Experimental Study on Profile Grinding of Titanium Alloy with Axial Rotating Heat Pipe Abrasive Wheel

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Abstract: Axial rotating heat pipe abrasive wheel (ARHPAG) could dissipate the grinding heat efficiently and avoid ground surface burnout. In order to explore the heat transfer performance of the axial rotating heat pipe abrasive wheel in different circumstances, experiments were conducted by profile grinding of Ti-6Al-4V, and the influence of the material removal rate, filling ratio and rotational speed on the heat transfer performance was investigated. The results indicated that the heat transfer performance of ARHPAG was improved with the increase of the material removal rates. The temperature of workpiece increased as the depth of cut increased, and decreased as the feedrate increased. The heat transfer coefficient of ARHPAG increased firstly and then decreased as the filling ratio increased. And the trend of heat transfer coefficient was to decrease firstly and then increase as the rotational speed increased. Under the optimal experimental parameters, the temperature of ground surface was controlled below 80℃ and the temperature difference is within 10℃.

1 Introduction

In the grinding of difficult-to-machine materials in aerospace industry such as superalloy and titanium alloy, the high temperature of the contact zone often causes ground surface burnout and poor surface integrity.Though conventional cooling of pouring large quantity of coolants into grinding zone could help dissipate grinding heat, it is confronted with environmental pollution. Consequently it is necessary to apply an efficient and environment-friendly technology for cooling the ginding process [1].

Heat pipes have been applied for the field of thermal management widely due to its reliable and efficient heat transfer capacity, such as electronic cooling, aircraft thermalcontrol and manufacturing [2]. It achieves the enhancement of heat transfer by evaporation and condensation of the working fluid to efficiently remove the heat [3]. Chiou et al. proposed a cutting tool with the heat pipe embedded, and conducted the turning experiments to study the temperature distributions of cutting tool [4]. The results showed that the heat generated at the tool-chip interface could be effectively removed by the heat pipe installed on the cutting tool. Jen et al. proved successfully the feasibility of the applicaton of heat pipe for drilling cooling by the combined numerical and experimental method. The result demonstrated that the inserted heat pipe could improve the temperature filed forceful [5]. In the term of grinding, Ma et al. [6] proposed a type of brazed diamond grinding wheel with a rotating heat pipe and the practicability of that was verified. Compared with the case without heat pipe, the temperature of contact zone decreased 30%. He et al. [7] manufactured the heat pipe abrasive wheel and carried out grinding experiments, the result of which indicated it was highly effective to reduce grinding temperature and prevent the burnout in the grinding. Chen et al. [8] investigated the effect factor on the heat transfer capacity of rotating heat pipe abrasive-milling tool. The results of simulation were consistent with that of experiments. And the use of rotating heat pipe abrasive-milling tool lowered the the temperature of evaporator section by 65.7% effectively, conpared to the same circumstance without heat pipe.

The application of heat pipe mentioned above is involved the turning, drilling and surface grinding mainly. As a result of the common application of the profile grinding, it is worth exploring the utility of heat pipe for profile grinding. In this study, profile grinding experiments of Titanium alloy was conducted to study the influence of the material removal rate, filling ratio and rotational speed on the heat transfer performance of ARHPAW. Besides, the temperature of axial rotating heat pipe abrasive wheel, the temperature and surface integrity of workpiece are the focus of analysis.

2 Experimental setup

The experiments were implemented on a motor spindle used for grinding, which can provide a maximum rotational speed of 40000 rpm. The outer face of ARHPAG is brazed with CBN grains. The filling ratio of ARHPAG are 78%, 84% and 89.5%, the corresponding working liquid volume are 4.1ml, 4.4ml and 4.7ml respectively. A workpiece with a length of 75 mm and a height of 18 mm was machined in the profile grinding experiments, whose material is titanium alloy Ti-6Al-4V. All of the test temperature is measured by the semi -artificial thermocouple. Besides, the 4 ℃ cooling air jet with the speed of 115 m/s generated by an Exair 3925 vortex tube is impinged on the condenser section. The vacuum degree of the axial rotating wheel needs to reach 10^{-2} Pa ahead of fluid injection. Details of the experimental conditions are shown in Table 1. The test platform of heat transfer performance is demonstrated in Figure 1.

