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Laser melt injection of hard particles with beam wobbling for wear protection of micro-injection molding tools

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Abstract

The micro-injection moulding is an important manufacturing technique for mass production of small plastic parts. The standard mould material is hardened steel, which presents difficult machinability and low precision. Alternatively, soft metals such as aluminum and bronze can be used, allowing better mould precision. However, they offer low service times due to poor surface wear resistance. A solution to this problem is the reinforcement of the mould surfaces with hard particles, such as spherical fused tungsten carbides, with laser melt injection, thus creating metal matrix composite (MMC). The homogeneity of MMC layer, which is required for better wear resistance, is affected by irregular temperature accumulation and other factors. We solve the heat accumulation problem for a laser melting by measuring the molten pool temperature with a 2-color pyrometer and regulating laser power. Additionally, we present results for laser melt injection with beam wobbling, creating 4 mm wide tracks.

Keywords: laser melt injection; surface wear protection; temperature regulated laser melting

1. Introduction

Micro-injection is undoubtedly the most common technique for mass production of plastic and polymer microparts (Cioufu et al., 2013). Numerous application examples include the constantly growing market of microelectronics for cameras, phones and laptops, bio-, chemical- and medical technologies. This manufacturing technique offers low productions costs as well as high variety of materials for injection.

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One of the main problems with the micro-injection technique is the local wear of molds. During the injection process, the mold surfaces are subject to abrasive wear from the flow of the molten material, corrosion and thermomechanical stresses which limit the service life of the tool and cause the need for tool replacements (Griffiths et al., 2010). The abrasive wear becomes significantly stronger during the micro-injection of composite materials, such as cellulose or glass fibers reinforced plastics, commonly used in automotive industry (Silva et al., 2017).

The common material for micro-injection molds is hardened steel due to its strength and wear resistance (Zhong et al., 2011). This however comes with a cost of low machinability and rapid wear of the cutting tool, increasing the production cost. The wear of the machining tool significantly limits the precision of the resulted mold and consequently, of the injected parts as compared to other materials. Alternatively, aluminum and copper alloys can be used for mold material. Aluminum has the advantage of low price, high machinability and is usually used for fast prototyping of molds. However, the low strength, hardness and the heat resistance during the molding process lead to rapid surface wear, thus limiting the applications. The service life is particularly low for molding of previously described composite parts. On the other hand, molds from copper alloys offer better thermal conductivity, while having equivalent wear in addition to higher material price.

This problem can be solved by reinforcing the copper or aluminum surfaces with hard particles, such as spherical fused tungsten carbides, via laser melt injection. This idea allows to keep the advantage of simple and precise machinability of main mold body, while having high hardness in the required areas and therefore larger service times of the tools. During the laser melt injection process the substrate surface is melted with laser and hard particles are injected with the help of a carrier gas into the molten pool. After the melt pool solidification, a so-called metal matrix composite (MMC) layer is created. This reinforced layer increases the average surface hardness and improves its wear resistance, as demonstrated by Hilgenberg et al., 2014 on copper samples. Vreeling et al., 2000 have shown that the process window is limited by the melting temperature of the substrate material and of the hard particles.

For a better surface wear protection, it is necessary to create homogenous MMC layer. This means, the layer depth as well as the spatial distribution of the hard particles should be constant. However, during an unregulated (constant laser power and advance speed) laser melt injection process the heat accumulation becomes a problem, gradually increasing the melting depth, especially if overlapping tracks are performed. An example from preliminary work is represented in Fig. 1.

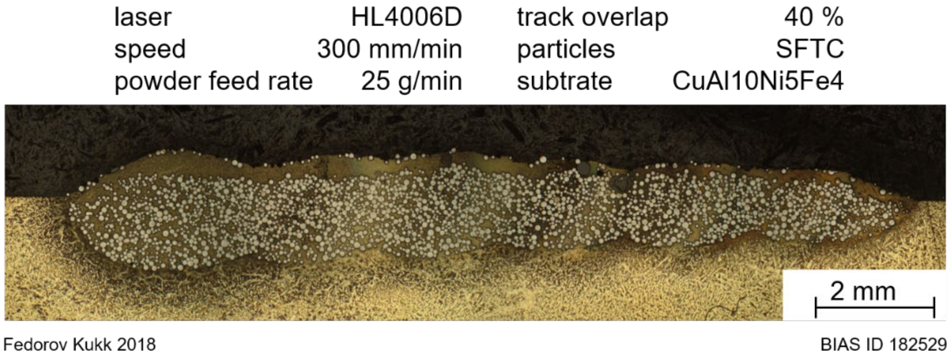

Fig.1. Cross section of 6 overlapping single MMC (spherical fused tungsten carbides in CuAl10Ni5Fe4) tracks from preliminary work, with the first track on the right side of the figure. The layer presents a gradual increment of MMC layer depth as well as irregular distribution and sinking of the carbides

Tang et al., 2009 have shown that the depth of the injected hard particles is mainly dependent on the temperature of the melt pool, which means that the heat accumulation affects negatively the particle distribution as well. The heat accumulation for an unregulated laser melting process can be demonstrated by measuring the temperature of the molten pool with a 2-color pyrometer. This quotient temperature can be used as process variable for a PID controller for regulation of the laser power, achieving constant molten pool temperature.

