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ORIGINAL PAPER

Effects of Controlled Modulation on Interface Tribology and Deformation in Machining

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Abstract The effects of superimposed, low-frequency modulation on contact conditions at the tool–chip interface and mechanics of machining are analyzed. It is shown that modulation can disrupt the severity of the tool–chip contact, enabling enhanced lubrication of this contact; and discretize chip formation to small dimensions with controlled size and shape. The deformation strain in the chip is also reduced, suggesting a 40% reduction in energy of machining due to the modulation. Conditions of frequency and amplitude for achieving these effects are presented and confirmed using a compact modulation device that can be retro-fitted onto conventional machine platforms. Implications for enhancing efficiency of industrial machining processes are briefly discussed.

Keywords Cutting · Contact mechanics · Energy conservation

1 Introduction

The machining process is unique in two respects. First, 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—the so-called region of intimate contact [1–4]. These severe conditions make it difficult to lubricate the contact, with fluid action typically being confined to the very edges of the contact bordering the intimate contact region [3–8]. The interactions occurring in the intimate contact region play an important role in controlling the mechanics of machining (e.g., energy consumption, type of chip), and type and rate of tool wear. Second, in the process of chip formation leading to generation of a machined surface, the chip material is subject to very large plastic strains quite atypical of conventional deformation processes [1, 2]. These strains are confined to a narrow (primary) deformation zone, often idealized as a shear plane. The severe plastic deformation at the shear plane and frictional dissipation at the tool–chip contact are the principal reasons for the high specific energies recorded in machining of metals, with the former typically constituting $\sim$70% of the energy dissipation and the latter, the remainder [1]. Any reductions in deformation level in the chip and in friction at the tool–chip interface (e.g., via enhanced fluid action) can therefore be expected to favorably impact the energy efficiency of machining. The tool–chip contact condition and shear plane deformation may be altered by controlled perturbation of the mechanics of the chip formation process. In this study, we demonstrate effects of machining with a controlled, superimposed low-frequency modulation (<1,000 Hz)—Modulation-assisted machining (MAM). It is shown that such a modulation can effect extraordinary control of chip formation, enhance lubrication of the tool–chip contact and reduce deformation levels in the chip.

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2 Background

It is difficult to place the first known application of a controlled modulation or vibration to machining processes.

There is certainly discussion of consequences of "chatter vibration" on chip formation in the 1950s [9]. A patent by Findley [10] gives detailed consideration of modes of application of vibration to machining processes and some of its consequences on chip formation; but the underlying scientific details received less than adequate consideration. The major body of work on use of controlled vibration, mainly in the ultrasonic regime, to "assist" machining processes appears to have emerged from the studies of Kumabe [11]. Specifically, the application of the modulation has been one of two types.

(a) Modulation in the direction of cutting velocity (Fig. 1a)—velocity-modulation—examples in the ultrasonic regime that demonstrated diamond turning of steel [12], a process difficult to achieve with "small" tool wear in the absence of modulation; and in the low-frequency regime [13] showing important changes in the tool–chip contact condition. These studies, in quite different machining regimes, highlight the benefits of velocity-modulation in modifying the severe conditions at the tool–chip contact.

(b) Modulation with a major component in the direction of tool-feed or undeformed chip thickness (Fig. 1b)—feed-modulation—examples include elliptical vibration cutting at ultrasonic frequencies, where by reducing the relative velocity between tool and chip (and even reversing the direction of this velocity), significant reduction in friction and "tool-forces" were demonstrated [12, 14]; low-frequency modulation to control chip formation and facilitate chip evacuation in drilling [15, 16]; and control of chip shape to produce fiber and various types of particulate materials [17, 18], also with low-frequency modulation. These studies indicated that the chip formation mechanics can be influenced and, indeed, controlled to an extraordinary degree by feed-modulation.

3 Velocity-Modulation

Figure 1a shows a schematic of plane–strain machining with a sinusoidal velocity-modulation. The cutting velocity varies continuously in this modulation configuration. In particular, the direction of instantaneous velocity is reversed and the tool–chip contact is completely disrupted (separation of tool from chip) during each cycle of modulation when the superimposed modulation velocity exceeds the mean (steady) cutting velocity, that is when $\omega A > V$, where ω is the angular modulation frequency and $2A$ is the peak-to-peak amplitude. In practice, ωA would need to be increased beyond V to account for the compliance of the system. We have studied this configuration at low machining speeds with superimposed low-frequency modulation. The experimental arrangement used a linear motor with a DC field to impose the steady cutting speed and an AC field to effect the modulation [13, 16]. In the absence of the modulation, the tool and chip were found to be in intimate contact over much of the secondary deformation zone with little visible penetration of an applied fluid into this contact region, even at low cutting speeds (<100 mm/s). This was established by dispersing luminescent molecular sensors into the cutting fluid and carrying out the machining with an optically transparent sapphire tool, the latter enabling the tool–chip contact to be imaged in situ for luminescence [8]. However, in the presence of the modulation, there was visible penetration of the fluid over the entire contact region, as revealed by high-speed photography of the contact [13].

