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ORIGINAL PAPER

In Situ Measurement of Fluid Film Thickness in Machining

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Abstract A novel method using luminescent molecule sensors is described for in situ measurement of fluid film thickness along the tool rake face in machining. The method uses an optically transparent sapphire tool to access the rake face, and measurement of radiation emitted by luminescing molecules dispersed in a machining fluid. By measuring the intensity of the emission, the film thickness is estimated. Implications for tool-chip contact boundary conditions and near-dry machining are discussed.

Keywords Machining · Fluid · Lubrication · Contact mechanics

Introduction

The tool-chip interface represents an extreme tribological condition where important phenomenological events occur over small spatial and short time scales. This interface is characterized by contact between pristine surfaces under conditions of high normal pressure and speed, wherein, over much of the contact, the real and apparent areas are essentially equal, making lubrication a difficult task [1, 2]. Such a contact condition is far removed from those prevailing in typical sliding or rolling contacts. It has long been held that the interactions occurring at this interface play an important role in controlling the mechanics of machining (e.g., energy consumption, type of chip) and type and rate of tool wear. However, because of the inherent difficulties involved in observing and characterizing this interface condition directly, quantitative details of the frictional boundary condition along this interface have been less than adequate [3]. This has posed barriers to accurate modeling of machining processes. There has been much debate about penetration of machining fluid into the tool-chip contact and its lubrication action, thereof, because of the severity of the contact condition and the aforementioned difficulties in accessing this interface directly [2, 4–6]. This has posed barriers to answering questions regarding quantity and type of fluid needed to achieve adequate lubrication, and development of efficient, environmentally-friendly machining processes that involve minimal fluid usage. The need for enhanced understanding of performance of machining fluids is also driven by the high burden these fluids impose in terms of cost (up to 16% of total machining costs in many operations), infrastructure demands, and impact on health and environment [7].

While snapshots of the interface condition have been obtained using various techniques, a new opportunity has recently emerged [8, 9]. This is based on a novel combination of optical, luminescence, and image analysis techniques that offer the possibility of characterizing the complete interfacial condition, in situ, at high resolution.

The present study describes a new technique using luminescent molecule sensors to characterize fluid action in the tool-chip contact region along the rake face. It builds on an observation approach using optically transparent tools that enables the chip-tool interface to be imaged, in situ, while cutting is in progress [1, 10–13]. Preliminary results pertaining to thickness of fluid film in the contact are presented together with a brief discussion of an extension

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of this technique for studying other interface parameters such as temperature.

Background

Tool-Chip Contact

It is instructive to briefly review the tool-chip contact condition in the context of fluid action along this interface. Direct observations of the rake face made through transparent tools and indirect study of this face using quick stop methods have shown the contact region to be composed of two distinct zones [1, 5, 11, 12]. Figure 1 shows an image of the rake face of a sapphire tool, taken in situ, while cutting lead that highlights the two zones. A zone of intimate contact extends from the cutting edge to some distance up the rake face wherein the real and apparent areas are equal; this is followed by a zone of metal deposit that extends to the edge of chip-tool contact, wherein conventional sliding contact prevails. When a fluid is applied to the machining zone, the region of metal deposit disappears, compare Fig. 1a and b. This suggests that the fluid is certainly active around the edges of the chip-tool contact. But it is unclear if any fluid has actually penetrated into the intimate contact zone.

Several models have been proposed to explain the action of a fluid at the chip-tool interface. These models suppose that the rate-controlling step in lubrication is transport of fluid molecules into the chip-tool contact region and only fluids with certain characteristics (usually not suitable for utilization in machining) can be transported effectively [5, 14]. Mechanisms suggested for fluid access to the intimate contact region include fluid flow through a network of connected capillaries between tool and chip along the rake face [2, 5]; and fluid penetration through voids and fissures in the chip [2, 15]. Vapor phase lubrication of the chip-tool contact has also been demonstrated under specific conditions [16], indicating that vapor molecules can penetrate the contact.

Observational attempts to infer fluid penetration into the intimate contact zone when machining with transparent tools have generally been unsuccessful even when using fluids with colored dispersions. However, since the tool rake face is directly accessible when cutting with a transparent tool, the use of luminescent molecule sensors as a means of mapping fluid action in the intimate contact zone is an attractive experimental option.

