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A new understanding of the wear processes during laser assisted milling 17-4 precipitation hardened stainless steel

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ABSTRACT

Laser assisted machining is known to improve the machinability of several difficult to cut materials. For the first time, this study investigates the tool wear rates and the wear mechanisms associated with milling a precipitation hardened martensitic stainless steel with and without the assistance of laser preheating. Across both traditional low feed milling and emerging high feed milling techniques, laser assistance was found to reduce the tool wear rates by up to 50% and lower the cutting force by up to 33% in comparison to conventional room temperature machining. In all cases it is observed that tool coating breakdown by abrasive and adhesive wear processes is the dominant tool failure mechanism. Laser assisted milling is effective in prolonging tool life by delaying these processes in comparison to conventional machining.

1. Introduction

Thermally assisted machining (TAM) has been employed for over a century to improve the machinability of difficult to cut materials. Believed to be first pioneered by B.C Tilghman in 1889 [1], the principle involves using heat to soften materials thereby making them easier to remove with a cutting tool. The process was slow to gain interest but around the 1950s research efforts accelerated to investigate the merits of the process [2–5]. Since this time a great deal of research has been performed and in the last few decades alone, it has been well established that thermally assisted machining is a viable method for improving the machinability of numerous materials. In ferrous alloys, the process is beneficial in terms of reducing cutting forces and improving tool life compared to conventional machining [6–16]. The process is also reported to improve the surface finish and reduce chatter during machining [13,14,17]. In addition, TAM is also capable of extending the machining speeds to levels not otherwise possible during conventional machining due to limitations of catastrophic tool failures [7], thus, the process has great potential to improve productivity [8,18]. When machining hardened steels it is reported that TAM significantly reduces the rate of abrasive wear, notching wear and chipping [7,13].

It is believed that the most dramatic improvement in the machinability of ferrous alloys using thermally assisted machining practises occurs for alloys at the harder end of the spectrum. For example, Chung-Fai [19] performed TAM on AISI 4140 heat treated to different hardness levels and reports that the tool life during TAM increases by 100%, 600% and 900% at 330 HV, 380 HV and 400 HV respectively. Other reports also suggest that TAM is most effective on alloys with higher hardness than softer alloys [18]. It is understood that alloys with high hardness have high yield strengths and are prone to strain hardening, which is reduced by increasing the temperature during thermally assisted machining. However, in machining softer alloys, increasing the temperature has less effect on reducing the shear stress since the material already has a weak tendency to strain harden at room temperature [19].

17-4PH is a common precipitation hardened martensitic stainless steel used in numerous applications including oil field valve parts, aircraft fittings, fasteners, pump shafts, gears, nuclear reactor components, missile fittings and jet engine parts [20]. Unlike some applications where machining is performed in a softened state followed by post-machining heat treatments, hardened steels including 17-4PH used in aerospace applications are commonly machined in their fully hardened final state to ensure the highest possible quality products (i.e. no risk of dimensional changes or contamination from post-machining heat treatment). Machining steels in the fully hardened state can also lower costs associated with the alternative traditional approach of machining in the annealed state followed by heat treatment, grinding and manual finishing [21]. In a survey of aerospace machining manufacturers, The Cincinnati Milling Company reported that an

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average of 40% of all machining operations on these materials occur when they are hardened as high as 58 HRC [18]. The practise of machining aerospace components from ferrous materials in their fully hardened state still occurs today. Consequently, hardened 17-4PH may be a candidate for thermally assisted machining processes.

Despite the quantity of research undertaken in developing thermally assisted machining technologies for ferrous alloys, few studies have applied the concept to milling and no literature is available on thermally assisted milling 17-4PH stainless steel. The aim of this research is to compare laser assisted milling (LAM) and conventional room temperature milling of 17-4PH and determine if LAM can reduce the rate of tool wear and extend cutter life. This study also aims to thoroughly characterise the dominant wear mechanisms during the cutting process. In this study two different types of milling cutters are explored. Firstly, milling is performed using a traditional low feed square shoulder carbide cutter at 'conventional' cutting speeds and feeds, a practise common in industry. In addition to this, a cutting trial using high feed milling tools is also performed. High feed milling is an emerging roughing process that is believed to reduce cutter vibrations through efficient cutter design. The key difference between traditional low feed milling and high feed milling is that the feed rate is significantly larger (i.e. 5 times larger) and the depth of cut is much smaller (typically <1 mm) in high feed milling compared to traditional low feed milling. We hypothesis that laser assisted high feed milling may be an effective process considering that laser preheating is fundamentally localised to shallow depths, and therefore, traditional low feed milling processes that employ deep cutting depths are less suitable for laser preheating.

