Lasers in Manufacturing Conference 2019

Water Jet Guided Laser Machining of Metal Matrix Composites

S. Marimuthu[a*], J. Dunleavey[a], B. Smith[a]

[a]*The Manufacturing Technology Centre, Ansty Business Park, Coventry, CV7 9JU, UK*

Abstract

Laser cutting or drilling of monolithic materials like metals and alloys is a well-established process, used extensively in various applications including aerospace, medical and automotive. However, traditional laser processing (thermal based) of materials like metal matrix composites (MMC) is challenging due to the differences in the chemical and physical properties of the matrix and reinforcement particles. The main investigation on this paper concentrates on the water-jet guided nanosecond laser (WJG) cutting of aluminium metal matrix composite (Al MMC) reinforced with aluminium oxide fibre and WJG drilling of Al MMC reinforced with silicon carbide particles. The results of the WJG laser process was compared with the results from the conventional long pulse/continuous wave laser process.

Keywords: Laser; water; nanosecond; Al MMC; micro-machining; cutting; drilling;

1. Introduction

Metal matrix composite (MMC) is a relatively new type of material, which combines lightweight metallic matrices like aluminium with hard ceramic particles like silicon carbide. Compared to conventional monolithic materials like metals and alloys, MMCs have enhanced properties however, their use is currently limited due to low machinability compared to conventional metals and alloys (***Baburaja, et al., 2017***). Mechanical machining of MMC’s is challenging due to the abrasive nature of the ceramic particles within the MMC, like silicon carbide and often results in high tool wear (***Khandey, et al., 2017***) and burr formation. Consequently, considerable research in the field of manufacturing science is directed towards the development of non-conventional machining (***Müller, et al., 2000***) of MMC’s such as laser processing, abrasive water jet machining and electrical discharge machining. Of all the non-traditional machining processes, laser processing is considered to be the ideal technique for the cutting and drilling process

* Corresponding author. Tel.: +44 7892891997.
E-mail address: Sundar.Marimuthu@the-mtc.org.

(machining) due to its high productivity (***Marimuthu, et al., 2017***), quality and ease of automation. Continuous wave (CW) laser cutting and millisecond (ms) pulse laser drilling is the current state-of-the-art for processing of monolithic materials, however, CW and ms laser processing is predominantly a thermal process and it may not be the equipment of choice for materials like composites including metal matrix composites (MMC).

The water jet guided (WJG) laser processing, demonstrated by Richerzhagen (***Richerzhagen, 1994***), has securely established itself and is making a big impact in various industrial applications. Figure 1 shows the basic principle of WJG laser, in which the beam is been guided through the pressurized water-jet by means of total internal reflection (at air/water interface). A Q-switch diode-pumped solid-state laser operating at nanosecond pulse duration and a wavelength of 532 nm is commonly used as the laser source. The water jet also offers additional benefits including efficient removal of melted material and reduced conventional thermal defects.

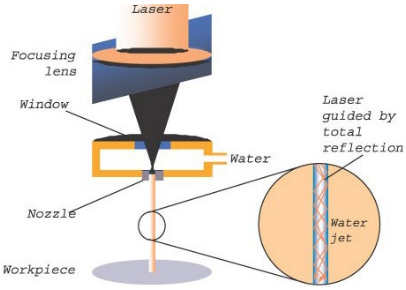
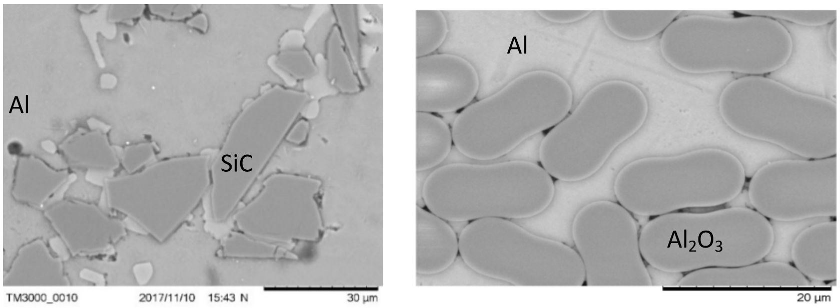


Fig. 1. Schematic showing the basic principle of water jet-guided laser

This research aims to investigate the characteristic of water-jet guided laser machining (drilling and cutting) of Al MMC and compare it with conventional fibre laser drilling/cutting of Al MMC. Two types of Al MMC were investigated, i.e. cutting of alumina fibre based Al MMC and drilling of silica carbide (SiC) particle-based Al MMC.



