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515 nm wavelength laser for laser melt injection of high-quality MMC in Cu-ETP

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Abstract

Laser melt injection (LMI) is used to improve abrasive wear resistance by building a metal matrix composite (MMC) layer in highly loaded tool surfaces. But LMI for highly conductive and highly reflective materials like copper can be very challenging. Nowadays high-power laser beam sources with visible wavelengths are available enabling LMI in these materials.

This paper shows a suitable process window for LMI with 515 nm wavelength laser in pure copper with spherical fused tungsten carbide as reinforcing phase. High-quality MMC can be manufactured by using laser power intensities in the range of 10^4 W/cm² and conduction heating of the matrix material between 300 °C and 400 °C. The microstructure exhibits only a few imperfections and has a high particle content of 44 %.

Keywords: laser melt injection, metal matrix composite, tungsten carbide, Cu-ETP, visible wavelength laser

1 Introduction

Laser melt injection (LMI) is used as a surface modification technology to improve the abrasive wear resistance of metallic surfaces. During LMI metal matrix composites (MMC) are generated by blowing hard particles into the laser induced melt pool. Different to laser metal deposition the powder is not melted during the process and remains in its initial shape forming a heterogenous MMC microstructure. These MMC are very beneficial to reduce abrasive wear volume of highly loaded tools, like injection molds, welding jaws, bearings etc. which are often steel-, aluminum- or copper-based [1]. As reinforcing phase chromium, tungsten and silicon carbide particles are often used [2].

Especially laser processing of materials with poor absorptivity for common laser wavelengths around 1 µm like pure copper (e.g., Cu-ETP) can be very challenging. This can be countered on the one hand by using very high intensities which lead to high quality results for deep-penetration weld seams [3]. And on the other hand, by using laser with a shorter wavelength, which are absorbed better by copper surfaces and show good results as well [4]. The latter option is beneficial for LMI since high intensities during LMI can lead to agglomeration of the reinforcing hard particles [5]. Within the last few years frequency-doubled disk lasers emitting a wavelength of 515 nm are commercially available and can reach a maximum output power of > 1 kW, which is very advantageous for LMI in pure copper. Besides the laser beam source additional preheating can improve the welding quality in copper by compensating for the high thermal conductivity [6].

This paper addresses a process window for a stable LMI process yielding high-quality MMC made of Cu-ETP reinforced with spherical fused tungsten carbide (sFTC). Microstructural analyses were conducted to determine the effect of the process parameters on the MMC quality.

2 Experimental set-up

For laser melt injection a 2 kW Trumpf laser with 515 nm wavelength (TruDisk 2021) was used. The laser beam was guided via a 0.6 mm core diameter laser light cable to the processing head. The processing head was

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made of an optical unit, Trumpf BEO D70 with 200 mm collimation length and focal length, equipped with a coaxial three-jet powder nozzle (Ixun) with 16 mm working distance. The laser beam was defocused to a spot diameter of 1.9 mm during LMI. See Fig. 1 for the beam caustic and laser power distribution at different working positions.

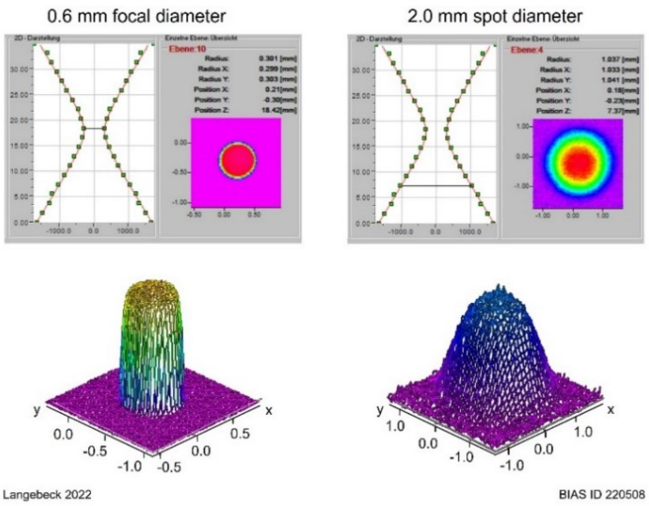

Fig. 1: Laser beam caustic and power distribution for TruDisk 2012, with 0.6 mm laser light cable, 200 mm collimation and focal length