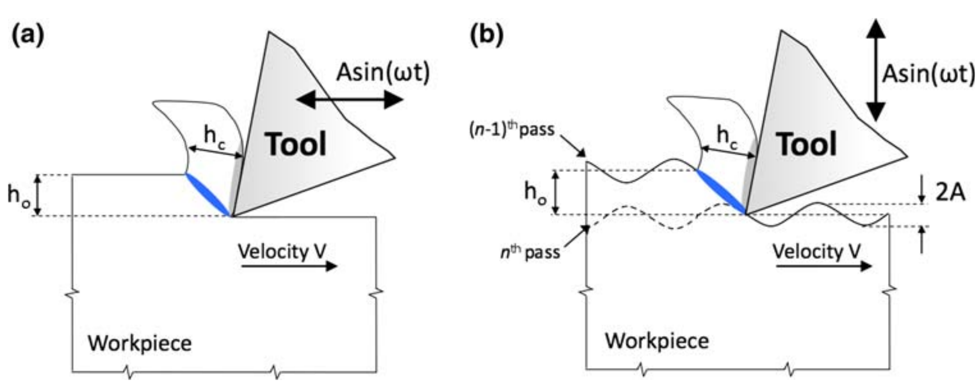

Fig. 1 Schematic of machining with superimposed modulation **a** velocity-modulation and **b** feed-modulation. V is the mean (steady) cutting velocity, h_o is the undeformed chip thickness, A is the amplitude of modulation and ω is $2\pi * f_m$, where f_m is the frequency of modulation. The *darker* and *lighter* shaded regions indicate the regions of primary and secondary shear, respectively. In **b**, the surface created during two successive machining passes is shown. For example, in turning, each pass would be along the circumference of the workpiece

Penetration of fluid into the contact at a critical amplitude–frequency condition typically coincides with a substantial reduction in the "friction coefficient" (i.e., ratio of tangential to normal force on tool rake face) at the contact. Figure 2 shows the variation of this friction coefficient with modulation amplitude (A), as estimated from force measurements, for machining of Al alloy 6061-T6 in the presence of a vegetable-oil based, metal cutting fluid (Coolube 2210 composed of triglycerol and propylene glycol esters of C8 and C10 acid). The fluid was applied to the machining zone as a gentle stream/mist. The two plots shown in the figure are for a standard cutting tool, and for a special, restricted-contact tool wherein the tool–chip contact area was constrained to be within the region of intimate contact by the appropriate grinding away of the tool rake face (see inset). At the lower amplitudes of modulation, the friction coefficient is $\sim$0.45, while at the higher amplitudes it settles to a relatively low value of $\sim$0.1. The critical condition for fluid penetration and the friction reduction is complete disruption of the tool–chip contact, a fact established by the forces reaching a value of zero over part of the modulation cycle for $A > 0.03$ mm at this machining condition. Similar large reductions in friction coefficient concomitant with disruption of the contact were observed for a variety of tool-workpiece combinations, as shown in Table 1.

Fluid penetration into the contact region under conditions of disruption of the tool–chip contact has also been inferred from an examination of flow lines in the chip region in the immediate vicinity of the contact. Figure 3a and b shows the microstructure of flow lines in OFHC copper chips produced by conventional cutting, and cutting with