2. Experimental

2.1. Experimental design

Linear face milling tests were performed to evaluate the tool performance across a number of different cutting scenarios. High feed milling cutters and traditional square shoulder low feed milling cutters were tested in conventional (room temperature) and laser assisted milling.

All machining was performed on a 5-axis HASS VF3 YTR CNC in climb milling. Two cutting speeds were tested for each tooling condition with the lower speed of each test determined by the tooling manufacturer's recommended parameters and the upper speed increased 50% beyond the recommended speed. Speeds were increased beyond the recommended speed because the ambition of laser assisted milling is to enable higher than usual cutting speeds and thus, improve productivity. The feed rate (chip load) was kept constant during all tests, consequently, as the cutting speed increased the table speed also increased in order to maintain a constant feed rate (which was 0.11 mm/tooth during the traditional low feed milling experiments and 0.5 mm/tooth with the high feed milling experiments). Table 1 shows a summary of the cutting parameters used during testing. It is worth noting that the tools used for this test are generally considered 'roughing' tools and are not suited for final 'finishing' machining operations due to the tendency to produce poor surface finish.

2.2. Work-piece material

Milling was performed on martensitic precipitation hardened 17-4 stainless steel (nominal composition 17 wt% nickel, 4 wt% chromium, and 4 wt% copper) in the H900 heat treated condition (solution treated at 1040 °C plus aging/tempering at 480 °C for 1 h, bulk hardness 450 ± 20 HV0.05). The material was supplied in a $178\text{x}109 \times 100$ mm^3 block and milling was performed in a linear direction parallel to the edge of the work-piece. After machining the entire length of the block (cutting along the 178 mm edge) with the depth and width of cut specified in Table 1, a parallel step over was performed and milling resumed on the adjacent row. A rotating force dynamometer (Kistler 9124B) was used to measure the cutting forces during machining.

2.3. Laser assisted machining

A 2.2 kW diode laser was used to preheat material directly ahead of the cutter. Details of how this system is integrated with

Table 1
Details of machining experiments.

Test details		**Justification**
Low feed (traditional) milling:		
Cutter body	Seco R217.69-1616.3-09-2A	Ø16 mm twin insert square shoulder milling cutter. Single insert used to conserve material
Tool type	Seco XOEX090304FR-ME06 MP1500	CVD-coated Ti(C,N)–Al_2O_3 carbide grade for medium rough milling, recommended for milling hardened steels
Speed	V_c=78, 117 m/min	Standard recommended cutting condition is V_c=60 m/min, f=0.08 mm/tooth at full width of cut (a_e=16 mm).
Feed	f=0.11 mm/tooth	Seco recommend increasing speed and feed by 1.3 × at 37% radial cutter engagement. Single insert cutter used per test to conserve material
Table speed	171, 256 mm/min	
Spindle speed	1552, 2328 RPM	
Depth and width of cut	a_p=1 mm, a_e=6 mm	Width of cut limited by laser spot size for LAM trials. Depth of cut selected to conserve material
High feed milling:		
Cutter body	R217.21-0816.RE-LP06.2A	Ø16 mm twin insert high feed milling cutter. Two inserts used
Tool type	Seco LPHW060310TR-MD07 MP2500	CVD-coated Ti(C,N)–Al_2O_3 carbide grade for milling difficult stainless steels
Speed	V_c=100, 150 m/min	Recommended cutting condition is V_c=100 m/min, f=0.08 mm/tooth at full width of cut (a_e=16 mm). Seco recommend increasing speed and feed by 1.3 × at 37% radial cutter engagement. Two inserts were used for testing
Feed	f=0.5 mm/tooth	
Table speed	2000, 3000 mm/min	
Spindle speed	2000, 3000 RPM	
Depth and width of cut	a_p=0.5 mm, a_e=9.9 mm	Width of cut is limited by laser beam size for LAM trials and recommendation from Seco to use large cutter engagement during high feed milling. Depth of cut also recommended from Seco and limited by tool geometry
Room temperature machining	No coolant or compressed air used, machining performed at room temperature	
LAM	2.2 kW Laserline diode laser. Traditional milling cutter: circular beam size approximately 4–5 mm, Power 210 W and 260 W; High feed milling: Line beam (10 × 1 mm^2), Power 1500 W and 2100 W (more details in Section 2.3)	