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Design, fabrication and dry cutting performance of pulsating heat pipe self-cooling tools

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ABSTRACT

Three kinds of pulsating heat pipe self-cooling tools with four, six and eight turns are designed and fabricated respectively. The machining performance of the prepared self-cooling tools and conventional tool in dry turning of Ti-6Al-4V alloy is assessed in terms of cutting temperature, cutting force, tool wear and tool life. Compared to the conventional tool, the self-cooling tools can reduce cutting temperature by 5–15% and improve tool life by 5–25%. A simulation based on 3-D model is developed. It is proved that the self-cooling tools can reduce simulated maximum temperature by 7–15% and can shorten the period in which the temperature reaches to the steady state effectively. The main purpose of this work is to seek a new way of eradicating the ill effects associated with cutting fluids by shifting towards sustainable machining techniques. To be achieved on industrial uptake, the quality of machined material as well as machining efficiency of the self-cooling tools in cutting of more kinds of workpieces will be investigated in future study.

1. Introduction

In metal cutting process, the used cutting fluids often contain environmentally harmful or potentially damaging chemical constituents which are difficult to dispose, as a result, could cause environmental pollution as well as skin and lung disease to the operators (Shokoohi et al., 2015). Because of the negative effects associated with the cutting fluids and also the stringent environmental policies, the convention to move away from cutting fluids has led to technological progress towards dry cutting (Chetan et al., 2015; Ghani et al., 2014; Sreejith and Ngoi, 2000). With the aid of advanced tool materials and improved geometric parameters, it is feasible for dry machining of ordinary metals, such as carbon steel and aluminum alloy. However, it is still inconvenient for completely dry cutting of difficult-to-cut materials (Ezugwu and Wang, 1997; Ezugwu et al., 2003), especially in high cutting speed. For example, titanium alloy is a typical difficult-to-cut material which could make high cutting temperature as its low thermal conductivity (Vazquez et al., 2015; Xie et al., 2013). In dry cutting of the titanium alloy, the diffusion wear and oxidation of the tool insert are intensified at elevated cutting temperatures, consequently, reduces tool life and produces damaging white layers on the machined surface, directly influencing the surface integrity (Shaw, 2005). In order to conquer the obstruction presented in dry cutting operations of difficult-to-cut metals, a variety of new cooling technologies are proposed in recent years (Davim et al., 2007; Nandi and Davim, 2009), thereinto, the internal cooling (Zhao et al., 2002, 2006) and heat pipe assisted cooling (Sharma et al., 2009) are considered more potential and effective approaches for heat transfer, which allow cutting operations to be carried out in a dry and "green" fashion (Davim, 2013).

The common characteristic of both internal cooling and heat pipe assisted cooling is that the heat transfer through the cutting insert, namely indirect cooling which is influenced by the thermal conductivity of cutting insert. The indirect cooling also requires the heat generated on the rake face of the insert to be extracted via a point which is suitably removed from the cutting zone as to not damage the cooling equipment. Jefferies and Zerkle (1970) indicated that both the intensity and the position of the cooling source in relation to the cutting zone play a pivotal role in the effectiveness of any indirect cooling operations. Dry turning of Grade 2 commercially pure titanium with an internally cooled tool combined with diamond coating was carried out by Minton et al. (2013). Results indicated that the heat from the cutting operation could be rapidly diffused over the entire surface of the insert and thus successfully drawn away from the tool via recirculation of

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coolant through the tool holder, as a result, the tool wear was inhibited and tool life was prolonged. The cutting operations with heat pipe assisted tools were also investigated by few researchers and proved to be effective in cutting cooling. For example, Haq and Tamizharasan (2006) reported a research of hard turning operations with installed heat pipe cooling. Jen et al. (2002) presented an investigation of heat pipe cooling in drilling applications. Chiou et al. (2007) investigated the dry machining with embedded heat pipe cooling by finite element analysis and experiments. Liang et al. (2011, 2013) presented a quantitative investigation of tool-chip interface temperature in dry turning assisted by heat pipe cooling. Both the internal cooling and the heat pipe assisted cooling have been proved to be effective advancement for dry cutting process. However, the heat pipe assisted cooling needs no other assisted device to drive and its cooling medium is hermetic. As a result, the heat pipe assisted cooling would be more convenient and potential compared to the generic internal cooling without heat pipe.

In the family of heat pipes, a relatively young member named pulsating heat pipe (PHP) (Faghri, 1995) is invented, which consists of a long and sealed capillary tube bent into many turns. Compared with the conventional heat pipe (Zhang and Faghri, 2002), the pulsating heat pipe has the advantages of smaller bulk, better adaptability and more effective in heat transferring. In order to investigate the effect of PHP on dry cutting performance, systematic research was carried out. In the present work, three kinds of pulsating heat pipe self-cooling tools were designed and fabricated. The machining performance of these tools in dry turning of titanium alloy was assessed in terms of cutting temperature, cutting force, tool wear and tool life. Particular attention of this paper was paid to the potential effectiveness of PHP assisted cooling in ameliorating dry cutting process.

