Challenges in laser-assisted milling of titanium alloys

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Received 15 May 2020
Accepted for publication 19 October 2020
Published 13 November 2020

Abstract
Several detailed studies have comprehensively investigated the benefits and limitations of laser-assisted machining (LAM) of titanium alloys. These studies have highlighted the positive impact of the application of laser preheating on reducing cutting forces and improving productivity but have also identified the detrimental effect of LAM on tool life. This paper seeks to evaluate a series of the most common cutting tools with different coating types used in the machining of titanium alloys to identify whether coating type has a dramatic effect on the dominant tool wear mechanisms active during the process. The findings provide a clear illustration that the challenges facing the application of LAM are associated with the development of new types of cutting tools which are not subjected to the diffusion-controlled wear processes that dominate the performance of current cutting tools.

Keywords: laser-assisted machining, tool life, tool wear, titanium alloys

(Some figures may appear in colour only in the online journal)

1. Introduction

It is widely recognised that titanium alloys are difficult-to-machine materials because of their relatively high strength, ductility, toughness and work hardening tendency [1]. This means that machining is usually characterised by high cutting forces and temperatures and short tool life [2]. Straight tungsten carbide (WC/Co) tools are still generally considered as the best cutting tools for machining titanium alloys [3]. Furthermore, the comparatively low thermal conductivity of titanium alloys means that a large proportion of the generated heat remains at the cutting interface5 [4]. Finally, titanium is chemically very reactive to many elements at high temperatures, and in particular, has a high solubility for the cobalt binder used in tungsten-carbide tools. Not surprisingly, adhesion and diffusion are significant tool wear mechanisms [5] that limit productivity when machining titanium alloys [6].

Improving productivity when machining titanium alloys may only be achievable by additional assisted technologies [7, 8]. This has led to the investigation and development of thermally assisted machining (TAM). The TAM process involves the use of an external heat source to reduce the flow stress of the workpiece material by locally heating the workpiece surface in front of the cutting tool, which reduces the
cutting forces thereby reducing the heat generated from cutting. When the heat source used for preheating the workpiece is a laser beam, then the process is referred to as laser-assisted machining (LAM). Many researchers have investigated TAM methods with the view to improve the machining productivity of titanium alloys, and it is well known that the cutting forces are reduced compared to conventional machining, typically by 15%–50% [4, 9–20].

LAM can be utilised for materials with high hardness and brittleness, such as ceramics materials [21]. Ren et al. [22] concluded that the machinability using LAM is much improved which is attributed to the maintenance of excellent performance of the polycrystalline diamond (PCD) tool when machining the fused silica even though the authors indicated that the effect of temperature on machinability and tool wear should be investigated.

Despite this, only a few researchers have investigated the effects of TAM on tool life. Many of the authors who reported that TAM improves tool life refer to an ‘optimal heating temperature’ at which tool life is maximised. Dandekar et al. [4] and Sun et al. [19] reported that the optimal temperature when machining Ti-6Al-4 V is approximately 250 °C. Although, Sun et al. noted that the optimal temperature could increase to 330 °C with concurrent air cooling. For the Russian alloy BT3-1 (Ti-6Al-1.5Cr-2.5Mo-0.5Fe-0.3Si), Nurul Amin and Talantov [13] reported that the optimum temperature was approximately 500 °C, whereas Ginta et al. [18] reported maximum tool life at 650 °C when milling Ti-6Al-4 V. However, the optimum temperature has been reported to be very dependent on the processing conditions and as a result, exits over a significant range between 200 °C–600 °C [23]. Bermingham et al. [10] reported that the optimum temperature in turning Ti-6Al-4 V was around 150 °C–250 °C. However, the tool life rapidly deteriorated when the material was heated to 350 °C. More recently, the investigation carried out by Woo et al. showed that multi-heat source TAM drastically (more than 70%) improved the tool life and the surface finish of the final product when machining of Inconel 718 alloy [24].

The heat generated during machining can be significant; for example, of the total heat at the cutting interface during LAM Ti-10 V-2Fe-3Al, Rahman Rashid et al. [25], found that up to 60% is attributable to cutting processes, whereas the laser can contribute as little as 40% of the total heat. The contribution of the laser to the cutting temperature increases as the cutting speed is decreased. At very high speeds, it is possible that laser heating offers a negligible contribution towards the total heat of cutting [26]. Feng et al. stated that when laser power is low, the machining induced temperature rise cannot be ignored [27]. Sun et al. reported that the chip formation when machining pure titanium becomes continuous during the LAM process as the machining speed increases, compared to the sharp and segmented chips encountered during traditional machining [15]. Over the past 10 years, the current authors have comprehensively investigated the TAM of titanium alloys [2, 10, 19, 20, 25, 26, 28–41]. In these studies, significant reductions in cutting forces have been achieved with LAM, but the rate of diffusion-controlled tool wear has increased when using the laser, although the chipping has been significantly reduced.