Luminescent Molecule Sensors

Luminescent molecule sensors offer extraordinary capabilities for quantitative characterization of fluid action along the tool-chip interface and, potentially, measurement of temperature along the rake face. This suite of techniques relies on volume (number of molecules), temperature, and pressure dependence of luminescence, a phenomenon known for many years and widely exploited for temperature measurement elsewhere [17–19]. For example, luminescent molecule sensors embedded in a polymer (called Temperature-Sensitive Paint (TSP)) have been used recently to obtain temperature maps on aerodynamic test model surfaces at high-resolution. From these measurements, quantitative data pertaining to heat transfer, transition from laminar to turbulent flow, and shock location have been obtained.

A luminescent molecule sensor is made by mixing an appropriate 'luminescent' molecule with a binder that enables attachment of the molecule to a surface. The binder can be a solvent or a fluid medium; in the present study a cutting fluid performs this function. The luminescent molecule has the characteristic that upon irradiation by a light source like an Ultra-Violet (UV) LED, the molecule is excited to a higher energy state. Following the excitation, the molecule returns to its initial energy state by emitting light of a wavelength (luminescence) that is different from that of the excitation. Due to the different wavelengths of excitation and emission, these two signals can be separated using optical filters. The emission intensity and its time dependence can be calibrated as a function of thickness,

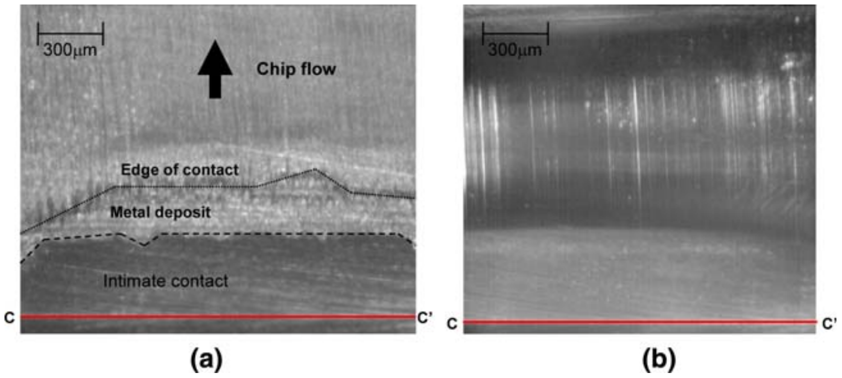

Fig. 1 Direct images of rake face of sapphire tool in (**a**) dry cutting and (**b**) cutting in presence of fluid. CC′ is the cutting edge. The cutting speed is 10 mm/s and the undeformed chip thickness is 200 μm. The work material is lead

temperature, or pressure, depending on the characteristics of the sensor. If a luminescent molecule sensor with emission characteristics independent of pressure and temperature is selected, then the intensity of emission is governed by the number of molecules present in the emitting region. Assuming uniform distribution of molecules over the region of interest, this emission intensity can be calibrated in terms of the thickness of the oil film containing the luminescent sensor. The emission intensity is usually measured with a photo detector like a CCD camera, to obtain a global map of film thickness distribution at high spatial resolution. An overview of luminescent sensor methods and their applications can be found in Ref. [20].

Experimental Details

Figure 2 shows a schematic of the experimental set-up used to study fluid action along the tool-chip contact in plane-strain (2D) machining. A sharp sapphire tool is used, the tool shaped like a parallelepiped with an additional inclined facet (Fig. 2), that allows for the rake face and chip-tool interface along this face to be imaged, in situ, through a side of the tool. The tool is designed such that light rays leaving the cutting edge and the rake face are internally reflected by the facet and transmitted perpendicular to a side face of the tool and parallel to the cutting edge. This arrangement has been described in greater detail elsewhere [11, 12].

The luminescent molecule sensor consisted of 0.4 mg of fluorescent pigment (Aurora pink, from Day-Glo Color Corp.), dispersed in 5 mL of a commercial cutting fluid (Tap Magic aluminum cutting fluid, Steco Corp); henceforth this combination is referred to as the fluid. This molecule was selected for the relative insensitivity of its emission to temperature. The fluid was applied onto the tool surface prior to the cutting, as well as drip-fed into the cutting region during the cutting.