Wang et al., 2016 have demonstrated for Laser beam melting of aluminum-based composites that the homogeneity of the particle distribution is significantly improved with Marangoni convection inside the molten pool. Since the Marangoni forces are proportional to thermal gradient on the substrate surface, they can be reinforced utilizing laser beam wobbling which creates alternating heat fluxes. In this work the first results of laser melt injection with beam wobbling are presented and the effect of wobbling on the obtained MMC structure is discussed.

2. Experimental methods

The laser melting was done with a 4 kW Nd:YAG laser HL4006D (TRUMPF), using a 600 µm diameter optical fiber. With collimator and focusing lenses of 200 mm and 250 mm respectively, a focal spot with diameter of 0.75 mm is obtained. The beam wobbling was done with a custom 1D galvoscanner DCY DIM-48 (ILV), which was set to scan 4 mm wide tracks in perpendicular direction to the travel speed, with frequencies between 10 Hz and 150 Hz. For substrate material the aluminum bronze (CuAl10Ni5Fe4) with melting temperature of 1070°C was used. For hard particles spherical fused tungsten carbides (SFTC, Oerlikon Metco) with diameter in range from 45 µm to 106 µm were used, which are commonly used for surface wear protection due to their high hardness of 3,500 HV (Freiße et al., 2017). The carbides were injected into the molten pool coaxially to the laser beam using a 6-jet powder nozzle PN 6625 (GTV Verschleißschutz GmbH) at a constant feed rate of 43 g/min, with 3 l/min argon as carrier gas and argon shielding with 20 l/min. The powder focus was measured at 4 mm in diameter and was brought to the focal plane of the laser. A sketch of the experimental setup is depicted in Fig. 2 and the process parameters are summarized in Table 1.

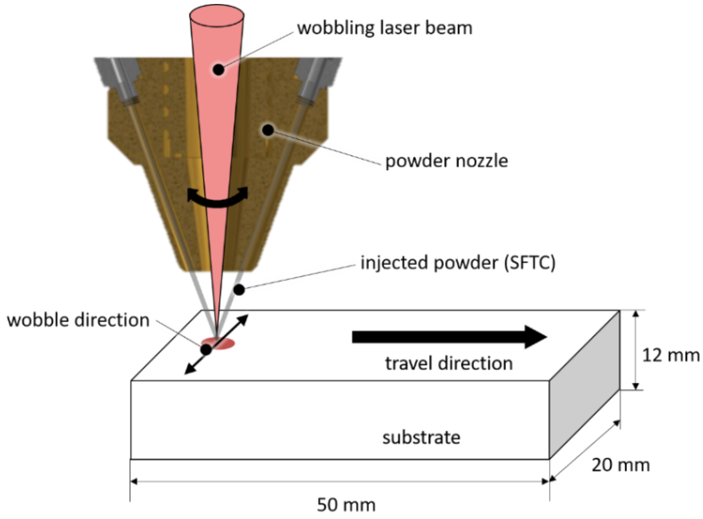

Fig.2. Sketch of the setup for laser melt injection with beam wobbling

Table 1. Process parameters, equipment and material of the laser melt injection process

Laser	Trumpf HL4006D	Substrate	CuAl10Ni5Fe4
Wavelength	1064 nm	Dimensions	12 x 20 x 50 mm³
Fiber diameter	600 µm	Particles	SFTC
Collimation length	200 mm	Particle size	-106+45 µm
Focusing length	250 mm	Powder feeding rate	43 g/min
Spot diameter	0.75 mm	Feeding gas	Argon
Scanner	ILV DCY DIM-48	Feeding gas flow rate	3 l/min
Shielding gas	Argon	Powder nozzle	GTV PN 6625
Centric flow rate	20 l/min	Powder focus size	4 mm
Wobble track width	4 mm	Travel speed	500 mm/min

For the analysis of the MMC layers the substrates were cut in the middle of the track with wire electrical discharge machining and the surfaces were embedded, grinded and polished for examination with a Zeiss type AX10 microscope. The thicknesses of MMC layers were measured in image processing software ImageJ.

