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Experimental study and empirical analysis on effect of ultrasonic vibration during rotary turning of aluminum 7075 aerospace alloy

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ABSTRACT

Turning with rotary tool is a newly developed alternative of conventional turning process in which cutting edge of a round insert rotates about its axis, so that a continuously indexed cutting edge is fed into the cutting zone. This paper presents the experimental investigation and analysis of the machining parameters while turning aluminum 7075 alloy, using a driven rotary tool that is assisted by high-frequency vibration. The experiments were designed by use of three-factors and three levels face-centered central composite design taking into account cutting velocity, tool rotary speed and feed rate as continuous factors and the induced ultrasonic vibration as categorical factor. In order to analyze influence of aforementioned factors on cutting force and surface roughness, empirical model of each response was developed using response surface methodology. The adequacy of developed models was then checked and verified by statistical analysis of variances. To find optimal parameter setting regarding minimum cutting force and surface roughness, desirability function approach was utilized. Results indicated that applying high-frequency vibration to rotary tool significantly reduces the cutting force and surface roughness. By performing multi-response optimization, it was obtained that in rotary turning (RT) process setting of 5.94 m/min cutting velocity, 214.9 tool rotary speed and 0.08 m/min feed rate causes achieving minimum cutting force and surface roughness, simultaneously. While, in vibratory-rotary turning (VRT) process setting of 9.71 m/min cutting velocity, 98.63 tool rotary speed and 0.08 m/min feed rate simultaneously minimizes cutting force and surface roughness. The results were then verified by performing confirmatory experiments.

1. Introduction

In metal machining processes, chip formation is accompanied by heat generation, which influenced by mechanical and physical properties of both workpiece and the cutting tool. Rising temperature in tool-work interface causes thermal softening of the tool and subsequent tool wear. In order to overcome this problem, many researchers have so far focused on trying to increase both the wear resistance and cutting speed by applying CBN and/or ceramic-made tools. As a lot of coolant is required to cool down these tools, a bad effect on the natural environment is inevitable, and research has thus been carried out to realize the so-called dry cutting. Interrupted cutting is an effective way that provides cooling cycles to remove heat generation and temperature rise during metal cutting. The idea is to use a cutting edge in the form of a disk that rotates about its principal axis [1]. It is called machining with rotary tool that provides a rest period for the cutting edge that enables the edge to be cooled and a continuously fresh portion of the edge to be engaged with the workpiece [2]. As is well known, the tool itself can rotate during rotary machining. It is expected that the tool face can be cooled down during air cutting, and that tool wear may be averaged around the whole tool circumference [3]. For instance, a reduction of 500 °C in machining of mild steel was reported by Venuvinod et al. [4]. Also, in a work carried out by Lei and Liu [5], they reported that the tool life in rotary turning process has more than 60 times improvement compared to conventional turning process. Though the temperature field and its transitional change have an impact on tool wear, turning with rotary tool significantly influence cutting temperature and improves tool life. As a result of this improvement in tool life, some performance such as cutting force and surface quality are also improved [6]. According to what discussed above, the advantages of rotary turning over conventional turning can be listed as follows:

- Less cutting temperature
- Higher tool life
- Less cutting force
- High surface quality

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In the case of turning with rotary tool, due to its novelty, there are not huge body of works that studied machining efficiency. Lei and Liu [5] used both single point cutting toll and rotary tool for turning of titanium alloy. They showed that by increase in machining time, thermal history and cutting force in rotary turning process are relatively lower than those in single point cutting. Kishawy and Wilcox [6] analyzed cutting forces during rotary turning of SAE 1045 with self-propelled rotary tool. They showed that increase in feed rate causes increase in thrust force, radial force and cutting force. Further, by increase in cutting force and feed rate the friction coefficient in interface decreases but normal force and surface roughness increases. Li and Kishawy [7] studied tool wear and chip formation mechanism in turning with self-propelled rotary tool. They showed that the main mechanism of tool wear was flank wear and there was no evidence of crater wear in the rotary tools. The heat analysis showed that there is an optimum rotational speed of the tool at which the tool temperature is minimum. Kishway et al. [8] analyzed chip flow direction in rotary turning with self-propelled tool. Variations of absolute and relative flow angle were investigated with changes of cutting speed and feed. Results indicated that in various cutting speeds, absolute flow angle changed about 10% by increasing the cutting speed and increases from 22.6° to 26.6°. Hosokawa et al. [9] studied rotary turning of Inconel 718 under dry machining and minimum quantity lubrication conditions. Research findings showed that at low tool rotary speed, the tool temperature is relatively high in both near dry and dry machining. By increasing tool rotary speed, tool temperature decreases and the temperature of cutting point in near dry machining was less than in that in dry machining.