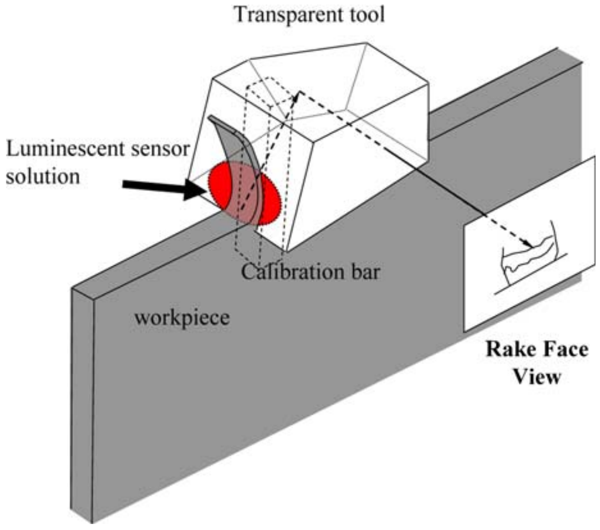

Fig. 2 Schematic of set-up for direct observation of tool rake face when machining with a sapphire tool

The workpiece was pure lead in the form of a block, 2 mm wide by 165 mm long by 38 mm high. Machining was carried out at a speed of 10 mm/s, undeformed chip thickness of 0.2 mm and a tool rake angle of 10°. The tool was held stationary while the workpiece moved with respect to the tool at the pre-set speed. A calibration bar made of lead was attached to part of the rake face, next to the cutting region, as shown in Fig. 2, so that fluid of a known film thickness could be confined to this region called the calibration region, while cutting was taking place. This enabled luminescence from the cutting and calibration regions of the rake face to be simultaneously recorded during the cutting, enabling in situ calibration while making the film thickness measurements. The rake face images were recorded by a 12 bit CCD camera (SenSYS) with 768 × 512 pixel resolution. A 55 mm macro camera lens with 12 mm extension tube was used with the camera, enabling a spatial resolution of 12 μm per pixel. A mercury lamp with UV filter was used as the excitation light source to induce the luminescence.

Results

By measuring the intensity of the emission from the fluid introduced into the cutting region, it was possible to determine the extent of fluid penetration into the tool-chip contact region and the thickness of the fluid film therein. This analysis required careful in situ calibration of the fluid film luminescence in a configuration similar to that of the cutting.

Calibration

In situ calibration was carried out by constructing a calibration setup that could be embedded within the machining setup, thereby enabling the calibration procedure to be executed along with the measurement procedure. For this purpose, a 2 mm wide calibration bar, cut from the same pure lead work piece, was attached to part of the rake face of the sapphire tool immediately adjoining the cutting region. The bar was inclined at a small angle of ~3° to the rake face so that a small gap existed between the rake face and the calibration bar (Fig. 3). The precise thickness of the gap could be measured from a side view image taken with the microscope as shown in Fig. 4. This gap increased linearly with distance from the cutting edge from a value of ~24 μm at the edge.

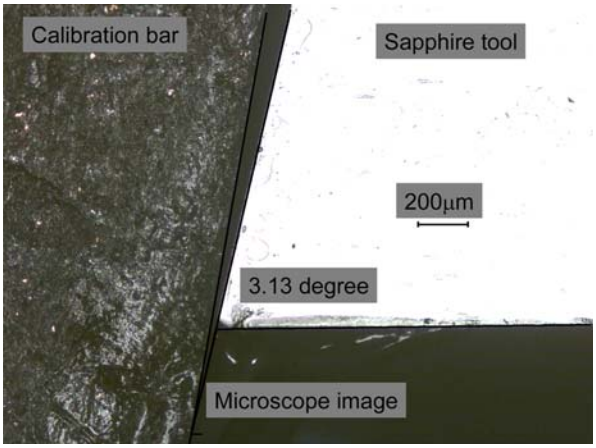

Fig. 3 Calibration bar attached at a small inclination to the rake face. Image shown is a side view

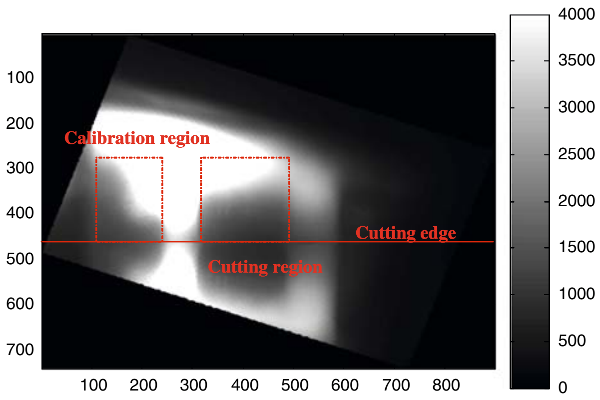

Fig. 4 Intensity image of rake face including calibration and cutting regions. The units of intensity are counts recorded by the CCD camera