To maintain a sufficient and stable melt pool size during the process a heating device (G. Maier Elektrotechnik) was used to preheat the substrate material before LMI and was also used during LMI. The necessity of a substrate heating is known from earlier studies [7]. A Metis H322 two-color pyrometer (Sensortherm), with 700 °C to 2300 °C measuring range, was used to track the melt pool temperature during LMI. The pyrometer was laterally integrated onto the processing head. Fig. 2 shows the experimental set-up.

Pure copper (Cu-ETP) with a high thermal conductivity of 394 W/m·K (at 20 °C) was used as substrate material. The substrates were cut into small bricks with 50 mm length, 20 mm width and 12 mm height. Spherical fused tungsten carbide particles (sFTC), supplied by Oerlikon Metco WOKA GmbH, with -106 µm +45 µm particle size were used to reinforce the Cu-ETP substrates during LMI.

With this set-up the effects of the heating device temperature and laser power on the MMC microstructure and process zone temperature were examined in fivefold determination. For this five MMC single tracks per parameter-set were manufactured on one Cu-ETP substrate. Between every single track the substrates cool down in order to provide similar starting conditions for each of the five single tracks. See Tab. 1 for the varied and constant process parameters. The process window ranged from 1.6 kW to 1.8 kW laser power which corresponds to a laser power intensity of $5.7 \cdot 10^4$ W/cm² and $6.4 \cdot 10^4$ W/cm², respectively. The heating device temperature ranged from 300 °C to 400 °C.

To characterize the microstructure optical microscopic (OM) images of the MMC tracks were recorded. The particle content of the MMC was calculated by using an automated image processing based on binarized OM images of the MMC cross-sections.

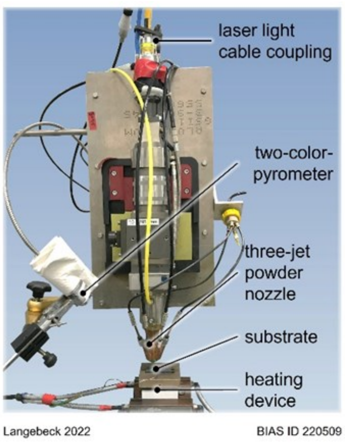

Fig. 2: Experimental set-up

Tab. 1: Process parameters

Process parameter	Value(s)
Laser power	1.6 kW; 1.8 kW
Heating device temperature	300 °C; 400 °C
Powder mass flow	5.5 g/min
Process velocity	150 mm/min
Carrier gas flow (Ar)	3.5 l/min
Shielding gas flow (Ar)	15 l/min
Track length	40 mm

3 Results

Fig. 3 shows cross-sections of MMC single tracks manufactured within the proposed process window (Tab. 1). With increasing the laser power (Fig. 3, top to bottom) the MMC track geometry increases as well. Same applies for increasing heating device temperature (Fig. 3, left to right). A more detailed evaluation of the influence of the process parameters on the track geometry can be found here [7].

From these cross-sections the particle content of the MMC tracks was determined (see Tab. 2). No impact of the used laser power, the used heating device temperature, or an impact of the interaction between both factors were detected for the examined process window. The mean particle content was between 43% (for 1.6 kW laser power, 300 °C heating device temperature) and 45% (for 1.8 kW laser power, 300 °C) with a standard deviation ranging between 1.3% and 3.3%.

