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Influence of electric-magnetic compound field on the WC particles distribution in laser melt injection

Liang Wang [a,b], Jianhua Yao [a,b,*], Yong Hu [a,b], Qunli Zhang [a,b], Zhuo Sun [a,b], Rong Liu [c]

[a] *Institute of Laser Advanced Manufacturing, Zhejiang University of Technology, No.18 Chaowang Road, Hangzhou 310014, China*
[b] *Zhejiang Provincial Collaborative Innovation Center of High-end Laser Manufacturing Equipment, Hangzhou 310014, China*
[c] *Department of Mechanical and Aerospace Engineering, Carleton University, 1125 Colonel By Drive, Ottawa, Ontario K1S 5B6, Canada*

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ABSTRACT

An advanced particle distribution controlling approach is proposed for laser melt injection process, which applies an electric-magnetic compound field to assist the laser melt injection process. The electric-magnetic synergistic effect on the reinforcement particle distribution in laser melt injection is investigated using numerical and experimental methods. Spherical WC particles are used as the reinforcement and their distribution in the longitudinal sections of the laser melt injection layers is examined with SEM and studied with computer graphics processing. The distributions of fluid temperature, fluid velocity and reinforcement particles in the molten pool are simulated using a 2D multi-physics model coupled with the equations of heat transfer, fluid dynamics, drag force, Lorentz force and phase transition. The results show that, the directional Lorentz force due to an electric-magnetic compound field, as a sort of volume force, can change the equivalent buoyancy acting on the particles. When the Lorentz force and gravity force are in same direction, majority of particles are trapped in the upper region of laser melt injection layer, while when the Lorentz force and gravity force are in opposite direction, most particles are concentrated in the bottom region. As a result, the distribution gradient of WC particles can be controlled by the electric-magnetic compound field, instead of the time-consuming adjustment of process parameters.

1. Introduction

Metal matrix composites (MMCs) reinforced with ceramic particles display a number of advantages over monolithic alloys and have been used extensively in various industries such as automotive, aviation, aerospace and thermal management, etc. [1–3]. Laser melt injection (LMI) method is commonly employed to prepare a MMC layer on a metallic substrate, which exhibits special characteristics including low particle dissolution rate, high surface performance and low cracking tendency [4–7]. LMI has been mainly applied for improving the surface hardness and wear resistance of metallic substrates, for example, stainless steels [6,8], aluminum alloys [9,10], titanium alloys [1,4,11–13], low carbon steels [14–18] and tool steels [5,7,19]. Different from laser cladding process, the reinforcement particles (usually ceramics) that are injected in the molten pool without any other metal–matrix powders and move with the melt flow preserve solid state or micro melt state due to the rapid solidification in LMI process [9].

The graded distribution of reinforcement particles in metal matrix composites is a crucial optimization objective for LMI process, which can be designed at a microstructural level to tailor specific materials for their functional performance in particular applications [12]. The controlled gradient in mechanical properties offers attractive challenges for the design of surfaces with resistance to contact deformation and damage [11]. In order to optimize the particle utilization ratio, the machinable property and the gradient distribution performance of LMI layers, it is necessary to better control the distribution of reinforcement particles. Existing LMI processes usually use a special designed lateral nozzle as a powder delivery nozzle for avoiding the excessive dissolution of reinforcement particles [18]. In this case, the injection angle with respect to the surface normal [20], the relative position between the powder spot and laser spot [21] and powder injection velocity [9,22] are the key process parameters for powder injection, because they influence the distribution of reinforcement particles significantly. However, it is difficult and time-consuming to control the distribution of reinforcement particles through optimizing the processing parameters because the adjustable window for lateral nozzle powder delivery system is very narrow [8,9].

For the efficient control of the distribution of WC particles, an external force is introduced during the LMI process, which applies an electric-magnetic compound field to the molten pool. A common coaxial nozzle can still be used to replace the special designed lateral nozzle thus to simplify the adjusting process of the powder delivery system.

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* Corresponding author at: Institute of Laser Advanced Manufacturing, Zhejiang University of Technology, No.18 Chaowang Road, Hangzhou 310014, China.
E-mail address: laser@zjut.edu.cn (J. Yao).

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The application of an electromagnetic field is a positive practice in laser welding and laser alloying to alter the distribution of added elements. The effect of electromagnetic stirring on the element distribution in laser welding was investigated in numerical and experimental methods. It was shown that the change of the distribution of the filler material resulted from a modulation of the melt flow due to the periodic induced electromagnetic volume forces [23]. The frequency was a main parameter to determine the spatial distribution of elements, whereas the magnetic flux density was the main parameter determining the overall scale of the magnetic manipulation [24,25]. A numerical model was built to investigate a laser molten aluminum pool under the influence of a steady magnetic field. The damped flow situation in the melt resulted in a variation of the solute distribution in the solid and in shallower alloyed layers, depending on the applied magnetic induction [26]. The other effects of electromagnetic field included suppressing surface undulation of laser remelting [27], damping the velocity of molten pool [28,29], reducing the defects of laser welding [30,31], preventing gravity dropout of the melt during laser full-penetration welding [32], etc. The previous investigations in electromagnetic field were mostly focused on the influences of elements, temperature, velocity and defect distribution on the molten pool during laser process, where an AC magnetic field or the melt flow in a steady magnetic field was present. Different from the solute distribution, the drag force and the buoyancy can highly influence the distribution of the reinforcement particles in the molten pool. The control effect of an electric-magnetic compound field on the distributions of fluid temperature, fluid velocity and reinforcement particles in the molten pool has not been investigated yet.