Table 1 Experimental parameter

Processing parameters	Values
Filling ratio FR	78%, 84%, 89.5%
Rotational speed n (r/min)	5000, 8000, 10000, 12000, 15000
Feedrate v_w (mm/min)	80, 100
Depth of cut a_p (mm)	0.05, 0.1
Cooling condition	115 m/s cooling air jet at 4 ℃

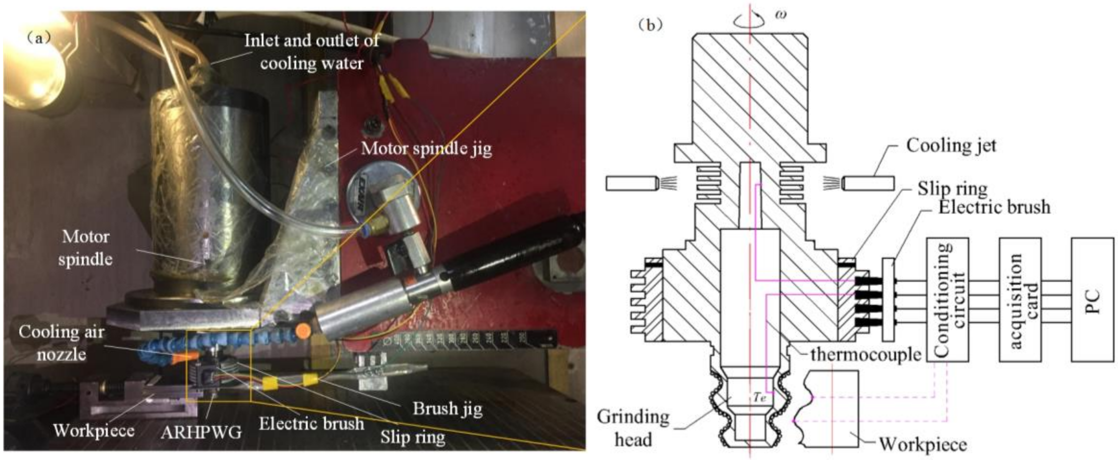

Fig. 1 (a) Physical drawing of the test platform (b) Schematic of heat transfer test platform

3 Result and discussion

3.1 Effects of the material removal rates

In grinding experiments, the heat flux of ground surface of ARHPAG is changed with the material removal rate. Keeping the filling ratio and rotational speed of ARHPAW as invariables, different material removal rates can be obtained by changing feedrate and depth of cut. When the grinding parameters are (1) v_w= 80 mm/min, a_p=0.05 mm, (2) v_w= 80 mm/min, a_p=0.05 mm, (3) v_w= 80 mm/min, a_p=0.05 mm, the corresponding material removal rates are 1.07, 1.33 and 2.13 mm^3/s.The effect of material removal rate on heat transfer performance are shown in Fig. 2 and 3.

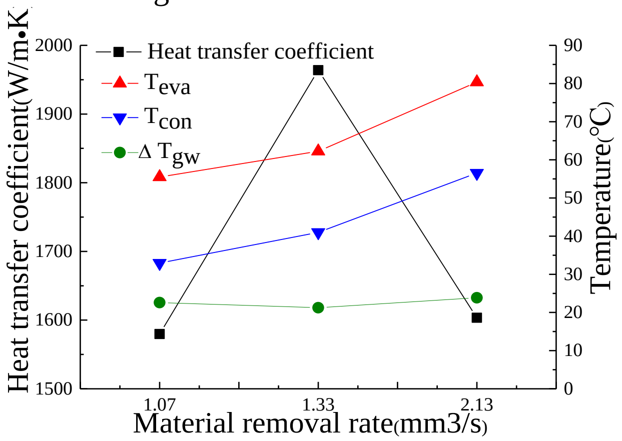

Fig. 2 Temperature and heat transfer coefficient vs. different material removal rates

