Surface Integrity of Turned 6061 Aluminum Alloy using Liquid Nitrogen as Cooling Medium

Duo Pan\textsuperscript{a}, Xiangyu Wang\textsuperscript{b}, Jintao Niu\textsuperscript{c}, Yang Qiao\textsuperscript{d}, Peiquan Guo\textsuperscript{e}\textsuperscript{*}

School of Mechanical Engineering, University of Jinan, Jinan, Shandong, China

\textsuperscript{a}email: 761376232@qq.com, \textsuperscript{b}email: me_wangxy@ujn.edu.cn, \textsuperscript{c}email: me_niujt@ujn.edu.cn, \textsuperscript{d}email: me_qiaoy@ujn.edu.cn

\textsuperscript{e}Corresponding author: \textsuperscript{e}email: oss_guopq@ujn.edu.cn

Abstract: Aluminum alloy is widely used in automobile, aerospace and other fields due to its excellent strength-to-weight ratio. And machined surface integrity is an important factor affecting the service performance of parts. In this paper, surface integrity of turned 6061 aluminum under liquid nitrogen cooling condition was studied. The results shows that, cryogenic cooling cutting with liquid nitrogen could effectively reduce the surface roughness, inhibit the generation of residual tensile stress and improved the surface microhardness compared with dry and emulsion cooling cutting. Cryogenic cooling processing has great advantages in cutting machining.

1. Introduction

The high strength-to-weight ratio of aluminum alloy makes this type of material dominating in aerospace and other fields\cite{1}. As a typical AlMgSi alloy, 6061 aluminum alloy has good overall properties\cite{2}. Moreover, its price is lower than other aluminum alloys, which also makes it widely used in industry.

In order to take full advantage of metal material in application fields, it is necessary to ensure the surface quality in the manufacturing process. The surface quality of the finished product is generally measured by the surface integrity of the workpiece\cite{3-4}. As a ductile material, 6061 Al-alloy is generally considered to have good processing properties. However, its high ductility will increase the cutting force and heat generation due to its high ductility, resulting in poor surface finish and difficulty in chip control\cite{5}. Therefore, it is particularly important to adopt appropriate processing technology to obtain better surface finish.

In the cutting process, the optimization of cooling conditions is one of the effective strategies to improve the surface integrity of the workpiece\cite{6}. Traditional emulsion cutting helps reduce the friction of the cutting surface and lower the temperature of the cutting area. However, the use of emulsion will pollute the environment and even cause harm to workers’ health. Therefore, from the perspective of environmental protection, cryogenic cooling technology provides a potential choice. Cryogenic cooling cutting is a processing technology that uses a special device to transfer a cryogenic medium (such as liquid nitrogen, liquid CO\textsubscript{2}, etc.) to the cutting area to assist traditional cutting\cite{7}. The method can greatly reduce the cutting temperature, increase the tool life, and significantly improve the machining accuracy and surface quality. In this paper, a single factor cutting test was conducted on turning 6061 Al-alloy to discuss the effect of different cooling media. Machining results was proposed and discussed according to surface roughness, residual stress and microhardness.
2. Experimental preparation

2.1. Workpiece
In order to analyze the surface integrity of 6061 Al-alloy with various cooling conditions, radial turning tests were carried out. The 6061 Al-alloy rod was used for the test, and its chemical composition is shown in Table 1. The mechanical properties are shown in Table 2. The rod was processed into a disc-shaped workpiece with 100 mm diameter and 10 mm thickness by Wire Electrical Discharge Machining (WEDM).

| Table 1. The chemical composition of 6061 Al-alloy (wt. %) |
|-----------------|-----|-----|-----|-----|-----|-----|-----|-----|
| Cu              | Cr  | Mn  | Mg  | Si  | Ti  | Zn  | Fe  | Al  |
| 0.15-0.4        | 0.04-0.35 | 0.15 | 0.8-1.2 | 0.4-0.8 | 0.15 | 0.25 | 0.7 allowance |

| Table 2. The mechanical properties of 6061 Al-alloy |
|-----------------|-----|
| Properties      | Units |
| Tensile strength| 205GPa |
| Yield strength  | 55.2MPa |
| Elastic modulus | 68.9GPa |

2.2. Experimental equipment and procedure
Radial turning tests were performed on CNC CAK3665 lathe. The disc-shaped workpiece was installed on the machine via a specific fixture. The uncoated carbide insert TPGN220408 produced by Kennametal with the grade of K313 was selected. Cutting speed was 300m/min, feed was 0.1mm, and depth of cut was 0.3 mm. Three cutting experiments were carried out under the same cutting parameters but different cooling conditions, namely dry, emulsion and cryogenic cooling conditions. The emulsion used was 0058 emulsion which was suitable for aluminum alloy cutting. The main body of the liquid nitrogen cooling device used was self-pressurized liquid nitrogen tank. The outlet pressure of liquid nitrogen tank was nearly stable at 1.5MPa during the cutting process. Liquid nitrogen and emulsion were continuously injected into the cutting area of the workpiece through circular nozzles. The experimental device is shown in Fig. 1.

