Experimental study of machined surface quality in ultrasonic vibration-assisted turning of 5A06 Al-Mg alloy

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Abstract. The 5A06 Al-Mg alloy is a soft material, and the phenomenon of knife sticking is extremely serious during cutting, likewise, it is easy to generate build-up edges. Therefore, it is difficult to acquire good surface quality in turning. For this purpose, the ultrasonic theory and cutting theory are fully combined in this study, and the machining mechanism of conventional turning (CT) is changed by applying ultrasonic vibration (UV) to the cutting tool, so as to build up the machining results. The turning experiments of 5A06 Al-Mg alloy with or without UV are carried out under different process parameters, and through which the effects of ultrasonic amplitude (UA), feed rate (FR), cutting depth (CD) and cutting speed (CS) on the surface roughness of machined workpiece are investigated and analyzed. The consequences show that the process parameters have a different degree of effect on surface roughness. And there are special process parameters suitable for UV assisted turning (UAT), under which the processing results of UAT is obviously better than that of CT. In addition, it is found that by contrast experiment of surface topography under ideal process parameters built-up edges, surface scratches and other phenomena are not easy to arise in UAT to obtain the better surface topography than CT.

1. Introduction
Considering from the machined surface quality, the material removal rate, the equipment utilization rate and the production efficiency, the turning is still a machining method of practicability, economy and extensive adoption[1-4]. Nevertheless, with continuously emerge and use of multitudinous precision instruments and parts requirements of machining accuracy and machining quality are more demanding than ever before[5-7]. In the meantime, in the field of machinery manufacturing, the diversified difficult-to-cut materials (DCM) are increasingly widely used and the number of turning processing increases, so that the difficulty of turning processing continues to enhance[8,9]. For the CT process, due to accompanying with the large cutting temperature and cutting force, the difficult chip breaking and chip removal, the severe tool wear and other serious problems in the course of turning, the processing quality becomes poor and the processing efficiency decreases, likewise, the processing cost also aggrandizes[10,11]. The CT technology has great limitations. As a newfashioned special processing method, the UAT technology offers a new idea for high efficient and quality processing of DCM[12-14].

The manufacturing equipments for UAT have been exploited in the both domestic and overseas, whereas, there exist shortcomings of expensive factory cost, incapacious existing applications and
low-grade commonality in this manufacturing equipment, as a consequence, it is difficult to popularize[15,16]. In view of the above reasons, the UV system is fixed on the generic turning-lathe in this investigation to satisfy the claim of the UAT in down-to-earth production. Meanwhile, a diffusely adopted and classic DCM is put into use to the empirical studies, and the processed outcomes of UAT is analyzed emphatically in terms of finished surface quality. This research can furnish advocation on paper and trial fundation for the exploitation and existing adhibition of the UAT of DCM.

2. Experiment

2.1. Experimental materials and conditions
Using the designed UV turning system, the turning experiments with or without UV are put into effect under the dry conditions. In the experiment, the workpiece material is selected as 5A06 Al-Mg alloy (i.e. LF6), the chemical elements of which are listed in Table 1, and the mechanical and physical performance of which are displayed in Table 2. The chemical element of 5A06 Al-Mg alloy is mainly Al. Al is a kind of viscous material with the low density and the soft texture. The phenomenon of sticking knife is very serious in the course of processing, which greatly increases the difficulty of turning Al-Mg alloy.

| Table 1. Chemical elements of 5A06 Al-Mg alloy. |
|-----------------------------------------------|
| Chemical elements | Al   | Mg   | Mn   | Fe   | Cu   | Si   | Ti   | Others |
| Content (%)       | 92.22| 6.53 | 0.63 | 0.18 | 0.10 | 0.08 | 0.06 | 0.20 |

| Table 2. Mechanical and physical performance of 5A06 Al-Mg alloy. |
|---------------------------------------------------------------|
| Mechanical and physical performance | Values | Mechanical and physical performance | Values |
|--------------------------------------|--------|-------------------------------------|--------|
| Thermal conductivity (W/m·K)         | 118    | Brinell hardness                     | ≥64    |
| Specific heat capacity (J/kg·K)      | 924    | Elongation (%)                       | ≥15    |
| Elastic modulus (GPa)                | 70     | Inner stress (N/mm²)                 | ≥160   |
| Density (kg/m³)                      | 2750   | Tensile strength (MPa)               | ≥315   |
| Poisson’s ratio                      | 0.35   | Resistance (20°C, nΩ·m)              | 68     |

