding transducer, horn and workpiece. This Frame had some functions, holding the horn, being attached to the dynamometer table and providing enough space for cables and fastening devices. Besides, it should be rigid enough to stand for the drilling force. Fig. 1, illustrates the experimental setup for UAD. The dynamometer was attached to the table of drill machine directly.

2.2. The feature of the vibration system

The power for vibration is generated using a generator and subsequently transferred to a transducer which converts it to vibration. A 1000 Watt generator with the maximum output current of 5A (Nasr Mouj Gostareh Co.) and a piezoelectric transducer with a frequency of 20 KHz was used to generate two different vibration amplitudes of 10 and 15 µm. These vibrations are conducted to the workpiece using a concentrator piece called “Horn”, see Fig. 1. The horn amplifies the vibration amplitude and then transmits it to the workpiece in the feed direction. This part is fabricated by Al 7075 which has appropriate acoustic properties. The horn was fixed in a frame through nodal point of oscillation. The nodal point is the point where the amplitude of oscillation is about zero so clamping the horn from this point has no influence on transmission of the wave to the cutting zone. The position of this point is obtained from FEM simulation. Due to the considerations of the horn design, the supporting points have little effects on operation. But, for more accurate results, the seat plates have been covered with four elastic seats, see Fig.1.

![Fig.1. (a) Schematic of setup; (b) Drilling setup.](image)

To attach the samples on the horn, a torque-meter wrench was used to ascertain the fastening condition to be the same for all of the samples. A layer of polyester material was located between the horn and the sample to fill any possible gap, preventing frequency loss.

Regarding the experimental study requirements and the expected vibratory behavior of the horn, it would be reasonable to calculate the geometrical shape of the horn via numerical method first and to be evaluated through FEM method. Because of some considerations like avoiding from stress concentration and ensuring the vibration amplitude strengthening, exponential shape has been selected among other known shapes of horns like cylindrical, conical and stepped ones. As the study was considered to perform at the frequency of 20 KHz, the shape of the horn should be in a way that be resonated in this frequency. For this reason, the approximate length and form of the horn was calculated. The bigger diameter of the horn should not exceed the wave length, so:

$$c = k \frac{E}{\rho}$$

where $c$ is the sound velocity, $E$ is the elasticity module, $\rho$ is the density of the horn, $k$ is the angular frequency constant, $L$ stands for the length of the horn in meter, and $\nu$ is the poisson ratio, $D_0$ is the bigger diameter, and $A$ is the wave length.

$$D = D_0 e^{-\beta s}$$

In which $\beta$ is the shape factor.

$$\beta = \frac{\omega}{c} \frac{\ln N}{\left(\frac{\pi}{3} + (\ln N)^2\right)^{1/2}}$$

In which $\omega$ is the angular frequency constant, $L$ stands for the length of the horn in meter, and $N$ is magnification factor.

$$L = \frac{c}{2f} \sqrt{1 + \left(\frac{\ln N}{\pi}\right)^2}$$
Using these known calculations, an approximation was derived for the length of the horn which was 120 mm. FEM analysis was applied to validate the calculation for the final shape and length of the horn. A radial slot is situated around the horn as the seat, for attaching the horn to the frame to prevent vibration transmission to the fixture and alternatively dynamometer. Due to the high frequency of the test, damped modal analysis was selected. The tenth (10th) mode showed adequate compatibility, see Fig. 2.

2.3. Measuring equipment

To measure the drilling thrust force a Dynamometer (Kistler 9255-B) was used. The data extracted from DynoWare software, see Fig. 3.

3. Results and discussion

Fig.4 and 6 presents the output of the dynamometer. Fig.4 shows variations of the thrust force during drilling time for CD and UAD with vibration amplitudes of 10 and 15 μm, respectively. The cutting speed was 12 m/min, and the applied feed rate was 0.07 mm/rev. Considering Fig.4, it could be drawn that the thrust force in UAD was lower than that obtained for CD. Meanwhile, with increasing the amplitude of vibration, the thrust force decreased significantly. Furthermore, it can be concluded that in all the drillings, the thrust force was increased with lengthening time, due to the tool wear during the drilling process and also distancing from the peak point of vibration.

In UAD, the ultrasonic vibration causes the cut to become discontinued and ultrasonic impact action (UIA) occurs. Additionally, in ultrasonic assisted drilling, the cutting speed is different from zero in the center of the part due to vibration velocity, and thus the material removal takes place easier than conventional machining. By increasing the vibration amplitude, the impact force is increased between tool and workpiece due to the traversal motion of the drill tip, which in turn results in higher reduction of the drilling force. Likewise, when higher vibration amplitude is applied, a smaller feed of tool will be achieved per each vibration. In UAD chips are thin and segmented; whereas in CD, chips are thick and continuous, see Fig. 5. Thinner and segmented chips cause lower drilling force. Besides, friction between tool and workpiece diminishes in UAD compared to CD, which in turn leads to a lower drilling force.

According to the database extracted from DynoWare software, a reduction of 57 percent of the thrust force was obtained in UAD, compared with CD which improved to 62 percent while increasing the amplitude up to 15μm.
Fig. 5. (left) Chip segmentation in CD; (right) Chip segmentation in UAD

Fig. 6 represents the effect of feed rate on drilling force. The drillings were performed in the cutting speed of 10 m/min. In UAD, the amplitude of vibration was tuned to 10 μm. In drilling process, feed rate acts as depth of cut in turning, so with increasing the feed rate in UAD and CD, the thrust force increases noticeably.

Fig. 6. The effect of feed rate on drilling thrust force, Vc=10 m/min

Fig. 6 shows that the improving effect of UAD was deteriorated as the feed rate increased. In other words, UAD improved the cutting condition during a certain amount of feed rates. As the feed rate exceeds an optimum threshold, the fruitful influence of vibration weakens.

4. Conclusion

In this paper, the effect of vibration method on cutting force of drilling was investigated. For this purpose, high-alloyed steel X20Cr13 was drilled by HSS drill tool with and without ultrasonic vibration. According to experimental study, the thrust force of drilling in UAD, on average, was approximately 60 percent lower than that in CD. Furthermore, with increasing the vibration amplitude, the drilling force was slightly increased. In UAD, with increasing cutting speed, the drilling force was gently increased due to the higher tool wear in higher cutting speeds. However, in CD with increasing cutting speed, the drilling force dropped and then raised up. In higher cutting speeds, BUE reduces and causes lower drilling forces. In UAD, built-up edge was not observed and the drilling force was increased with increasing cutting speed. But, in higher cutting speeds in CD, the temperature was elevated dramatically, which caused a high tool wear owning to the abrasive phase of Cr in the workpiece. So at the higher cutting speed in CD, the drilling force was lightened. In all the tests, the drilling force was lower in UAD than that of CD. Altering feed rates presents improvements in certain range of feed rates where the vibratory condition is effective.

The experimental study corroborates the effectiveness of this technique, however maintaining the peak of vibration in cutting zone will lead to an enhanced outcome. Hence, facilitating the machining with a control system would be a complementary method.

References