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Understanding the Behaviour of Workpieces' Bulk Temperature during Laser-assisted Turning of Ti6Al4V Alloy and Heating of Al-SiC Metal-Matrix Composite Rods

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Abstract

Although laser-assisted turning (LAT) has been studied for decades, little is known on the effect of bulk temperature rise and residual temperature in the workpiece. Here we report an investigation on a comparison of bulk temperature characteristics in LAT of Ti6Al4V alloy and laser heating of Al/SiC metal matrix composite (MMC) as the two materials have significant differences in thermal conductivities. The research shows that at a low cutting speed with a low laser power density, and a larger laser beam spot, commonly used in previous LAT processing of Ti6Al4V alloy and Al/SiC MMC processes, it may cause too much heat accumulation inside the bulk material, particularly for the material with higher thermal conductivity. A new processing strategy for LAT is proposed based on this study, which combines high cutting speed, high laser power density, and a smaller laser beam spot size to avoid heat accumulation in the workpiece bulk and energy wastage during LAT of materials with high thermal conductivities. Besides, it is found that the cutting tool temperature at 0.3 mm cutting depth is higher than that at 0.5 mm cutting depth during LAT of Ti6Al4V, which is opposite to that in conventional machining.

Keywords: Temperature, bulk, workpiece, laser-assisted turning, Ti6Al4V alloy, Al/SiC metal-matrix composite, conductivity, laser-assisted machining
1. Introduction

Metal-matrix composites (MMCs), consisting of a metallic matrix with hard ceramic particles or fibres as reinforcements, are ideal candidates for the next generation aerospace and automotive industries because of their high strength-to-weight ratio and stiffness, better wear resistance, and designable thermal expansion coefficients compared with monometallic materials and alloys [1]. Another widely used material for the aerospace and medical industries is a titanium alloy, which is well known for its lightweight, high strength, excellent fatigue performance, high resistance to aggressive environments, and excellent biocompatibility [2]. Conventional machining (CM) of MMCs and titanium alloy is challenging because the high hardness ceramic reinforcement particles in the metal matrix usually lead to severe tool wear and poor surface integrity of machined components [3]. Gupta et al. [4] explained that some of the specific material properties of titanium alloys make it difficult to machine. Titanium alloys have a low Young’s modulus, causing parts to chatter during machining, which further leads to the inferior surface quality of processed parts. The movement of the cutting tool is significantly affected by the work hardening of titanium alloy during its deformation. The tool surfaces are also easily adhered with the sticky titanium alloy, which affects the performance of the cutting tools.

Laser-assisted machining (LAM), including laser-assisted turning (LAT) and laser-assisted milling (LAML), provides an alternative approach for the machining of hard alloys and MMCs [5]. Such a technology utilises a laser beam to locally preheat the workpiece material just before the cutting tool, resulting in softening the material locally. The MMC materials can then be machined off in the form of continuous chips because of visco-plastic deformation, contributing to lower cutting force with better surface finishes, higher efficiency, and longer cutting tool lives [6].

LAM of Al, Mg, Ti, Cu MMCs and titanium alloys have been widely investigated. Dandekar and Shin [7,8] reported that the optimum material removal temperature was 300 °C for Al-2%Cu MMC reinforced with 62 vol% alumina fibres and A359 MMC reinforced with 20 vol% silicon carbide particles (SiCs). As recrystallisation of aluminium alloy occurs after the surface temperature exceeds half of the melting point (approximately 300 °C), aluminium grains at the shear deformation zone starts to slip at the grain boundaries resulting in a lower cutting force [9]. Wei et al. [10] reported that previous investigations on LAT of Al/SiC MMCs usually used a low cutting speed (40-150 m/min), a large laser beam spot (2-4 mm), low laser power (1000-1500 W), and low laser power density (1.4×10^4 - 3.18×10^4 W/cm²). Such a parameter combination would cause a waste of laser energy and lead to workpiece bulk temperature rise.

Rahman Rashid et al. [11] found that the optimum laser power and cutting speed for LAT of Ti10V2Fe3Al alloy ranged from 800 to 1200 W and 55 to 100 m/min, respectively. Ayed et al. [12] found that the distance between the laser
beam spot and the cutting tool was the critical laser processing parameters to reduce the cutting force during LAT of Ti6Al4V for more than 50%. The work on laser-assisted finish turning of Ti6Al4V by Habrat et al. [13] showed that higher laser power (1200 W) contributed to a lower cutting force, and LAT did not improve the chip formation. The tool life could be increased by up to 180% in LAT of Ti/TiC MMC [14].

