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ARTICLE

# Adhesive Wear, Surface Roughness, and Cutting Forces of Ti-6Al-4V Alloy Machining with Graphene Nanofluids

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**Abstract:** A novel machining method based on the graphene nanoparticles dispersed in canola oil as the cutting fluid to provide lubrication/cooling effect for the processing area was proposed. The effects of the nanofluid on the chip adhesion layer of the cutter were determined. Compared with the dry cutting method, the thicknesses of chip adhesion layers on the flank face and rake face of cutter decrease by 38.8% and 28.8% with the canola oil+graphene nanofluid, respectively. In addition, the cutting force and workpiece surface roughness decrease by 51.4% and 50.1%, respectively. The relatively high thermal conductivity of graphene can reduce the temperature of the cutting zone. In addition, the graphene can penetrate the contact zone between the chip adhesion layer of cutter and the workpiece, which effectively protects the coating of cutting tool and decreases the chip adhering to the workpiece surface. Besides, the graphene can fill the pits on the workpiece surface, thus improving the cutter surface quality.

**Key words:** graphene nanofluid; chip adhesion layer; cutting force; surface roughness; cutting heat

The titanium alloys have high chemical reactivity, excellent strength and hardness, and low thermal conductivity, which lead to the high cutting force and large friction heat during the machining[1]. The friction heat generated by machining accumulates in the cutting zone and causes very high local temperature. Besides, the high temperature also occurs at the interface between the cutter and workpiece, causing wear of the cutter[2], which influences the quality, cutting force, and cutting temperature of the processed surface. Therefore, reducing the cutter wear is of practical significance. Currently, the oil injection method is a widely used way, and thereby the application of cutting fluid is inevitable, which may cause problems to human health and environment[3]. In addition, the metalworking fluids have been identified as the detrimental factor to human health, which may lead to the dyspnea and even cancer[4]. Therefore, the amount of coolant used in metal removal operations should be reduced. The minimum quantity lubrication (MQL) is a popular method to deal with this problem and it gradually replaces the traditional lubrication system. MQL is a near-dry processing method to provide lubricants: the high pressure air-oil mixtures are used in the processing areas[5]. Sun et al[6] observed that in the final milling process of titanium alloy, the cutting force is significantly reduced during MQL treatment, compared with that during the perfusion and dry cutting treatments. In addition, Gelfi et al[7] found that the wear rate of cutting tools with MQL treatment is lower than that with dry machining. Sreejith et al[8] used the cemented diamond-coated carbide tools to process the 6061 aluminum alloy and compared the surface roughness of workpiece processed in dry and MQL environment. It is reported that the surface in MQL environment is significantly smoother than that in dry machining environment. Although MQL method provides the lubrication, the lubrication effect of the processing area is insufficient under heavy processing conditions.

The nanofluid minimal quantity of lubricant (NMQL) is an

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advanced and environmental-friendly precision processing technique[9], which can also improve the cutting performance[10,11]. The nanoparticles serve as the solid lubricant at the cutter-workpiece interface and can even form a physical/chemical lubrication film, thereby improving the lubrication performance and heat absorption at the cutter-workpiece interface. Various nanoparticle additives have been used as lubricants, such as graphite, titanium dibromide ($TiB_2$), calcium fluoride ($CaF_2$), molybdenum disulfide ($MoS_2$), tungsten disulfide ($WS_2$), aluminum oxide ($Al_2O_3$), silicon dioxide ($SiO_2$), carbon nanotubes (CNTs), copper oxide (CuO), carborundum (SiC) [12,13], phosphate, and hydrocarbons[14]. Although the existing nanoparticles can provide cooling and heat exchange to promote the high surface quality and high-precision processing, further improvements of the lubricants are still in need. Particularly, the lubrication and friction performance of nanoparticles in the cutting zone should be deeply investigated[15].

Graphene has excellent thermal conductivity, superb lubrication performance, and high thermal conductivity[16], presenting great potential in the enhancement of lubrication and heat absorption in the cutting zone as the cutting fluid additive. Although various types of tool wear exist, only the adhesive wear of the tool was investigated in this research. In order to observe the effect of nanoparticles on the adhesive wear, the cemented carbide-coated tool was selected for the experiment. In this research, the influence of graphene on the cutter chip adhesion layer and the influence of this layer on the workpiece surface roughness and cutting force were studied. For comparison, the experiments under the dry cutting and the simple canola oil conditions were also conducted.

## 1 Experiment

In the preparation of nanofluid, the mixing of nanoparticles with the base fluid is crucial due to the stability of nanoparticles. The diffusion of nanoparticles in the solution is generally accomplished by the two-step method[17] because of the simple preparation process and low cost. Moreover, the two-step method can prevent the adhesion of nanoparticles caused by the interaction during the transportation and storage, which results in the inhomogeneity[18].

The 0.5vol% nanoparticles were initially added into the botanical-based cutting oil and then mixed to prevent nanoparticle aggregation. Cui et al[19] studied the tribological properties of four nanofluid lubricants, and their friction coefficient could be arranged as follows: $MoO_3$>HBN>$MoS_2$> graphene. It is revealed that the graphene nanoparticles have good friction resistance and better lubrication effect than other nanoparticles do. Besides, the carbon materials usually have excellent anti-wear characteristics. Thus, the thin sheet graphene with specific self-lubricating properties has great potential to be the “molecular ball (axis)” lubricant additive, thereby significantly reducing the friction coefficient. In addition, based on its excellent thermal conductivity, the graphene can simultaneously achieve the enhancement in heat transfer by adding nanoparticles as nanofluids[20]. The high-precision electronic balance (precision=0.001 g) was used to weigh the canola oil and graphene nanoparticles (step I). The solution mixture was stirred at 1500 r/min for 90 min by the SUNNE (China) magnetic stirrer (step II). Finally, the solution was dispersed by ultrasound for 2 h (step III). The preparation process is shown in Fig.1.

