

Effects of Controlled Modulation on Surface Textures in Deep-Hole Drilling

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ABSTRACT

Deep-hole drilling is among the most critical precision machining processes for production of high-performance discrete components. The effects of drilling with superimposed, controlled low-frequency modulation - Modulation-Assisted Machining (MAM) - on the surface textures created in deep-hole drilling (ie, gun-drilling) are discussed. In MAM, the oscillation of the drill tool creates unique surface textures by altering the burnishing action typical in conventional drilling. The effects of modulation frequency and amplitude are investigated using a modulation device for single-flute gun-drilling on a computer-controlled lathe. The experimental results for the gun-drilling of titanium alloy with modulation are compared and contrasted with conventional gun-drilling. The chip morphology and surface textures are characterized over a range of modulation conditions, and a model for predicting the surface texture is presented. Implications for production gun-drilling are discussed.

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INTRODUCTION

Component machining in the aerospace industry requires demanding applications of deep-hole drilling (length to diameter > 10) in a wide range of high-temperature alloys, including titanium, Inconel, tantalum and stainless steels. Deep-hole drilling is often accomplished by a special class of drilling operations referred to as gun-drilling - which, as the name implies, originated in the drilling of gun bores in the early nineteenth century [1]. In mechanical drilling, the machined chip can be difficult to evacuate from the drilled hole as the depth of the hole becomes greater than the diameter. When the relative depth of the drilled hole increases beyond ten diameters - as in the case of gun-drilling - the evacuation of chips becomes even more difficult, as the chips can become bound or jammed in the drill flute, often causing premature failure of the drill tool. Consequently, in many gun-drilling applications the drill feed-rates are substantially reduced, and high pressure fluid is applied at the drill tip to help break the chips and eject them from the hole. The ability to efficiently manufacture components with deep

gun-drilled holes while maintaining quality requirements, including size and form, finish, and near surface microstructure is critical. Gun-drilling is required in the production of aerospace components ranging from large-scale landing gear actuator cylinders to small-scale turbine shafts, crank shafts, or special fasteners. Outside the aerospace industry, gun-drilling plays a role in every manufacturing sector with applications in automotive power-train systems, orthopedic implant devices, industrial hydraulic systems, automotive fuel system components, and weapons systems. The implementation of new technology and processes that can address both rate of production and quality of gun-drilling processes is essential for development of more efficient and sustainable manufacturing systems.

Recently, a new technology, called Modulation-Assisted Machining (MAM), has been adopted in commercial deep-hole drilling processes, including gun-drilling applications [2]. In MAM a low-frequency, controlled oscillation is superimposed on the drilling process to alter the mechanics of chip formation [3,4,5,6].

BACKGROUND

Modulation-Assisted Machining applies a low-frequency oscillation at the tool-workpiece interface, typically at frequencies up to 1000Hz [4, 7]. While MAM has similarities with vibration-assisted machining (VAM) [8,9,10], modulation-assisted machining is unique in its underlying kinematics and the range of operating frequency. The modulation is effected by superimposed sinusoidal motion of either the tool or the workpiece at a peak-to-peak amplitude (2A) and frequency (fm). When the modulation conditions are ‘effective’, an intermittent disruption and instantaneous separation occurs between the cutting tool and the workpiece. The modulation can be applied in either the direction of the cutting velocity (velocity modulation) or in the direction of the tool feed-rate (feed-modulation), with different relative process effects for each type of modulation [5,7]. Feed-direction modulation is particularly adaptable to deep-hole drilling operations because it offers a direct route to controlling chip formation and a pathway to increased drilling efficiency. However, the relative effect of modulation on bore surface quality for gun-drilling processes needs further investigation. Previous research has characterized the effects of feed-direction MAM on chip formation and surface roughness in twist flute drilling of aluminum, steel, and cast iron and found that modulation did not have a statistically significant influence on surface roughness [11]. The application of ultrasonic vibration during drilling has shown improved surface quality and chip control in deep-hole gun-drilling of electrolytic copper [12]. Given the range of industrial applications involving gun-drilling, additional experimental investigation of the effects of controlled modulation will help establish the characteristic ranges and benefits of the process.

