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Material transfer during machining of aluminum alloys with polycrystalline diamond cutting tools

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ABSTRACT

An analysis of a polycrystalline diamond (PCD)-tipped tool after drilling 40,000 holes in aluminum (Al) 319 alloy under fully lubricated conditions is reported. It is found that aluminum adheres to the PCD tip surface during the machining process under lubricated condition. The aluminum transferring leads to poor surface finishing. Surface morphology analysis and element mapping suggests that the cobalt (Co) binder in the PCD tips is responsible for the adhesion of aluminum to the PCD surface, due to the chemical affinity between aluminum and cobalt. Approaches to prevent the adhesion of aluminum to the tool are discussed.

1. Introduction

Aluminum castings are used in the automotive industry for engine blocks, transmission housings and valve bodies, to reduce vehicle weight, improve fuel economy and lower emissions. The majority of these components have precise tolerances and/or threaded holes which require finishing machining operations, such as drilling, reaming and/or tapping. These operations take on average 30% of the total machining time and generate 70% of chips, as shown by Rivero et al. (2006).

Currently these operations are carried out under lubricated conditions (so called "wet machining") where the working zone of the machine is flooded with copious amounts of machining fluids. The machining fluids cool and lubricate the workpiece and tool and facilitate chip removal. The fluids also minimize the adhesion of aluminum to the tool and help to achieve a good surface finish. However, machining fluids increase machining costs and pose health and environmental risks. According to Dasch et al.'s study (2006), the cost of machining fluids constitutes up to 16% of total machining costs, which makes the development of dry and/or near-dry machining processes very desirable.

Attempts have been made to drill aluminum dry. In particular, dry drilling of 319 Al alloy has been studied by Hu et al. (2008), but was found impractical due to very short drill life since the chips adhered to the flutes of the drill, formed a build-up on the drills, and prevented further chip evacuation. This build-up rubs against the walls of the drilled hole, makes them rough and increases the torque acting on the drill, leading to its rapid failure.

Almeida et al. (2006) and Arumugam et al. (2006) proposed that diamond coatings on drills would prevent aluminum from sticking to the drill, since aluminum does not adhere to diamond, especially when the diamond is properly terminated with hydrogen, as shown by Qi and Hector (2004). Together with high hardness and wear resistance, it makes diamond coating a perfect candidate for cutting tools for machining of aluminum, even though the interaction between the diamond coating and the tool substrate is still greatly studied.

Another approach to achieve dry machining of aluminum is to use currently available polycrystalline diamond tools (PCD). PCD is comprised of micro-sized diamond particles held together with a metal binder, which is usually chosen from the group of transition metals such as Co, Ni or their alloys. PCD tools are produced by sintering the diamond particles under high pressure and temperature, and contain up to 15% (by volume) of binder. The binder helps PCD achieve higher fracture toughness (fracture energy) than single crystal diamond. Usually, PCD is used as an insert (or "tip") that is brazed to the body of the tool, which is made of WC–Co cemented carbide.

PCD-tipped cutting tools are commonly used where superior surface finish and a long tool life are required. Examples are the cutting tools employed at GM Warren Transmission Plant for machining valve bores in the transmission valve body. Fig. 1 shows a typical PCD-tipped tool; 0.8 mm thick PCD tips (black) are brazed to WC–Co tool body. Machining fluid is supplied through

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Fig. 1. Typical cutting tools with PCD tips on the cutting edges.

coolant-through holes. It is an established practice at GM Warren Transmission Operations to send the PCD tools to the manufacturer for inspection after machining 40,000 holes. During this inspection, some tools are found to require a refurbishment, while some others are returned to the plant.

PCD-tipped tools are widely used for other machining operations, such as milling and turning. Chip evacuation in these operations is easier than in drilling and some of these operations are conducted dry, which suggests the possibility of dry or near-dry drilling using PCD-tipped tools. The goal of the current communication is to report our analysis of the failure mode of the PCD tool for machining of Al, and to investigate the feasibility of using PCD tools for dry or near-dry machining of Al.