The Ti6-Al4-V alloy specimen with the diameter of 30 mm and length of 200 mm was used for experiments. The cutting tool had a carbide blade (DCMT11T304-SMIC907) with the titanium nitride coating. The processing was conducted in turning mode. To compare the chip adhesion layers of cutter under different processing conditions, the cutting tool blades were changed before each test. The parameters of the cutting tool are shown in Fig.2.

The turning tests were performed on a numerically controlled lathe (CAK4085nj, Shenyang Machine Tool Plant, China). The cutting temperatures were measured by the FLIR T630sc thermal infrared imager. The working temperature was −40~600 °C and the image acquisition frequency was 50~200 Hz. The temperature error of the equipment was less than 0.1 °C. Firstly, the infrared thermal imager was installed at about 1 m away from the lathe. Secondly, adjust the observation area of the infrared thermal imager for clear observation of the contact area between the tool and workpiece. Finally,

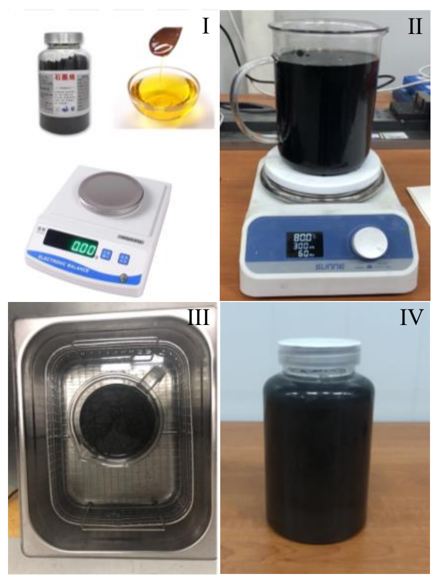



Fig.1 Preparation process of cutting nanofluid

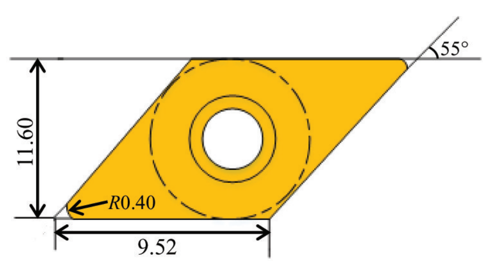



Fig.2 Schematic diagram of cutting tool

identify the highest cutting temperature in the processing area. In addition, the chip adhesion layer of cutter was observed by the field emission scanning electron microscope (SEM, ZEISS). The energy-dispersive X-ray spectroscope (EDS) was used to detect the delamination of the tool adhesion layer. The cutting force was measured by the Kistler9257B three-dimensional measuring cell with supporting Kistler 5070 type charge amplifier. The cutter was installed on the measuring cell by the specially designed clamp. Then, the signal processing software DynoWare was used to acquire and process of force data. The dynamometer collected a lot of force data, and only the average cutting force could represent the stability of the cutting process. The workpiece surface roughness after turning was measured by the surface roughness measuring instrument (TR240). The sampling length was 0.8 mm. The bar was divided into four segments with equal length. In each segment, six measurement points were chosen randomly along the circumference of the workpiece. Hence, the surface roughness at 24 points was measured and the mean surface roughness was used for analysis. In this experiment, the outlet temperature of the MQL equipment was −10 °C, the air source pressure of the air compressor was 1 MPa, and the fluid flow of the nozzle was 70 mL/h. To insure the sufficient lubrication and cooling of the cutter point and the sufficient liquid spraying pressure, the distance from the nozzle to the cutter point was 30 mm. Meanwhile, the angle between the nozzle and cutter rake surface was 45° . The experiment equipment setup is shown in Fig.3.

The turning tests were conducted under three processing conditions: (1) canola oil+graphene; (2) simple canola oil; (3) dry cutting. The cutting speeds of 60 and 100 m/min were used. The feeding rate *f* was 0.1 mm/rev, the cutting depth was 0.5 mm, and the turning length was 80 mm. All experiments were conducted at 0.1 MPa and the cutting speed was adjusted by changing the number of lathe turns. Each experiment was repeated at least three times. After the cutting process, the canola oil on the cutter and workpiece surfaces was cleaned for the subsequent surface element detection. In addition, a small part of the workpiece was cut by the linear cutting equipment for surface element detection.

## 2 Results and Discussion

### 2.1 Maximum temperature

In the process of material removal, the plastic deformation occurs, and 90%~95% mechanical energy is converted into heat. The temperature accumulation in the cutting area can soften the material and reduce the cutting force in the machining process. In addition, the high cutting force is also unfavorable to the mechanical processing. Although the partial heat transfers from the machining area to the tool, it still causes severe tool wear and reduces the surface quality of the workpiece. Therefore, the reduction of heat accumulation in the processing area is crucial. Fig. 4 presents the temperatures in the chip adhesion layer and workpiece contact zone under different processing conditions.