In modulation assisted gun-drilling presented here, the controlled modulation is applied directly to the drill in the axial (feed-rate) direction by modulating the gun-drill (Fig. 1b). The range of modulation conditions is defined by geometric constraints and a relationship between the tool-path equations of motion [13]. Because the sinusoidal motion is superimposed on the steady feed motion of the machine axis, the effective feed-rate (e.g. undeformed chip thickness) varies over a range determined by the modulation parameters. The so-called ‘effective’ application of modulation in this configuration is defined as the ideal modulation conditions causing periodic disruption of the contact at the tool/workpiece interface. This separation occurs due to the intersection of successive tool paths, as is shown in Fig. 2 (cases b and c). Each separation event corresponds to the instantaneous undeformed chip thickness reaching zero or becoming “negative” during each cycle of modulation. Concomitantly, an instantaneous separation or gap occurs at the tool/workpiece interface during each cycle of modulation. The otherwise severe contact conditions are interrupted and the chip formation is altered. From Fig. 2(b) and 2(c), it is clear that a range of modulation conditions can be considered

‘effective’, and these can be achieved by simultaneous adjustment of the modulation parameters of frequency and amplitude.

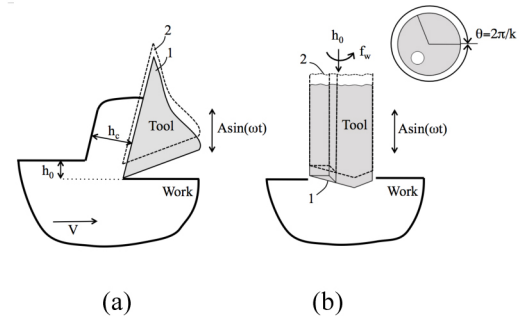


Figure 1. (a) Two-dimensional model of feed-direction modulation-assisted machining (MAM) (b) Feed-direction modulation in drilling with a single-flute gun-drill with k flutes ($k=1$).

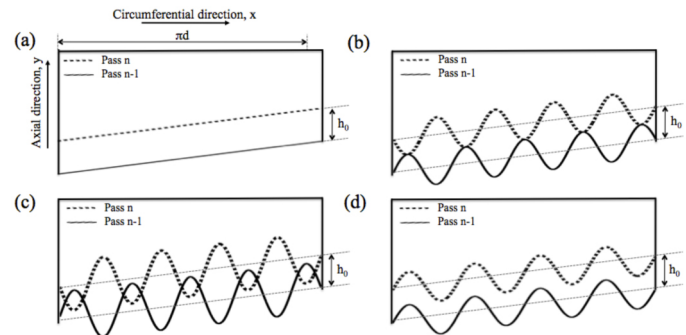


Figure 2. Unfolded views of the drill feed-rate and the path that the drill cutting edge follows during two full revolutions of the workpiece for single-flute gun-drilling ($k=1$ cutting edge) and diameter d : (a) Conventional gun-drilling without modulation (b) effective modulation conditions $fm/fw=4.5$, $2A=h_o/k$, (c) effective modulation conditions with amplitude $2A$ exceeding the feed-rate $fm/fw=4.5$, $2A=1.2h_o/k$, and (d) ineffective modulation conditions $fm/fw=4$, $2A=h_o/k$.

A range of feed-modulation conditions can be effective [7]. Of practical interest is the ‘ideal’ or optimal set of effective modulation conditions for single flute gun-drilling ($k=1$) wherein the ratio of the modulation frequency, fm , (Hz) to the drill rotational frequency, fw (RPS or Hz) is an odd integer divided by two. The critical modulation frequencies that lead to ‘ideal’ modulation conditions can be calculated directly by equation (1).

$$fm = k/2 * fw * (2N+1), 2A > h_o$$

(1)

where h_o is the feed-rate (mm/rev), k is the number of cutting edges ($k=1$ for a single flute gun-drill) and N is any integer. When these ‘ideal’ conditions occur, the amplitude of the

modulation, $2A$, required to achieve zero or negative undeformed chip thickness is minimized. A partial set of the modulation conditions required to effect contact separation is shown in Fig. 3. The optimal conditions correspond to the minima of the U-shaped curves. Adjusting the amplitudes beyond $2A > h_0$ can have significant consequences on the magnitude of separation at the tool/workpiece interface and amount of time between cutting each discrete cutting event. Although this is not discussed in the present experimental results, the selection of amplitude alters the undeformed chip thickness. Furthermore, it is anticipated that the modulation amplitude will influence the local cutting temperature [14], effectiveness of cutting fluid, and resulting surface integrity (ie, microstructure).

In contrast, when the modulation conditions are 'ineffective', no separation occurs at the tool/workpiece contact, and chip formation is continuous with the undeformed chip thickness either constant or varying over a range of positive values. For example, in single flute gun-drilling ($k=1$) if the modulation frequency is an integer multiple of the workpiece (or drill tool) rotational frequency (ie, $f_m/f_w=N$) then the feed paths of the drill cutting edge during each revolution occur in phase and the undeformed chip thickness is constant. In this case the chip formation is continuous regardless of the level of the modulation amplitude. An example of this is shown in Fig. 2(d), where the modulation frequency is an integer multiple of the workpiece rotational frequency (e.g., $f_m/f_w=N$). In this situation, successive cutting passes are in phase and the undeformed chip thickness is constant regardless of the level of the modulation amplitude. A constant chip thickness is also present in conventional machining. A visual comparison of chips formed using conventional gun-drilling, ineffective modulation and effective modulation is shown in Fig. 4(a), (b) and (c), respectively.