The hardness and strength of 5A06 Al-Mg alloy are not very high. The difficulty of turning lies in high plasticity. It is easy to produce built-up edges during cutting, and excellent surface quality is difficult to be obtained. In the cause of achieving the high efficient and quality processing of 5A06 Al-Mg alloy, sharp cutting edge, high wear resistance, anti-adhesion of rake face, large positive rake angle, low surface roughness of cutting tool, smooth chip breaking and chip removal are required when choosing cutting tool. According to the above requirements, the CCMT120404-HM YBM251 type cemented carbide coated cutting tool is selected in this research, the geometry characters and specifications of which are revealed in Table 3.

| Table 3. Geometry characters and specifications of cutting tool. |
|----------------------------------------------------------------|
| Geometry characters and specifications | Values | Geometry characters and specifications | Values |
| Nose angle of cutting tool (°)           | 80     | Relief angle of main cutting edge (°)  | 7      |
| Cutting edge length (mm)                 | 12.9   | Cutting tool thickness (mm)            | 4.76   |
| Corner radius of tool nose (mm)          | 0.4    | Mounting-hole diameter (mm)            | 5.56   |
| Inscribed circle diameter (mm)           | 12.7   | Cutting tool coating                  | TiC-Al2O3-TiN |
2.2. Experiment scheme design

The assistant effect of UV can ameliorate the turning effect to a certain extent, especially when opting for the suitable process parameters, the UAT is obviously superior to the CT. In this investigation, the machined surface quality is compared and researched mainly through the UAT experiment of 5A06 Al-Mg alloy with or without UV. The influence of UA and cutting parameters on surface roughness is also discussed. In the light of the characteristics of UAT, the process parameters are adopted in the experiment. The vibration frequency is 20 kHz, the UA and cutting parameters and their standards are represented in Table 4.

| Designation | Symbol (unit) | Standards 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|-------------|---------------|-------------|---|---|---|---|---|---|
| UA          | A (μm)        | 0           | 10| 15| 20| 23| 26| 30|
| FR          | f (mm/rev)    | 0.08        | 0.1| 0.15| 0.2| — | — | — |
| CD          | ap (mm)       | 0.05        | 0.1| 0.15| 0.2| — | — | — |
| CS          | Vc (m/min)    | 28          | 35| 42| 47| 52| — | — |

3. Results and discussions

3.1. Surface roughness

The turning experiments of 5A06 Al-Mg alloy with or without UV are put into effect under different process parameters. The two-dimensional surface roughness parameter $R_a$ is measured by British Form Talysurf Series 2 Taylor Hobson roughness profiler measurement. Each experiment is measured six times, a maximum value and a minimum value are get rid of, and then the average value is taken to get the final surface roughness.

Under the process parameter of the FR of 0.08 mm/rev, the CD of 0.1 mm, the CS of 42 m/min, 5A06 Al-Mg alloy is turned, the column diagram that the surface roughness of machined workpiece varies with UA is achieved as shown in Figure 1. With the help of the figure it can be seen that the surface roughness of machined workpiece in UAT first decreases and then increases in the wake of the increase of UA. When the UA is 10 and 30 μm, the surface roughness in UAT is close to that in CT. The gained surface roughness of machined workpiece is ideal when the UA ranges from 20 to 26 μm, and when UA is 23 μm, the effect is perfect.

Under the process parameter of the UA of 23 μm, the CD of 0.1 mm and the CS of 42 m/min, turning the outer circle of 5A06 Al-Mg alloy bar can receive the column diagram of surface roughness changing with the FR as shown in Figure 2. Sees from the figure, the general change trend of the surface roughness of machined workpiece in UAT and CT is basically consistent, both increase with the increase of FR, and the growth rate is almost identical, however the surface roughness of UAT is much lower than that of CT. Compared with CT, the rate of the surface roughness reduction of machined workpiece in UAT gradually decreases in the wake of the increase of FR. Therefore, in actual application relatively small FR is recommended as far as possible.

Under the cutting conditions of the UA of 23 μm, the FR of 0.08 mm/rev and the CS of 42 m/min, the column diagram of surface roughness transforming with the CD is scored through experiments as shown in Figure 3. With the help of the figure it can be seen that the surface roughness of UAT and CT both increases in the wake of the increase of CD, but the roughness value of UAT is obviously less than that of CT. The surface roughness of machined workpiece in UAT has little change when the CD of 0.05 and 0.1 mm, and is close to that in CT at the CD of 0.2 mm. Therefore, the smaller CD is preferred in practical application.