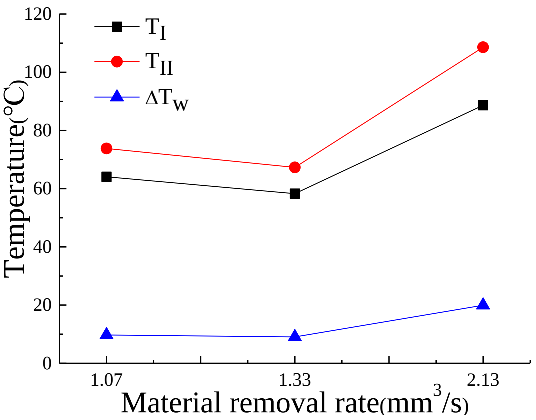

Fig. 3 Temperature of ground surface vs. different material removal rates

With the increase of material removal rates, the inner wall temperature of the evaporator, i.e., T_{eva} in the graph and the inner wall temperature of condenser, i.e., T_{con} in the graph rose, and the temperature difference between evaporator and condenser, i.e., ΔT_{gw} in the graph was about 22 ℃, meanwhile the ground surface temperature of concave and convex piont, i.e., T_I and T_{II} in the graph decreased firstly then increased. And when material removal rate was 1.33 mm^3/s, the temperature difference of ground surface, i.e., ΔT_w in the graph was minimum of 9 ℃. This is because with the increase of the cutting depth, more energy was consumed per unit time and more heat was generated from the grinding zone, resulting in the rise of grinding temperature. With the action of heat pipe, the temperature of the ground surface increases slightly. And with the increase of feedrate, more grinding heat was generated per unit time, and the heat into the workpiece decreased. Under the function of heat pipe the temperature of ground surface decreased. Moreover, with the increase of material removal rate, the heat flux into the evaporator section increased, the phase transformation form of the working fluid was changed from surface evaporation into nucleate boiling, the phase transformation rate of evaporator section and condensation rate of condenser section were accelerated, leading to the improvement of heat transfer performance of ARHPAW.

3.2 Effects of filling ratios

In order to investigate the suitable filling range of ARHPAG, a series of experiments were carried out under the circumstance of v_w= 80 mm/min, a_p=0.05 mm and n=10000 r/min. Besides, the filling ratios were 78%, 84% and 89.5%, the corresponding working fluid volume were 4.1ml, 4.4ml and 4.7ml respectively.

According to Fig. 4 and 5, the trend of heat transfer coefficient of ARHPAW increased firstly and then decreased as the filling ratio increased. The temperature difference between evaporator and condenser (ΔT_{gw}) reached minimum of 22 ℃ when FR was 84%, and meanwhile the temperature difference of ground surface (△T_w) reached the minimum. This is because the evaporator section had enough working quality to participate in the process of heat transfer at that moment, and there was no distribution of liquid phase occur in condenser section, which was helpful to form a continuous process of evaporation and condensation. From the above it can know the optimal filling ratio of heat pipe should be around 84%.

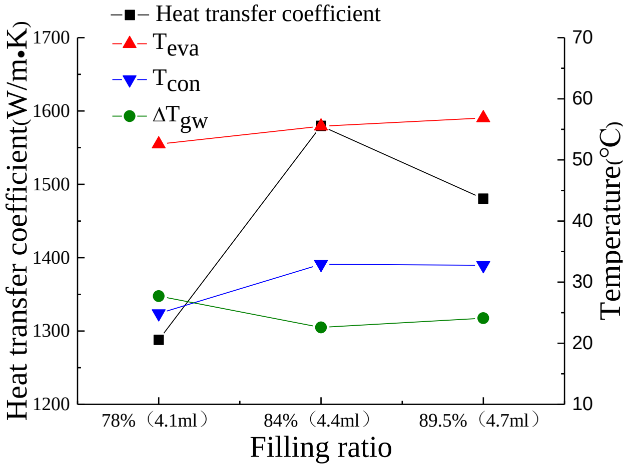

Fig. 4 Temperature and heat transfer coefficient vs. different filling ratios

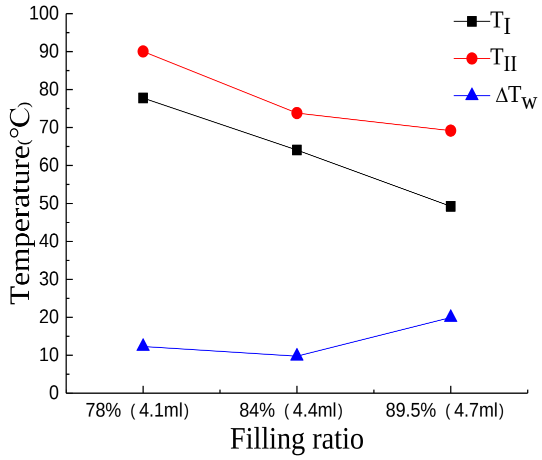

Fig. 5 Temperature of ground surface vs. different filling ratios

3.3 Effects of rotational speeds

In order to explore the appropriate rotational speed range of ARHPAG, on the condition of v_w= 80 mm/min, a_p=0.05 mm and FR= 84%, a series of experiments were carried out by changing rotational speed from 5000 to 15000 r/min.The effects of rotational speed on heat transfer performance and temperature control of ground surface of workpiece are shown in Fig. 6 and 7.