All the above previous investigations show that LAT could be an effective solution to machining hard-to-cut materials. On the other hand, it is notable that little attention is placed on the machined components’ bulky temperature variation during LAT. Laser heating in the LAT process introduces a new heat source into machined workpieces in addition to the cutting-force induced heat, which is the primary heat source in conventional turning [15]. The thermal images presented by Kong et al. [9] indicate that the laser-induced heat is unable to be entirely removed by the cutting tool, leading to machined bulk component’s heating-up. Arrizubieta et al. [16] reported that the laser heat-affected zone (HAZ) was much larger than the machining area. Attia et al. [17] showed that the surface temperature of the LAT processed Inconel 718 workpiece was higher than 700 °C. At such a high temperature, although it was acceptable for materials with high melting points, for instance, ceramics, it must be avoided during machining materials sensitive to elevated temperatures, including aluminium/SiC MMC with a melting temperature of 660 °C [18]. Besides, it would lead to serious thermal expansion and poor dimensional accuracy of machined workpieces. More seriously, the mechanical properties of machined workpieces may be changed due to the high-temperatures [19]. Besides, the excessive laser-induced heat would lead to significant temperature-dependent work hardening for certain metallic materials with high melting points including Ti6Al4V alloy [20], giving rise to increased hardness, brittleness, micro-cracking and reduced toughness, which should be avoided in practice.

Nickel-based superalloys including nickel-copper alloy, nickel-chromium alloy and nickel-molybdenum–chromium alloy are widely used in aero-engine components serving under heavy loads and high temperatures [21]. The work of Ding et al., [22] indicated that LAT of Waspaloy, a nickel-chromium alloy contributed to a 20% decrease in energy consumption, a two- to three-fold improvement in surface roughness and a 50% increase in ceramic cutting tool life compared with CM. The dendritic microstructure present in the HAZ of the Inconel 718 alloy after LAM lead to better material machinability [23]. The surface temperature of the Inconel 718 rod was mainly determined by the laser power and incident laser beam angle [24]. Xu et al., [25] reported that LAM was promising for roughing machining of nickel superalloy, but it led to tensile residual stress which was widely distributed on the deep subsurface of LAM-processed workpiece and then caused cracks, which affected the fatigue life of the part. Therefore, the authors recommended finishing or shot peening the workpieces after rough machining with LAM.
Kim et al. [26] stated that the annual increase in the global LAT market is 11%. It is essential to investigate machined components’ bulk temperature characteristics during the LAT of certain materials before utilising this technology for commercial applications. Ideally, after LAT, the residual heat caused by the laser in the part body should be close to room temperature, so that overheating and subsequent thermal deformation of Al/Si MMC and titanium alloys can be avoided.

In this paper, we report a comparison of bulk temperature characteristics of two aerospace materials with a distinct difference (about 20 times difference) in thermal conductivities during LAT of Ti6Al4V alloy and heating of aluminium MMC with a 15 vol% 10 µm SiC reinforcement. The effects of material thermal conductivities, heating time, cutting speed, and laser beam spot size on the temperatures of bulk workpieces, cutting tools, and the cutting force were investigated. A contribution of this research is to clarify the influence of the above processing parameters on the bulk temperature and residual heat of the parts after LAT and guide the subsequent detailed research to achieve zero residual heat LAT.

2. Experimental materials and procedure

2.1. Materials

Fourier’s Law shows the relationship between the temperature rise, heat input and material thermal conductivity:

\[
\Delta T = \frac{P \cdot L}{A \cdot k}
\]  

Where \( k \) is the thermal conductivity, \( P \) is conduction heat transfer, i.e., power, \( L \) is the length, \( A \) is the area, \( \Delta T \) is a temperature difference.

In this study rods with a 30 mm diameter and 100 mm length were selected in this investigation. Ti6Al4V alloy and Al/SiC MMC rods with 15 vol% 10 µm SiC reinforcements were supplied by Baoji Titanium Industry Co., Ltd. and Baohang Advanced Materials Ltd. respectively. Their physical properties are given in Table 1.

<table>
<thead>
<tr>
<th>Material</th>
<th>Typical Value</th>
<th>Ti6Al4V alloy</th>
<th>Al/SiC MMC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm(^3))</td>
<td></td>
<td>4.42</td>
<td>2.82</td>
</tr>
<tr>
<td>Melting point (°C)</td>
<td></td>
<td>1649.00</td>
<td>548.00</td>
</tr>
<tr>
<td>Specific heat (J/kg.°C)</td>
<td></td>
<td>560.00</td>
<td>-</td>
</tr>
<tr>
<td>Thermal conductivity (W/m.K)</td>
<td></td>
<td>7.20</td>
<td>140.00</td>
</tr>
<tr>
<td>Thermal expansion 0-100°C (10⁻⁶/K)</td>
<td></td>
<td>8.60</td>
<td>18.40</td>
</tr>
</tbody>
</table>
Carbide cutting tool inserts (DCMT 11T308EN-F43 CTC2135) with a 0.8 mm nose radius and a 107.5° angle tool holder (SDHCR 2525 M11) supplied by Ceratizit Group were used in this study. Process parameters for cutting titanium alloy are: cutting speed \( V_c = 15-35 \) m/min, feed rate \( f = 0.05-0.25 \) mm/rev, and cutting depth \( a_p = 0.5-2.5 \) mm [27].