According to Fig. 4, it can be seen that the temperature is the highest under dry cutting condition, reaching 305.0 and 340.0 °C at cutting speed of 60 and 100 m/min, respectively. The temperatures under the canola oil condition are medium, reaching 159.2 and 180.3 °C at cutting speed of 60 and 100 m/min, respectively. The lowest temperatures are obtained under the canola oil+graphene condition, which are 119.2 and 129.0 °C at cutting speed of 60 and 100 m/min, respectively. In addition, the temperature is obviously increased with increasing the cutting speed. It can be concluded that the maximum cutting temperature occurs under the dry machining condition, and the application of cooling lubrication can significantly reduce the cutting temperature. Thus, compared with that under dry cutting condition, the activation of the machining process with NMQL system under the canola oil+graphene condition decreases by 62.1%. During the chip removal, the heat is generated in the primary and secondary deformation zones and the side (aperture) surfaces, but the temperature at the chip-tool interface is the highest[21]. The application of lubricant at the contact interface between the tool and workpiece is a common method for temperature control. The atomized oil droplets enter into the contact interface between the tool and workpiece by the compressed air. The strong pressure of compressed air can effectively transport the oil droplets to the place with the highest temperature, thereby greatly reducing the contact temperature between the tool and the workpiece. Similarly, the graphene in the canola oil can also be transported to the contact area between the tool and the workpiece. When the solid lubricant particles are uniformly dispersed in the base coolant, its thermal conductivity can be improved. Therefore,

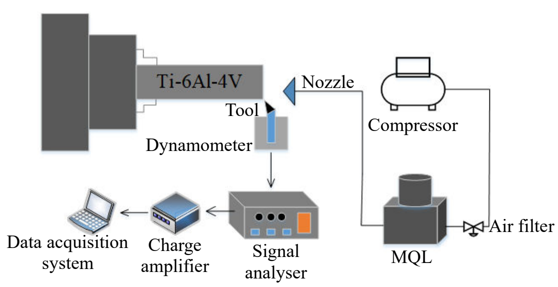



Fig.3 Schematic diagram of experiment equipment setup

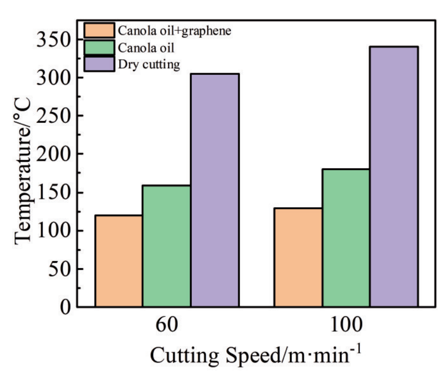



Fig.4 Temperatures in chip adhesion layer and workpiece contact zone under different processing conditions

the temperature in the cutting area can be discharged faster[22], resulting in the reduced temperature.

### 2.2 Chip adhesion layer

The tool wear directly affects the tool life and quality, thereby affecting the processing cost[23]. The tool wear is related to the mechanical, chemical, and thermal interactions between the tool and the workpiece, involving various mechanisms, such as flank wear, nose wear, crater wear, notch wear, built-up edge, plastic deformation, thermal cracks, and edge chipping/breakage[24]. Yldrm et al[25] found that during the turning of the nickel-chromium iron (Inconel 625) alloy, both the flank wear and pit wear are in the dominant position at the cutter point. In addition, the built-up edges and the shape of the adhesion layer can be observed at the cutter edge according to the adhesive force. Liang et al[26] processed the Ti-6Al-4V alloy by a fine-grain cutter, studied the wear behavior of the cutter and processing surface morphology during the high-speed milling, and reported that the pit wear is attributed to the comprehensive effect of the adhesion-diffusion abrasive particle phenomenon, while the flank wear is produced by the adhering abrasive particles. Therefore, it is a common occurrence for workpiece materials to adhere onto the cutter surface, thereby causing serious wear of the cutter and influencing the quality of the workpiece surface. In this research, in order to study the effect of nanoparticles on the adhesive wear, the titanium nitride-coated blades were used to avoid the tool wear. Actually, only the adhesion wear is obvious in this research, because the Ti element in titanium alloy has a strong affinity with the Ti element in the blade coating material, which leads to more titanium alloy chips adhering to the tool surface. Consequently, the chips cover the tool surface, effectively hindering the mechanical, chemical, and thermal interactions between the tool and the workpiece[27]. Therefore, the adhesion wear is the main wear type of tools.

Fig. 5 and Fig. 6 show SEM morphologies of tool surfaces under different conditions. It can be seen that the blade has no evident damage. The flank face and rake face of the blade have serious chip adhesions. In addition, the thickness of the chip adhesion layer increases in order under the condition of canola oil+graphene, canola oil, and dry cutting. At cutting speeds of 100 and 60 m/min, the thicknesses of the chip adhesion layers on the flank face under the canola oil+ graphene condition decrease by 30.4% and 38.8%, respectively, compared with those under the dry cutting condition. Similarly, the thicknesses of the chip adhesion layers on the rake face under the canola oil+graphene condition at cutting speeds of 100 and 60 m/min decrease by 28.3% and 28.8%, respectively, compared with those under the dry cutting condition.