In the present research, a common coaxial nozzle is used with both an external steady electric field and a steady magnetic field applied in the molten pool synchronously during the LMI process. The Lorentz force is generated by the electric-magnetic synergistic effect, which is mainly a sort of directional volume force in the molten pool of LMI, similar to gravity. This Lorentz force can function as an additional volume force acting on the melt flow with variable direction. Consequently, the positions of WC particles trapped in the melting pool can be altered without changing LMI process parameters. A 2D transient multi-physics numerical model is employed to study the distribution mechanism of reinforcement particles during LMI under an electric-magnetic compound field. The partial differential equations, concerning Lorentz force, fluid dynamics, drag force acting on the particles, heat transfer and phase transition, are solved with COMSOL Multiphysics® 5.0. The simulation results are compared with experimental measurements and the influence of electric-magnetic compound field on the LMI process is discussed.

2. Experimental methods

AISI 316 L austenitic stainless steel with dimensions of 200 × 20 × 10 mm was used as the substrate because of its paramagnetic property. The chemical composition of AISI 316 L is listed in Table 1. Spherical WC particles were chosen as the reinforcement particles, because of good tracing performance in the melt flow. Accordingly, this shape was also used for the particles in the simulation study. The size of the WC particles was 75–150 μm, as shown in Fig. 1. Fig. 2 illustrates the LMI process setup with an electric-magnetic compound field applied. The electromagnets were chosen to provide a steady magnetic field (max magnetic flux density of 2.0 T) and large capacity lead-acid batteries (2 V, 500 Ah) were used to provide high current (steady electric field) for the molten pool. The magnet poles with the size of 80 × 20 mm were applied in the experiment and numerical model. The specimen was placed in the center zone of the magnetic gap, where the distribution of magnetic flux density was uniform. AISI 316L is a sort of austenitic stainless steel, whose relative magnetic permeability ($\mu_r = 1$) is almost the same with the air. It is possible to measure the magnetic flux density in the position where the specimen will be placed before the experiment. In the molten pool zone, the magnetic flux density was about 0.4–1.2 T and the average current density was about 5 A/mm^2.

Table 1
Chemical composition (wt.%) of AISI 316.

C	Si	Mn	P	S	Ni	Cr	Mo	Fe
0.02	0.55	1.55	<0.03	<0.03	10.0	16.5	2.08	Bal.

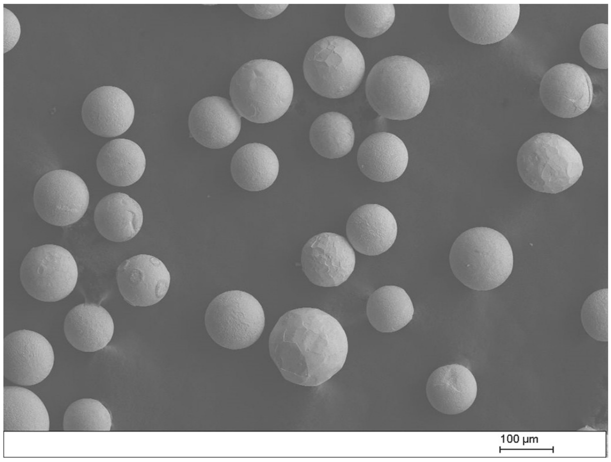

Fig. 1. SEM image of spherical WC particles.

The LMI experiment was conducted using a 2 kW Laserline diode laser,self-made powder feeder and coaxial nozzle. Argon was used as the shielding gas to reduce oxidation of the specimen and WC particles. The laser beam diameter, optimal laser power, scanning speed and powder feeding ratio in this experiment were 4 mm, 1.7 kW, 4.25 mm/s and 15 g/min, respectively. The distributions of WC particles in the molten pool were examined using SEM (Carl Zeiss SIGMA HV-01-043).

3. Numerical simulation

3.1. Governing equations

During the LMI process, the particles are injected in the liquid molten pool, move with the melt flow and then be trapped in the solidification interface with the rapid cooling process of the molten pool. A classical computational fluid dynamics approach is applied to calculate the fluid flow field and pressure as well as the temperature of the molten pool. The movement of injected particles was computed using the Lagrangian approach with fluid–particle coupling [33]. The Lorentz force, as a sort of volume force, was included in the source term of momentum equations. The 2D finite element model was composed of a rectangle of 30 × 5 mm. The necessary assumptions for the simulation model are made as follows.

- The fluid flow is laminar and incompressible Newtonian fluid [32,34]. The thermal conductivity, electrical conductivity, and heat capacity of the specimen material are temperature-dependent. The other material properties are constant.
- The radiation losses and Joule heat induced by the current are negligible due to the short action time and the strong heating of the laser source [27].
- The Boussinesq approximation is used to take into account buoyancy inside the molten pool.
- The distribution of magnetic flux density in the active area is uniform.
- Under the conditions of the experiment setup, the distance between nozzle and substrate sample is at defocusing state (focus + 3 mm).