2. Experimental details

The PCD-tipped reamer was manufactured by Unimerco Inc. It was used to machine 40,000 holes in 380 Al alloy transmission valve bodies at the GM Warren Transmission Operation, Michigan. The machining was done under fully lubricated regular production conditions. The cutting speed was 8000 rpm and the feed rate was approximately 3000 mm/min.

The surface morphology of the PCD tips was measured with a Vecco Optical Interferometer. The tips were also observed under a scanning electron microscope LEO 230 and composition maps were analyzed with a Thermo Energy Dispersion X-ray Detector.

3. Results and discussions

3.1. PCD cutting edge

Fig. 2 shows SEM images of a PCD tip near the cutting edge after drilling 40,000 holes under lubricated conditions and Fig. 3 shows the results of optical surface profile measurements. A slight

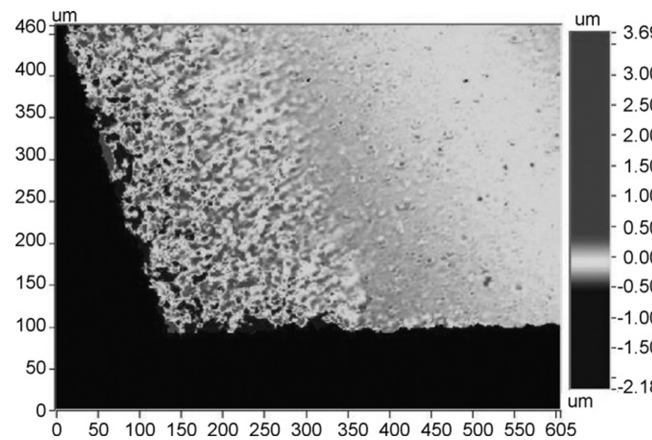

Fig. 3. Vecco optical profile of the cutting edge.

aluminum build-up can be observed around the cutting edge and on the rake face of the tool. Some diamond particles have been chipped off from the cutting edge, as shown in Fig. 3 where blue areas correspond to the cavities left by the removal of diamond particles.

The structure of the 380 Al alloy is comprised of silicon (Si) particles that precipitate out in the primary solid solution of Si in Al (Kaufman, 2006). In addition, there are intermetallic particles of CuAl and other relatively hard phases (Bardetsky et al., 2007). However, all the constituents are relatively soft compared to diamond. For example, the hardness of Si is Hsi = 12.3 to 12.9 GPa, as shown in Kaufman's book (2006), while the hardness of diamond is Hdiam = 100 GPa. The hardness of the other intermetallic particles is even lower than the hardness of Si. Therefore, it is unlikely that any of these particles mechanically abrade diamond. On the other hand, the fatigue of the metal binder in the PCD tip is likely to occur

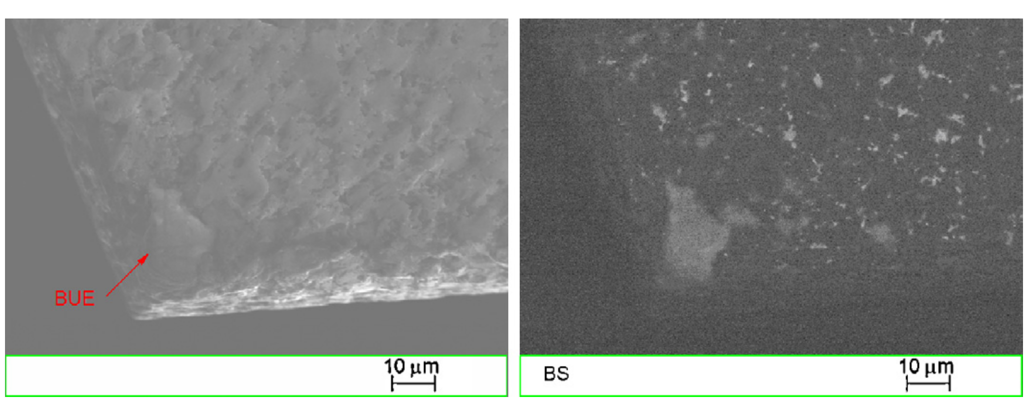

Fig. 2. SEM images of the cutting edge of a PCD tip after drilling 40,000 holes (left: secondary electron image, right: backscattering image).