Under the dry cutting condition, due to the poor thermal conductivity of titanium alloys, the heat in the contact zone between the cutter and workpiece cannot be released effectively. Due to the high temperature in the cutting zone and the high cutting speed, the workpiece material flows more easily through the tool surface, promoting the adhesion of workpiece material onto the tool, and thereby increasing the thickness of the adhesion layer. However, the fatty acids in canola oil significantly decrease the friction between the cutter and workpiece, therefore eliminating the heat at the interface[28,29]. In addition, the addition of graphene nanoparticles into the canola oil significantly increases the thermal conductivity of lubricant, because the graphene nanoparticles absorb a lot of heat in the contact zone between the cutter and workpiece. The low-temperature environment reduces the adhesion between the cutter and workpiece, thus

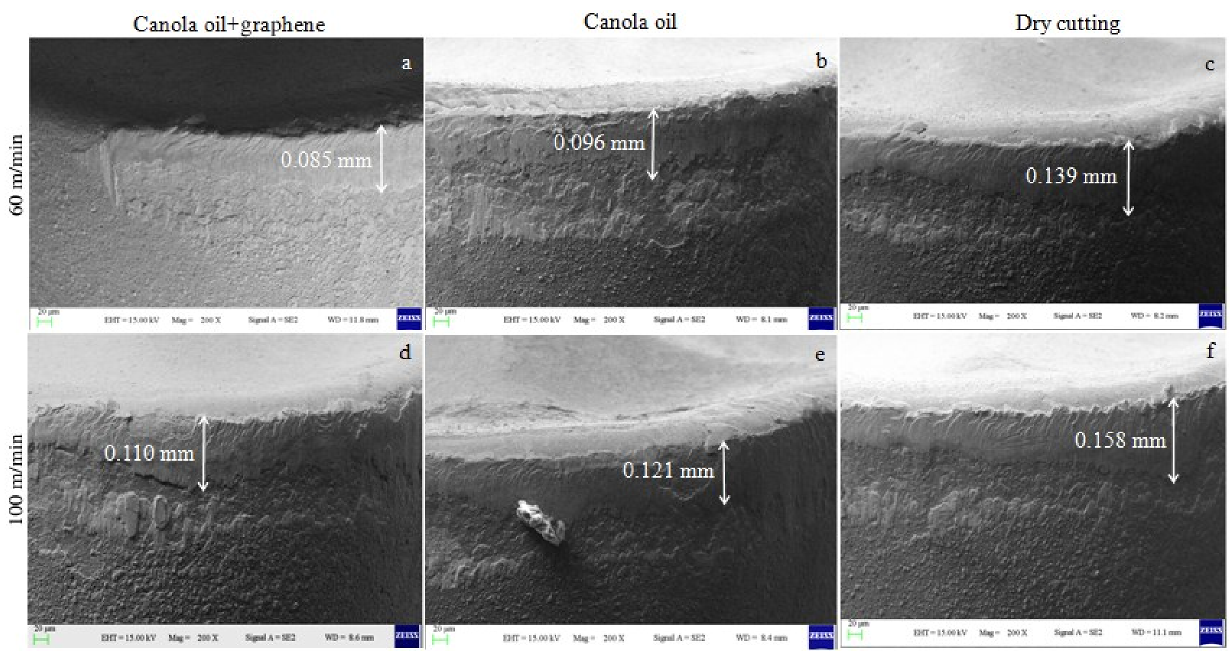



Fig.5 SEM morphologies and adhesion layer thicknesses of flank face under different conditions

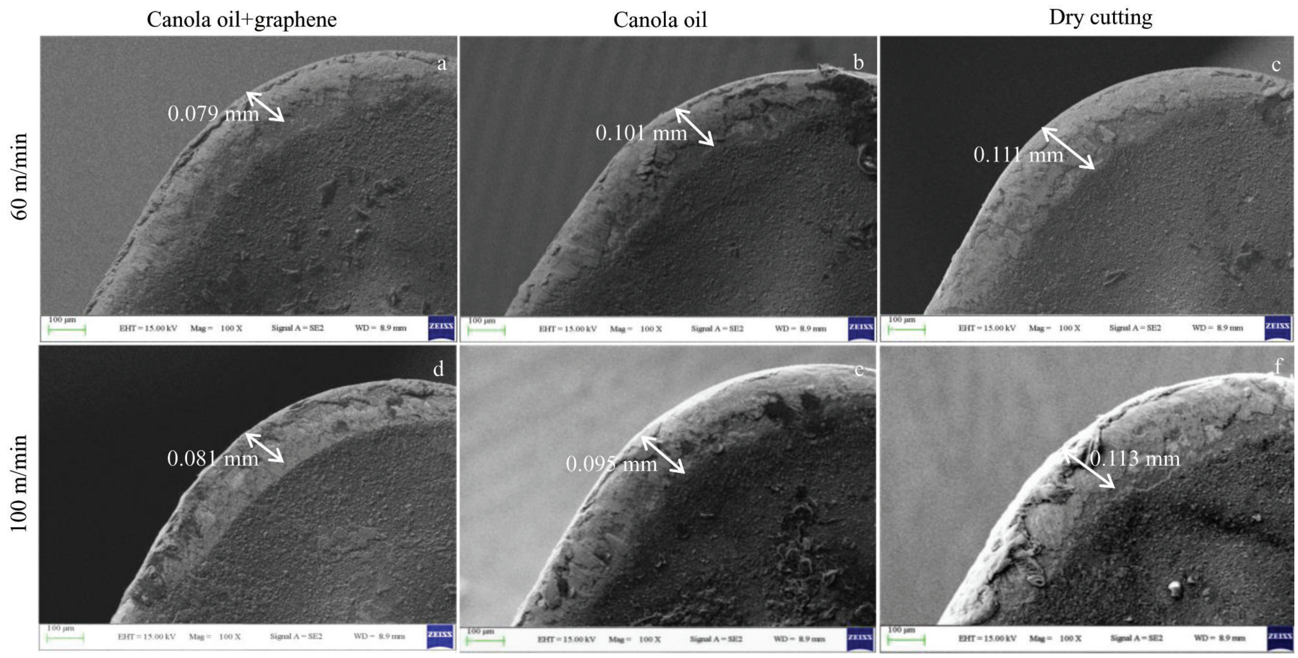



Fig.6 SEM morphologies and adhesion layer thicknesses of rake face under different conditions

