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Increasing efficiency of Ti-alloy machining by cryogenic cooling and using ethanol in MRF

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ABSTRACT

Generation of high and localized cutting zone temperatures leading to dissolution wear hinders machining of titanium (Ti) alloys using uncoated carbide tools. In addition, the thermo-plastic instability exhibited by Ti alloys promotes serrated chip formation that causes fluctuations in the cutting forces leading to chatter and severe flank wear. This work considers two methods to mitigate the problems that occur during cutting of Ti-6Al-4V, namely, cryogenic machining and the use of ethanol blended metal removal fluids (MRF). Cryogenic machining decreased the cutting force and surface roughness compared to dry machining under the ambient conditions. The decrease in the fracture energy of Ti-6Al-4V (as measured by Charpy impact tests) and brittle type fracture led to formation of shorter chip segments during cryogenic machining. Alternatively the use of ethanol blended MRF further reduced the cutting force by over 65% compared to dry machining. Ethanol blended MRF facilitated adsorption of OH groups from ethanol by the carbon at the surfaces of the cutting tool resulting in negligible adhesion to the cutting tool.

Introduction

Ti-6Al-4V alloy is a versatile material for industrial applications because of its high strength-to-weight ratio, combined with high ductility and corrosion resistance but at the same time considered as a difficult-to-machine material [1]. Past studies [1–8] indicated that some reasons for difficulty in machining Ti and its alloys include (i) high temperatures generated in a narrow adiabatic shear band (ASB) as a result of localized shear concentration and poor heat dissipation due to low thermal conductivity of Ti [2,3], (ii) segmentation in chips due to non-homogenous deformation and localization of heat resulting in the formation of ASB. It was reported that the formation of ASB is usually associated with cyclic variation in the cutting forces. This in turn causes vibrations affecting the work piece-tool machine system stability [4–6], (iii) continuous contact at or near the apex of the tool with the segment being formed due to lack of relative motion between the segment and the tool face for a considerable portion of the chip segmentation cycle [6], (iv) unusually small contact area with the cutting tool (about one-third of that of steel at same feed rate and depth of cut) that causes high stresses at the tip of the tool [7], (v) high reactivity of titanium with conventional tool materials such as cemented carbides, borides, or nitrides resulting in dissolution wear at high temperatures [8]. Thus, to maintain a reasonable tool life (flank wear less than 200 μm), current machining practices in industry employ various coolants to reduce the cutting zone temperature. Flooded machining and cryogenic cooling strategies have been employed in machining of titanium alloys to reduce the cutting zone temperature and influence chip segmentation.

When machining Ti alloys, a segmented chip is normally produced. Segmented chip formation is believed to be either due to the growth of cracks from the outer surface of the chip [9] or ASB formation [2,10]. For Ti alloys, the onset of shear localization was found to occur at low cutting speeds and results in variation of cutting and feed forces with large fluctuations in magnitude [11]. The consequent vibrations, coined as 'chatter' in the metal cutting process, limit the material removal rate and accentuate the problem of tool wear. Thus, understanding chip formation mechanism and its resulting morphology are important for machining as they yield important information on the cutting process itself. Various cooling strategies were applied and their correlations with cutting forces, tool wear and coefficient of friction (COF) have been investigated during machining of several alloys [12–28].

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The use of liquid nitrogen (liquid N_2) as a cryogenic coolant during machining of several difficult-to-cut materials has been reported in the literature [12–18]. Venugopal et al. [12] observed the progression of tool wear during dry and cryogenic machining of Ti-6Al-4V. Under dry machining of Ti-6Al-4V at a cutting speed of 1.2 m/s and feed rate of 0.2 mm/rev, a tool life of 6 minutes was recorded which increased to 27 minutes by injecting liquid N_2 at the tool-workpiece interface. Wang et al. [13,14] carried out an experimental investigation into the cryogenic machining of Ti-6Al-4V, Inconel 718 and tantalum. The results indicated a reduction in the cutting tool temperature and tool wear under cryogenic cooling over machining with regular MRF (vegetable oil). For machining Ti-6Al-4V, it was noted that the flank wear reduced from 200 μm for machining with MRF to 75 μm with the use of cryogenic coolant at a cutting speed of 0.5 m/s and feed rate of 0.12 mm/rev. The authors correlated the cutting zone temperature with the chemical reactivity of Ti at cryogenic conditions to explain the reduction in flank wear. Similar benefits of cryogenic cooling in reducing tool wear, surface roughness and dimensional deviation have also been reported during orthogonal turning of steel [15,16] and tantalum [17]. Hong et al. [18] studied the cutting forces and COF during cryogenic cooling in orthogonal cutting of Ti-6Al-4V at a speed of 1 m/s. It was reported that injecting liquid N_2 removed the heat effectively from the cutting zone, lowering the cutting forces and COF at the tool/chip interfaces compared to conventional lubricated machining using soluble oil. When liquid N_2 was sprayed to the tool tip, it formed a fluid/gas cushion between the chip and tool face and provided lubrication effect by absorbing the heat and evaporating quickly. This lubrication effect reduced the COF from 0.54 under the dry condition to 0.30 under the cryogenic condition. The COF at the tool-workpiece interface during metal cutting influences the deformation at the primary and secondary zones resulting in microstructural changes in the chip material [18–21]. Thus, the effect of cutting zone temperature and its influence on chip morphology is of considerable interest. Joshi et al. [21] reported that cryogenic cooling of the workpiece resulted in fracture of the material along the shear plane leading to shorter chip segments. The chip segment ratio (ratio of difference between maximum and minimum chip thicknesses to the maximum chip thickness) was reported to be higher at cryogenic temperature than at room temperature. Higher chip segment ratio at cryogenic temperatures reduced the fluctuation in cutting forces which was attributed to reduction in non-homogenous deformation along the shear plane.