2.2 Experimental setup

A manual miniature lathe (Warco® WM250, Warren Machine Tools Ltd) was modified and motorised, as shown in Figure 1a, on which a cutting tool was mounted via a vertical milling slide and a vice. A continuous-wave fibre laser beam of a 1070 nm wavelength from a ytterbium laser system (YLS-16000, IPG) was focused with a laser lens assembly (YW52, Precitec Group), which was mounted on an x-y-z linear stage, to a 1-3 mm spot size, and was traversed simultaneously with the cutting tool feeding along the machined rod axial direction. A specially designed in-house motion controller was utilised to control the laser, the lathe, and the CNC x-y-z stage.

The laser beam angle relative to the cutting tool was set as 30°. This angle value was widely used in previous publications [28]. The distance between the laser beam spot and the cutting position should be short enough to reduce the cooling of laser-induced heating. However, too short a distance would make the laser beam reflected onto the cutting tool directly. In this research, the distance was selected as 4 mm in all experiments, as presented in Figure 1b.

The shiny and curved surface of metallic rods resulted in low beam absorption and emissivity, which would reduce the infrared imaging resolution dramatically [29]. The aluminium alloy surface had a laser beam absorption as low as 20%. Kashani et al. [30] discovered that a black ink coating could effectively increase this value to 40%. Hence, in our study, a carbon black ink marker fixed on a flexible bracket was used to paint the surface of the rod automatically before the laser heating and machining, as presented in Figure 1c.

As shown in Figure 1a, an infrared (I.R.) thermal camera (T650sc, FLIR) was used to monitor the bulk temperature variation of workpieces during processing. A K-type perfluoroalkoxy alkanes (PFA) insulated fine wire thermocouple was used to measure the transient temperature of the cutting tool insert during the machining. The temperature measurement range of this thermocouple is from \(-200 \) °C to \(+1350 \) °C, and the error of this standard grade K-type thermocouple is \( \pm 2.2 \) °C. Owning to the small size of its welded conductor bead (0.2 mm diameter), the thermocouple was easily fixed between the cutting tool insert and the tool holder, as illustrated in Figure 1d. The distance between the temperature measurement point and the tip of the insert was 2 mm.
2.3 Experimental procedure

2.3.1 Laser heating of Ti6Al4V alloy and Al/SiC MMC

When the cutting depth is greater than or equal to the depth of the laser irradiation-induced heat-affected zone, the cutting chips can take away most of the laser radiation heat, avoiding the increase in the bulky temperature of the parts due to residual heat accumulation. Therefore, the temperature distribution,
especially the heat-affected depth, on the cross-section of the rod after laser heating was studied.

Laser heating of Ti6Al4V and Al/SiC MMC was investigated aiming to reveal the effects of material thermal conductivities and heating time on rods' bulk temperature distributions, based on the experimental parameters listed in Table 2. The laser beam irradiated on the workpiece's surface from one end of the rod initially and was subsequently moved inward for 10 mm continuously, and the spindle of the lathe kept rotating clockwise, as presented in Figure 2a. In the preliminary trials, we investigated the influence of the laser beam spot diameter on the melting status of Al/SiC MMC's surface, and the results showed that with 2 mm and 3 mm laser spots, it completely melted the Al/SiC MMC's surface. Therefore, further experiments of heating Al/SiC MMC with 2 mm and 3 mm laser beam spots were discontinued.

<table>
<thead>
<tr>
<th>Material</th>
<th>Ti6Al4V alloy</th>
<th>Al/SiC MMC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser power (W)</td>
<td>1200</td>
<td>1200</td>
</tr>
<tr>
<td>Laser beam spot size (mm)</td>
<td>1, 2, 3</td>
<td>1</td>
</tr>
<tr>
<td>Laser feeding speed (mm/min)</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Laser moving distance along rod's axis (mm)</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Spindle speed (rev/min)</td>
<td>200</td>
<td>200, 400, 600</td>
</tr>
</tbody>
</table>

Figure 2 a) illustration of laser feeding direction and the spindle rotation direction, b) illustration of the feeding direction of the laser beam and the cutting tool and the spindle rotation directions.