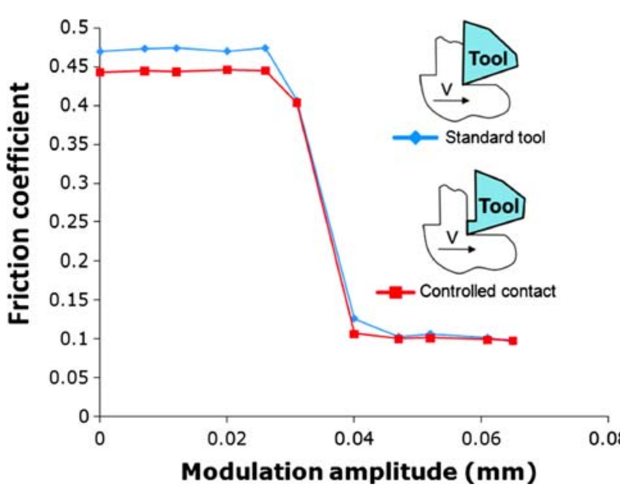

Fig. 2 Variation of friction coefficient with modulation amplitude (A) in velocity-modulated machining. Modulation frequency 75 Hz, cutting velocity 10 mm/s, undeformed chip thickness 0.20 mm, tool: high-speed steel, workpiece: Al6061-T6. The length of tool-chip contact was 0.3 mm for the controlled contact condition

Table 1 Friction coefficients (± one standard deviation) in conventional and modulation-assisted machining with a high-speed steel tool. Undeformed chip thickness of 0.1 mm and cutting speed of 10 mm/s. Modulation conditions were $f_m = 75$ Hz and $A = 52$ μm

Workpiece	Condition	Friction coefficient
Copper	No modulation	0.36 ± 0.04
	Modulation	0.12 ± 0.02
Lead	No modulation	0.38 ± 0.02
	Modulation	0.11 ± 0.01
1020 Steel	No modulation	0.32 ± 0.07
	Modulation	0.12 ± 0.01

velocity-modulation, respectively. The flow lines in Fig. 3a (conventional cutting) are highly curved in the immediate vicinity of the tool–chip contact, indicative of intense secondary shear, lack of fluid action, and higher friction in this region. In contrast, the flow lines are relatively straight in the immediate vicinity of the tool–chip contact when cutting with the velocity-modulation (Fig. 3b), indicative of significantly reduced secondary shear and lower friction [1, 2]. This is most likely a consequence of the enhanced fluid action in this case. Furthermore, the modulation-induced changes in the friction condition cause the chip formation to be much more uniform (Fig. 3b) in contrast to conventional machining (Fig. 3a). In the latter instance, the chip created from the soft, ductile OFHC copper shows some periodic variation in thickness due to a "stick-slip" type of condition occurring at the tool–chip contact.

While the velocity-modulation disrupts the severity of the tool–chip contact in the intimate contact region facilitating lubrication, with all the attendant benefits of reduced frictional dissipation, this approach has some practical limitations. The disruption condition of $\omega A > V$ is difficult, if not impossible, to realize even at ultrasonic frequencies except at the lower end of industrial machining speeds ($V < 0.5$ m/s) due to dynamic system level constraints [11]. Furthermore, this type of modulation is kinematically near-infeasible in machining processes such as drilling and broaching where the cutting occurs inside a cavity. Of more general applicability is the use of feed-direction modulation of low-frequency, wherein disruption of the tool–chip contact can be realized in a variety of machining operations even at machining speeds ($V >> 0.5$ m/s) typical of practice.

4 Feed-Modulation

Figure 1b shows a schematic of plane–strain machining with sinusoidal modulation superimposed in the direction of undeformed chip thickness (i.e., tool feed in turning). The instantaneous undeformed chip thickness depends on

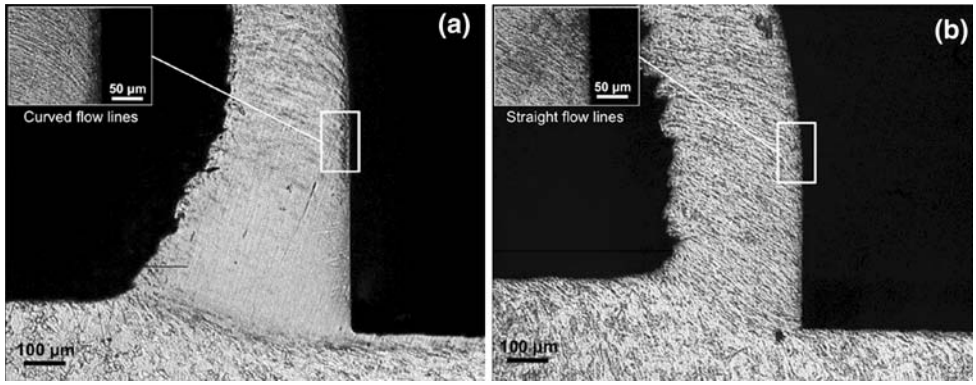

Fig. 3 Photomicrographs of chips as yet undetached from the workpiece in machining of OFHC copper **a** conventional machining and **b** modulation-assisted machining with $f_m = 75$ Hz, $A = 0.050$ mm. Insets are enlarged views showing flow lines in the immediate vicinity of the tool–chip contact. Undeformed chip thickness of 0.1 mm and cutting speed of 10 mm/s; vegetable-oil based fluid (Coolube 2210)