2. Experimental cutting trials

2.1. Preparation of the pulsating heat pipe self-cooling tools

The pulsating heat pipe (PHP) is a very effective heat transfer device, which is different from the conventional heat pipe in structure and working principle. It consists of a long and sealed capillary tube bent into many turns, and the inner cavity of the capillary tube is evacuated and filled partially with working fluid. Compared with the conventional heat pipe, the unique feature of pulsating heat pipe is that the wick structure is not required to return the condensate to the evaporator section (Holley and Faghri, 2005). The inner diameter of the pipe must be sufficiently small so that vapor bubbles can grow to vapor slugs in the tube. The PHP can be divided into closed loop PHP without check valve (CLPHP), CLPHP with check valve and open loop PHP (OLPHP) (Yang et al., 2008). The schematic of the open loop PHP is shown in Fig. 1. Due to the effect of surface tension, the working fluid would arrange in plug-train units in the PHP, and heat is transported from the evaporator to the condenser region by means of local axial oscillations and phase changes in the working fluid. When the evaporator section is heated, the vapor pressure is increased, as a result, the vapor slugs move toward the condenser region. The vapor is condensed to liquid in the condenser region and the liquid would be pushed back to the evaporator region along the inner wall of the pipe. The process is repeated, and the oscillation of the vapor–liquid plugs can be maintained. As the liquid moves, the trailing edge of the liquid leaves a thin liquid film on the pipe wall. The evaporation and condensation over this thin liquid film are the driving forces of pulsation flow in a pulsating heat pipe.

It is suggested that a pulsating heat pipe should be an ideal device for removing the heat generated in cutting process. In the present study, index-able turning inserts with pulsating heat pipe cooling system which were named pulsating heat pipe self-cooling tools (SCT) were designed. The schematic of the pulsating heat pipe self-cooling tool is presented in Fig. 2. The SCT consists of cemented carbide insert, pulsating heat pipe, metal coupon for location and protective cover. There is a ringed groove which is concentric with the central hole on the bottom surface of cutting insert, moreover, several via holes are evenly distributed along the ringed groove. There are also via holes on the metal coupon for location corresponding to the cutting insert. A long continuous tube is passed through the via holes of the cutting insert and the metal coupon repeatedly, and is bent into many turns to form pulsating heat pipe. The protective cover can protect the pulsating heat pipe to prevent chip winding in cutting process.

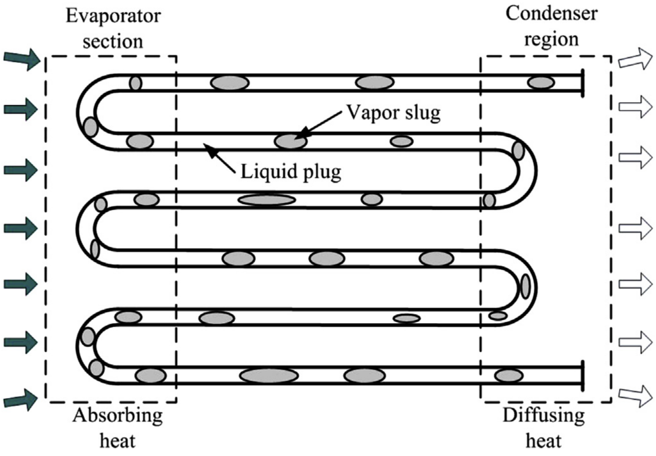

Fig. 1. Schematic of the open loop pulsating heat pipe.

The cutting tool material for preparation of the pulsating heat pipe self-cooling tools is cemented carbide (WC/Co). Composition and properties of the cemented carbide are listed as following: the weight percent of binder Co is 6%, the size of grain is 1.4–2.2 μm, the hardness is 91 HRA, the density is 14.8 g/cm^3, and the thermal conductivity is 50.2 W/m k. The dimensions of the cemented carbide insert are 19 mm width × 19 mm width × 7 mm thickness, with a central locating hole of 7 mm diameter. A ringed groove with external diameter of 15.2 mm, inner diameter of 11 mm and depth of 2.5 mm was fabricated by electrical discharge machining on the bottom surface of the cutting insert, and several via holes with diameter of 2.1 mm were fabricated along the ringed groove. Firstly, the copper tube was passed through the via holes of the cutting insert and the metal coupon repeatedly and was bent into many turns. To ensure good thermal contact, the thermal grease was used

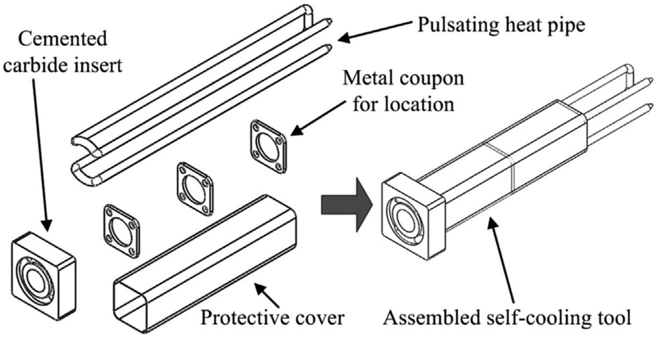

Fig. 2. Schematic of the pulsating heat pipe self-cooling tool.

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