

ABSTRACT

The increasing industrial emphasis on sustainable and high-efficiency manufacturing has necessitated the evolution of novel cooling methodologies that minimize coolant usage while maintaining or enhancing the machining performance of cutting tools. Traditional flood cooling methods, while effective in dissipating heat, are associated with significant operational costs, environmental concerns, and limited efficiency, particularly when machining low thermal conductivity materials such as titanium alloys. One of the principal challenges in machining operations lies in ensuring adequate penetration of the cutting fluid into the plastic contact (Cp) region—an intense heat generation zone formed due to plastic deformation and friction at the tool-workpiece interface. Inadequate thermal management in this region often leads to accelerated tool wear, dimensional inaccuracies, and poor surface integrity of the machined component.

Drawing inspiration from the thermal management capabilities of microchannel heat sinks used in electronic and aerospace applications, this research investigates the feasibility and performance enhancement potential of microchannel-textured cutting tools. The study is structured into four integral phases encompassing both numerical and experimental approaches. Initially, a numerical modelling scheme based on Finite Element Analysis (FEA) is developed and validated against experimental cutting force data using high-speed steel (HSS) tools in the machining of mild steel. The structural integrity of cutting tools integrated with various microchannel geometries—rectangular, semi-circular, trapezoidal, and V-shaped—is evaluated under simulated cutting loads. The validated models incorporate maximum principal stress (MPS) criteria to predict stress distributions and identify optimal microchannel configurations.

The second phase examines the performance of HSS tools with single and double microchannel designs positioned at varying proximities (0.5 mm to 2 mm) from the principal cutting edge (PCE). Simulation results indicate that trapezoidal and semi-circular microchannels positioned at or beyond 1.25 mm from the PCE provide superior stress mitigation and thermal regulation, without exceeding the material's yield strength. Subsequently, the analysis is extended to uncoated tungsten carbide (WC-Co) tools used for machining Ti-6Al-4V—a difficult-to-machine alloy characterized by high strength-to-weight ratio and poor thermal conductivity. A comprehensive structural analysis under static loads derived from literature and prior studies

reveals that microchannel-induced stress increments remain within the safe operational limits of the tool material, with trapezoidal geometries again outperforming other shapes in terms of mechanical resilience and thermal efficiency.

The final phase involves experimental validation through turning operations on mild steel using M42 grade HSS cutting tools integrated with laser-engraved microchannels. Two distinct trapezoidal microchannel configurations are examined under dry, small quantity lubrication (SQL), and microchannel-assisted cooling conditions. Cutting forces are measured via strain-gauge dynamometry, temperature distribution is recorded using infrared thermography, and surface finish is assessed with a stylus profilometer. Results consistently demonstrate that microchannel-integrated tools significantly reduce cutting and feed forces, suppress peak temperatures in the cutting zone, and yield superior surface finish compared to conventional cooling strategies. The performance enhancements are attributed to improved fluid penetration into the Cp region, enhanced convective heat transfer, and localized capillary-driven fluid flow within the channels.

In summary, this research confirms the technical feasibility and functional advantages of incorporating microchannels into cutting tools. The proposed design methodology ensures a balance between structural integrity and thermal performance, thereby presenting a viable pathway for the development of next-generation tooling systems. These findings hold considerable potential for extending tool life, improving machinability of advanced materials, and contributing to the realization of environmentally sustainable machining practices.