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Contents

The main objective of the FemtoSurf project is to develop, test, and demonstrate industrial-grade solid-state 2-3 kW-level fs laser with parameters suitable for metal surface patterning applicable in industrial settings. FemtoSurf industrial-grade 2-3kW-level fs laser will be integrated into a propose-built optical chain enabling multi-beam processing (100+ simultaneous beams) with individually tailored spatial distributions in each laser spot, integrated into a fully automated processing setup for efficient patterning arbitrary shaped metal components with sizes exceeding several meters while retaining micrometer level precision and on-the-fly quality assessment (zero faulty parts delivered).

1. Introduction

The present document is a deliverable "D6.4 – Report on testing in tooling applications" of the FemtoSurf project (Grant Agreement No.: 825512), funded by the European Union's Horizon 2020 Research and Innovation program (H2020).

The purpose of the DELIVERABLE is to provide a document that describes the development and testing process for tooling applications. In this document required information will be provided about the laser fabrication process, predetermination of texture patterns, fabrication, testing, and results for tooling applications, specifically to control and reduce friction and wear. Materials for samples were supported by the end-user, and whole fabrication and testing were made in several iterations.

The following document made use of the HORIZON 2020 FAIR DATA MANAGEMENT PLAN TEMPLATE and was written with reference to the Guidelines to FAIR (Findable, Accessible, Interoperable, and Reusable) data management in Horizon 2020.

2 Tooling case study

2.1 Summary

Using conditions determined from machining experiments, laboratory tribology investigations have been conducted to determine the influences of surface textures on elastohydrodynamic lubrication. Extended on-machine testing using combinations of periodic SEM imaging and cutting force capture provided compelling evidence of the benefits of textures on tool wear. The results are benchmarked against an uncoated and non-textured H13A carbide insert, and the optimum laser patterns will be reported to FEMTOSURF to be processed using the developed laser system.

In this case study, we use a laser as the fabrication method to develop micro-textures on turning inserts that can reduce the cutting/friction forces and subsequently study their influence on friction performance at the tool-chip interface. This study performed orthogonal turning (Fig. 1a) tests to capture cutting forces, laboratory-based tribological tests to capture friction forces, and SEM microscopy to monitor the tool's wear progress. The effect of micro-texture designs, including micro-dimpled, and perpendicular micro-grooves, on the aerospace-grade aluminum alloy (Al 2024) tool rake face are investigated during the turning experiments.

It was found that texturing of cutting tool surfaces using designs such as grooves and dimples with micro size features, offers several advantages. These include reducing cutting forces and frictional contact, better control of chip behavior and fluid delivery to the cutting zone, enhancing thermal conductivity, and reducing tool wear and work material adhesion to cutting tool surfaces during machining processes. Due to regulated contact pressures and frictional behavior between the tool rake face and the chip, the cutting forces and friction coefficient are reduced. In addition, because of the reduced material adhesion, the service performance of the tool is enhanced. Consequently, these factors contribute to the creation of wear-resistant and anti-adhesive cutting tool structures. This results in desirable and sustainable machining outcomes, such as improved tool service performance, reduced use of cutting fluids, and reduced costs.

2.2 Background

2.2.1 The Effect of Surface Texture on Friction

From the literature review, it is shown that developing micro-dimple and groove textures on turning inserts can have a significant effect on the cutting/friction forces. The modification of cutting tool and workpiece surface interactions potentially offers significant benefits in the extension of tool performance thresholds. The formation of micro-dimples and groove textures affects the surface interaction and lubrication regime at the tool-chip interface of cutting tools (Figure 1).

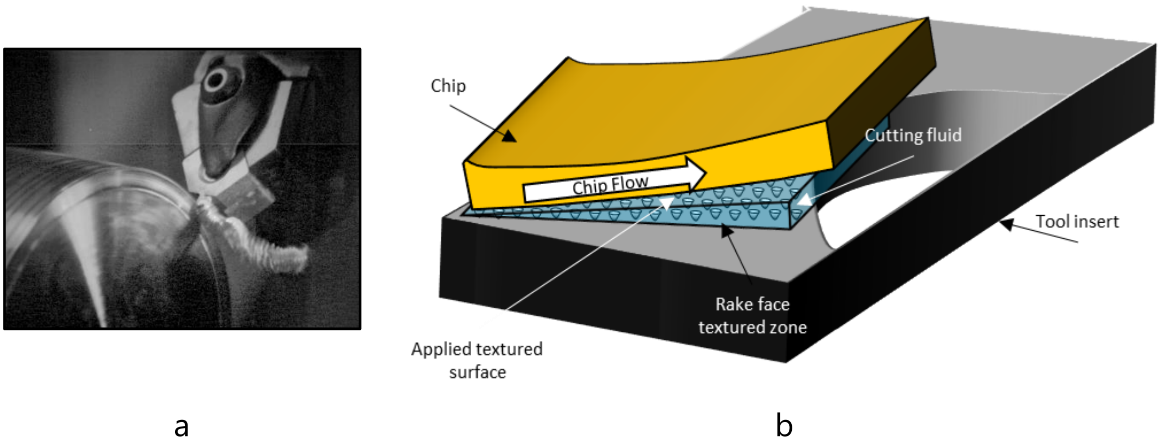

Figure 1: (a) Orthogonal turning and (b) The flow of chip on the surface of the insert during the turning process

