Research on surface integrity in graphene nanofluid MQL milling of TC21 alloy

Ming Li[1,a], Tianbiao Yu[1,b*], Hongyu Li[1,c], Lin Yang[1,d], Jiashun Shi[1,e], Wanshan Wang[1,f]

[1]School of Mechanical Engineering and Automation, Northeastern University, Shenyang 110819, China

[a]limingeducn@163.com, [b]tianbiaoyudyx@gmail.com, [c]m18640389373@163.com, [d]jwdcmyl1011@gmail.com, [e]jshshi@mail.neu.edu.cn, [f]wws@mail.neu.edu.cn

Keywords: graphene nanofluid; MQL milling; surface integrity; TC21

Abstract. TC21 is a new type of damage-tolerance titanium alloy and is widely used in aerospace. However, TC21 is a difficult-to-machine material owing to its low thermal conductivity, high chemical activity and low elasticity modulus. In this work, Minimum Quantity Lubrication (MQL) with graphene nanofluid was adopted in TC21 milling. In order to evaluate the effects of graphene nanoparticle on the surface integrity, a series of milling experiments were performed under the dry, gas, pure MQL and graphene nanofluid MQL condition respectively. Results showed that the graphene additive was effective for improving the surface integrity. Overall, the results could be explained that graphene additive could enhance the cooling and lubrication performances of the oil film formed in cutting zone. The findings of this work are expected to give a feasibility and some experimental basis for the application of the graphene additive in MQL milling.

1 Introduction

Surface integrity directly determines the serviceability and reliability of the workpiece. As a green and environment-friendly cooling and lubricating form, Minimum Quantity Lubrication (MQL) is widely used to improve the surface integrity in machining process.

Kishawy et al. [1] studied the machining characteristics of aluminum alloy A356 under different cooling conditions and found that MQL is effective for improving tool wear and surface integrity and revealed the relevant improvement mechanism. Ming Chen et al. [2] studied the optimization of machining parameters in MQL turning of titanium alloy by using CRSM and found that the optimization method was effective. Based on the theory of solid enhancing heat transfer [3], various nanoparticles were added into traditional cutting fluids to further improve the cooling and lubrication performances. Changhe Li et al. [4] evaluated the machining characteristics in different cooling conditions and found that MoS2 nanoparticle jet MQL condition achieved the best lubricating property. Marcon et al. [5] studied the effects of graphite nanoplatelet nanofluid under micro-milling of hardened steel and found that the lubricant was effective for reducing tangential force and had a negative impact on the dimensional accuracy. In addition, some other nanoparticles were also dispersed to the traditional cutting fluids, such as ZrO_2 [6], carbon onions [7] and polycrystal diamond [6].

Graphene is a two-dimensional material with excellent cooling and lubrication properties [8]. However, the cooling and lubrication properties of graphene nanofluid in MQL milling are rarely studied. To fill this gap, in this paper, graphene nanofluid was prepared and the effects of graphene nanofluid on surface integrity were evaluated by conducting systematic experiments. The influence mechanisms were discussed through experimental results. The findings of this work are expected to give a feasibility and some experimental basis for the application of the graphene additive in MQL milling.

2 Experiment

In this work, a series of milling experiments under the dry, gas, pure MQL and graphene nanofluid MQL condition were conducted to evaluate the effects of the cooling/lubrication condition on surface integrity respectively.

2.1 Two-step preparation of graphene nanofluid

In this study, the graphene-dispersed cutting fluids were prepared by using the two-step method. The prepared nanoparticles are dispersed into a cutting fluid to prepare the nanoparticle-dispersed cutting fluid, i.e., the preparations of nanoparticles and nanoparticle-dispersed cutting fluids are not performed at the same time. In addition, the process is simple, relatively inexpensive and therefore suitable for industrial applications. In this work, LB2000 (supplied by ITW Rocol North America Co., Ltd.) was selected as the base oil. Meanwhile, the few-layer graphene was used as the additive. The properties of LB2000 and graphene are shown in Tables 1 and 2, respectively.