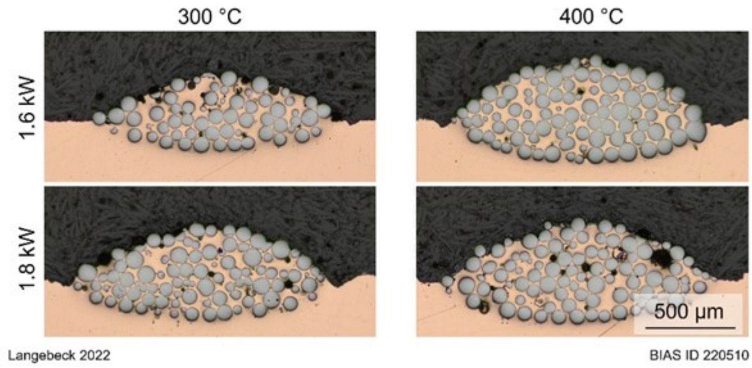

Fig. 3: Exemplarily OM images of MMC cross-sections manufactured with varying laser power and heating device temperature during LMI

Tab. 2: Particle content

		heating device temp.	
		300 °C	400 °C
laser power	1.6 kW	42.7% ±1.7%	44.7% ±3.3%
	1.8 kW	45.0% ±1.3%	43.5% ±1.9%

With all parameter-sets high-quality MMC were manufactured. Though in some cases, imperfections within the MMC tracks were visible (see Fig. 4). A few micro-cracks in the hard particles occurred as well as a few pores near by the sFTC particles. Some OM images show larger pore-like imperfections which can be attributed to particles which were chipped during the preparation process of the cross-sections. A significant impact of the examined process parameters on the imperfections was not detected.

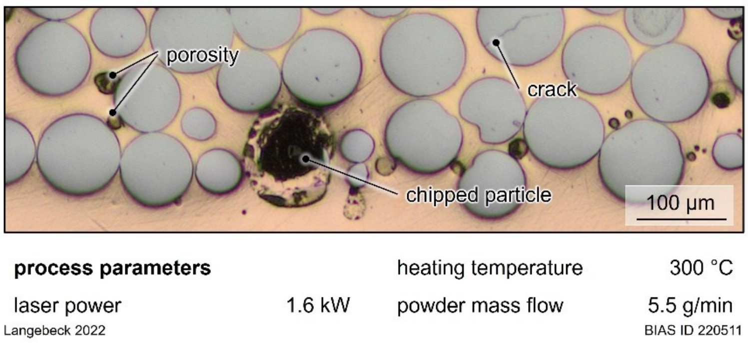

Fig. 4: OM image with higher magnification to exemplarily show imperfections within the MMC microstructure

The process zone temperature measured by two-color pyrometer was affected by the used laser power. With increasing laser power, the process zone temperature slightly increased from 1527 °C to about 1563 °C (see Fig. 5). For the heating device temperature, no impact on the process zone temperature was detected.

4 Discussion

Some imperfections within the MMC surface were observed. The cracks in the particles are caused by different coefficients of thermal expansion with $6.4 \cdot 10^{-6} K^{-1}$ to $7.4 \cdot 10^{-6} K^{-1}$ for tungsten carbide [8] and $16.5 \cdot 10^{-6} K^{-1}$ for copper [9]. This mismatch leads to micro-cracks during/after LMI which was shown for other material combinations as well [10]. The chipping of particles (see Fig. 4), which occurred during the preparation of the cross-sections can be a result of excessively cracked particles or can be an indicator for lack of fusion between sFTC and Cu matrix.

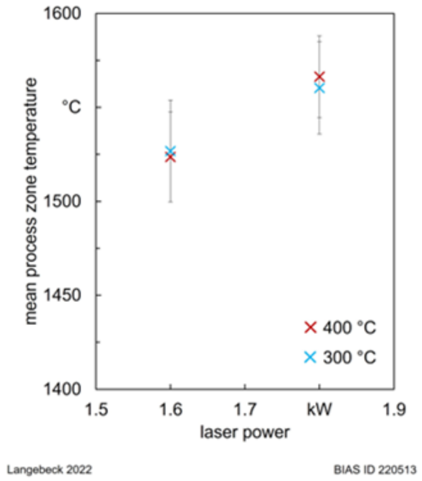

Fig. 5: Mean process zone temperature in dependence of the used laser power and heating device temperature