2.2.2 Friction at the Tool-Chip Interface

Depending on the boundary condition and location on the chip (which itself depends on machining condition, lubrication, and the type of the material) the following three types of frictions can occur at the tool-chip interface:

- **Near cutting edge - Boundary lubrication:** Solid surfaces come into direct contact, very thin lubricant film, load supported mainly by surface asperities, high friction.
- **Further along the cutting edge - Mixed lubrication:** Some asperities contact, some areas are separated by a lubricant film, sliding velocity increases, load supported by both asperities and the liquid lubricant, and lower friction (Figure 2).
- **Furthest from cutting edge and before the beginning of curl - Hydrodynamic lubrication:** Negligible asperity contact, thicker lubrication

film, the normal load is reduced, and load supported mainly by hydrodynamic pressure, lowest friction, mainly due to viscosity.

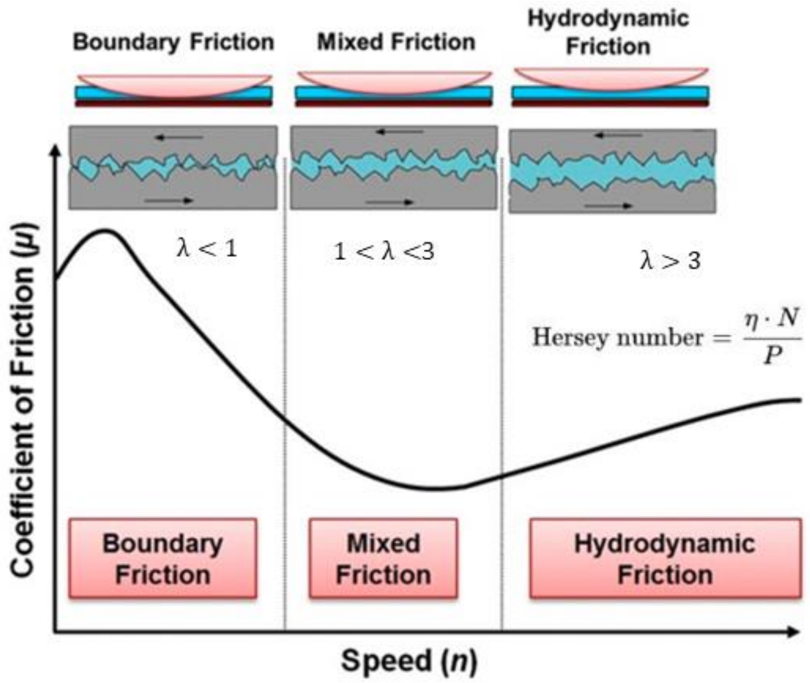

Figure 2: Stribeck Curve and the three types of frictions at the tool-chip interface during orthogonal turning

2.2.3 Pulsed Laser Ablation Mechanisms

This study utilized a Femtosecond pulsed laser to ablate material from (and thereby texture) the surface of the turning inserts.

Pulsed laser ablation refers to the removal of material from the surface of the sample by using short high-intensity laser pulses as the heating source. Pulsed lasers produce shorter bursts of energy, which result in much higher peak energy levels in comparison to continuous wave (CW) laser sources. Laser pulse durations can be categorized as short pulses (i.e., micro or nanoseconds) or as Ultra-Short Pulses (USP) (i.e., pico- and femtoseconds).

For pulse durations above 10 picoseconds (ps), the ablation process consists of heat conduction, melting, evaporation, and plasma formation as shown in Figure 3a. Pulse durations of less than 10 ps are shorter than the time required for electrons, which absorb the energy of the photons, to transfer their energy to the lattice. Therefore, ablation processes with ultrashort pulses involve no melting and virtually minimum little to no heat-affected zone. This allows the USP processing to have an extremely precise geometrical accuracy and removal rate for a wide range of insert materials. On the other hand, and despite the precise machining accuracy, the ablation rate and ablation efficiency are significantly lower in comparison to a nanosecond regime. Figures 3a and b show the laser material processing interaction for short and ultra-short pulse durations.