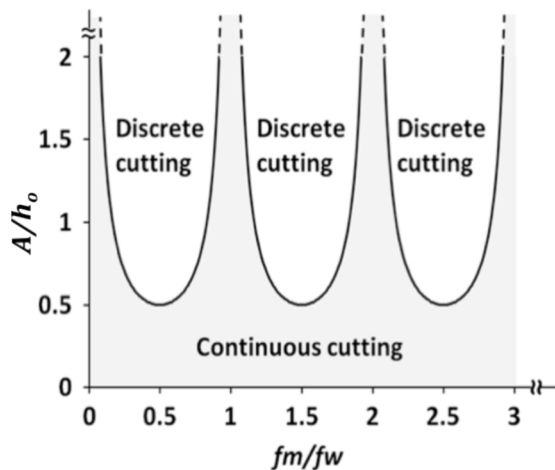


Figure 3. Boundary demarcating the critical conditions for effective disruption of the tool-workpiece contact in feed-direction single-flute gun-drilling with MAM ($k=1$) [7].

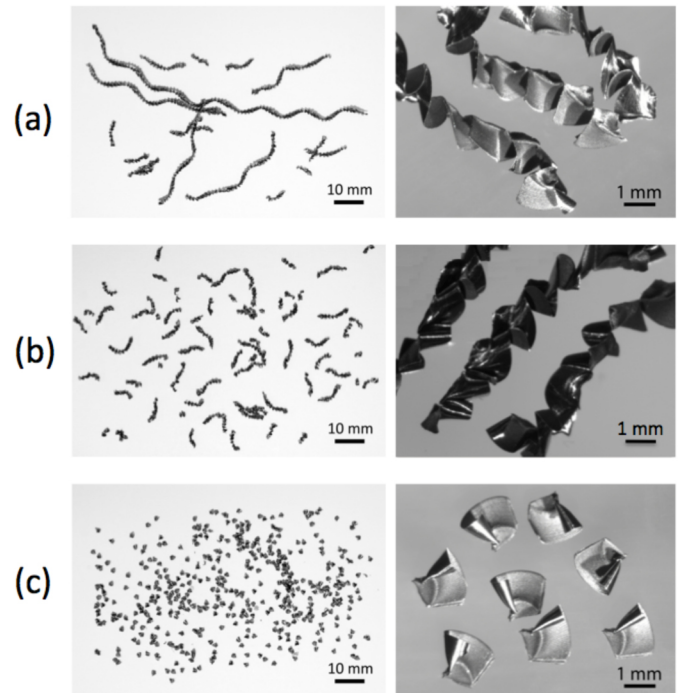


Figure 4. Range of drilling chip formation for 3.2mm diameter x 100 mm deep holes ($L/D \sim 31$) in Ti6Al4V alloy at $f_w=4200$ RPM, $h_0= 0.016$ mm/rev. Single flute carbide-tipped gun-drill (Botek) $k=1$, with high-pressure oil cutting fluid at 1000 psi (69 bar): (a) continuous chip formation in conventional gun-drilling (b) continuous chip formation in gun-drilling with ineffective modulation conditions $f_m = 70$ Hz ($f_m/f_w = N=70/70 = 1$) and $2A=0.020\text{mm}>h_0$ (c) discrete chip formation in gun-drilling with ideal effective modulation conditions $f_m = 105$ Hz ($f_m/f_w = 105/70 = 1.5$), $2A = 0.020$ mm $> h_0$

Figure 4 shows the similarity between chips produced by conventional gun-drilling and drilling with ineffective modulation, where in both cases the chip formation is continuous. In gun-drilling with effective modulation conditions the chip formation is discrete with a characteristic length related directly to the modulation frequency. If the MAM parameters are prescribed according to the effective conditions, then discrete chip formation occurs simultaneous to an intermittent separation between the drill cutting edge and the workpiece. A more general case of ineffective modulation occurs when the modulation amplitude is not sufficiently large enough to disrupt the tool/workpiece contact at a given f_m and f_w combination. In this situation, the chip thickness varies with the sinusoidal variation of the feed-rate.

The mathematical relationship that describes the kinematics of MAM and the set of 'effective' modulation conditions does not prescribe an *optimum* modulation frequency. With the exception of geometric constraints, including the relief geometry of the tool [15], the selection of