ON THE TRIBOLOGICAL EFFECTIVENESS OF CONTROLLED CUTTING FLUID APPLICATION IN MACHINING WITH COATED TOOLS

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ABSTRACT
Environmental and economic pressures are causing reevaluation of the use of Cutting Fluids (CFs) in machining operations, leading to recent efforts in promoting dry, as well as minimal quantity of lubricant (MQL), machining. This paper presents an experimental investigation into the effects of different CF application methods on various machining performance measures under modern cutting conditions using uncoated and coated cemented tungsten carbide tools. CF effects under dry, flood, and MQL conditions, were gauged through their influence on cutting forces, tool temperatures, tool-chip interfacial friction, and chip morphology during machining of AISI 1045 steel using commercially available uncoated, and mono- and multi-layer coated, carbide tools. The results show new trends on the individual cooling and lubricating effects of CF application methods, and the integrated effects of their interactions with tool material, on tribological performance.

INTRODUCTION
Cutting Fluids (CFs) are widely employed in many machining operations to perform three major claimed functions – lubrication, cooling, and chip transport away from the cutting zone. However, their use is now being questioned due to environmental and economic pressures [1], leading to recent efforts in promoting totally dry machining, as well as minimal quantity of lubricant (MQL) machining – a technique in which minute quantities of lubricant, atomized in a compressed air jet, are sprayed near the cutting zone. Although much work has been done to understand the fundamental mechanisms of CF action at low cutting speeds [2], their tribological influence at modern cutting conditions is less apparent. Specifically, the effects of different CF application methods (including the effects of CF flow rate in the case of MQL), and their interaction with tool-coating pairs, on the tribology of machining need further understanding. Of special interest is the partitioning of two major claimed CF actions – (i) Direct reduction in friction through lubrication; and (ii) Reduction in temperatures in the cutting zone.

This paper presents an experimental investigation into the effects of different CF application methods on various machining performance measures under modern cutting conditions using uncoated and coated cemented carbide tools. CF effects under dry, flood, and two different levels of MQL conditions were gauged through the influence on cutting forces, interfacial friction, tool temperatures, and chip morphology during orthogonal machining of AISI 1045 steel. A commercially available soluble oil was used as the CF.

EXPERIMENTAL RESULTS AND DISCUSSION
Disc shaped flanges of AISI 1045 steel, 3 mm wide, were orthogonally machined on a CNC lathe by means of a facing operation using straight-edged, flat-faced tools (Fig. 1). Table 1 provides details of the experimental plan. In all cases the CF was applied as an overhead jet directed towards the tool rake face, at a location approximately 2 mm from the cutting edge.

![Experimental setup](image)
Since CF delivery nozzles typically have a spray angle of 15-20°, this ensured that CF was delivered to all accessible locations of the tool face – including the side edges of the emerging chip, the sliding region where the chip breaks contact from the tool, and the chip back surface. Cutting forces were measured in-situ through a dynamometer interfaced with a charge amplifier. Temperature was also measured in-situ at the bottom of the cutting insert by seating a fine wire (0.25 mm) K-type thermocouple in a special channel, parallel to the cutting edge, machined into the shim below the indexable cutting insert.

The results showed that the effects of CF application method on cutting force, thrust force, and chip thickness ($t_c$) were negligible. Accordingly, the calculated average coefficient of friction at the tool face showed no significant variation with CF application. Under all conditions the Uncoated tool experienced the highest forces, while the PVD tool experienced the least. The Uncoated tool also had the maximum $t_c$, while this value was nearly identical for the PVD and CVD tools. Thus, there was no observable reduction in tool-chip friction through any direct lubrication arising from CF application. Future metallographical analysis of chips, especially the thickness of the severely deformed layer at the tool-chip interface, is expected to yield further information about whether these macro-scale effects are also observed at meso/micro-scales.

Thermocouple based temperature measurement at a remote location (base of the insert) showed that Flood application was most effective in curtailing the temperature rise during cutting, $\Delta \theta$, at regions removed from the cutting zone (Fig. 2). The two MQL conditions performed slightly better than the Dry condition, which experienced maximum $\Delta \theta$. The higher level MQL (MQL2) showed no significant improvement in $\Delta \theta$ over MQL1. Under all conditions except Flood, for which case all tools yielded approximately the same $\Delta \theta$, the Uncoated tool yielded the maximum $\Delta \theta$, while the PVD and CVD tools were approximately equally effective in controlling heat transfer into the tool.

The chips generated under all conditions were of up-curled morphology. For the Uncoated and CVD tools they were also coiled, with an up curl radius on the order of 10 mm, while in the case of the PVD tool they were only loosely coiled, most noticeably under the Flood condition, with an up curl radius on the order of 30 mm.

As mentioned by Venkatesh et. al. [3], the temperatures of chips formed during machining of plain carbon steels are reflected in their color, since this is in turn dependant on the thicknesses and types of oxide films (FeO, Fe$_2$O$_3$, Fe$_3$O$_4$) that form on the chip surface at high temperature. A light or golden yellow color indicates a thin oxide layer (relatively lower chip temperatures), while a dark blue color indicates a thick oxide layer (high temperatures). Varying shades of brown indicate intermediate temperatures. In this study it was found that chips produced by the Uncoated tool transitioned from light brown to dark brown as the CF application method was changed from Dry to MQL1, MQL2, and finally Flood. In the case of the PVD tool, the chips were light blue under Dry condition and transitioned to dark blue under MQL1 and MQL2. However, they were light brown under Flood. A similar situation was observed with the CVD tool, which had golden chips under Flood condition. Correlation with the temperature-chip color data of Venkatesh et. al. [3] suggests that CF application served to set up a temperature gradient that favored increased heat transfer into the chip, but the degree to which this occurred depended on the tool material. Thus, there is a an interaction between tool material (and coatings) and CF application that influenced the chip temperature, and further investigation of tool thermal properties is needed to understand this effect.

In summary, under the conditions tested there was no observable influence of CF application on tool-chip friction on the basis of cutting forces and chip thickness. However, application of CF did have an effect on tool, as well as chip, temperatures, and this effect depended on the interaction between tool (and coating) material and CF application method.

**REFERENCES**