shortening the thickness of the chip adhesion layer. Moreover, the strong injection pressure of the nozzle inhibits the adhesion of workpiece material to the rake surface, which also shortens the thickness of the chip adhesion layer.

Furthermore, the adhesion layers on the flank face peel off under the canola oil+graphene or the canola oil condition at cutting speed of 100 m/min, as shown in Fig. 7. This phenomenon is caused by the cold-welding of the blade and workpiece under the high pressure and specific temperature with the process proceeding. Due to the non-uniform temperatures in the processing zone, the high-temperature adhesion points in the blade-workpiece contact zone can be damaged more easily by the heat and friction.

It can be seen that the canola oil+graphene lubricant can better protect the cutter coating materials than the canola oil lubricant. According to EDS results of the pits caused by the peeling of the adhesion layer under the canola oil condition, the Co, W, and N elements can be detected (Fig.8a). Although the Co and W elements cannot be detected under the canola oil+graphene condition, N and C elements can be observed (Fig.8b). The turning tool used in this research is composed of a tungsten steel substrate with a titanium nitride coating layer. Therefore, the detected Co and W elements are the substrate components, which indicates that the tensile force at the peeling area of adhesion layer causes the ablation of not only the adhered chips but also partial titanium nitride coating of the tool, thus causing serious tool wear. In contrast, the undetectable Co and W elements under the canola oil+graphene condition may be because the tensile force is inadequate to damage the tool coating.

Meanwhile, the detection of C element demonstrates the existence of graphene nanoparticles, indicating that the canola oil+graphene lubricant protects the titanium nitride coating effectively. This is because the graphene nanoparticles can be transported to the contact zone between the chip adhesion layer and cutter point by the canola oil which is atomized by the pressurized cold air. Before adhering to the cutter point, the graphene can penetrate the contact zones under the air pressure due to its monolayer-networked structure and very small thickness. Moreover, the graphene can adhere tightly to the cutter surface and provide the lubrication between the cutter and the chip adhesion layer due to the high toughness.

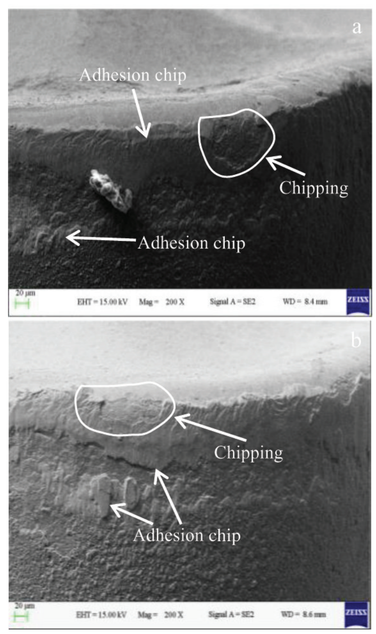



Fig.7 SEM morphologies of peeling off phenomena of adhesion layers under canola oil (a) and canola oil+graphene (b) conditions at cutting speed of 100 m/min

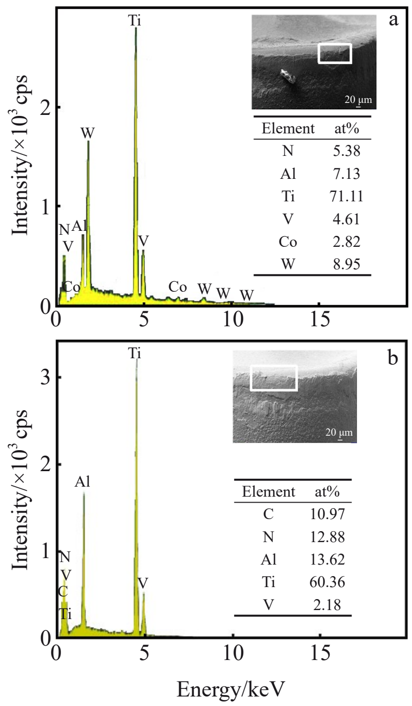



Fig.8 SEM morphologies and corresponding EDS results of peeling areas of adhesion layer under canola oil (a) and canola oil+graphene (b) conditions

