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Laser rapid manufacturing on vertical surfaces: Analytical and experimental studies

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A B S T R A C T

Analytical and experimental studies on geometrical aspects of the deposited tracks were carried out at different processing parameters for laser rapid manufacturing (LRM) in vertical surface configuration using AISI type 304 stainless steel powder on the substrate of the same material. The vertical downward shift of the deposited track and its peak due to the gravity flow of the melt were found to follow quadratic dependence on the track height. The downward rounded bulging was found to be quite significant for the scan speeds lesser than 200 mm/min, while this was insignificant for the scan speeds more than 400 mm/min. A set of consolidated processing parameters for continuous material deposition was identified. The threshold value of laser energy and powder fed, both per unit traverse length for the continuous deposition were found to be ~96 J/mm and ~0.006 g/mm respectively. The maximum powder catchment efficiency was ~42% for stand-off distances in the range of 15–18 mm. The surface waviness factor was found to decrease from ~0.95 to ~0.05 when the overlap index was increased from 30% to 80%. The study provides a deeper insight into the ensuing geometrical aspects of the tracks using LRM in vertical configuration.

1. Introduction

Laser rapid manufacturing (LRM) is one of the advanced additive manufacturing processes. It is similar to laser cladding/alloying at the process end with an extended capability of fabricating three-dimensional object directly from a solid model. LRM employs a high power laser beam as a heat source to melt a thin layer on the surface of the substrate/deposited material and fed material to deposit a new layer as per shape and dimensions defined in numerical control code as per the solid model. A number of such layers are deposited one over another resulting in three dimensional (3D) components. LRM offers many advantages over conventional subtractive techniques, such as reduced production time, better process control and capability to form functionally graded parts [1]. It employs a high power laser like CO_2, Nd:YAG, diode and fibre as energy source to melt and deposit a layer of the desired material in the form of powder or wire onto the substrates/previously deposited layers forming a sound metallurgical bond [2]. A wide variety of the deposit materials and substrates are reported in literature for various applications in automotive, aerospace, machinery, petrochemical, power generation and shipbuilding industries [1–6]. Since most of the laser rapid manufacturing applications involve deposition of materials on the horizontal surfaces, there have been theoretical and experimental studies of laser rapid manufacturing process in the horizontal configuration [7–13]. The technology is also being investigated for the laser rapid manufacturing of porous structures [14]. Alimardani et al. developed a comprehensive model to evaluate the track geometry [15]. The model used the conservation of mass within the process domain for material addition to predict local track height by incorporating catchment efficiency into powder feed on the molten substrate surface for each time interval. Hofman et al. developed a FEM based model for the determination of the track geometry and dilution during the process [16]. An analytical approach for estimating the track geometries (height and width) was presented by Wang et al. based on the mass conservation of powder feeding stream [17]. The simulation was capable of predicting the track width and height with reasonable accuracy at medium powder feed rate. Recently, Kumar et al. used a finer modelling approach for numerically predicting single track geometry in two dimensions [18]. The approach involved the calculation of excessive enthalpies above melting point for all nodal points in the process domain and using those for the computation of local track height at every node along the track width on the substrate. LRM in vertical configuration did not find much attention except for a few efforts reporting the development of laser vertical cladding system [19,20]. LRM on vertical surface substrate configuration is important for many engineering applications, such as surface cladding of turbine blade shroud and interlock, off-shore drilling heads, cylinder body, sleeve and mould side walls etc. This paper presents theoretical and experimental investigations on dynamic geometrical aspects of the tracks at different processing parameters for LRM on vertical surface configuration using AISI type 304 stainless steel powder on the surface of the same material. A newly designed LRM head was augmented to the existing laser workstation and successfully used for LRM on vertical surface substrate configuration. An analytical model incorporating gravity force was developed to understand its effect on molten deposits and its subsequent downward flow

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Nomenclature

a_i	activity of species i in molten pool, weight %
A_γ	constant in surface tension gradient, N/(m K)
C_p	specific heat capacity, J/(kg K)
D	thermal diffusivity of the material, m^2/s
E_l	laser energy per unit traverse length, kJ/m
g	gravity, m/s^2
h_c	combined heat transfer coefficient for radiative and convective boundary conditions W/(m^2 K)
ΔH_0	standard heat of adsorption, J/(kg.mol)
h_{max}	maximum height of the deposited/overlapped track, m
h_{min}	minimum height of the overlapped tracks, m
i	overlap index
j	waviness factor
k	thermal conductivity, W/(m K)
k_1	constant related to entropy of segregation (3.18×10^{-3})
L_1	melt pool length in the forward direction, m
L_2	melt pool length in the rear direction, m
L_m	latent heat of melting, kJ/kg
M	atomic mass
m_d	powder deposited per unit traverse length, kg/m
$\dot{m}_p$	powder feed rate, kg/s
$m_{p/l}$	powder fed per unit traverse length, kg/m
P_L	laser power, kW
P_p	laser power loss in the powder stream, kW
R_g	gas constant J/(kg.mol.K)
r_l	radius of laser beam, m
r_p	Gaussian powder stream radius, m
s_t	centre distance between the two successive overlap track, m
s	line element on the top boundary of the molten deposit, m
T	temperature, K
T_{amb}	ambient temperature, K
T_m	melting temperature, K
$U(z)$	local fluid flow velocity at distance z from the substrate
V	molar volume of the metal, m^3/mol
v	scan speed, m/s
W	overall track width, m
w	melt pool width, m
w_{max}	maximum melt pool width, m
X	dimensionless linear dimension ($=x/r_l$)
Y	dimensionless linear dimension ($=y/r_l$)
Z	dimensionless linear dimension ($=z/r_l$)