Fig. 1 The experiment device

The roughness value was obtained along the feed direction with Mitutoyo Sj-410 profilometer. Each group of measurements was repeated 5 times at different positions of the machined surface, and the average value was taken. The three-dimensional topography were also observed to further study the surface quality via the Usp-sigma white light interferometer. The surface residual stress along the feed direction was obtained by PROTO iXRD residual stress instrument. Cr target was used in the experiment.
with Bragg angle of 139°. The average value was calculated as the final data value after 5 times of measurement in each group. The surface microhardness was measured on the 402MVD microhardness tester. The measurement of the microhardness was carried out under a load of 0.25N with a holding time of 10s. In order to improve the accuracy of the measurement results, each group also selected 5 different positions for measurement and took the average value.

3. Results and discussion

3.1. Surface roughness

Surface roughness is generally considered as one of the important parameters to evaluate the machined surface quality[8]. The surface roughness values with various cooling conditions are compared in Fig. 2. The results show that under the same cutting parameters, the roughness processed by dry condition was the highest, followed by emulsion condition, and liquid nitrogen cryogenic cooling condition was the lowest.

![Fig. 2 The surface roughness with various cooling conditions.](image)

In the dry cutting process, there will be severe friction between the tool and the workpiece, and between the tool and the chips. Friction generates a lot of frictional heat, which causes the temperature of the cutting area to rise. Some studies[9-10] have shown that high cutting temperature will aggravate the formation of built-up edge and tool wear, and eventually lead to the continuous deterioration of machined surface quality. The use of emulsion or liquid nitrogen to assist the processing will desirably reduce the friction coefficient, which can greatly inhibit the generation of heat, improving the surface quality of the machined surface. In addition, micro plastic deformation occurs on the surface for plastic materials under the coupling effect of the extrusion of the tool and the cutting heat[11]. Among the three processing conditions, it is not difficult to know that the cutting temperature is the lowest in the cryogenic cooling cutting with liquid nitrogen. Therefore, under the action of liquid nitrogen, the plasticity of the material will be significantly reduced, and the plastic deformation ability of the workpiece surface will be reduced. Consequently, better surface finish can be obtained.
Fig. 3 shows the three-dimensional morphology of the generated surface. As shown in Fig. 3(a), the workpiece surface obtained by dry conditions has a lot of burr and flash. However, the workpiece surface obtained by emulsion and cryogenic cooling cutting in Fig. 3(b) and (c) is relatively smooth, and the surface quality is effectively improved. In particular, a smoother machined surface is produced under the cryogenic cooling condition with liquid nitrogen.

3.2. Surface residual stress

In the process of cutting, plastic deformation caused by thermal stress and mechanical stress and phase transformation effect of machined surface layer metal will lead to the generation of surface residual stress[12]. The existence of tensile residual stress is prone to produce microcracks on the machined surface, thus reducing the fatigue strength of the workpiece. The surface residual tensile stress with various cooling conditions are shown in Fig. 4.

By comparing the residual tensile stress values in Fig. 4, it can be seen that emulsion cutting and cryogenic cooling cutting with liquid nitrogen obtain lower residual tensile stress compared with dry cutting. The literature[13] has proved that high friction and cutting heat produced by dry conditions will aggravate plastic deformation and phase transformation of the machined surface. Thus, the use of coolant can reduce the effect of thermal stress on surface residual stress. The cooling effect of liquid nitrogen is more prominent compared with emulsions, which can suppress the generation of residual tensile stress to a greater extent. Therefore, the surface processed by liquid nitrogen cryogenic cooling cutting has the lowest tensile residual stress.
3.3 Microhardness

In machining, work-hardening is a common phenomenon on the machined surface of workpiece. As mentioned above, a series of plastic deformations occur on the metal material of the machined surface during the cutting process. With the increase of material flow stress and deformation resistance caused by plastic deformation, the surface strength and hardness of the workpiece increase, and the plasticity and toughness decrease. The phenomenon is called work-hardening[14]. Work-hardening affects the service life and performance of the workpiece. Generally, the microhardness is taken as the index of work-hardening. Fig. 5 shows the microhardness of the machined surface with various cooling conditions.