the modulation conditions, and the modulation changes the tool–chip contact condition as well. With a feed-modulation of appropriate amplitude and frequency, this chip thickness can become zero during part of each modulation cycle, resulting in "discrete chips". This is also a sufficient condition for complete disruption of the tool–chip contact because of physical disengagement of the tool from the workpiece [17, 18]. The amplitude necessary for the instantaneous undeformed chip thickness to become zero is $2A > h_o$, for a single cutting-edge tool, where h_o is the undeformed chip thickness in the absence of the modulation (Fig. 1b). This amplitude condition for contact disruption is independent of the cutting speed, in contrast to that of the velocity-modulation case. It is this independence that makes feed-modulation better suited for implementation at the higher speeds typical of industrial practice.

From the kinematic configuration of successive machining passes, the above amplitude condition is complemented by another condition involving the modulation frequency (f_m) and workpiece rotation frequency (f_w). The minimum amplitude condition $2A = h_o$ for discrete chip formation occurs when $f_m/f_w = ½(2N + 1)$, where N is an integer [17, 18]. This frequency condition will be referred to as the optimal condition. At other values of this frequency ratio, the minimum peak-to-peak amplitude, $2A$, for discrete chip formation is greater than h_o and may be estimated by numerical analysis [18]. The value of f_m/f_w represents the number of times that the chip thickness becomes zero (i.e., number of discrete chips) and the tool–chip contact is disrupted per revolution of the workpiece. An exception to this occurs when $f_m/f_w = N$. At this setting, successive machining passes are "in phase" and discrete chip formation is never realized; instead a continuous chip of constant thickness should form. It should be noted here that amplitude–frequency conditions for discrete chip formation can be established in an analogous way also for tools with multiple cutting edges, such as in drilling [17]. In practice, to achieve discrete chip formation, the modulation amplitude should be set somewhat higher than the minimum to compensate for system compliance. Since amplitudes as large as 0.2 mm can be achieved using piezo-type actuators in low-frequency modulation ($f_m < 1{,}000$ Hz), MAM with feed-modulation is capable of achieving discrete chip formation and complete disruption of the tool–chip contact even at cutting speeds as high as 600 m/min. Fluid action in the intimate contact region can thus be realized.

4.1 Discrete Chip Formation

A series of plane–strain turning experiments were carried out to demonstrate discrete chip formation and tool–chip contact disruption with feed-modulation. The experiments were structured around a compact, piezo-based modulation device capable of being retro-fitted onto various machine platforms [17, 18]. Various frequency ratios (f_m/f_w) were imposed to verify the discrete chip model with contact disruption; and deformation strain in the chip was characterized to assess energy dissipation. The workpiece material was Al6061-T6 in bar form, with an initial hardness of $\sim$110 kg/mm^2 and grain size of $\sim$50 μm. A tungsten carbide tool of zero-degree rake angle was utilized. Isopropyl alcohol was applied to the machining zone in the form of a gentle drip. Unless otherwise stated, all of the experiments were conducted with f_m/f_w set equal to $½(2N + 1)$, the optimal condition, and $2A$ set somewhat in excess of h_o.

Figure 4 shows photographs of chips created at increasing values of f_m/f_w. When $f_m/f_w = 0$ (conventional machining), the chip is continuous and of constant thickness. As f_m/f_w is increased, the chip length becomes increasingly small, consistent with discrete chips being formed more frequently per the model at a rate of f_m/f_w per second. This is also the rate of disruption of the tool–chip contact. High-speed photography of the chip formation and microscopic examination of metal transfer onto tool surfaces confirmed that the fluid was active in the tool–chip contact under these modulation conditions. When f_m/f_w is set equal to an integer (e.g., 20), a continuous chip of