Singh et al. [42] recently investigated the tool life during machining of Ti alloys (not using laser assistance) and concluded that texturing on the tool, along with the use of the application of lubricant improved the tribological behaviour of cutting tool and machinability performance. Dandekar et al. [4] have also reported that applying either LAM or hybrid processes with TiAlN coated cutting tools could yield nearly 30% and 40% reduction in machining cost, respectively. Nouari et al. [43] studied various coated/uncoated tool types for when machining (Non-LAM) Ti alloys and pointed out that the adhesion of the workpiece material to the cutting tool is the main failure mechanism during dry machining. There are very limited reports comparing the performance and wear of different coating types during LAM of Ti alloys. This study addresses this gap in research and identifies the challenges associated with the performance of current tools.

It has been suggested that the development of a cutting tool with high-relaxation and higher hardness is vitally important for improved tool life and better machining tolerance [44]. Song et al. [45] studied the cutting performance and the tool life of PCD tools, polycrystalline cubic boron nitride tools (PCBN) and TiNcoated Al2O3/TiC ceramic tools during LAM of fused silica which has high hardness and brittleness. The PCD tool showed excellent performance during cutting and high strength for cutting was retained with a good surface finish due to semi-continuous chips obtained by plastic deformation. The other tools showed severe amberation (PCBN) or the coatings were delaminated at high temperatures (ceramic coated).

In view of these considerations, it is apparent that TAM by way of laser heating has practical limitations on possible productivity improvements unless suitable cutting tools can be identified or developed.

This paper seeks to assess a range of coating types on a series of high performing cutting tools that have been used extensively in machining of titanium alloys. Four coated carbide tools have been tested at two different speeds during

| Test parameters |
|-----------------|
| CUTTER BODY     |
| Tool Type 1     | R217.21–0816.RE-LP06.2 A |
| Tool Type 2     | LPHT060310TR-M06, F40M   |
| Tool Type 3     | LPHT060310TR-M06, MP2500 |
| Tool Type 4     | LPHT060310TR-M06, MS2505 |
| Cutter body     | R217.69–1616.3-09-2 A    |
| Tool Type 5     | LPHW060310TR-ME05 F40M   |
| Speed           | \(V_c = 100, 150 \text{ m min}^{-1}\) |
| Feed            | \(f = 0.5 \text{ mm tooth}^{-1}\) |
| Table Speed     | 2000, 3000 mm min\(^{-1}\) |
| Spindle Speed   | 2000, 3000 RPM           |
| Depth and width of cut | \(a_p = 0.5 \text{ mm, a.e. = 9.9 mm}\) |
| Room Temperature machining | 2.2 kW Laserline diode laser |
| LAM             | Line beam (10 mm x1 mm)  |
|                 | Power 1382 W & 2200 W    |
Figure 1. Ti-6Al-4 V workpiece material supplied in the β-annealed heat treated condition (bulk hardness 315HV ± 17). The microstructure consists of typical Widmanstätten α + β and α-colonies.

Figure 2. Conventional milling without the laser (A) Milling was conducted with a speed of 3000 mm min⁻¹. Laser-assisted milling (B) showing the position of the laser, force sensor and milling operation (reproduced from [46]).

conventional (at room temperature) and laser-assisted milling. The tool wear has been measured and analysed using scanning electron microscopy and energy dispersive spectroscopy (EDS). The results provide an essential insight into the typical limitations of current cutting tools and highlight the need for the development of new and improved cutting tools suitable for application in LAM.

2. Experimental procedure

A detailed description of the experimental set up utilising a five-axis HASS VF3 YTR CNC machine along with the laser-assisted milling procedure has been provided by the current authors in a previous publication [37]. In this study, four commercial cutting tools considered best practice for titanium alloy machining were evaluated under high feed milling conditions. A fixed feed rate was maintained during the trials (0.5 mm tooth⁻¹). Table 1 provides a summary.

Flank wear was measured during the trials using well-established procedures described in detail in previous publications [34, 39]. Tests were interrupted at regular intervals, and tool wear was measured using an optical microscope. Once measurements were complete, the tool was returned to the tool holder and milling machine for further cutting. The rate of wear development and tool condition were thus monitored during the experiments. Milling was performed on 100 × 100 × 40 mm block of ASTM Grade 23 Ti-6Al-4 V alloy in a linear direction parallel to the edge of the work-piece, i.e. cutting lengths of 100 mm per pass.
Figure 3. Cutting force reductions, with the assistance of the laser, measured when milling with the ME05 F40M and M06 MP2500 cutting tools.