Table 1. The properties of LB2000

Property	Density (g/cm^3)	Flash point (℃)	Pour point (℃)	Appearance
Value	0.92	320	-20	Dark blue fluid

Table 2. The properties of graphene

Property	Average layer thickness (nm)	Mean diameter (μm)	Number of layers	Specific surface area (m^2/g)	Appearance
Value	< 5	10	1-5	360-450	Black powder

A certain amount of graphene nanoparticles were dispersed into LB2000 with the weight concentration of 0.1 wt.% by a two-step method. The dispersion process of the cutting fluid included first stirred on a magnetic stirrer (for 30 min) and then dispersed on an ultrasonic dispersion instrument (40 kHz, 80 W) (for 1 h), as shown in Fig. 1. The graphene nanofluid was steady and no settlement was found during the entire experiment process.

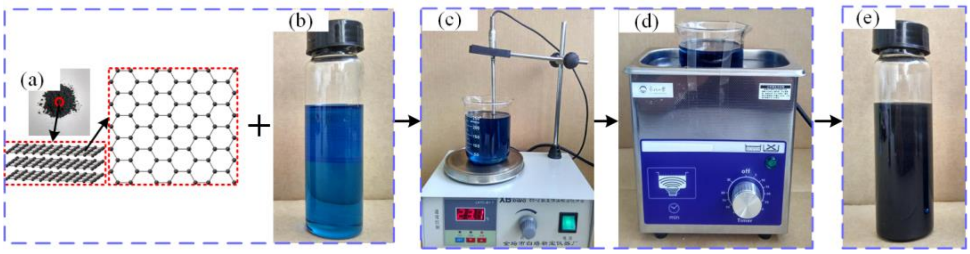

Fig. 1. This preparation process of graphene nanofluid ((a) the few-layer graphene, (b) pure LB200, (c) magnetic stirrer, (d) ultrasonic dispersion instrument and (e) graphene nanofluid)

2.2 Experimental equipment

In this work, the experiments were performed on a five-axis machining center (DMG-DMU50), as shown in Fig. 2(b). Meanwhile, Accu-Lube MQL system (supplied by ITW Rocol North America Co., Ltd.) was adopted to carry out the MQL milling experiments, as shown in Fig. 2(c). The main MQL parameters included: the MQL gas pressure of 0.6 MPa and the MQL flow rate of 60 mL/h. In addition, a 3D force-measuring system (9257B, Kistler Co., Ltd) and a temperature-measuring system were adopted to measure milling force and milling temperature respectively. The sample frequency of milling force and milling temperature were set at 4000 and 20 KHz respectively.