It is expected that the combination of the laser melt injection process with a molten pool temperature regulation coaxially to the laser beam will reduce the heat accumulation effect and thus create more homogenous MMC layers. Since the powder jet represents a noise source for the measurement by blocking the view of the molten pool, it is necessary to use a ratio pyrometer (2-channel pyrometer) which compensates for irregular transmission. For demonstration of temperature regulation for simple laser melting process a 2- color pyrometer METIS H322 (Sensortherm) was used, which outputs emissivity compensated temperature by measuring spectral range between 1.45 µm and 1.8 µm, with sampling frequency of 10 kHz. The 2-color temperature was used as process variable for PID controller, which regulated laser power using current between 0 mA and 20 mA. For the setup the following PI parameters were found with Autotune (Open-loop Test) function: proportional band Xp = 113.6 %, integral time Ti = 2.6 ms (the derivative term D was left at zero). The temperature readings were processed in MATLAB.

3. Results and discussion

Fig. 3 shows the results for MMC layer thickness at constant wobble frequency of 40 Hz. Within the measured parameter range the layer thickness demonstrates approximate linear dependency for increasing laser power. Doubling of laser power leads to roughly tripling of layer thickness.

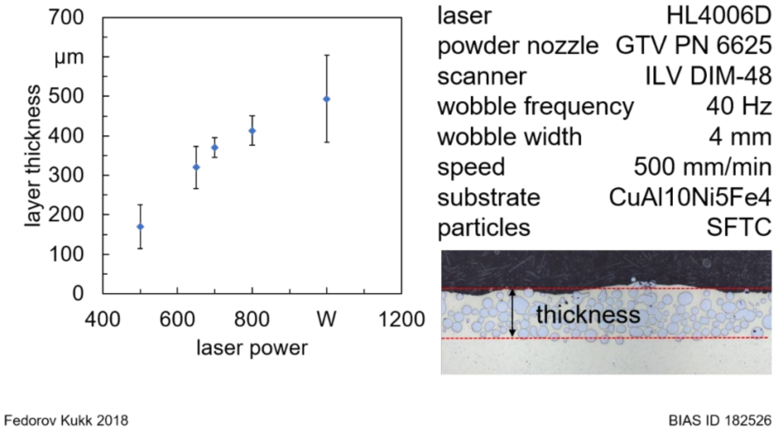

Fig.3. Results for MMC layer thickness for increasing laser power

At high laser powers it was noted that the carbides start to build large agglomerations at the MMC surface, lose their spherical form and result in uneven surface, as shown in Fig. 4. It is unclear if those agglomerations represent a problem for surface wear protection.

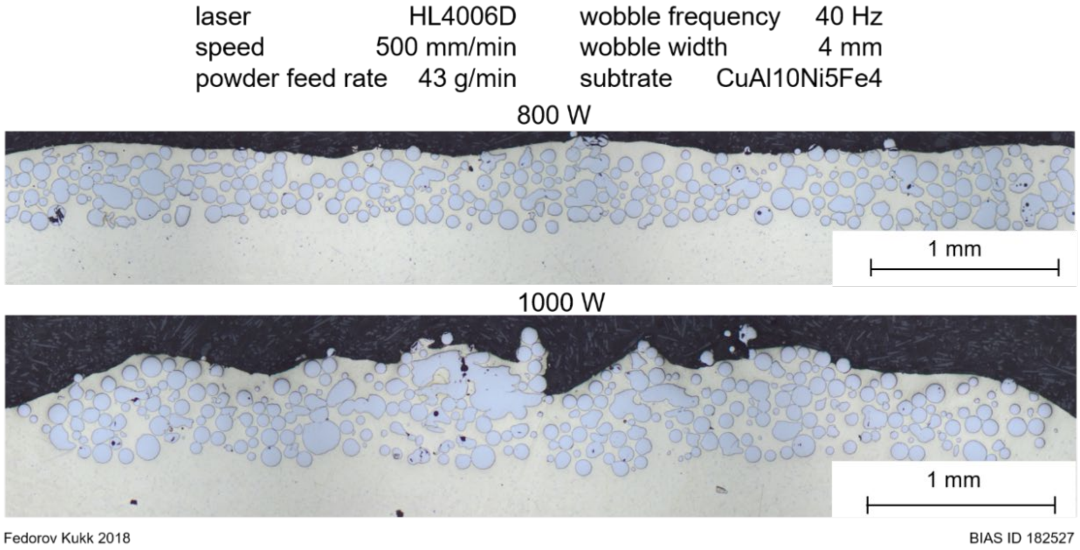

Fig.4. Cross-section of MMC layer at 800 W (upper picture) and 1 kW (lower picture) laser power, where carbide agglomeration is demonstrated. The full process parameters are indicated in Table 1

Fig. 5 shows the comparison of sinusoidal and triangular beam wobbling for a singular track. The sinusoidal motion shows slightly deeper particle penetration the wobble track edges due to the stronger heat accumulation which is caused by the longer exposure due to the slower motion. On the other hand, the triangular motion presents a rather deeper layer at the center. The supposed reason is the larger heat transfer rate to the sides, which reduces the molten pool temperature.