2.3.2 LAT of Ti6Al4V alloy

The experimental result on laser heating of Al/SiC MMC to be discussed later indicated that the whole Al/SiC MMC workpiece would be heated to a temperature higher than 220°C in 12 seconds and showed little temperature difference between its surface and its inner part. The relevant work has been reported elsewhere [10]. As a result, we will only present the result of on LAT of Ti6Al4V in this paper and compare with the LAT of Al/SiC MMC in the published
work we previously reported. The processing parameters for the LAT of Ti6Al4V are listed in Table 3.

The laser beam and the cutting tool fed forward synchronously with a feeding rate of 0.1 mm/rev (i.e., 20 mm/min) along the axis of the rod, as presented in Figure 2b. Also, the spindle rotated clockwise to feed the laser-heated material to the cutting tool for machining.

<table>
<thead>
<tr>
<th>Material</th>
<th>Ti6Al4V alloy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser power (W)</td>
<td>1200</td>
</tr>
<tr>
<td>Laser beam spot size (mm)</td>
<td>1, 2, 3</td>
</tr>
<tr>
<td>Laser feeding speed (mm/min)</td>
<td>20</td>
</tr>
<tr>
<td>Laser moving distance along rod’s axis (mm)</td>
<td>10</td>
</tr>
<tr>
<td>Spindle speed (rev/min)</td>
<td>200</td>
</tr>
<tr>
<td>Cutting depth (mm)</td>
<td>0.3, 0.5</td>
</tr>
<tr>
<td>Cutting tool feeding rate (mm/rev)</td>
<td>0.1 (20 mm/min)</td>
</tr>
<tr>
<td>Cutting speed (m/min)</td>
<td>18.84</td>
</tr>
</tbody>
</table>

2.4 Material characterisation procedure

The temperature of the cutting tool insert was monitored with a K-type fine wire thermocouple attached to the bottom of the insert and collected using a thermocouple data logger (USB-2416, Measurement Computing Corporation).

A thermal imaging camera (T650sc, FLIR) was used to measure the temperature distribution of the workpieces during processing. The measurement range and frame rate of the camera were set as 100 to 650 °C and 30 frames per second (FPS), respectively. Temperature distributions on the ends of the rods were captured with the thermal camera during laser heating of Ti6Al4V alloy and Al/SiC MMC, and LAT of Ti6Al4V alloy experiments. Temperature distributions of cylindrical surfaces of rods were also observed using the thermal camera in the LAT of the Ti6Al4V alloy experiment. All data were analysed via ResearchIR software.

A power meter (CH2802, Beich electronic technology Co., Ltd.) was utilised to measure the electrical current of the stepper motor driving the cutting tool because the cutting forces during LAT were related to the output torques of the stepper motor. As a result, the electrical current of the stepper motor could be used to understand the cutting force change qualitatively.

3. Results and discussion

3.1 Laser heating of Ti6Al4V alloy and Al/SiC MMC

3.1.1 Effect of thermal conductivities on cross-section temperature distribution
after a single turning

Heat-affected depth is a good indicator to represent the heat transfer speed. Here, we present the temperature distribution on the ends of the Al/SiC MMC rod and the Ti6Al4V rod after the spindle rotated and laser-heated the sample for a single turn (i.e. laser heating the workpiece for 300 ms in this case). As shown in Figure 3a and Figure 3b, Al/Si MMC had a deeper heat-affected depth (i.e. 6.63 mm) compared with that of 1.87 mm for the Ti6Al4V rod respectively because the thermal conductivity of Al/SiC MMC was 19.44 times that of Ti6Al4V alloy based on the data given in Table 1.

A rectangle area (15 mm × 1.5 mm) as shown in Figure 3c was selected as a region of interest to investigate the temperature distribution from the rod’s surface to the rod’s centre. The above two materials appeared a similar temperature variation trend where the peak temperature was found at the sub-surface of the rods (0.33 mm from the rod surface for Al/SiC MMC, 0.44 mm from the rod surface for Ti6Al4V respectively as shown in Figure 3), because the radiation heat transfer, between the hot surface of the rod and the cooler ambient air, made the rod surface temperature drop slightly [31].

As shown in Figure 3a and Figure 3b, although the time for the material to rotate from the laser irradiation point to the cutting point was very short (25 ms in this experiment), the surface temperature of the material to be machined dropped sharply after rotating from the laser irradiation point to the machining point. For the Al/Si MMC rod, the temperature dropped by 225.2 °C (from
439.4 °C to 214.2 °C), and for the Ti6Al4V rod, the temperature dropped by 142.9 °C (from 296.0 °C to 153.1 °C).