During machining, the fluid was applied continuously to the machining region using a droplet nozzle and also filled the gap in the calibration region. Intensity values from the emission accompanying excitation of the luminescent molecules were simultaneously recorded (in the same image) from the cutting and calibration regions through the tool rake face, under the same experimental condition. This in situ calibration minimized errors that could have accrued due to motion of excitation light source, noise from extraneous sources including internal scattering within the sapphire tool, and variations in transmittance/reflectance of the sapphire tool.

Figure 4 shows an intensity image of the rake surface taken during machining in the presence of the fluid. The calibration region is seen along with the cutting region in the measurement area. The intensity varies from 1,500 to 4,000 counts inside the cutting and calibration regions. An extrapolation of the intensity versus film thickness data for the calibration region showed a finite intensity value (~950 counts) at zero film thickness. This value was taken to be the background noise and was subtracted from the calibration data to get a true calibration curve of intensity versus film thickness. Figure 5 shows true calibration curves relating the measured fluid film thickness in the calibration region to the measured emission intensity (corrected for the background noise) from the same region. The curves are plotted for film thicknesses values greater than ~24 µm, this thickness being that of the fluid at the cutting edge as noted above. The two calibration data sets shown in the figure were made at different stages in the same machining pass but simultaneous with the fluid film thickness measurements; these are essentially two different experiments performed under the same machining condition. The data sets in Fig. 5 are overlapping with a high R2 value for a linear fit. And the excellent linear fit for the emission intensity with film thickness is to be expected for this luminescent molecule sensor. The calibration relation derived from this experiment was applied to the cutting region of the rake face to estimate the fluid film thickness. The film thickness measurements were carried out concurrent with the calibration experiments.

Fluid Film Thickness

Figure 6 shows a map of the film thickness distribution along the rake face. Intensity images of the rake face such as those shown in Figs. 4 and 6 indicate that the fluid does penetrate into the intimate contact region. The fluid film in Fig. 6 is seen to be uniformly distributed in the intimate contact region, over the width of the chip. The intimate contact region extended ~400 µm along the rake face from the cutting edge. Figure 7 shows the variation of fluid film thickness with distance from cutting edge in the mid-section of the intimate contact

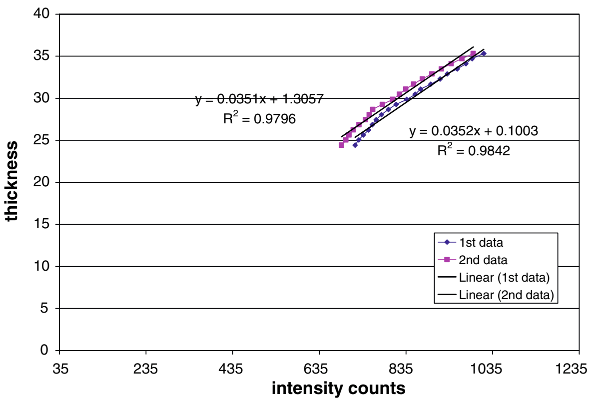

Fig. 5 Intensity calibration curves for the luminescent sensor. The two calibration data sets are from measurements made during the machining pass concurrent with the fluid film thickness measurements reported

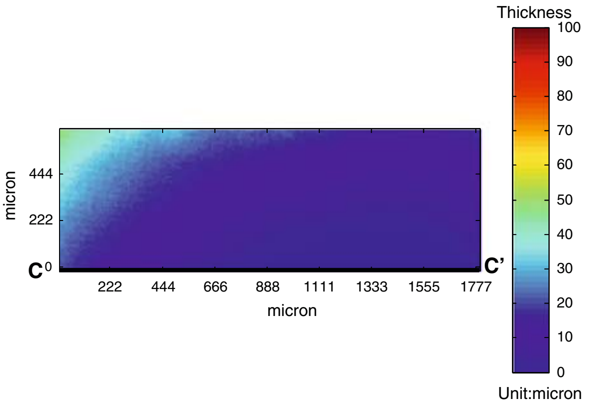

Fig. 6 Two-dimensional map of fluid film thickness map in the cutting region along rake face. The horizontal line CC′ is the cutting edge. The intimate contact zone extends to a distance of ~ 400 µm along the rake face from the cutting edge