(a) SiC particle reinforced Al MMC (b) Alumina fibre reinforced Al MMC

Fig. 2. Microscopic images of the base material

2. Materials and Methods

The base material used in this study for drilling was a 2mm thick cast aluminium silicon carbide metal matrix composite (Al MMC), shown in Figure 2a. Cast unidirectional alumina (Al_2O_3) fibre reinforced with pure aluminium matrix composite (Al MMC) of 2mm thickness was used for cutting experiments and is shown in Figure 2b.

Water-jet guided (WJG) laser drilling and cutting of over 2mm thick Al MMC was accomplished using a 3-axis Synova laser-microjet MCS 300 system, fitted with a 535nm Q-switched diode pumped solid state laser that can operate in nanosecond pulse duration. The conventional laser cutting and drilling were carried out using an IPG fibre laser that can operate at a maximum average power of 2kW (continuous wave (CW)), maximum peak power of 20kW and pulse duration ranging from 0.2ms -20ms. Conventional laser cutting and drilling experiments were performed with continuous wave and millisecond pulse respectively. Initial trial experiments were performed to identify the range of laser parameters that can be used for both conventional and WJG laser drilling and cutting of 2mm thick Al MMC.

3. Results and Discussions

3.1. WJG and Conventional Laser Cutting of Fibre based Al MMC

In line with the general quality requirements of laser cutting, it is ideal to achieve cutting with good surface roughness over the cut surface, low kerf width, low heat affected zone and a low degree of cut surface taper. Delamination and protruding fibre (matrix recession) are the key issues surrounding the laser cutting of fibre based composites, including carbon fibre reinforced polymer or ceramic matrix composites.

Figure 3 shows the effect of laser power on characteristics of the CW laser cutting process. As shown in Figure 3, an increase in CW laser power beyond 1700W results in fibre delamination, which is directly related to the higher energy input on to the material. Fibre delamination is a common, but unacceptable defect normally observed in fibre based composites. As noticed from Figure 3, fibre delamination can be controlled in continuous wave fibre laser cutting of Al MMC, by reducing the laser power.

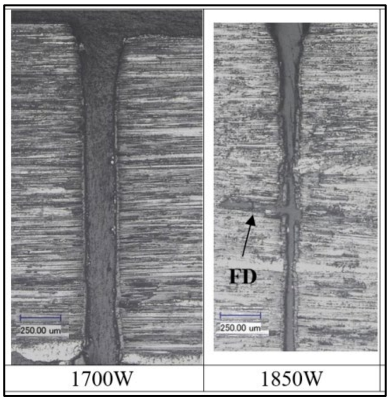


Fig. 3. Effect of CW laser power on cutting performance

Figure 4 shows the effect of assist gas composition on cut surface morphology. As noticed from the figure, irrespective of the gas composition, a thick oxide layer was observed over the cut surface. The oxide layer observed in Figure 4a (using nitrogen gas) over the laser cut surface should be predominantly from the Al_2O_3 fibre. The oxide layer thickness is relatively higher with oxygen assist gas (as shown in Figure 4b) and is contributed by both alumina fibre and the oxidation of the melted aluminium matrix.

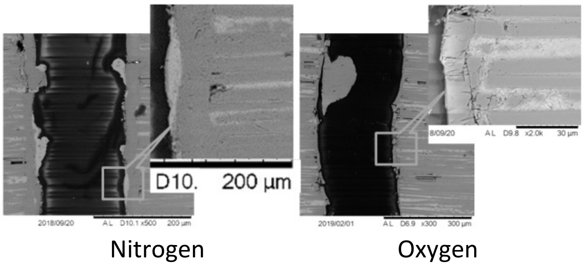


Fig. 4. Effect of gas composition on CW laser cutting of Al MMC (2500mm/min; 1700W; 9.5bar)

Figure 5 shows the characteristic of water jet guided laser cut Al MMC samples. No thermal defects like heat affected zone or recast layer thickness were observed on the WJG laser cut surface, Figure 5 (a, b, c and d). The cut surface was very similar to a surface normally observed with wire electrical discharge cutting process. As noticed from the highly magnified cut surface (Figure 5c and 5d) the cut surface is free from any oxide layer deposition.