![Graph showing microhardness with various cooling conditions](image)

As shown in Fig. 5, the surface microhardness after cutting has been improved compared with the matrix hardness of the material. Obviously, the surface microhardness obtained by dry condition is the lowest, followed by emulsion condition, and the highest by cryogenic cooling condition with liquid nitrogen. Due to the cutting heat generated by dry cutting, the surface of workpiece will be affected by thermal softening effect under certain conditions, and the surface microhardness will be reduced to a great extent. Cutting in a low temperature environment can restrain the influence of thermal effect on the machined surface. Hence, the hardness of the machined surface is the highest under the cryogenic cooling condition with liquid nitrogen.

4. Conclusions

The same cutting tool and cutting parameters were used to turn 6061 Al-alloy with various cooling conditions. The surface integrity of machined surface was discussed from three aspects of surface roughness, residual stress and microhardness. The following conclusions can be drawn from this study:

1)The surface quality of the workpiece obtained by dry cutting is poor, which is mainly manifested in high roughness, large residual tensile stress and low microhardness. Consequently, dry cutting is not recommended for 6061 Al-alloy.

2)The use of emulsion and liquid nitrogen can effectively reduce the surface roughness, restrain the residual tensile stress and improve the surface microhardness. Moreover, cryogenic cooling cutting with liquid nitrogen can obtain the best surface quality due to its outstanding cooling effect.

Generally speaking, cryogenic cooling can be regarded as a promising cooling and lubrication strategy to improve the cutting performance and service performance of the workpiece by improving the surface quality of the machined surface.

Acknowledgments

This work was supported by National Natural Science Foundation of China (Grant No.52005215), Key R&D Program of Shandong Province (Grant No. 2018GX03010, 2019GGX104096), and Project of Shandong Province Higher Educational Science and Technology Program (Grant No. 2019KJB021).
References

[1] Demir, H., Gündüz, S. (2009) The effects of aging on machinability of 6061 aluminium alloy. Materials and Design, 30(5): 1480-1483.

[2] Rahman, M. S. U., Jayahari, L. (2018) Study Of Mechanical Properties and Wear Behaviour of Aluminium 6061 Matrix Composites Reinforced with Steel Machining Chips. Materials today: proceedings, 5(9): 20117-20123.

[3] Jawahir, I. S., Brinksmeier, E., M'Saoubi, R., et al. (2011) Surface Integrity in Material Removal Processes: Recent Advances. CIRP Annals - Manufacturing Technology, 60(2): 603-626.

[4] Toh, C. K., Kanno, S. (2004) Surface integrity effects on turned 6061 and 6061-T6 aluminium alloys. Journal of Materials Science, 39(10): 3497-3500.

[5] Santos, M.C., Mário, C., Machado, A. R., Sales, W. F., et al. (2016) Machining of aluminium alloys: a review. International Journal of Advanced Manufacturing Technology, 86(9–12): 3067-3080.

[6] Ashrafi, S. A., Davoudinejad, A., Niazi, A. (2013) Investigations into Effect of Tool Wear on Surface Integrity in Dry Turning of Al6061. Advanced Materials Research, 622-623: 375-379.

[7] Yildiz, Y., Nalbant, M. (2008) A review of cryogenic cooling in machining processes. International Journal of Machine Tools & Manufacture, 48(9): 947-964.

[8] Persson, B. N. J., Albohr, O., Tartaglino, U., et al. (2005) On the nature of surface roughness with application to contact mechanics, sealing, rubber friction and adhesion. J.phys.condens.matter, 17(1): 1.

[9] Pattnaik, S. K., Bhoi, N. K., Padhi, S., et al. (2017) Dry machining of aluminum for proper selection of cutting tool: tool performance and tool wear. International Journal of Advanced Manufacturing Technology, 98(1-4): 55-65.

[10] Parida, A. K., Rao, P. V., Ghosh, S. (2019) Influence of cutting speed and nose radius in the machining of Al-6061: FEM and experimental validation. Materials Today: Proceedings, 27.

[11] Shankar, M. R., Chandrasekar, S., Compton, W. D., et al. (2005) Characteristics of aluminum 6061-T6 deformed to large plastic strains by machining. Materials Science & Engineering A, 410: 364-368.

[12] Singh, A., Agrawal, A. (2015) Investigation of surface residual stress distribution in deformation machining process for aluminum alloy. Journal of Materials Processing Tech, 225: 195-202.

[13] Sreejith, P. S. (2008) Machining of 6061 aluminium alloy with MQL, dry and flooded lubricant conditions. Materials Letters, 62(2): 276-278.

[14] Pan, Z., Feng, Y., Liang, S. Y. (2017) Material microstructure affected machining: a review. Manufacturing Review, 4: 5.