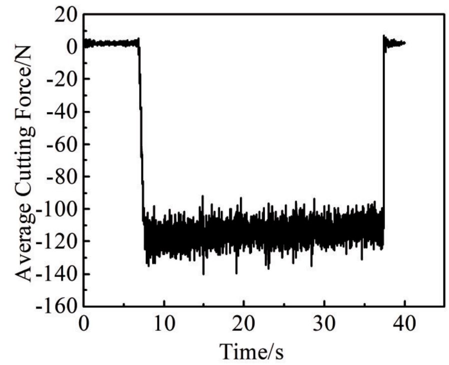



Fig.9 Average cutting force in cutting process

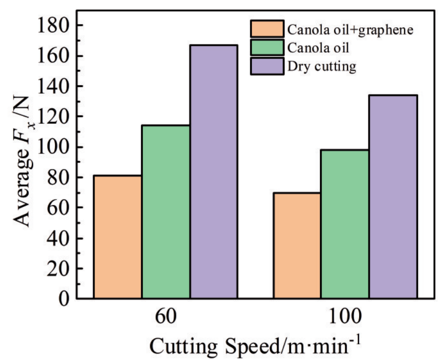



Fig. 10 Comparison of cutting forces under different processing conditions

The adhesion layer can be pulled out by the external force and immediately transported to other places due to the lubrication effect of the graphene nanoparticles, thus protecting the blade coating effectively.

## 2.3 Cutting force

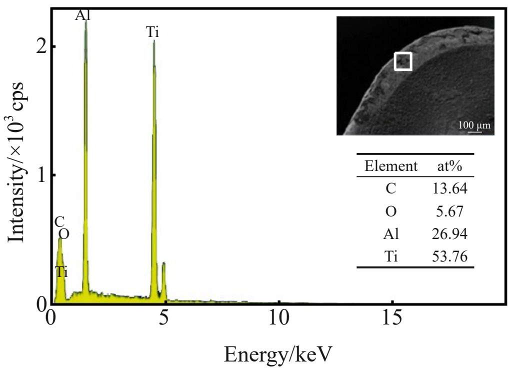
The cutting force is an important parameter in machining, which is related to the cutting heat, service life, and surface integrity of cutter. For the convenience of measurement and application, the cutting force is usually decomposed into three mutually perpendicular cutting forces. The main cutting force ($F_x$) is largely related to the cutting speed ($V_c$) and accounts for 85%~90% of the total cutting force. $F_x$ consumes the main power of the machine tool, which is the basis for the calculation of cutting power, the selection of the motor power of machine tool, and the design of main drive mechanism of the machine tool. In addition, the average cutting force is calculated by DynoWare software, as shown in Fig.9.

According to Fig. 10, the cutting force decreases in order under the condition of dry cutting, canola oil, and canola oil+graphene. The cutting force under the canola oil+graphene condition is 51.4% and 47.9% lower than that under the dry cutting condition at cutting speed of 60 and 100 m/min, respectively. Besides, the cutting speed has a great influence on the cutting force: the larger the cutting speed, the higher the temperature in the machining area and thereby the larger the cutting force, which is attributed to the thermal softening effect. This phenomenon is similar to that in the laser-assisted machining of titanium: the increasing temperature of the cutting zone results in the increase in the cutting force[30].

Under the dry cutting condition, the tool-chip contact area is large and more heat is generated at the cutting edge, which easily causes the chip adhesion and welding to the tool. In addition, the chip curl diameter is large, which also increases the cutting force[31]. The cutting force under the graphene+canola oil condition is the lowest, mainly due to the lubrication and cooling effects of the graphene nanoparticles. Furthermore, the graphene can be found on the rake face of the tool, as shown in Fig. 11. The graphene nanoparticles reduce the chip curl diameter, tool-chip contact area, and tool wear of rake face, resulting in the reduction in cutting force[32]. In addition, regardless of the lubrication conditions, with increasing the cutting speed, the cutting force is decreased. This is mainly because the high cutting speed increases the workpiece temperature, which softens the workpiece material and leads to the easy formation of chips[33].

## 2.4 Surface roughness

The surface roughness is widely used to determine the surface quality of mechanical parts and it is crucial to the functional behavior of the mechanical parts. The chip adhesion to the workpieces has a great influence on the surface roughness. During the processing, the high temperature and high pressure are achieved, the chip adhesion layer on the cutter point may adhere to the workpiece, and the surface quality is thereby influenced. Fig. 12 shows the average surface roughness under different lubrication conditions at




| Element | at% |
|---|---|
| C | 13.64 |
| O | 5.67 |
| Al | 26.94 |
| Ti | 53.76 |