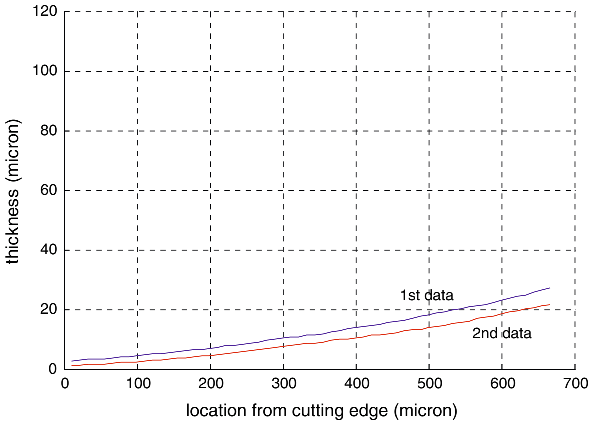

Fig. 7 Variation of fluid film thickness with distance along the rake face. The two data sets are for measurements made at different stages in the same machining pass and concurrent with the calibration data sets

region. The film thickness is nearly zero at the cutting edge and increases to about 15 µm at a distance of about 400 µm from the cutting edge, which is the approximate edge of the intimate contact zone. The two data sets in Fig. 7 correspond to measurements made at two different stages during the machining and coincident with the calibration data measurements of Fig. 5. The negligible difference in the film thickness between the two data sets in Fig. 7 highlights the consistency and repeatability of the machining and the measurements. While these measurements show fluid penetration into the intimate contact zone, the fluid film thickness is seen to be small over much of this zone. The film thickness needed to realize effective lubrication is a question that remains to be answered.

Concluding Remarks

A new technique using luminescent molecule sensors is described for characterizing fluid action at the tool-chip contact along the rake face. It is shown that there is some amount of fluid penetration, albeit small, into the zone of intimate contact between tool and chip wherein the contact stresses are high, and the real and apparent areas of contact are essentially the same. The thickness of the fluid film is seen to be essentially zero close to the cutting edge, and increases approximately linearly with distance from the cutting edge reaching a thickness of about 15 µm at the edge of the intimate contact zone. This penetration of the fluid into the intimate contact zone could not be detected in earlier observation work that utilized colored suspensions in conjunction with optically transparent tools. While the luminescent molecule technique has been demonstrated here for low speed cutting of metals, it is equally well-applicable to machining at industrial cutting speeds, with some enhancements in the imaging capability. This aspect will be taken up in the near future, together with parameter studies of fluid film action.

It is unclear at the present time as to what extent of fluid penetration is necessary for adequate lubrication. Force measurements carried out under conditions similar to those used in the present study indicate that the friction coefficient at the tool-chip contact is reduced by some amount in the presence of the fluid. But this decrease is much more dramatic, with a 2–3 fold decrease in the friction coefficient seen, when a low-frequency modulation is superimposed on to the cutting process [21]. Such a large decrease has been attributed to the effectiveness of the modulation in disrupting the tool-chip contact, thereby, enabling a ‘thick’ stable fluid film to be established at the tool-chip interface. These observations taken together suggest that fluid penetration into the intimate contact zone alone may not suffice for effective lubrication but that a sufficiently ‘thick’ stable film needs to develop along this contact for significant reduction in friction, and wear. The luminescent molecule technique is well-suited for providing answers to such questions, which are critical for effective development of near-dry machining technologies.

Luminescent molecule sensors also offer much scope for study of other interfacial phenomena in machining. Most noteworthy among these is measurement of tool-chip interface temperature while machining in the presence of a fluid. Such a measurement would rely on characterization of time decay of the luminescence, which is a strong function of temperature. Hence, simultaneous measurement of temperature and fluid film thickness in the rake face region is likely feasible. Measurements of velocity, strain rate, and strain in deformation zone of chip formation have already been demonstrated using a Particle Image Velocimetry (PIV) technique [8]. An adaptation of this PIV technique to characterize these strain field parameters in the secondary deformation (friction) zone adjoining the tool rake face is in progress. When these high-resolution interface measurements are assembled in the appropriate topology with the relevant machining modeling tools, various interfacial phenomena such as fluid action, frictional boundary condition, strain, and temperature, can likely be characterized with extraordinary level of accuracy.

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