Nowadays, with advancement of new materials, ultrasonic assisted modifications are developing to yield higher quality characteristics of machining process [9]. In turning process, turning tool vibrates by piezoelectric actuator in regular amplitude with specified frequency. Here, because of swinging contact between tool and work, cutting forces with respect to ordinary turning process [10–13]. Other improvements are increase in tool life, increase in dimension accuracy, and decrease in surface roughness [14–17]. Association of vibratory and rotary tool for first time was reported in our previous work [18]. Where, the axial vibration applied to a rotary tool and cheap breaking mechanism, surface modification and machining force were analyzed.

However, selection of optimal parameter setting (i.e. tool rotary speed, cutting speed and feed rate) through a systematic approach in rotary and vibratory-rotary turning process has not been reported so far. In the present work, an attempt is made to simultaneously optimize the machining force and surface roughness in both rotary turning and vibratory-rotary turning operations considering cutting velocity, tool rotary speed and feed rate as main factors. Face centered central composite design method was used here to design experiments considering three factors with three levels in both RT and VRT operations. Then, the machining performance of RT and VRT is compared. The study also aims to develop a model, with the help of the response surface methodology (RSM) for predicting the cutting force and surface roughness in both RT and VRT condition. The multiple performance optimization of the machining parameters is carried out, using the RSM, based on the desirability function approach. Finally, the obtained results are verified by conducting further confirmatory experiments.

2. Materials and method

2.1. Horn design

As a common method, modal analysis was used to find the resonance frequency of vibrational parts including horn, insert, and screw. The CAD model of these parts have firstly been provided by consideration of couple of requirements [20]. Accordingly, the diameter of horn part (D) should be lower than one-fourth of its wavelength ($D < \lambda/4$) and not to be lower than booster's diameter in the connect location. In addition, the frequency of these parts should be resonated in the limitation of transducer resonance frequency which was 20 ± 1 kHz. Regarding the requirements, sound speed (c) and wavelength according to following equations:

$$c = \sqrt{\frac{E}{\rho}} \quad (1)$$

$$\lambda = \frac{c}{f} \quad (2)$$

Where E, ρ and f are modulus of elasticity, density and estimated frequency.

Afterwards, modal analysis was carried out by using ABAQUS software. In this process, the geometrical alternation is repeatedly implemented so that the resonance frequency of vibration tool lies in the required limitation. In this study, tetrahedral meshed type has been used for performing modal analysis of vibratory apparatus. According to design limitations (horn diameter that discussed above) and modal analysis, a 140 mm length taper like horn with large diameter of 37 mm and small diameter of 10 mm was utilized. The resonance frequency of designed horn was 20,618 Hz that was within the range of transducer. The designed horn was fabricated according to modal analysis. Both the designed and fabricated horn were illustrated in Fig. 1.

2.2. Experimental setup

To perform vibratory-rotary turning process, a designed attachment was mounted on TABRIZ universal lathe machine model TN50 BR as shown in Fig. 2. The vibratory-rotary attachment that produces rotary motion of round tool along with vibratory motion in direction of velocity includes DC motor, chain, sprocket, holding structure and ultrasonic horn. The DC motor converts rotary motion to the round tool through chain and sprocket. The rotary speed of the tool is controlled by a digital inverter. In the ultrasonic apparatus, electrical power from a power supply (MPI GENERATOR) converts to transducer and then to a hand-made horn with 3000 W power. During process, the horn can vibrate rotary tool in a way that vibration does not affect other parts. It is worth mentioning that the peak-to-peak amplitude of vibration was set on approximately 10 μm through controlling the output power of generator.

2.3. Material and measurement equipment

The material used for performing experiments is aluminum 7075 rod with diameter of 40 mm and length of 400 mm. Also, round insert of tungsten carbide material RCMT10T3 MO Lamina Co was used as rotary turning tool. The tool was connected on tip of the horn and rotates with rotation of DC motor. Fig. 2a illustrates workpiece and tool that used in experiments.

To monitor and measure the cutting forces, a KISTLER multi-components dynamometer model 9257B with 3.5 kHz natural frequency was employed. Surface roughness of turned parts was measured by MAHR-PS1 surface profile meter with cut-off of 0.8 mm. Also, a view measuring machine was utilized to analyze tool wear and surface topography of machined specimens. Fig. 3b demonstrates equipment that used for measuring surface quality and cutting force. The value of vibration amplitude was measured through eddy current sensor model PU09 manufactured by AEC corporation and the measured amplitude was close to those set on MPI generator.