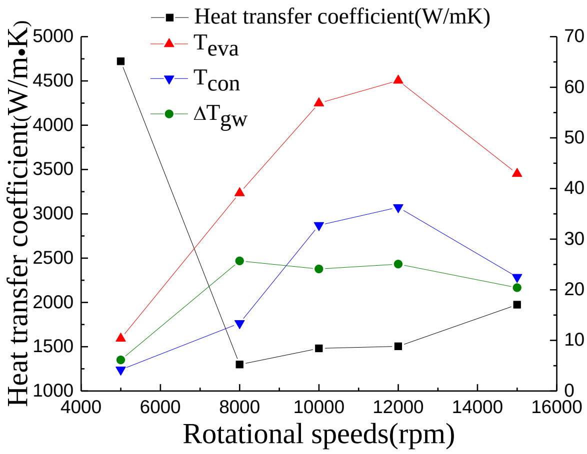

Fig. 6 Temperature and heat transfer coefficient vs. different rotational speeds

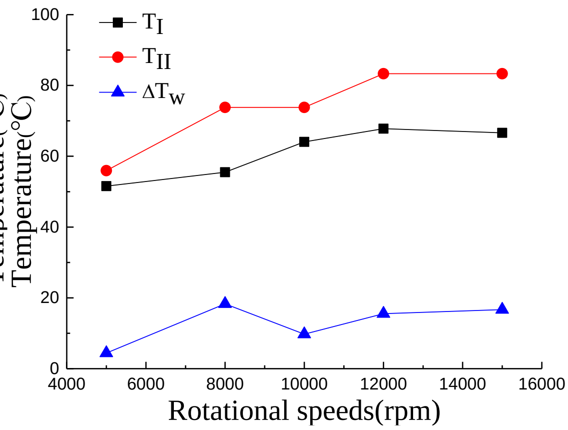

Fig. 7 Temperature of ground surface vs. different rotational speeds

As the rotational speed increased, the heat transfer coefficient of ARHPAW decreased firstly and then increased. And the trend of temperature difference of evaporator and condenser (△Tgw) increased with the increase of rotational speed, similar to the trend of ground surface temperature of concave and convex points (T_I and T_{II}).

This is because the form of heat transfer in the heat pipe was mainly efficient boiling heat transfer when *n* was below 10000 r/min. And when *n* was over 10000 r/min, the heat transfer form was converted to convective heat transfer, and the forced convection between the external wall of the condenser section and the cold air jet was enhanced with the rotational speed increased, leading to slight improvement in the heat transfer performance of ARHPAW. Meanwhile, as the rotational speed increased, the friction between the abrasive wheel and the workpiece became more violent and more heat was generated in the grinding zone. Therefore when *n* was more than 10000 r/min, the temperature of ground surface rose somewhat though the heat transfer performance of the axial rotating heat pipe abrasive wheel was improved. In other words, the increase of rotational speed had a positive effect on the improvement of the heat transfer coefficient, but it had limited influence on lowering the grinding temperature.

3.4 Ground surface integrity

The experimental results show that when v_w= 100 mm/min, a_p= 0.05mm and FR= 84% ARHPAG has good heat transfer performance, which could lower the temperature of ground surface effectively. Figure 8 depicit the entity of the workpiece after grinding with that experimental parameters mentioned above.

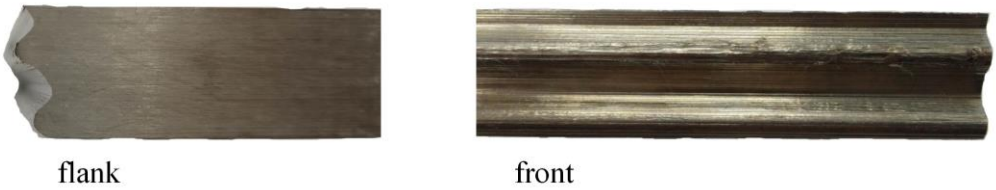

Fig. 8 The entity of the workpiece after grinding

By obseving the metallographic structure in Figure 9 further, it is apparently that there is no white layer existed almost, indicating that there is no burnout on the ground surface of the workpiece.