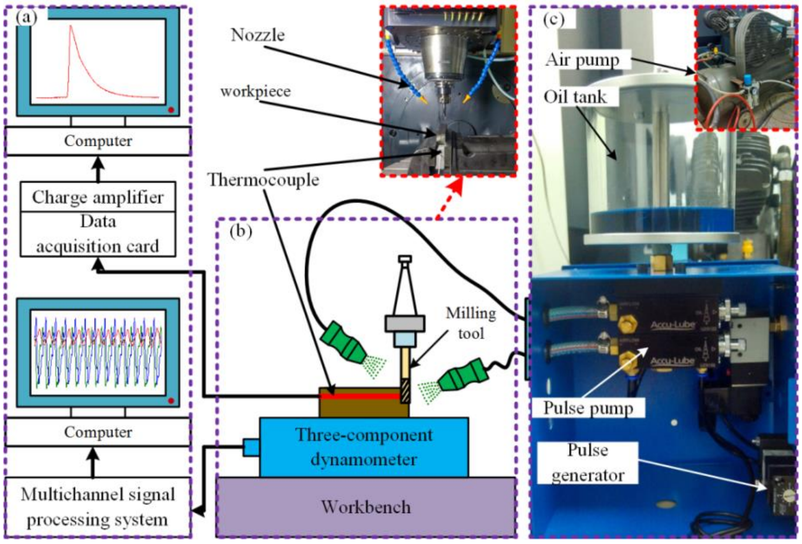

Fig. 2. (a) Measurement system, (b) machine tool and (c) MQL system

2.3 Workpiece material and cutting tool

In this work, the workpiece material was the titanium alloy TC21. The chemical composition and mechanical properties of TC21 are shown in Table 3 and 4, respectively. In addition, the milling tools used were solid carbide end mill (OSL, Taiwan 7-Leaders Corp.) with a diameter of 8 mm, a spiral angle of 35-degree and four flutes. The matrix material was ultra-fine tungsten steel and the coating material was TiAlN.

Table 3. The chemical composition of TC21 [9]

Element	Ti	Si	Zr	Nb	Mo	Sn	Al	Cr
Composition (wt.%)	Balance	0.09	2.19	2.31	2.87	2.32	6.78	0.77

Table 4. The mechanical properties of TC21 [9]

Property	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)	Percentage of area reduction (%)	Plane strain fracture toughness (MPa$\cdot\sqrt{m}$)
Value	1174	1083	11.3	20	90.6

2.4 Experimental scheme

In order to evaluate the effects of the cooling/lubrication condition on surface integrity, a series of milling experiments were designed. In order to measure the surface integrity more conveniently, the side milling strategy (i.e., the partial immersion milling) was chosen to evaluate surface integrity. The main machining parameters were as follows: the spindle rotation speed (N = 1194 rpm), the feed rate per tooth (f_z = 0.02 mm), the radial cutting depth (a_e = 0.1 mm) and the axial cutting depth (a_p = 1 mm). As shown in Fig. 3(a), the machined surface was observed by using the laser confocal microscope (LEXT OLS4100, Japan Olympus Corporation). In addition, the micro-hardness tester (TUKON1102, Wilson) was adopted to measure the micro-hardness, as shown in Fig. 3(b). In addition, the milling force and the milling temperature were measured simultaneously, as shown in Fig. 2(a).

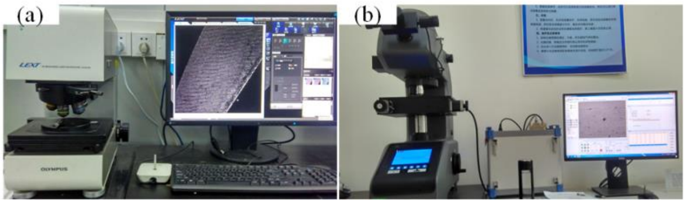

Fig. 3. (a) Laser confocal microscope and (b) micro-hardness tester

3 Experimental results and discussions

Confocal microscope photos of the machined surface are shown in Fig. 4. Obviously, adhesion, large furrow and feed mark were observed on the machined surfaces under the dry and gas condition and yet only feed mark was observed under the pure MQL and graphene nanofluid MQL condition. The surface roughness of the machined surface was measured respectively, as shown in Fig. 5(b). By comparison, the maximum roughness (1.143 μm) is obtained by the dry condition. The surface roughness of the machined surface under the gas, pure MQL and graphene nanofluid MQL condition is 1.108, 0.753 and 0.528 μm, which is 3.06%, 34.12% and 53.81% smaller than that of the dry condition, respectively.