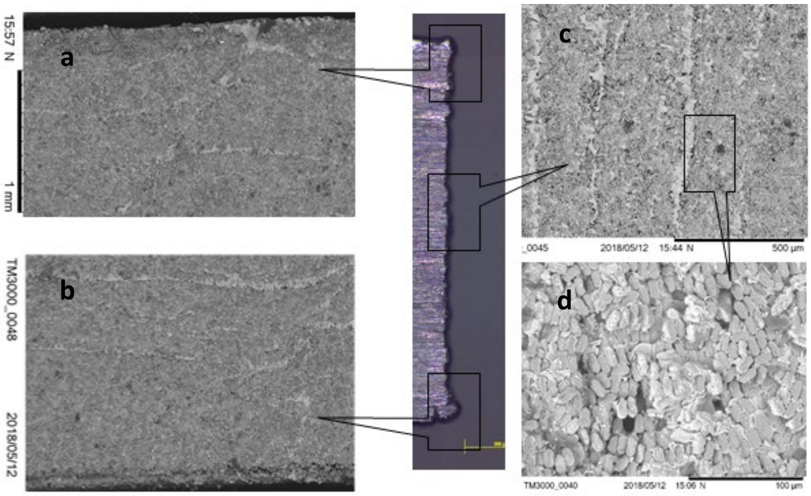


Fig. 5. WJG laser cutting of Al MMC

3.2. WJG and Conventional Laser Drilling of Particle-based Al MMC

Figure 6 shows the optical microscopic image of the holes drilled using a water-jet guided laser process. Irrespective of laser power and speed, WJG laser drilling produced holes of excellent circularity. In general, no spatter nor dross nor hole erosion were observed at the hole entrance and exit. The microscopic images of hole entrances and exits drilled with the conventional millisecond pulse laser are shown in Figure 7. All the millisecond laser holes were drilled with one trepanning orbit and with nitrogen assist gas. As can be seen, the holes produced with the millisecond laser show typical surface defects, including spatter (material deposited over the hole entrance), dross (material deposited at the hole exit) and issues with hole circularity. Unlike WJG laser drilling, a slight change in the laser parameters has a huge influence on hole drilling quality.

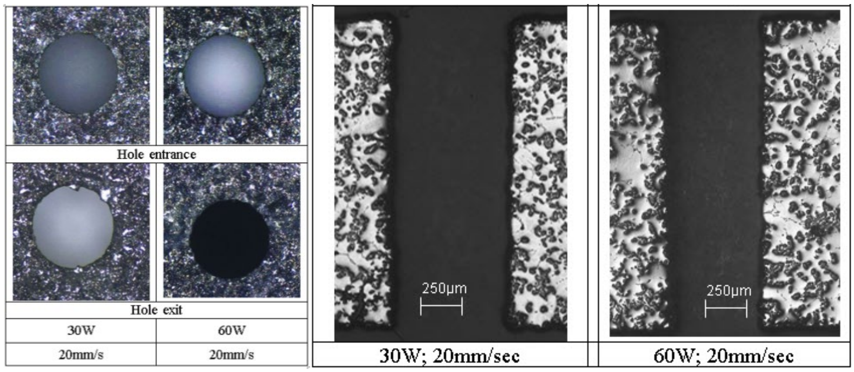


Fig. 6. Hole characteristics of WJG laser drilled Al MMC

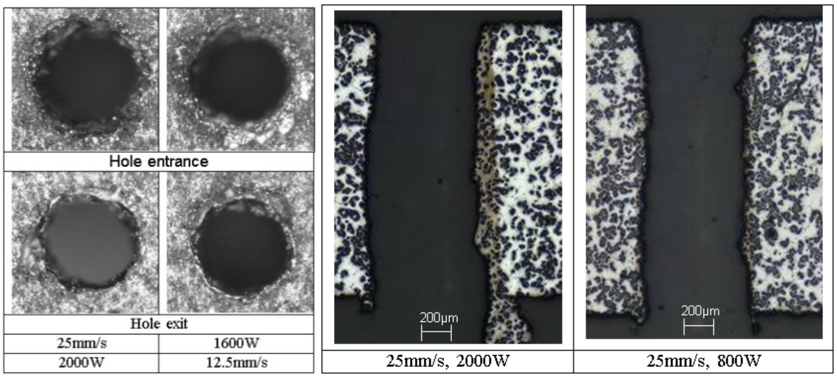
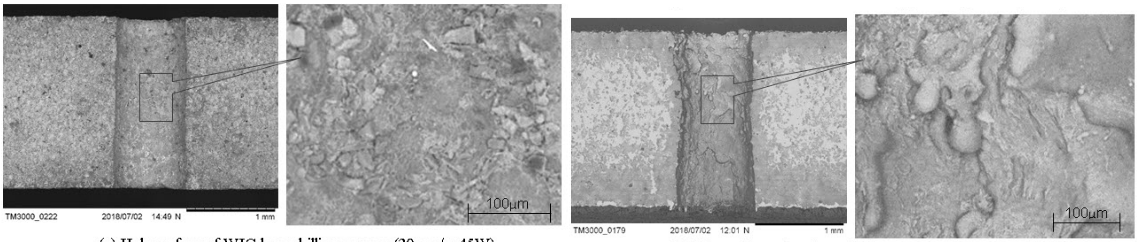


Fig. 7. Hole characteristics of Fibre laser drilled Al MMC

As noticed from Figure 6, irrespective of laser drilling parameters, no thermal damage such as recast layer, oxide layer, heat affected zone or bell mouth were observed during the WJG laser drilling process. The nanosecond laser pulse width combined with the water-jet helps to avoid the thermal defects which are commonly observed in the conventional laser drilling process. As noticed, the microstructure of the WJG laser drilled hole surface is similar to the base material with no noticeable heat affected zone or recast layer or oxide layer.