This experiment shows that the material with a lower thermal conductivity (i.e. Ti6Al4V alloy in this study) would have a thinner heat-affected depth, as expected. This means that under the same laser input energy and the same cutting parameters, the residual heat of LAT-processed titanium alloy parts will be less than that of Al/Si MMC parts, so the thermal deformation of titanium alloy parts would be expected to be smaller. The temperature drop from the laser-irradiated point to the cutting point is larger for the Al/SiC MMC because of its higher thermal conductivity compared with the Ti6Al4V material. The excessive temperature drop may cause the material to fail to reach the required softening temperature at the cutting point, even if the material is already semi-melted or even melted at the laser radiation point. The above two factors show that it is more challenging to precisely control the bulk temperature of Al/Si MMC parts during LAT to avoid overheating and unrecoverable thermal deformation.

3.1.2 Effects of spindle speed and laser beam spot size on temperature distribution after a single turning operation

Increasing the spindle speed from 200 rev/min to 600 rev/min effectively reduced the heat-affected depth of the Al/SiC MMC rod from 6.63 mm to 4.25 mm, as presented in Figure 4a1-a3. The maximum temperature appeared at the sub-surface of the rod and dropped quickly from 240 °C to 86 °C (see Figure 4c) due to that a higher spindle speed led to a shorter time for materials to absorb the laser energy [32]. Hence it is critical to enhancing the laser power density, including higher laser peak power or smaller focal laser beam spot, to make up the temperature reduction for higher speed turning [33].

Figure 4b1-b3 and Figure 4d verify that the smallest focal laser beam spot (1 mm) generated the highest sub-surface temperature (261 °C). Figure 4b1-b3 indicates that the laser beam spot size had a contribution to the laser heat-affected depth where the heat-affected depth was increased from 1.87 mm to 2.51 mm after the laser beam spot was enlarged from 1 mm to 3 mm.

From the above experimental findings, it can be seen that a higher lathe spindle speed would contribute to a thinner laser-induced heat-affected depth, and a smaller laser beam spot led to higher workpiece’ subsurface temperature and a smaller heat-affected depth. It means that the processing parameters combining a high cutting speed and a small laser beam spot can reduce the residual heat of the bulk component and increase its surface temperature. However, too high a cutting speed would prevent the material from reaching the softening temperature, so a higher laser power density must be used to compensate for the temperature drop.
Figure 4. Temperature distributions on the Al/SiC MMC rod end after a single turn as spindle speed increased from a1) 200 rev/min, a2) 400 rev/min to a3) 600 rev/min, at a laser power of 1200 W, a laser beam spot size 1 mm, and a laser feeding speed of 20 mm/min, b1) to b3) the temperature distributions on a Ti6Al4V rod as the laser beam spot size increasing from 1 mm to 3 mm, while laser power was 1200 W, laser feeding speed 20 mm/min, spindle speed 200 rev/min, c) and d) the temperature variation plots from the surface to the centre of the Al/SiC MMC rod and the Ti6Al4V rod respectively.

3.1.3 Effect of laser heating time on temperature distribution in the bulk rods

The laser beam heated the Al/SiC MMC rod and the Ti6Al4V rod at a 20 mm/min (i.e., 0.1 mm/rev) feeding rate along the rod’s axis for a 10 mm distance (i.e., 30 sec). The cross-section temperature distributions are presented in Figure 5 a1-a6 and b1-b6, respectively. Figure 5 c and d show the temperature variation from the surface to the centre of Al/SiC and Ti6Al4V rods captured from the rectangle regions of interest marked in Figure 5 a2 and b2.

Figure 5c indicates that the whole cross-section of the Al/SiC MMC rod achieved almost the same temperature level at 220 °C after the rod was heated for 12 sec and was synchronously heated gradually in the further heating process.

A significant different temperature variation trend of Ti6Al4V alloy was observed in Figure 5d. The temperature of the rod surface was increased to its
maximum value at 6 sec and dropped to 210 °C in the further heating time due to radiation heat loss to the surrounding air. The centre of the rod was warmed up gradually and achieved a temperature of 170 °C after it was heated for 18 sec. The final surface temperature was lower than its centre temperature.

It should be noted that the above infrared (IR) temperature measurement results only present the temperature distribution at the end of the rod. Although it cannot completely show the temperature distribution of the entire part, especially the temperature distribution inside the rod, it would provide the trend of bulk material temperature distributions.

![Temperature Distribution Diagram](image)

Figure 5 a1) to a6) and b1) to b6) the temperature variations on the end of the Al/SiC MMC rod and the Ti6Al4V rod as heating increasing with 6 sec interval. Their process parameters were the same: laser power 1200 W, laser beam spot size 1 mm, laser feeding speed 20 mm/min, spindle speed 200 rev/min, heated length 20 mm. c) and d) the temperature distribution plots from the surface to the centre of Al/SiC MMC rod and Ti6Al4V rod respectively with 6 sec interval.
This experiment used a parameter combination of low spindle speed and low laser power which was commonly used in the previous investigations for LAT. The results showed that this combination indeed heated up the surface of parts in a short time. However, it was notable that the whole workpiece with was heated up to the same high-temperature level in a short time as well, regardless of their thermal conductivities. It is unacceptable for the manufacturing of hard-to-cut materials with low melting points with a small bulk size. Because the overall heating of a whole component would not only cause thermal deformation of the whole workpieces, which will affect the dimensional accuracy after machining but also make the mechanical properties of the parts irreversibly changed. It is therefore essential to restrain the laser-induced heat-affected depth as thin as possible and only let the workpiece surface reach the ideal softening temperature. As mentioned in Section 3.1.2, the combination of a high cutting speed, a small laser beam spot, and a high laser power density would be a promising solution.