Greek symbols

α_l	laser absorptivity
γ	surface tension on the top boundary of the molten deposit, N/m
Γ	dimensionless time $\left(=\sqrt{2Dt}/r_l\right)$
Γ_s	surface excess at saturation J/(kg mol m^2)
ε	emissivity of the deposit surface
η_c	powder catchment efficiency
μ_L	kinematic viscosity, m^2/s
ρ	density, kg/m^3
ρ_L	density of liquid metal, kg/m^3
Ω	dimensionless speed ($=r_l v/D$)

tendency before solidification for prediction of track geometry. The consolidated processing parameters for various values of laser energy per unit length of track, powder fed per unit length of track and overlapping indices for this process were experimentally identified. The effect of powder catchment efficiency at various stand-off distances and overlap indices on waviness factor of the overlapped tracks was also experimentally evaluated.

2. Experimental setup

LRM head was specially designed for vertical configuration and augmented with LRM work station consisting of a 2 kW fibre laser system, a 5 axis workstation in a glove box, a computerized numerical controller and a twin powder feeder [1]. The schematic arrangement of LRM head is presented in Fig. 1.

The external size of the nozzle is 63 mm × 63 mm × 60 mm and is capable of depositing material on the inside diameter (ID) of a circular tube having minimum ID of 75 mm. This head has two sub-assemblies: (a) laser processing head and (b) side blown powder feeding tube. While designing the LRM head for vertical configuration, two major objectives were considered: first to achieve the compact-design for processing the components having narrow passage/opening and second to provide the least perturbation in the powder-gas stream avoiding sudden or sharp bends. These two objectives were met by providing the powder feeding from the bottom of the LRM head. This configuration also facilitated the same laser–powder-interaction zone and associated phenomena on the vertical surface during the deposition of the material by the movement of the LRM head in either direction horizontally. However, the powder catchment efficiency in the present configuration was compromised as compared to that of conventional in-line/side-blown powder feeding configuration [2]. The laser processing head has a Quartz lens of 200 mm focal length to focus the laser beam. The focusing laser beam is reflected normal to the vertical plane by a water cooled Au-coated plane mirror (diameter: 25 mm and 6 mm thick) mounted at 45° to the incoming laser beam axis in beam-bender. There is a provision of moving beam-bender up and down to match the laser beam size to the powder stream size at the substrate to facilitate the maximum powder catchment efficiency. The laser beam diameter of 2 mm was used in the present study. A port for inert gas is provided at the upper part of laser processing head to protect the Au-coated mirror from ricocheted powder particles which may enter the beam-bender and damage the mirror. This gas also assists the shielding of molten metal from oxidation. The laser processing head has suitable water flow arrangement to cool the processing head during the deposition of tracks. The side blown powder feeding tube has inside diameter of 2 mm and is mounted at the bottom of the laser head at an inclination angle of 35° to the laser beam axis. The material used for the construction of laser head is copper due to lower laser absorption and higher thermal conductivity.

3. Analytical modelling

For LRM on vertical surfaces, the powder is sprayed by a lateral nozzle into the process zone. A moving laser beam with known intensity profile melts the powder particles and a thin layer of the vertical substrate. As shown in Fig. 1, the laser beam strikes the substrate through powder particles cloud. A fraction of the laser power is absorbed, reflected and scattered by the powder particles and the rest reaches the substrate. Some portion of its power is reflected and the remainder is absorbed forming a molten pool on the substrate. The absorbed power is carried away from the melt pool surface into the feed powder and the substrate by thermal conduction and thermo-capillary (Marangoni) flow. Once the powder particle reaches the substrate surface, one of the following processes takes place influencing the powder catchment efficiency:

a. Solid particle–solid surface impact leading to ricochet.
b. Solid particle–liquid surface leading to catchment.
c. Liquid particle–solid surface leading to catchment and quenching of substrate.
d. Liquid particle–liquid surface leading to catchment.