When the UA is 23 μm, the FR is 0.08 mm/rev and the CD is 0.1 mm, the turning experiment is implemented. The column diagram of surface roughness varying with the CS is acquired as shown in
Figure 4. With the help of the figure it can be seen that electing the appropriate CS can ensure the surface roughness of UAT is better than that of CT, and the surface roughness of machined workpiece in UAT first decreases and then increases in the wake of the increase of CS. The CS can not be too small or too large. UAT of 5A06 Al-Mg alloy has a first-rank CS range.

3.2. Surface topography
In the equal cutting conditions, 5A06 Al-Mg alloy is processed by UAT and CT respectively. The super-depth-of-field optical image of machined surface enlarged 500 times with or without UAT is demonstrated in Figure 5 and 6. From the figure, it can be seen that the workpiece surface topography in UAT is quite differ from that in CT. The workpiece surface of UAT is covered with regular and delicate stripes, and the wheel-like vibration marks on the workpiece surface are particularly clear and symmetrical, while there are obvious groove defects, scratches and built-up edges on the workpiece surface of CT.

The three-dimensional surface topography of the machined workpiece, which scanning range is 0.1×0.1 mm², are exhibited in Figure 7 and 8. With the help of the figure it can be seen that not only the three-dimensional surface topography of the machined workpiece in UAT is more excellent than that in CT, but also the height of three-dimensional surface topography is less than that of CT by observing the Z-axis range, which proves that the roughness value of UAT is less and better surface quality can be acquired.
Figure 5. Optical image of machined surface enlarged 500 times in UAT.

Figure 6. Optical image of machined surface enlarged 500 times in CT.

Figure 7. Micro-morphology in UAT: three-dimensional surface topography.

Figure 8. Micro-morphology in CT: three-dimensional surface topography.

Figure 9. Height distribution curve of three-dimensional surface topography in UAT.

Figure 10. Height distribution curve of three-dimensional surface topography in CT.

The frequency distribution of the height of three-dimensional surface topography is revealed in Figure 9 and 10. By contrast with the cutting effect of UAT and CT, the frequency of the height of three-dimensional surface topography of 0.002 is the boundary. It can be seen through observing
curves that the density of the height of three-dimensional surface topography in UAT is mainly concentrated in the range of ±3 μm (viz. the surface height of machined workpiece is 3-9 μm), while that in CT primarily focuses on the range of ±4 μm (viz. the surface height of machined workpiece is 4-12 μm). And beyond that, the frequency of the height of three-dimensional surface topography of machined workpiece higher than 6 μm in CT is much greater than that in UAT, which further proves that the surface quality of machined workpiece in UAT is more eminent than that in CT.

4. Conclusion
In this article, turning test of 5A06 Al-Mg alloy with or without UV is implemented, similarly, the workpiece surface is researched and analyzed. The conclusions go as following:

(1) Using UAT method, better results when machining 5A06 Al-Mg alloy can be obtained than those by CT, nevertheless, such results can be gained only processing within the range of the best process parameters.

(2) For the constituted machining system of UAT, the first-rank process parameter ranges of processing 5A06 Al-Mg alloy are as follows: \( A = 20-26 \) μm, \( f = 0.08-0.1 \) mm/rev, \( ap = 0.05-0.1 \) mm, \( Vc = 42-47 \) m/min. In practice, the first-frank process parameters can be selected if conditions permit, namely \( A = 23 \) μm, \( f = 0.08 \) mm/rev, \( ap = 0.05 \) mm, \( Vc = 42 \) m/min.

(3) Compared with CT, under the condition of selecting proper process parameters, the machined surface quality in UAT of 5A06 Al-Mg alloy can be improved in different degrees. It is further proved that UAT is fit for machining DCM, which are similar to 5A06 Al-Mg alloy properties.

In the subsequent research work, the machining method of UAT can be used to cut more kinds of new materials and DCM and study the influence of process parameters on machining different materials. The consistency and difference are found out to further improve the relevant theories and methods. Furthermore, the constituted machining system of UAT can be also applied to drilling, milling, grinding and other machining ways, and modified into corresponding machining system to research the effect of application of ultrasonic technology on machining results in different machining ways. The related research fruits are conducive to the promotion and application of ultrasonic machining technology, as well as the popularization and application of new materials and DCM.

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