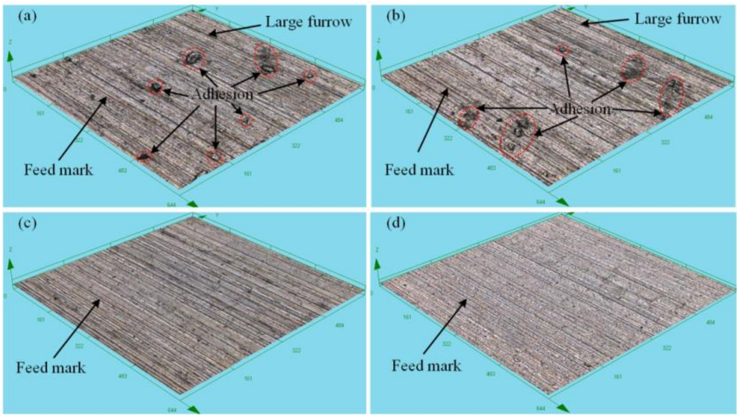

Fig. 4. Confocal microscope photos of the machined surface ((a) dry, (b) gas, (c) pure MQL and (d) graphene nanofluid MQL)

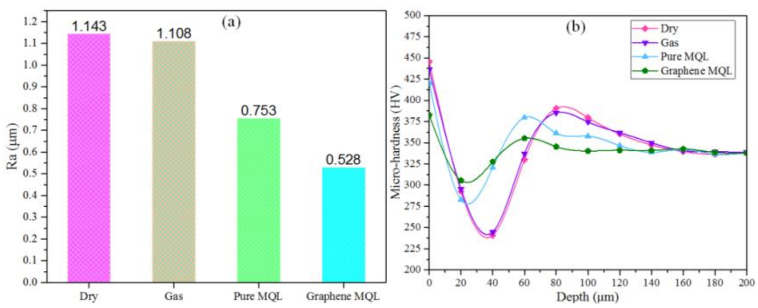

Fig. 5. (a) The surface roughness and (b) the tendency of micro-hardness

Among the four cooling/lubrication conditions, the machined surfaces obtained in the pure MQL and graphene nanofluid MQL condition are much better than those obtained under the dry and gas condition. This may be because the oil films formed in the cutting area have a good load-bearing capacity and separate the tool flank from the machined surface to reduce adhesion, large furrow and surface roughness. The surface roughness obtained by the graphene nanofluid MQL condition is smaller than that obtained by the pure MQL condition. This may be due to the fact that the graphene additives could enhance the load-bearing capacity of the oil films to improve the lubrication performance of the cutting fluid.

Meanwhile, the measured micro-hardness is shown in Fig. 5(b). The tendencies of micro-hardness under the four cooling/lubrication conditions almost follow a similar rule: the micro-hardness on the machined surface is the largest, and with the increase of depth the micro-hardness first decreases and then increases, and eventually reaches the micro-hardness of the matrix material (338 HV). Among the four cooling/lubrication conditions, the dry condition yields the largest micro-hardness (445.57 HV). The micro-hardness on the machined surface under the gas, pure MQL and graphene nanofluid MQL condition is 436.43, 420.51 and 382.73 HV, which is 2.05%, 5.62% and 14.10% smaller than that of the dry condition, respectively.

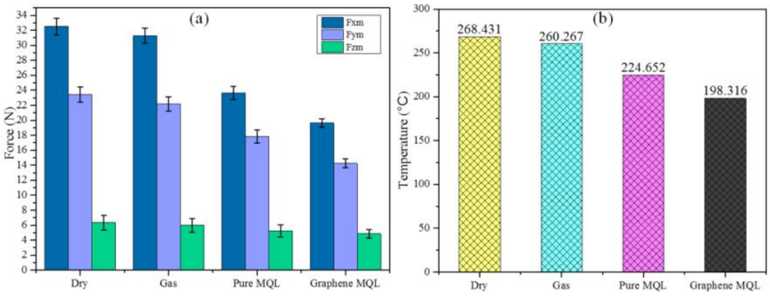

Fig. 6. (a) The maximum of milling force and (b) the maximum of milling temperature