The use of liquid N_2 as a coolant is a specific method that has the potential to improve machining of Ti alloys on an industrial scale as reviewed above. Large scale industrial machining of Ti-6Al-4V demands a wear resistant cutting tool and consequently the use of polycrystalline diamond (PCD) tools are preferred over the conventional tungsten carbide (WC-Co) tools. Amin et al. [22] studied the performance of uncoated carbide and PCD inserts by conducting dry milling experiments on Ti-6Al-4V and suggested that the maximum cutting speed for the uncoated carbide inserts was 40 m/min, beyond which catastrophic tool wear initiated, whereas PCD tools did not fail at speeds as high as 120 m/min. Rahman et al. [23] compared the performance of PCD tools with the uncoated carbide tools as a function of cutting distance with varying cutting speeds. A cutting distance of 11 m was achieved using PCD tools before extensive adhesion of Ti on the cutting tool initiated tool failure compared to uncoated carbide tools that failed at 2 m. Nabhani [24] studied the performance of uncoated carbide, PCD tools and cubic boron nitride (CBN) coated carbide inserts in turning of Ti-4Al-8Si alloy. In addition to crater wear, adhesion of workpiece materials to the uncoated carbide and CBN coated tools was observed, resulting in high surface roughness for both uncoated carbide (10 μm) and CBN (8 μm) compared to PCD tools (1 μm). Oosthuizen et al. [25] studied the performance of PCD tools during high-speed milling of Ti-6Al-4V by considering tool life and cutting forces. Application of PCD tools yielded longer tool life than the carbide tools at cutting speeds above 100 m/min. A slower wear progression was observed with an increase in cutting speeds for the PCD tool, whereas an exponential increase in tool wear was recorded for the carbide tools. Extensive adhesion of Ti was noted during cutting with carbide tools, hence, a higher surface roughness than the PCD tools occurred.

The effect of passivation of carbon surfaces by hydroxyl (OH) groups has been investigated to reduce the COF of the tool-workpiece interface. Erdemir [26] showed that hydrogenated diamond like carbon (H-DLC) coatings tested in dry N_2 atmosphere against H13 grade steel disks generated a COF of 0.005, while the non-hydrogenated diamond-like carbon (NH-DLC) coating produced a COF of 0.75. The very low COF value of H-DLC was attributed to the passivation of σ-carbon bonds at the contact surface by the hydrogen atoms. Konca et al. [27] reported a high COF of 0.52 for NH-DLC sliding against an Al-6.5%Si alloy, under vacuum (6.65×10^{-4} Pa). The same NH-DLC when tested in an ambient atmosphere (47% RH) produced a low COF of 0.16. The COF

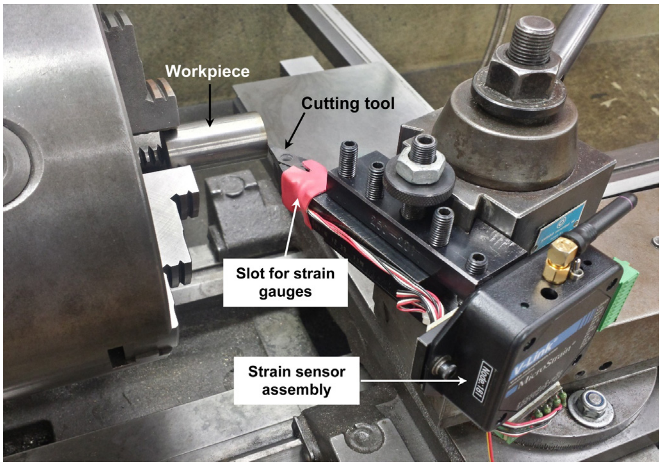

Fig. 1. Experimental setup for orthogonal machining showing the position of the cutting tool and the strain sensor assembly used for measuring the cutting forces.

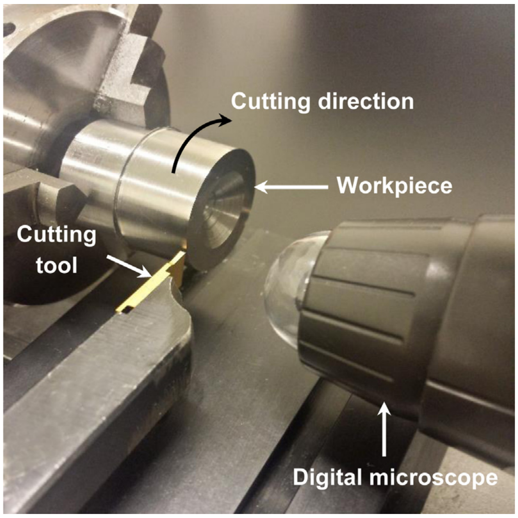

Fig. 2. In situ experimental setup with the shear plane of the workpiece on a plane normal to the light beam of the microscope..

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