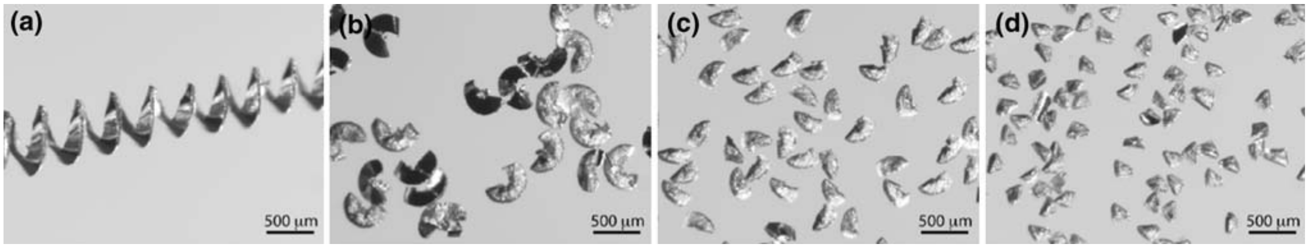

Fig. 4 Photographs of Al 6061-T6 chips created at f_m/f_w of **a** 0 **b** 5.5 **c** 15.5, and **d** 30.5, where $f_w = 3$ rps (3 Hz). When $f_m/f_w = 0$, conventional machining, the chip is continuous and of constant thickness. As f_m/f_w is increased, the chip length is seen to becoming increasingly smaller. Undeformed chip thickness of 0.01875 mm, depth-of-cut of 0.150 mm, modulation amplitude 2A ≈ 0.025 mm

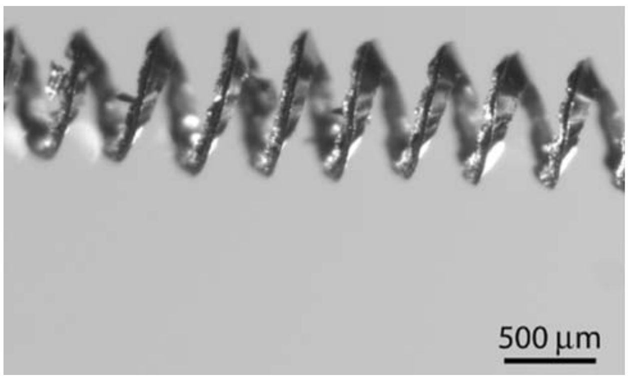

Fig. 5 Continuous chip in modulation-assisted machining formed when $f_m/f_w = 20$ and $f_w = 3$ rps (3 Hz). Undeformed chip thickness of 0.01875 mm, depth-of-cut of 0.150 mm, modulation amplitude 2A ≈ 0.025 mm

constant thickness is seen to form as predicted by the model (Fig. 5). The distribution of chip size at a specific modulation condition was determined from measurement of chip lengths using optical microscopy. The chip lengths were found to be tightly distributed with a standard deviation of less than 3% of the mean, demonstrating the control of chip formation achievable by MAM. While the surfaces created by the MAM showed distinctly different textures, there was no significant change in statistical roughness parameters such as Ra in comparison to surfaces created by conventional machining.

Besides chip size, the shape and aspect ratio of the chips can be controlled to an extraordinary degree by appropriate selection of machining and modulation conditions. Examples of this can be seen in Fig. 6 which show platelet, equiaxed, and needle (fiber) shaped particles created by MAM. This approach has been used to produce chip (wear) particles with cross-section size in the range of 0.03–1 mm, including fibers with aspect ratio as high as 150 in a variety of materials, e.g., alloys of Ti, Al, and Fe. This repeatable, deterministic chip formation suggests that MAM can be developed as an efficient process for producing metal particulate. Furthermore, the creation of small discrete chips offers an effective solution to the problem of chip control and management in industrial machining operations, such as in deep-hole drilling.

The shear strain (γ) imposed in chips was estimated from measurement of deformed and undeformed chip lengths, l_c and l_o, respectively, using the equation $\gamma = r + (1/r)$ for a zero-degree rake angle tool, where $r = l_c/l_o$ is the usual chip thickness ratio [1]. For this purpose, a specific experiment that involved creation of platelet particles was carried out. The modulation frequency f_m was varied between 31.5 and 91.5 Hz in discrete steps such that $f_m/f_w = ½(2N + 1)$, while keeping $f_w = 3$ Hz (3 rps), $h_o = 0.01875$ mm rev^{-1} and $2A \approx 0.025$ mm. Figure 7 shows the shear strain for the different modulation conditions and for conventional machining ($f_m = 0$). The strain is greatest ($\sim$5.5) in the chip produced without modulation and decreases with increasing modulation frequency, approaching a limiting value of $\sim$3.5. This limiting strain value is approximately 35% lower than in conventional machining. The lower strain, together with the reduced friction coefficients (Fig. 2 and Table 1), indicate a 40% reduction in the machining energy for a typical 70/30 partition of the shear plane and frictional energy dissipation in machining.