Fig.11 SEM morphology and EDS results of rake face

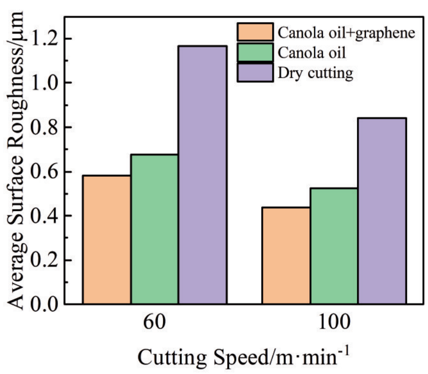



Fig.12 Average surface roughness under different processing conditions

different cutting speeds. Apparently, the lowest surface roughness is achieved under the canola oil+graphene condition. The surface roughness under the canola oil condition is medium and that under the dry cutting condition is the highest. At the cutting speed of 60 and 100 m/min, the surface roughness is 50.1% and 48.0% lower under the canola oil+graphene condition than that under the dry cutting condition, respectively. The surface roughness of 0.439 μm is the lowest under the canola oil+graphene condition at 100 m/min. Fig.13 shows the surface morphologies of the workpieces at the same position under different processing conditions. Under the dry cutting condition, more chips and scratches can be observed on the workpiece surface, which leads to the deterioration of the surface quality of the workpiece. Under the canola oil condition, the sticking chips and scratches are significantly reduced, and the surface quality is improved. After adding the graphene nanoparticles into the canola oil, the surface quality of the workpiece is further improved and almost no scratches can be observed. Kvak et al[34] reported that the surface roughness can be reduced by ~20% under the graphene nanoplatelets mixed nanofluid condition in the machining process of cemented carbide-coated tools. In this research, the improvement in surface quality is attributed to the physical properties and the better lubrication performance of graphene nanoparticles. The friction reduces and the graphene nanoparticles can adhere tightly to the cutting area. Due to the dry cutting condition, the frictional forces are high and the heat cannot diffuse, which strengthens the adhesion between the workpiece surface and chip adhesion layer, thereby increasing the workpiece surface roughness[35]. However, a layer of the high-strength lubricating oil film can be formed after the canola oil is sprayed onto the contact zone between the chip adhesion layer and workpiece[36], which effectively hinders the adhesion of chips to the workpiece surface, thus reducing the surface roughness. In addition, the graphene can further strengthen the lubrication performance of the oil film[37]. Consequently, the friction coefficient of the contact zone between the chip adhesion layer and workpiece decreases, and the oil layer can slip away from the workpiece surface after the cutting process. Moreover, the additive graphene can decrease the heat accumulation in the contact zone, which also inhibits the adhesion. As shown in Fig. 14, EDS analysis results of the chip adhesion layer show that the C element adheres to the workpiece surface. This result indicates that the graphene nanoparticles can enter the contact zone. In addition, it can be concluded that the surface roughness is increased significantly with increasing the cutting speed. Because when the cutting speed is very low, it is easy to form the extruded chip on the rake face for a long time, which causes the cutting layer instead of the tool to form the tensile stress on the machined surface, therefore leading to the fracture[38].

Moreover, the chip adhesion layer accumulates and thickens continuously during the turning process and becomes part of the tool to complete the machining process. Hence, an irregularly shaped adhesion layer may lead to the scratching along different directions on the workpiece surface, causing

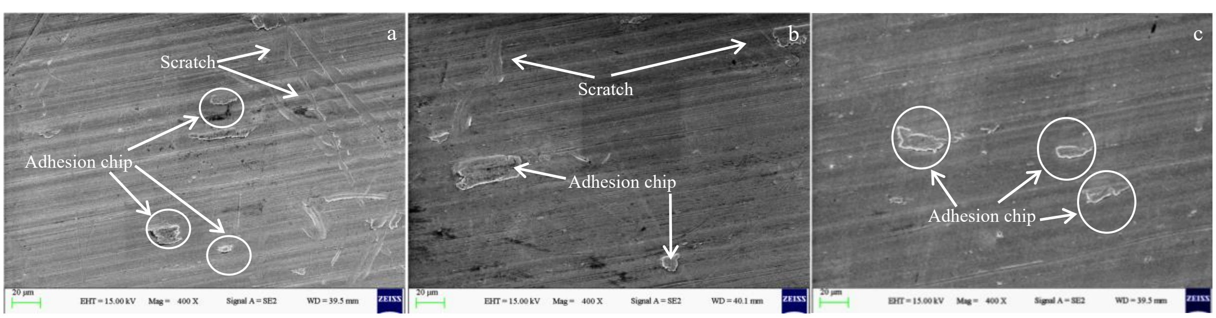



Fig.13 Surface morphologies of workpieces under dry cutting (a), canola oil (b), and canola oil+graphene (c) conditions

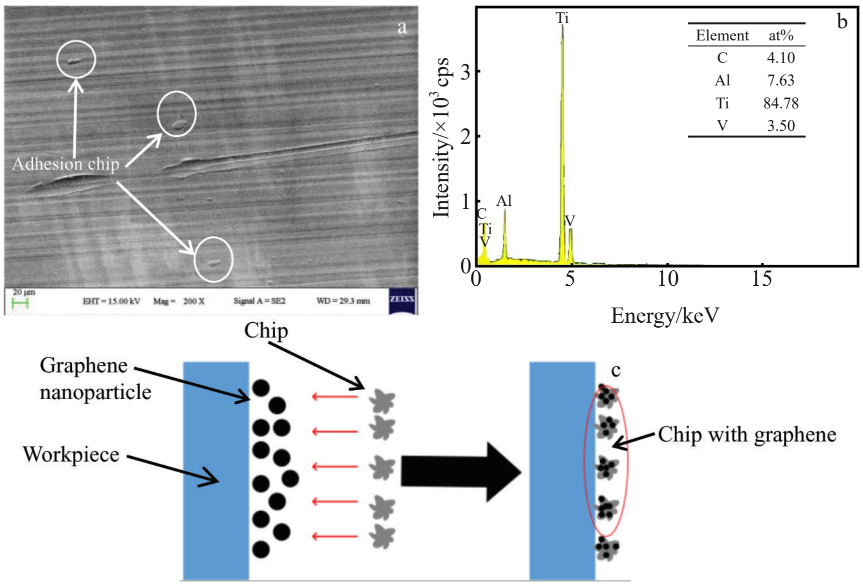



Fig.14 SEM morphology (a) and EDS results (b) of adhesion chips on workpiece surface; schematic diagram of chip adhesion to workpiece surface (c)