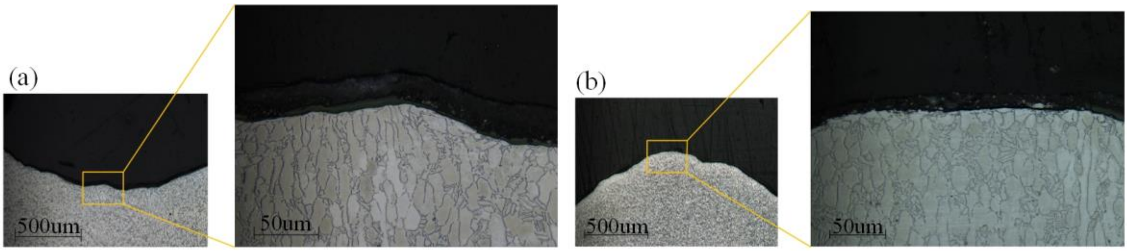

Fig. 9 The metallographic structure of the workpiece after grinding:
(a) concave point of ground surface ; (b) convex point of ground surface

4 Conclusion

In this paper, the profile grinding experiments of Ti-6Al-4V alloy by axial rotating heat pipe abrasive wheel has been successfully conducted. Some conclusions are obtained as follows:

(1) The heat transfer performance of ARHPAG improved with the increase of the material removal rates. The temperature of workpiece increased with the increase of depth of cut and decreased with the increase of feedrate. Keep the filling ratio and rotational speed as invariables, when v_w= 1000 m/min and a_p= 0.05 mm, the temperature of ground surface reached minimum of 9 ℃.

(2) The heat transfer coefficient of ARHPAG increased firstly and then decreased as the filling ratio increased. Keep the feedrate, rotational speed and depth of cut as invariables, when FR= 84%, the temperature of ground surface reached minimum of 9.7 ℃.

(3) The trend of heat transfer coefficient was to decrease firstly and then increase as the rotational speed increased. At the rotational speed of 10000 r/min, the temperature of ground surface was below 70 ℃, meanwhile it could maintain high processing efficiency

(4) Under the optimal experimental parameters, the temperature of ground surface was controlled below 80℃ and the temperature difference is within 10℃. And there is no workpiece burnout existed.

5 Nomenclature

ARHPAG	axial rotating heat pipe abrasive wheel
FR	filling ratio
T_{eva}	inner wall temperature of evaporator (℃)
T_{con}	inner wall temperature of condenser（℃）
$\triangle T_{gw}$	temperature difference between evaporator and condenser (℃）
T_{I}	ground surface temperature of concave point (℃）
T_{II}	ground surface temperature of convex point (℃)
$\triangle T_{w}$	temperature difference of ground surface (℃）

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References

[1]. H C Zhang, T C Kuo, H Lu and S H Huang, Environmentally conscious design and manufacturing: A state-of-the-art survey, Journal of Manufacturing Systems. 16 (1997) 352–371.

[2]. K Vafai and W Wang, Analysis of flow and heat transfer characteristics of an asymmetrical flat plate heat pipe, International Journal of Heat & Mass Transfer. 35 (1992) 2087-2099.

[3]. K H Do and S P Jang, Effect of nanofluids on the thermal performance of a flat micro heat pipe with a rectangular grooved wick, International Journal of Heat & Mass Transfer. 53 (2010) 2183-2192.

[4]. R Y Chiou, J S J Chen and L Lu, The Effect of an Embedded Heat Pipe in a Cutting Tool on Temperature and Wear, ASME 2003 International Mechanical Engineering Congress and Exposition. (2003) 369-376.

[5]. T C Jen, G Gutierrez, S Eapen, G Barber, H Zhao, P S Szuba, J Labataille and J Manjunathaiah, Investigation of heat pipe cooling in drilling applications.:part I: preliminary numerical analysis and verification, International Journal of Machine Tools & Manufacture. 42 (2002):643-652.

[6]. K Ma, H J Xu and Y C Fu, The Effect of a Rotating Heat Pipe in a Brazed Diamond Grinding Wheel on Grinding Temperature, Key Engineering Materials. 416 (2009) 274-278.

[7]. Q S He, Y C Fu, J J Chen and W Zhang, Heat Pipe Grinding Wheel in Grinding Titanium Alloy Ti-6Al-4V, Advanced Materials Research. 797 (2013) 534-539.

[8]. J J Chen, Y C Fu, Z B Gu, H F Shen and Q S He, Study on heat transfer of a rotating heat pipe cooling system in dry abrasive-milling, Applied Thermal Engineering. 115 (2017)736-743.