The reduction in deformation levels in the chip in MAM appears to arise from two factors. First, it is known that a reduction in tool–chip contact friction results in a reduction in the shear deformation at the primary deformation zone [1, 2]. Thus enhanced fluid action along the tool–chip interface arising from disruption of the intimate contact by the modulation should reduce the intensity of deformation, in addition, of course, to the frictional dissipation. Second, the deformation associated with chip formation appears to not reach a steady state level for most of the modulation conditions explored herein, in contrast to conventional machining. This is supported by finite element analysis results [19] and, more directly, by microstructure observations showing the chip to have a much less refined and more heterogeneous subgrain microstructure (consistent with chip or wear particle formation with lower deformation levels) than in conventional machining. The transient deformation hypothesis suggests that increasing the frequency ratio f_m/f_w should result in a greater reduction in

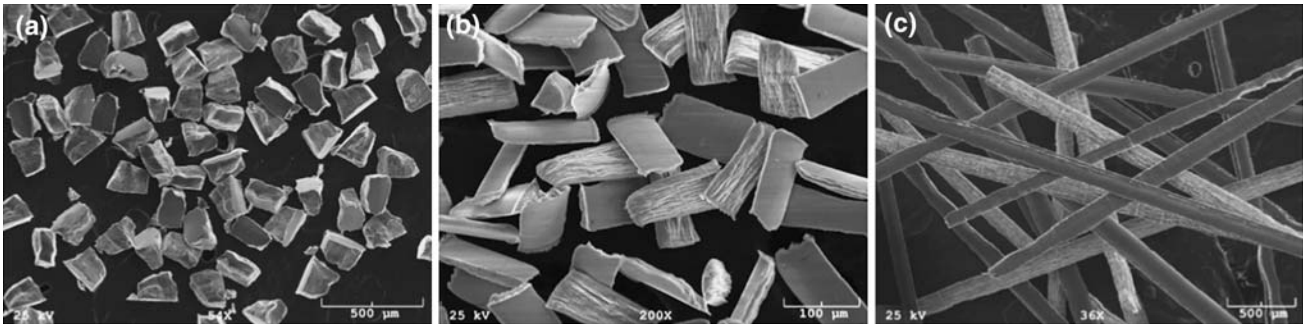

Fig. 6 Scanning electron microscope images of equiaxed, platelet and needle (fiber) shaped particles of Al6061-T6 created by MAM. The particle dimensions and shape are determined by the modulation and machining conditions

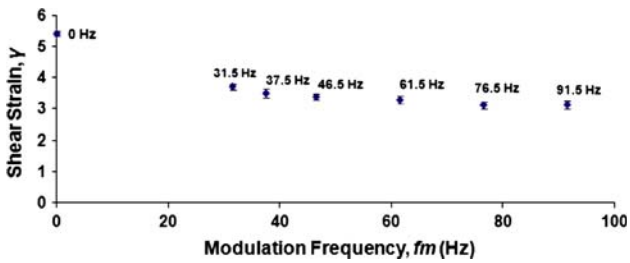

Fig. 7 Variation of shear strain with modulation frequency (f_{m}) in Al6061-T6 chips at a modulation amplitude of 2A $\approx$ 0.025 mm, f_{w} of 3 rps (3 Hz), undeformed chip thickness of 0.01875 mm and depth-of-cut of 0.150 mm. $f_{\mathrm{m}} = 0$ represents conventional machining

deformation levels, a consequence of the more frequent disruption of the contact. This aspect, together with detailed microstructure analysis of chips produced by MAM, will be undertaken in the near-future. This will be complemented by direct measurement of machining forces, which could not as yet be implemented with the compact feed-modulation device.

5 Concluding Remarks

It is shown that the application of a controlled, superimposed low-frequency modulation in machining is effective at disrupting the severe conditions prevalent at the tool–chip contact, enhancing lubrication of this contact and discretizing chip formation to extraordinary levels. Deformation levels in the chip are found to be significantly lower under appropriate modulation conditions. These observations suggest improved energy efficiency in MAM. A geometric model of chip formation describes the critical amplitude–frequency conditions necessary for realizing these beneficial effects and was confirmed using plane–strain machining experiments across a range of machining processes. The model and observations suggest a framework for industrial implementation of MAM. The relative contributions of modulation in reducing machining energy through changes in the primary deformation characteristics and through effects on the tool–chip friction condition; systematic assessment of energy reduction and tool wear (if any); and optimization of modulation conditions with respect to specific objective functions, however, remain to be explored.

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