3.1.4 Temperature distribution in the sub-surface of the Ti6Al4V rod along the circumference during a single turn operation

The sub-surface, i.e., 0.44 mm under the surface, was the hottest on the end of the Ti6Al4V rod as described above. This would be the cutting tool tip position during machining. Hence, the temperature variation within this depth was further analysed during a single turn machining (i.e., laser heating time was 300 ms), which was plotted in Figure 6a with a 30 ms interval. The key points are marked in Figure 6b.

Notably, the highest temperature was always found at point P₁ at 2.25 ° relative to the laser beam incident position at point P₀, resulting from the preheating via the conduction heat transfer in the last heating step before a new laser-heating round [34]. However, point P₁ could not be chosen as the cutting position, as the tool insert was too close to the laser beam and would be damaged easily by the reflected laser beam. Besides, newly formed chips would always cover the laser beam spot position and block the laser beam transmitting to the workpiece, affecting the laser heating process. Our preliminary experiments verified all of these statements.

The second high-temperature point was found at the position around point P₂ around 30 ° relative to the laser beam shooting position at point P₀. Such an angle was sufficient to avoid reflected laser beam from damaging the insert and chips blocking laser beam transmitting. That confirmed the choice of a 30° beam angle used in a previous publication [35].
3.2 LAT of Ti6Al4V alloy

3.2.1 Effect of laser beam spot size and cutting position on the workpiece's bulk temperature during long-time machining

Figure 7a1–a3, b1–b3 show the 20th sec instantaneous temperature distribution on the front view of a Ti6Al4V rod with the 1-3 mm laser beam spot sizes and different cutting positions. Temperature distributions in the regions of interest captured from the rectangle areas marked in Figure 7a1 and b1 are plotted in Figure 7c and d.

Figure 7c and d indicate that a larger beam spot (3 mm) contributed to a higher temperature level of the whole workpiece bulk compared with a small beam spot (1 mm), although the small beam spot having a higher laser beam intensity could generate the higher single-point surface temperature which is described in Figure 4d. In other words, a larger beam spot could warm up the whole bulk of a small workpiece quickly because a larger laser beam spot allowed more region on the rod's surface to absorb the laser energy directly, although the laser power density is relatively low due to the defocused laser beam. Also, the time accumulation effect made the whole workpiece warm up more quickly. This phenomenon may explain why previous research [9,14,15] always chose larger laser beam spots for LAT processing.

The valleys on the curves, marked by arrows in Figure 7c and d, are the cutting positions. These indicate that chips were only able to remove some of the heat directly under the cutting position because the nose radius of the cutting tool insert was smaller than the laser beam spot diameter in this study (0.8 mm and...
Cutting position relative to the rod end also had an obvious influence on the temperature of the whole workpiece. The LAT processed region transmitted heat to both sides of the workpiece and the cutting tool via solid heat conduction if the cutting started at the position 10 mm relative to the end of the rod, as shown in Figure 7 a1-a3. The LAT processed region transmitted heat to the left side via conduction and to the right side by radiation if starting at the end of the rod, as shown in Figure 8 b1-b3. The first condition had higher thermal transfer efficiency than the second condition, resulting in a lower temperature of the whole workpiece.

From the above experimental findings, it can be seen that a larger laser beam
spot led to a higher temperature level of the whole workpiece.

The above experimental results show that the large-diameter laser spot widely used in the previous research causes two problems. First, a large-diameter laser spot leads to a higher temperature level of the whole workpiece. Secondly, if the laser spot diameter is larger than the nose radius of the cutting tool, the area irradiated by the laser beam cannot be completely removed by the cutting tool, and the heat absorbed by the uncut part transfers to the part body through thermal conduction and accumulated, aggravating the residual heat problem. Therefore, to achieve net residual heat after LAT of Al/Si MMCs and Ti6Al4V, the laser spot with a diameter smaller than the radius of the tool should be used. In the work of Wei et al., [10] the laser beam spot for LAT was smaller than the cutting tool nose radius (0.7 mm and 0.8 mm respectively). Their experimental result verified that such a strategy could effectively remove laser-irradiation-induced heat and less residual heat was detected after machining.