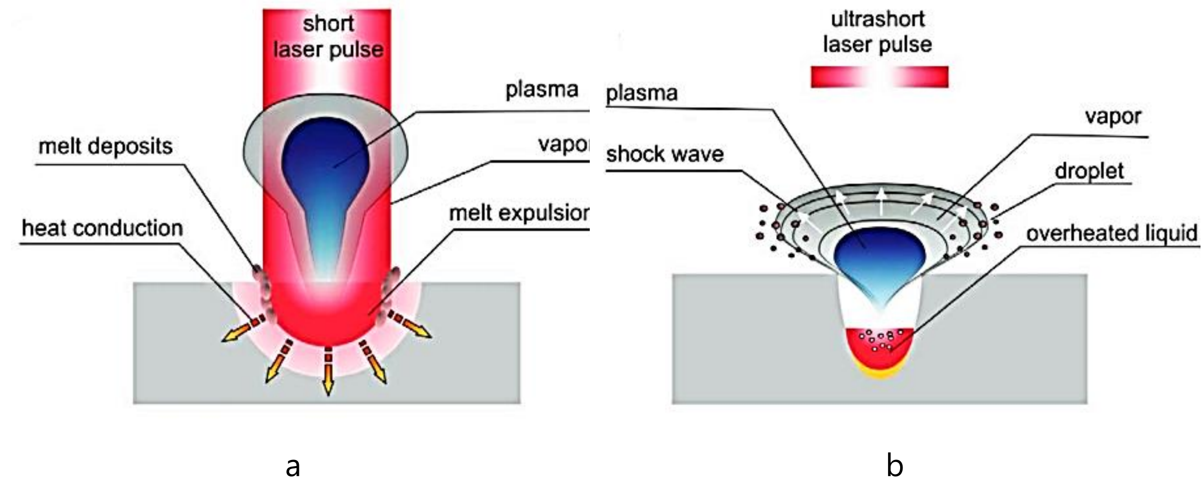

Figure 3: Pulsed laser beam and matter interaction (a) short-pulse laser (μs, ns) - matter interaction; (b) ultrashort pulse (ps, fs) beam-matter interaction

Key findings from this study:

- The wear sequences for all the tested inserts showed increased wear scaring and accumulated surface contamination (transfer layers) with their accumulated cutting distances.
- The textured inserts exhibited reduced contact with the workpiece both in wear scars (boundary lubrication conditions) and in surface contamination on their rake faces compared with the un-textured reference insert. The samples with higher populations of texture features (D1-S4 and G5-S4) exhibited significantly reduced surface contamination compared with those with the lower texture population (G3-S4).

- All textured inserts produced lower cutting forces for all wear cycles compared with the un-textured reference sample, with the higher texture populations of G5-S4 and D1-S4 producing the lowest forces.

2.3 Discussion

A sequence of tests was designed to assess the machining performance of laser textured cutting tool inserts which were designed based on studies presented in the reviewed literature. Turning tests revealed that the cutting forces for most of the textured inserts were lower than those produced by the un-textured inserts. Studies were set up using a laboratory tribometer to independently study the surface friction of the three inserts which produced the lowest cutting forces in the turning tests. Results from the tribometer tests using a nominal contact load of 10 N for the three different pin diameters exhibited boundary, mixed, and hydrodynamic lubrication conditions across the selected oscillation frequency range. Effective contact pressures were used to normalize the influences of material removed from the surface of the inserts by texturing. For an effective pressure of 12.7 MPa, the G5-S4 groove texture produced the lowest CoF values at 40 Hz and above. While for an effective pressure of 3.18 MPa, the D1-S4 dimpled texture produced the lowest CoF values for the same conditions. At the selected effective contact pressure of 12.7 MPa, the dimpled texture showed a lower sensitivity to the changes in entrainment area produced by the three different pin sizes, in comparison to the groove textures.

The SEM images of the progressive wear of the cutting tool inserts for each cycle revealed that the textured inserts exhibited significantly lower surface contamination than the un-textured reference insert. Both the dimple texture D1-S4 and the groove texture G5-S4 also outperformed the more sparsely populated groove texture G3-S4, by exhibiting lower surface contamination.

From the cutting force results and the surface friction and progressive wear analyses, for machining conditions where the tool and workpiece contact pressure is likely to be high, the groove G5-S4 would be expected to outperform the other textures considered. While at lower contact pressure, the D1-S4 is likely to outperform the best. In addition, the results from the study on entrainment area indicate that the G5-S4 texture would be likely to perform best where the contact areas between the tool and workpiece are large, while the D1-S4 texture would perform better where contact areas are smaller.

2.4 Future Steps

This study demonstrates the benefits of laser texturing the rake faces of cemented tungsten carbide cutting tools for the machining of aluminum alloys. The advantages of laser texturing are also likely to be realized in far wider areas of application and machining setups for an extensive range of workpiece materials and for other machining processes, such as milling and drilling both in continuous and interrupted cutting. Future studies of laser texturing of rake and other contact faces of cutting tools are therefore recommended to explore the benefits of reducing tool surface friction and increasing tool service lives in an expanded range of machining applications and workpiece materials.

In addition, it is recommended that detailed studies are carried out on the coolant flow characteristics across different texture designs to enhance an understanding of the interaction between selected textures and cutting fluids. Information from such studies will facilitate the selection of optimal texture designs for targeted machining environments and applications.