The mean particle content for all cross-sections was independent from the used parameters at approx. 44% ± 2.4%. This leads to the assumption, that for all examined parameter-sets the powder supply was at least sufficient to completely fill the entire melt pool volume with hard-particles or was even higher. This can be supported by the low powder catchment efficiency of around 13.5%. The particle content could be further increased by reducing the rapid solidification. A theoretical maximum of the particle content is the apparent density of the powder. For the used sFTC powder in this study the supplier specifies an apparent density of 9.6 g/cm³ which is 58% of the bulk density of 16.5 g/cm³ specified for sFTC.

The heating device temperature had no measurable impact on the process zone temperature. Nevertheless, the heating device is necessary for a stable LMI process and has a significant impact on the substrate temperature [7]. These results were gained via additional tactile measurements in the substrate near the process zone during LMI. Further information can be found here: [7].

5 Conclusion

High-quality MMC can be manufactured by using laser power intensities in the range of 10^4 W/cm² and additional conduction heating of the matrix material between 300 °C and 400 °C. Within this process window a stable particle content of 44% can be reached.

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References

[1] Zou, Y.; Tan, C.; Qiu, Z.; Ma, W.; Kuang, M.; Zeng, D.: Additively manufactured SiC-reinforced stainless steel with excellent strength and wear resistance. In: Additive Manufacturing 41 [1] (2021) p. 101971

[2] Nurminen, J.; Näkki, J.; Vuoristo, P.: Microstructure and properties of hard and wear resistant MMC coatings deposited by laser cladding. In: International Journal of Refractory Metals and Hard Materials 27 [2] (2009) p. 472-478

[3] Heider, A.; Stritt, P.; Weber, R.; Graf, T.: High-power laser sources enable high-quality laser welding of copper. ICALEO® 2014: 33rd International Congress on Laser Materials Processing, Laser Microprocessing and Nanomanufacturing; October 19–23, 2014; San Diego, California, USA; Hrsg.: S. Kaierle. In: ICALEO 2014: 33rd International Congress on Laser Materials Processing, Laser Microprocessing and Nanomanufacturing; Laser Institute of America; Orlando, FL (2014) p. 343-348

[4] Hess, A.; Schuster, R.; Heider, A.; Weber, R.; Graf, T.: Continuous Wave Laser Welding of Copper with Combined Beams at Wavelengths of 1030 nm and of 515 nm. In: Physics Procedia 12 (2011) p. 88-94

[5] Fedorov Kukk, A.; Freiße, H.; Bohlen, A.; Vollertsen.F.: Laser melt injection of hard particles with beam wobbling for wear protection of micro-injection molding tools. Lasers in Manufacturing Conference (2019)

[6] Auwal, S. T.; Ramesh, S.; Yusof, F.; Manladan, S. M.: A review on laser beam welding of copper alloys. In: The International Journal of Advanced Manufacturing Technology 96 [1-4] (2018) p. 475-490

[7] Langebeck, A.; Bohlen, A.; Seefeld, T.; Zhang, X.; Kornmeier, J. R.; Hofmann, M.; Alameddin, S.; Alessio, R. P.; Fritzen, F.: Laser melt injection of spherical fused tungsten carbide in Cu-ETP with 515 nm wavelength laser. In: Procedia CIRP 111 [1] (2022) p. 726-731

[8] Lynch, C. T.: Practical Handbook of Materials Science. CRC Press (1989)

[9] CRC handbook of chemistry and physics - A ready-reference book of chemical and physical data. CRC Press; Taylor & Francis; Boca Raton, Fla., London (2011)

[10] Wang, J.; Li, L.; Tao, W.: Crack initiation and propagation behavior of WC particles reinforced Fe-based metal matrix composite produced by laser melting deposition. In: Optics & Laser Technology 82 (2016) p. 170-182