3.2.2 Effect of cutting depth and laser beam spot size on cutting tool temperature during long-time machining

Temperature variations of the insert during 30 sec (machined length of the Ti6Al4V rod 10 mm) under different laser beam spots and cutting depth were collected by a thermocouple and plotted in Figure 8.

A deep cutting depth usually caused a high cutting tool temperature and quick tool wear in conventional machining due to a strong cutting resistance force resulting from more interaction between the material and the cutting tool [36]. Hence, the experiment with a 0.5 mm cutting depth (refer to the black dotted curve in Figure 8) led to higher tool temperature compared with that with 0.3 mm cutting depth in a conventional dry machining process, plotted as a black dotted curve in Figure 8.

After the laser heating was introduced in the experiment, an opposite phenomenon in temperature behaviour from that of machining without a laser beam heating was discovered. Experiments, using a 0.5 mm cutting depth, showed lower cutting tool temperatures than that with 0.3 mm cutting depth, where a beam spot size was 1 mm or 2 mm, marked as blue and green curves in Figure 8. This result indicates that the initial heat source, i.e., cutting heat, was replaced by the laser-induced heat, and the tip of the insert at the condition with 0.3 mm cutting depth should be much closer to the hottest region at the subsurface described above in Figure 4d. The solid red curve and dotted curve in Figure 8 show that the contribution of cutting depth on the cutting tool temperature would be reduced by the relatively low instantaneous temperature on the laser-heated surface caused by the big beam spot 3 mm, which is described in Figure 4d.
Small slopes of the black solid curve and dotted curve in Figure 8, representing CM process, signified that the temperature of the cutting tool would achieve a thermal steady state, meaning the cutting heat could be effectively removed by chips. On the other hand, the slopes of the other curves in Figure 8, representing the LAT experiments, indicate that the temperature of the cutting tool would continuously rise, meaning that excessive heat was introduced by laser heating and could not be removed by the chips. It was a piece of indirect evidence showing the temperature increasing trend of the workpiece described in Figure 5 b1-b6. In the work of Wei et al., [10], due to the high cutting speed and small laser spot processing strategy, LAT-induced workpiece bulky temperature rise in Al/SiC MM was small, so the cutting tool temperature was significantly lower than the experimental results for LAT of Ti alloy in the current study. Wei et al. reported that the maximum cutting tool temperature was lower than 100 °C under the optimal processing parameters for cutting Al/SiC MMC rods.

3.2.3 Effect of cutting depth and laser beam spot size on cutting force during long-time machining

The current of the cutting tool feed drive motor is a direct indicator to reveal the cutting force changing during machining [37]. The original current plots under different cutting depths and different laser beam spot sizes during LAT of
Ti6Al4V rods are presented as periodic waves, as shown in Figure 9a. The reason for this phenomenon is that, in this experiment, one end of the rod was fixed by the chuck and the other end was suspended. During the turning process, the rod vibrated radially. Wei et al., [10] used a revolving centre to fix the dangling end of the rod and solved such a problem. To make the current data in this study readable, the data were further linearly fitted according to the linear regression model as described in Eq. (2) and then plotted in Figure 9b.

\[ y = \beta_0 + \beta_1 x \]  

where \( \beta_0 \) is the intercept and \( \beta_1 \) is the slope.

Regardless of the cutting depth, experiments with a 1 mm beam spot presented lower currents (solid red curve and dotted curve as shown in Figure 9b) than those with 2 mm or 3 mm beam spots, indicating the smallest cutting forces during LAT. This is because a 1 mm focused laser beam spot formed the highest temperature at the cutting region to soften the material to be machined, which is described in Figure 4d. The cutting force in the experiments with a 3 mm beam spot was slightly higher than that with a 1 mm beam spot based on the blue current curves presented in Figure 9b. Although the 3 mm defocused beam spot led to the lowest temperature at the cutting region based on the data in Figure 4d, such a beam spot could effectively warm up the whole workpiece quickly and preheat the uncut region heated by the laser beam directly which is described in Figure 7 of this article. This 'thermal conduction preheating + laser directly heating' hybrid heating phenomenon made the material at the cutting region to reach the required soften temperature at 300 °C. However, the mechanical performance and physical properties of the workpiece may be degraded resulting from long-time high-temperature exposure of the whole workpiece.