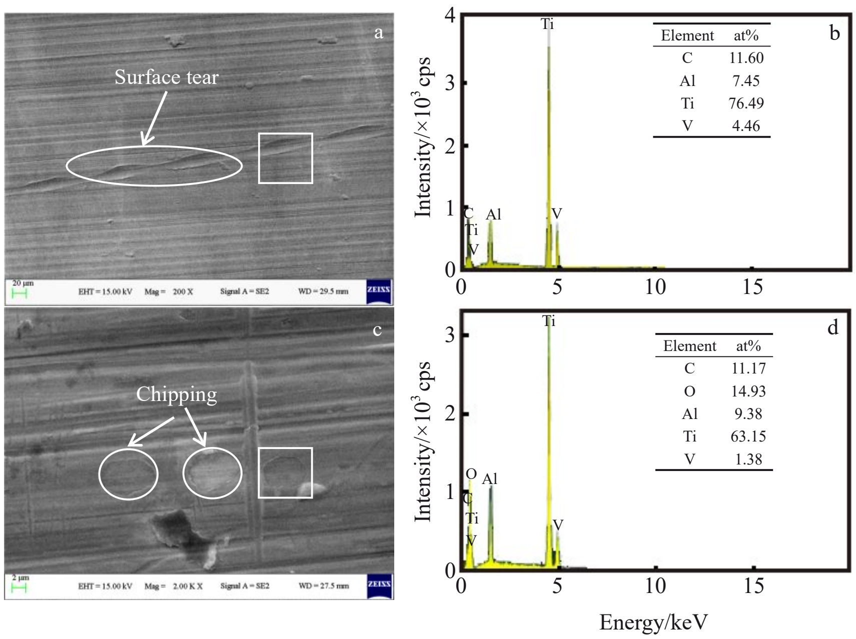



Fig.15 SEM morphologies (a, c) of workpiece surfaces after machining under canola oil+graphene condition; EDS results of marked rectangle area in Fig.15a (b) and Fig.15c (d)

surface damage (Fig. 15a). Similarly, the chip adhesion layer on the workpiece surface peels off by the external forces, forming pits (Fig. 15b). Accordingly, the C element can be detected. This may be due to deposition and accumulation of graphene nanoparticles in the contact zone between the chip adhesion layer and the workpiece, which produces the instantaneous high temperature with pits on the workpiece. Therefore, the graphene nanoparticles adhere to the pits of the workpiece and fill them. Due to the nanometer size of graphene, even a weak filling effect can improve the surface quality of the workpiece, as shown in Fig.16.

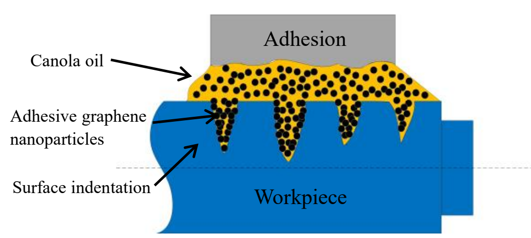



Fig.16 Schematic diagram of pits in workpiece surface filled by graphene nanoparticles

## 3 Conclusions

1) The thickness of the chip adhesion layer is the shortest under the canola oil+graphene lubrication condition. At the cutting speeds of 100 and 60 m/min, compared with that under the dry cutting condition, the thickness of the chip adhesion layer is 30.4% and 38.8% lower on the flank face, and 28.3% and 28.8% lower on the rake face under the canola oil+ graphene lubrication condition, respectively. The lowest cutting temperature is achieved with the canola oil+graphene lubrication. The low-temperature processing zone prevents the adhesion between the cutter layer and workpiece, thus shortening the adhesion layer thickness. Moreover, the graphene can better protect the cutter coating.

2) At the cutting speeds of 60 and 100 m/min, the cutting force under the canola oil+graphene condition is 51.4% and 47.9% lower than that under the dry cutting condition, respectively. The graphene can provide cooling and lubrication effects in the machining area, thereby reducing the tool wear and cutting force. In addition, regardless of the lubrication conditions, with increasing the cutting speed, the cutting force is decreased.

3) The lowest surface roughness is achieved under the canola oil+graphene lubrication condition. At the cutting speed of 60 and 100 m/min, the surface roughness under the canola oil+graphene condition is 50.1% and 48.0% lower than that under the dry cutting condition, respectively. The surface roughness of 0.439 μm is the lowest under the canola oil+ graphene condition at 100 m/min. The graphene can penetrate the contact area between the tool and workpiece, which therefore improves the cooling and lubrication performance of the oil film, hinders the chip adhesion, and ameliorates the surface quality. In addition, the graphene nanoparticles in the pits on the workpiece surface can also improve the surface quality.

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# 石墨烯纳米流体加工Ti-6Al-4V合金的黏着磨损、表面粗糙度和切削力

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**摘　要**：提出了一种基于石墨烯纳米颗粒分散在菜籽油中的切削液为加工区域提供润滑/冷却的新加工方式，确定了该纳米流体对刀具切屑粘附层的影响。与干切削相比，使用菜籽油+石墨烯加工后的刀面和前刀面的切屑粘附层厚度分别降低了38.8%和28.8%，切削力降低51.4%，工件表面粗糙度降低50.1%。石墨烯较高的导热系数可以降低切割区域的温度。此外，石墨烯可以渗透到刀具与工件之间的接触区域，有效地保护了刀具的涂层材料，减少了粘附在工件表面的切屑，并且填充了工件表面形成的凹坑，从而提升了表面质量。

**关键词**：石墨烯纳米流体；切屑附着层；切削力；表面粗糙度；切削热

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