The work hardening in the cutting process is mainly caused by the interaction of friction, extrusion and cutting heat. The friction and extrusion could enhance the work hardening, yet the cutting heat could reduce the work hardening. The micro-hardness measured on the machined surface is higher than the matrix material. This may be because the enhancing effects produced by the friction and extrusion play a leading role on the machined surface. The tendencies of micro-hardness with the increase of depth may be due to the interaction of the enhancing effects and the reducing effect. The graphene nanofluid MQL condition yields the smallest micro-hardness on the machined surface. This may be because graphene additives could enhance the lubrication properties of the oil film to reduce the extrusion caused by milling force and the friction in the tool-workpiece interface. It could be concluded from the tendencies of micro-hardness in Fig. 5(b) that the depth of the influence layer under the graphene nanofluid MQL condition is smallest. This may be because graphene additives could enhance the lubrication and cooling properties of the oil film to reduce the extrusion, friction, and cutting heat so that the depth of the influence layer is reduced.

4 Conclusion

In this work, the effects of the graphene additive on surface integrity of machined surface are analyzed. The conclusions are as follows:

(1) The graphene nanofluid is prepared by a two-step method. The graphene nanofluid is steady and no settlement is found during the entire experiment process. Hence, the preparation method of graphene nanofluid is feasible.

(2) While applying the graphene nanofluid MQL to the milling process, adhesion and large furrow are significantly reduced. Meanwhile, the graphene nanofluid MQL condition achieves the smallest surface roughness. This may be due to the fact that the graphene additives could enhance the load-bearing capacity of the oil films to improve the lubrication performance of the cutting fluid.

(3) Regarding the work hardening, the surface micro-hardness under the graphene nanofluid MQL condition is smallest. In addition, the depth of the influence layer under the graphene nanofluid MQL condition is smallest. This is likely because graphene additives could enhance the lubrication and cooling properties of the oil film to reduce the extrusion, friction, and cutting heat.

Acknowledgement

This study was supported by grants from the Major Project of Ministry of Industry and Information Technology of China (201675514) and the Key Laboratory Special Project of Shenyang City (F15153100).

References

[1] Kishawy H A, Dumitrescu M, Ng E G, et al. Effect of coolant strategy on tool performance, chip morphology and surface quality during high-speed machining of A356 aluminum alloy[J]. International Journal of Machine Tools & Manufacture, 2005, 45(2):219-227.

[2] Liu Z Q, Xu J, Han S, et al. A coupling method of response surfaces (CRSM) for cutting parameters optimization in machining titanium alloy under minimum quantity lubrication (MQL) condition[J]. International Journal of Precision Engineering & Manufacturing, 2013, 14(5):693-702.

[3] Choi S U S. Enhancing thermal conductivity of fluids with nano-particles[J]. Asme Fed, 1995, 231(1):99-105.

[4] Zhang Y, Li C, Jia D, et al. Experimental evaluation of MoS_2, nanoparticles in jet MQL grinding with different types of vegetable oil as base oil[J]. Journal of Cleaner Production, 2015, 87(1):930-940.

[5] Marcon A, Melkote S, Kalaitzidou K, et al. An experimental evaluation of graphite nanoplatelet based lubricant in micro-milling[J]. CIRP Annals - Manufacturing Technology, 2010, 59(1):141-144.

[6] Jia D, Li C, Zhang D, et al. Experimental verification of nanoparticle jet minimum quantity lubrication effectiveness in grinding[J]. Journal of Nanoparticle Research, 2014, 16(12):1-15.

[7] Sayuti M, Sarhan A A D, Tanaka T, et al. Cutting force reduction and surface quality improvement in machining of aerospace duralumin AL-2017-T4 using carbon onion

nanolubrication system[J]. International Journal of Advanced Manufacturing Technology, 2013, 65(9-12):1493-1500.
[8] Berman D, Erdemir A, Sumant A V. Graphene: a new emerging lubricant ☆[J]. Materials Today, 2014, 17(1):31-42.
[9] Sun T, Fu Y C, He L, et al. Machinability of plunge milling for damage-tolerant titanium alloy TC21[J]. International Journal of Advanced Manufacturing Technology, 2016, 85(5-8):1315-1323.