The contribution of the cutting depth on cutting force was smaller than that by the beam spot size, as all experiments with the same beam spots and different cutting depths were located in narrow regions of current signals, as shown in Figure 9b. Reducing the cutting depth from 0.5 mm (the green dotted curve in Figure 9b) to 0.3 mm (the solid green curve in Figure 9b) in experiments with a 2 mm laser beam spot could effectively reduce the cutting force. Because rods in the experiments with the 2 mm beam spot were not raised to the suitable soften temperature and the material should still be completely solid, hence decreasing of cutting depth in such a condition could cause cutting force drop significantly. The cutting depth-induced difference in experiments with a 3 mm beam spot was limited as the whole workpiece was already warmed up to a high temperature for the machining, due to the large laser energy absorption area formed by the 3 mm defocused beam spot. Reducing cutting depth decreased the cutting force slightly in the experiments with the 1 mm beam spot and resulted in the most stable and smallest cutting force, as shown in the flat red solid curve in Figure 9b.
To summarise, a small beam spot (1 mm) and a thin cutting depth (0.3 mm) led to the minimum cutting force in this study.

![Diagram](image)

**Figure 9** a) The original current plots of the cutting tool driving motor as cutting time increasing, b) the linearly fitted current plots. LAT processing parameters are laser power 1200 W, laser beam spot size 1, 2, 3 mm, cutting depth 0.3, 0.5 mm, cutting length 10 mm, laser and cutting tool feeding rate 0.1 mm/rev, spindle speed 200 rev, LAT time 30 sec.

## 4. Conclusion

This paper has reported the temperature distribution of bulk components during the LAT of TiAl4V alloy and laser heating of Al/SiC MMC rods.

Experiments indicate that chips could not remove all the heat generated by the laser and the cutting force. Because the energy input speed was much higher than the material and energy removal speed caused by the machining process in the current range of experimental parameters.

The material thermal conductivity and the spindle speed were the two dominant factors determining the heat transfer speed. A lower thermal conductivity and a higher spindle speed led to lower heat-affected depth and would cause less excessive heat accumulation in the bulk material during LAT. The influence of the laser beam spot size on heat transfer speed was limited.

Previous publications claim that heating the surface of a workpiece to the soften temperature by laser irradiation is critical to reducing the cutting force. This study discovers that the maximum temperature is always at the sub-surface of the rods (0.33 mm and 0.44 under the cylindrical surface of a 30 mm diameter rod for Al/SiC MMC and Ti6Al4V respectively), rather than at the surfaces of the rods. This is because the surface of the rods is cooled down, resulting from heat radiation and conduction loss to air during turning. A smaller laser beam size (1 mm) and low spindle speed (200 rev per minute) result in the highest
subsurface temperature (240 °C for the Al/SiC MMC and 261 °C for the Ti6Al4V respectively) after a single turning of laser heating.

The temperature distribution during the 30 sec laser heating verified that chips are unable to remove all laser-induced heat as the temperature of components always increased. Notably, the whole Al/SiC MMC rod shows temperature rising synchronously. As for Ti6Al4V alloy rods, the temperature in the centre is higher than that on the surface after laser heating for 30 sec.

The analysis of temperature distribution on the subsurface of the Ti6Al4V rod along the circumference during a single turning found that the highest temperatures are always at the point at 2.25 ° relative to the laser beam shooting position. Moreover, the second high-temperature point is around the point at 30 ° relative to the laser beam shooting position. Besides, experiments reveal that the point at 2.25 ° is too close to the laser spot. If setting cutting positions there, the laser beam would be easily blocked by the chips just machined out by the cutting tool or be directly reflected onto the cutting tool. The point at 30 ° is ideal for turning. Moreover, the laser heat-affected area is limited in a region of 180 ° on the rod’s cylindrical surface.

Cutting tool’s temperature at 0.3 mm cutting depth is higher than that at 0.5 mm cutting depth during LAT. This is opposite to that of conventional machining. It indicates that the tip of the insert at the condition with 0.3 mm cutting depth should be much closer to the hottest region at the subsurface.

This study shows that the low cutting speed, low laser power density, and large laser beam spot processing strategies widely used in previous studies may cause the overheating of LAT-processed parts with a low melting point, and may further lead to irreversible thermal deformation. To solve this problem, a parameter combination of a high cutting speed, a high laser power density, and small laser beam spot (smaller than the cutting tool nose radius) should be used. Because the high cutting speed can reduce the heat transfer time from the surface of the part to its interior, and makes sure laser-induced heat is controlled in the workpiece’s skin layer and then is immediately entirely removed by the chips during machining. The high laser power density makes the part surface to reach an ideal softening temperature locally. The smaller laser spot ensures that the laser-irradiated area can be completely cut off by the tool immediately. This new processing strategy has been successfully used to process Al/SiC MMC by Wei et al., which not only avoids the thermal deformation of the Al/SiC MMC parts after LAT but also dramatically improves the production efficiency.

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References


[15] G.K. Hedberg, Y.C. Shin, L. Xu, Laser-assisted milling of Ti-6Al-4V with the consideration of


[32] M. Moradi, M. KaramiMoghadam, High power diode laser surface hardening of AISI 4130;


