Analytical assessment of the wetting capability of MQL supply and the mechanism of tool wear in micro-milling

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Abstract: During mechanical micro-milling, application of cutting fluid following the Minimum Quantity Lubrication (MQL) strategy helps improving machinability while ensuring sustainability. It is necessary to deposit the MQL oil droplets in the tribologically active chip-tool-workpiece region to perceive enhanced lubrication. An analytical model is first presented to assess the wetting capability of a given MQL oil supply considering the effects of nozzle orientation, droplet size, jet characteristics, inherent ploughing-to-shearing transition, etc. During micro-milling of Ti-6Al-4V using 500 μm diameter TiAlN-coated WC/6Co tools, 6.0 mL/h oil flow rate can adequately lubricate the entire tribo-contact region when the spindle speed is around 20,000 rpm. Beyond this spindle speed, this flow rate is inadequate for complete lubrication. Further, the concept of MQL "Shadow Zone" is introduced, and an analytical model is presented to assess the detrimental effects of the shadow zones in restricting the MQL oil droplets from depositing on the cutting edges. At 50 μm axial depth of cut, the shadow zone can restrict about 3.7% droplets from reaching the cutting edges. The deficiency rises to 16.4% at 200 μm axial depth. The influences of oil deficiency on tool wear, surface roughness, and top-burr are also discussed. During micro-milling, the fresh coated tool successively undergoes rapid abrasion, steady abrasion, coating delamination, adhesion, and edge-chipping. The error associated with microscopic measurement of worn-out tool outer diameter is very high. However, as the cutting edge radius increases with tool wear, the diameter of the tool also decreases. The relationship between the changes in the edge features and corresponding reduction in outer diameter is established. This eliminates the need for direct measurement of the worn-out tool diameter. Furthermore, an analytical model is presented to predict the condition for the onset of adhesion with progressive tool wear considering the dynamic growth of the dead metal zone (DMZ) and stress distribution at the interfaces. The form stability of the cutting edges is also assessed to understand the mechanism of edge-chipping with progressive tool wear. The effects of tool wear on machinability are also discussed.

Keywords: Micro-milling, Minimum Quantity Lubrication, Tool wear, Shadow Zone, Surface roughness, Burr