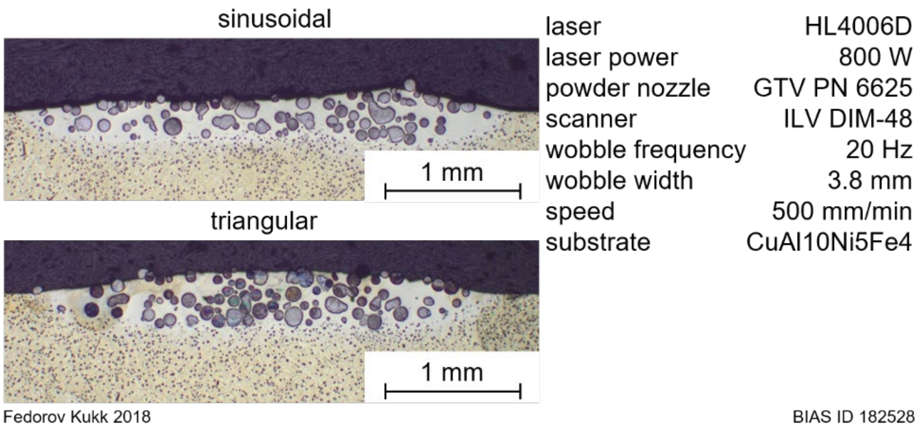

Fig.5. Comparison of sinusoidal and triangular beam wobbling motion of singular tracks

For laser melting, comparison between unregulated and regulated laser melting is represented in Fig. 6. As demonstrated, the PID controller was able to keep the setpoint temperature of the molten pool well within the pyrometer margin error of 7°C, as compared to the unregulated process where the heat accumulation resulted in temperature deviation of 79°C.

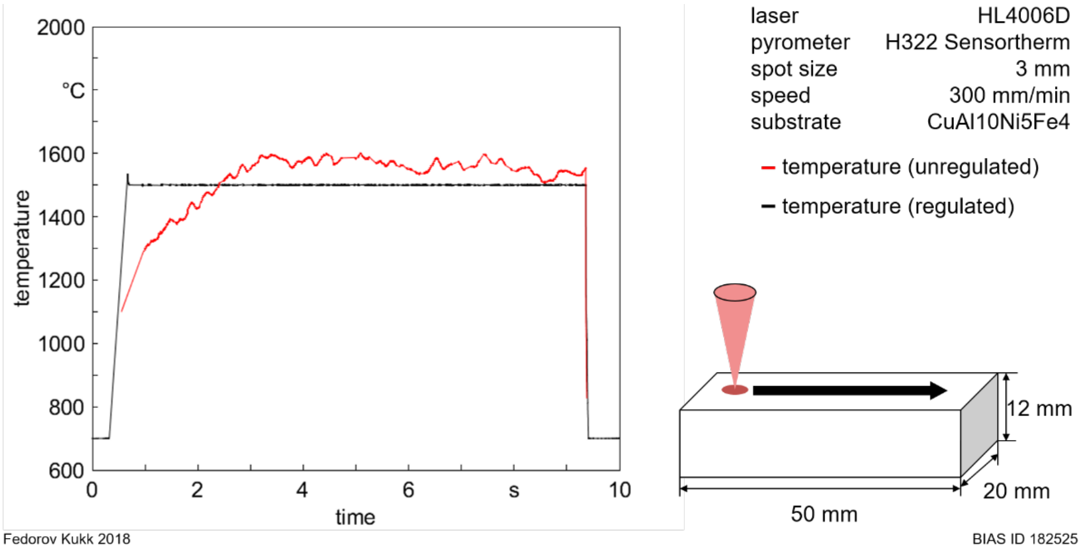

Fig.6. Temperature measurement comparison of unregulated (red line, laser power at 500 W) and regulated (black line, setpoint temperature of 1500 °C) laser melting of a single track. In regulated case the molten pool temperature remained constant (under the pyrometer precision of ± 7°C).

4. Conclusion

In this work the first results of laser melt injection of SFTC into aluminum bronze using with beam wobbling were demonstrated. The dependency of MMC layer depth for different laser powers was found and represented. The wobbling with sinusoidal motion displays deeper particle penetration at the track edges as compared to triangular function. For high laser powers, the agglomeration of carbides is demonstrated. For a simple laser melting, the temperature regulation using a quotient pyrometer was used to compensate the heat accumulation and keep constant molten pool temperature during the process.

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