Figure 1 shows the microstructure of the workpiece material. The different tool coatings will be discussed in the results section. Machining parameters were chosen with the depth and width of the cut listed in table 1. A rotating force dynamometer (Kistler 9124B) was used to measure the forces during machining.

The high feed milling experimental trials used a 2.2 kW diode laser that delivered a line beam immediately ahead of the cutting tool. The laser was integrated with the milling machine and configured in such a way to always preheat the workpiece directly ahead of the cutter [40, 46, 47]. Figure 2 provides an image of the laser-assisted milling trial set up.

The laser system was calibrated, and a target temperature of 300 ± 25 °C was maintained as recommended by Anderson and Shin [48]. The calibration procedure involved inserting K-type thermocouples into the titanium block at set distances from the surface before scanning the laser at a range of speeds and power settings across the surface as described in detail elsewhere [40]. Once the calibration was complete, laser-assisted milling trials were conducted with the distance between the milling tool and the laser kept constant. Detailed optimisation of the process parameters for the Ti-6Al-4 V alloy with alternative cutting tools has been described by the current authors in previously reported studies [40, 47].

3. Results and discussion

3.1. Force measurements

Four different milling tools were used to study the effect on LAM titanium alloy Ti-6Al-4V. Various parameters, including cutting force and tool wear, were measured, and the microstructure of the alloy after laser-assisted milling was examined.

The cutting forces were significantly reduced with the assistance of a laser, as shown in figure 3. In the two tool types shown (figures 3 and 4), forces were reduced by 6%–50% with the application of the laser. Characteristic fluctuations are present in the force data, and these have been regularly observed when machining titanium alloys but the implementation of the laser shows a consistent reduction in cutting force [40, 47].

The present results support observations that were previously reported, which show that the well-known high-frequency vibrations that are present when milling titanium are reduced by the application of the laser [40]. These oscillations in force are most pronounced at the lower speed (100 m min⁻¹), but laser assistance reduced the severity of the fluctuations significantly at both speeds that were investigated and for all cutting tool types.
3.2. Tool wear

Figures 5 and 6 show average flank wear plotted against machining time for both unassisted and LAM milling. It is important to note that periodic tool wear measurements were performed after specific cutting length intervals, and hence the time to reach that length of cut depends on the cutting speed given that each cutting pass was a fixed length of cut (100 mm). Laser-assisted milling reduced the tool life of all four tools examined in this study at both 100 m min$^{-1}$ and 150 m min$^{-1}$ cutting speeds compared to the tool wear produced during dry machining without the laser.

Average flank wear is shown in figures 5 and 6, and maximum flank wear are shown in figures 7 and 8. Maximum flank wear (figures 7 and 8) displayed the same trends as the average flank wear measurements.

It is clear from the information presented in figure 8 that although the laser has produced a reduction in force on the cutter and the extent of force fluctuations, it has also resulted in a general decrease in tool life for the four tool types examined in this work.

Although the exact coating technology is proprietary, Scanning Electron Microscopy was used to identify the type of coatings applied to the tools. EDS (figure 9) taken on unused tool exteriors showed the likely coatings for the four tool types are:

(a) ME05 F40M AlTiN coating
(b) M06 MP2500 Al$_2$O$_3$ coating
(c) M06 MS2050 Nb-B-Al based coating
(d) M06 MP2500 AlTiN coating

Close examination (figures 10–14) of the worn tools clearly shows that characteristic features of the underlying wear processes with all four tool types were similar. All tools showed a built-up edge (BUE) of work-piece material. In general, the dry machining produces some BUE, and the use of LAM causes a considerable increase in the size of the BUE.

Figures 10–14 provides significant evidence that both abrasion and adhesion are characteristics of the wear process of these tools and that these processes are enhanced for all tools after the introduction of laser assistance. A typical tool wear pattern is shown in more detail in figure 14. The workpiece material (Ti-6Al-4 V) has adhered to the top tool coating and even directly onto the uncoated tool area. Abrasion marks are visible in both layers suggesting that the top surface layers are being removed as a result of the combined action of temperature enhanced chemical diffusion and abrasion.

After the coating layers have been removed, the dominant wear mechanism of the underlying WC-Co tool material is most likely to be diffusion wear involving the chemical interaction between C and Co in the tool material. Enhanced
Figure 5. Comparison of the average flank wear for the four tool types during unassisted dry milling (R.T.) and Laser-Assisted Milling (LAM) at a speed of 100 m min$^{-1}$.