Millisecond pulse laser drilling is predominantly a thermal drilling process, where the material removal mechanism is dominated by melt ejection with slight vaporisation. The millisecond laser drilling involves absorption of the laser beam by the top surface, generation of a melt pool, and subsequent vaporization and melt ejection due to vapour pressure. The hole depth increases as the molten material continues to be generated and ejected out of the laser interaction zone, initially through the hole entrance. Once the hole depth reaches the material depth, material removal occurs through the exit of the hole. The thickness of the recast layer in ms laser drilling (Figure 7) ranges from 40µm to 200µm, depending on the laser parameters. This is in sharp contrast to WJG laser drilling in which no sign of thermal damage was observed. Unlike ms laser drilling, the WJG laser drilling operates with a larger process window. In WJG laser drilling, a 100% increase in laser power doesn't change the magnitude of recast layer formation, which is not the case in ms laser drilling, which works within a narrow set of operating parameters.



(a) Hole surface of WJG laser drilling process (20mm/s; 45W) (b) Hole surface of ms laser drilling process (25mm/s; 1000W)

Fig. 8. Scanning electron microscope (SEM) image showing the hole surface characteristic

Figure 8 shows the surface characteristic of the Al MMC hole obtained with WJG laser and conventional ms laser drilling process. As noticed from the Figure 8, the material removal characteristic of millisecond laser seems to be melting followed by melt ejection. Also, due to melt pool convection, no evidence of SiC particles were observed at the hole surface, produced by ms laser drilling. It seems due to the melt pool convection **(*Sharma, et al., 2018*)**, the SiC particles have migrated to the region close to the mushy zone of the melt pool. On the contrary, the surface condition of WJG laser drilled Al MMC, seems to be like a cold-machined **(*Phillips, et al., 2015*)** surface condition, i.e. no visible evidence of Al melting or SiC distribution.

Conclusions

Experimental investigations were performed to understand the characteristics of conventional and water-jet guided laser machining of aluminium metal matrix composites. Water-jet guided (WJG) laser drilling and cutting is an excellent choice for advanced materials like Al MMCs. During the WJG laser drilling/cutting of Al MMC, the material is removed by cold ablation, without leaving any residual melt layer within the bulk material. Both matrix and reinforcement particles are removed by the same process, similar to that of cold ablation. Conventional millisecond/continuous wave laser processing of Al MMC is faster than WJG laser machining, but can results in significant thermal damage compared to water-jet guided laser machining using a nanosecond laser.

Acknowledgements

The authors acknowledge the support from the UK HVM Catapult through the MTC core research funding 31880.

References

Baburaja, K., Teja, S.S., Sri, D.K., Kuldeep, J. and Gowtham, V., 2017, August. Manufacturing and Machining Challenges of Hybrid Aluminium Metal Matix Composites. In *IOP Conference Series: Materials Science and Engineering* (Vol. 225, No. 1, p. 012115). IOP Publishing.

Khandey, U., Ghosh, S. and Hariharan, K., 2017. Machining parameters optimization for satisfying the multiple objectives in machining of MMCs. *Materials and Manufacturing Processes*, *32*(10), p.1082-93.

Marimuthu, S., Antar, M., Dunleavey, J., Chantzis, D., Darlington, W. and Hayward, P., 2017. An experimental study on quasi-CW fibre laser drilling of nickel superalloy. *Optics & Laser Technology*, *94*, p.119-127.

Müller, F. and Monaghan, J., 2000. Non-conventional machining of particle reinforced metal matrix composite. *International Journal of Machine Tools and Manufacture*, *40*(9), p.1351-1366.

Phillips, K.C., Gandhi, H.H., Mazur, E. and Sundaram, S.K., 2015. Ultrafast laser processing of materials: a review. *Advances in Optics and Photonics*, *7*(4), p.684-712.

Richerzhagen, B., 1994. *Development of a System for Transmission of Laser Energy* (Doctoral dissertation, Ph. D. Thesis work, EPFL, Switzerland).

Sharma, S., Mandal, V., Ramakrishna, S.A. and Ramkumar, J., 2018. Numerical simulation of melt hydrodynamics induced hole blockage in Quasi-CW fiber laser micro-drilling of TiAl6V4. *Journal of Materials Processing Technology*, *262*, p.131-148.