Figure 6. Comparison of the average flank wear for the four tool types during unassisted dry milling (R.T.) and Laser-Assisted Milling (LAM) at a speed of 150 m min$^{-1}$.
Figure 7. Comparison of the maximum flank wear for the four tool types during unassisted dry milling (R.T.) and Laser-Assisted Milling (LAM) at a speed of 100 m min$^{-1}$.

Figure 8. Comparison of the average flank wear for the four tool types during unassisted dry milling (R.T.) and Laser-Assisted Milling (LAM) at a speed of 100 m min$^{-1}$. 
temperature results in enhanced diffusion of cobalt from the workpiece surface into the newly formed chips. This process ultimately results in weakening and removal of WC particles from the tool. Preheating the work-piece material to 300 °C by the laser appears to accelerate this process by increasing rates of chemical diffusion and subsequent removal of coatings and WC-Co tool material.

4. Conclusions

This paper investigates and compares the cutting forces, tool life, and wear processes of four different tool types while milling Ti–6Al–4 V under dry/laser-assisted-milling conditions at two cutting speeds. The key findings are:

(a) Laser-assisted milling resulted in lower cutting forces, but higher rates of tool wear with all cutting tools. All tools showed a BUE of work-piece material. In general, the dry machining produces some BUE, and the use of LAM causes a considerable increase in the size of the BUE.

(b) Though the literature and the theory of optimal heating temperature suggest that a decrease in the total heat at the interface is expected for LAM due to the decreased flow stress, the results show that the contribution from the laser to the total heat was dominant and this adversely affected tool wear, despite the observed cutting force reduction.

(c) The results suggest that none of the existing cutting tool coating packages will provide a suitable technical solution to the wear problem.

(d) For this reason, any future work in the field of LAM should focus on (1) the development of a new generation of cutting tools that are not vulnerable to the dominant diffusion-controlled tool degradation processes evident in existing tools; (2) implementation of effective cooling strategies on the cutting tools.
Figure 10. Images of the worn high feed milling inserts (ME05 F40M), (A), unassisted milling for 2 min at a speed $V_c = 100 \text{ m min}^{-1}$. (B) LAM for 1.9 min at a speed $V_c = 100$, (C), unassisted milling for 1.2 min at a speed $V_c = 150 \text{ m min}^{-1}$, (D) LAM for 0.6 min at $V_c = 150 \text{ m min}^{-1}$.
Figure 11. Images (Backscattered Electron) of the worn high feed milling inserts (M06 MP2500), (A), unassisted milling for 3.0 min at a speed $V_c = 100 \text{ m min}^{-1}$. (B) LAM for 4.6 min at a speed $V_c = 100 \text{ m min}^{-1}$. (C) unassisted milling for 2.7 min at a speed $V_c = 150 \text{ m min}^{-1}$. (D) LAM for 0.9 min at $V_c = 150 \text{ m min}^{-1}$. 
Figure 12. Images (Backscattered Electron) of the worn high feed milling inserts (M06 MS2050), (A), unassisted milling for 6.0 min at a speed $V_c = 100 \text{ m min}^{-1}$. (B) LAM for 3.5 min at a speed $V_c = 100 \text{ m min}^{-1}$. (C) unassisted milling for 2.4 min at a speed $V_c = 150 \text{ m min}^{-1}$. (D) LAM for 1.3 min at $V_c = 150 \text{ m min}^{-1}$. 
Figure 13. Images (Backscattered Electron) of the worn high feed milling inserts (M06 F40M), (A), unassisted milling for 4.6 min at a speed $V_c = 100 \text{ m min}^{-1}$. (B) LAM for 1.9 min at a speed $V_c = 100 \text{ m min}^{-1}$, (C) unassisted milling for 2.4 min at a speed $V_c = 150 \text{ m min}^{-1}$, (D) LAM for 0.9 min at $V_c = 150 \text{ m min}^{-1}$.
Figure 14. Images of the worn ME05 F40M inserts, machined using LAM for 1.9 min at the rate of $V_c = 100 \text{ m min}^{-1}$.

Acknowledgments

This paper includes research that was supported by DMTC Limited (Australia). The authors have prepared this paper in accordance with the intellectual property rights granted to partners from the original DMTC project. The authors would like to thank Mr Daniel Graham for assistance with wear measurements, data collection and analysis.

Conflict of interest

No conflict of interest between the current authors or/and any other researcher has been declared.

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