International Journal of Machine Tools & Manufacture 95 (2015) 97–104

Contents lists available at ScienceDirect

International Journal of Machine Tools & Manufacture

journal homepage: www.elsevier.com/locate/ijmactool

Laser polishing of selective laser melted components

S. Marimuthu [a,c,*], A. Triantaphyllou [a], M. Antar [a], D. Wimpenny [a], H. Morton [b], M. Beard [b]

[a] The Manufacturing Technology Centre, Coventry, UK
[b] 3T RPD Ltd., Berkshire, UK
[c] Loughborough University, Loughborough, UK

ARTICLE INFO

Article history:
Received 22 January 2015
Received in revised form
4 May 2015
Accepted 11 May 2015
Available online 12 May 2015

Keywords:
Melting
SLM
Laser
Polishing
CFD
Modelling
Simulation

ABSTRACT

The shape complexities of aerospace components are continuously increasing, which encourages industries to refine their manufacturing processes. Among such processes, the selective laser melting (SLM) process is becoming an economical and energy efficient alternative to conventional manufacturing processes. However, dependant on the component shape, the high surface roughness observed with SLM parts can affect the surface integrity and geometric tolerances of the manufactured components. To account for this, laser polishing of SLM components is emerging as a viable process to achieve high-quality surfaces. This report details an investigation carried out to understand the basic fundamentals of continuous wave laser polishing of SLM samples. A numerical model, based on a computational fluid dynamic formulation, was used to assist the understanding of melt pool dynamics, which significantly controls the final surface roughness. The investigation identified the input thermal energy as the key parameter that significantly affect the melt pool convection, and essentially controls the surface quality. Minimum meltpool velocity is essential to achieve wider laser polished track width with good surface finish. Experimental results showed a reduction of surface roughness from 10.2 μm to 2.4 μm after laser polishing with optimised parameters. Strategies to control the surface topology during laser polishing of SLM components are discussed.

1. Introduction

Currently, aero-engine components are produced by combined manufacturing processes that include forging, rolling and subtractive CNC mechanical machining [1]. Use of these processes to machine certain components from solid blocks can lead to massive material wastage [2] and high production times. The SLM process has, on the other hand, demonstrated its capability in the production of parts with complex 3D geometries [3]. Over the last few years this process has gained increasing attention due to the rapid development in the capabilities of additive manufacturing [4,5]. Despite the widely recognised merits of SLM in the manufacture of components in general, a negative aspect of the process is related to the unacceptable surface finish which could significantly limit the industrial uptake. High surface roughness can lead to unacceptable tolerances, increased friction and potentially becoming a source of fatigue crack initiation [6].

Conventional abrasive blasting and mechanical polishing do not offer an acceptable solution for precision components, which require selective processing [7,8]. Electro chemical polishing and electropolishing have been reviewed by some researchers to improve the surface finish of SLM parts, but were found to have environmental issues [9]. Recently, laser polishing [6,10] has gained interest as it has shown potential for selective polishing of metals and alloys. Laser polishing involves melting a thin layer of the substrate, with surface tension causing the material to flow from peaks to valleys. In laser polishing the material is not removed, but is relocated as a molten pool.

Laser polishing as a technique to reduce surface roughness has been investigated by various researches [11,12] who have shown promising results. Laser polishing of SLM sintered titanium and nickel-based alloys were studied by Kumstel [11], who concluded that the polished surface mainly depended on the surface material, initial topography and laser beam density. Laser polishing of Inconel-718 parts built by laser metal deposition (LMD) has been investigated by Dadbakhsh [13], who focused on identifying the optimum process parameters to achieve an 80% reduction in surface roughness. Laser polishing has been proven to enhance the surface roughness of metals, alloys and ceramics, with no significant distortion to the parts. However, majority of the available research concentrated on parametric studies of laser polishing without any analysis on the underlying significance of melt pool dynamics.

In the present study, an experimental investigation into the

* Corresponding author.
E-mail address: Sundar.Marimuthu@the-mtc.org (S. Marimuthu).

http://dx.doi.org/10.1016/j.ijmachtools.2015.05.002
0890-6955/

continuous wave fibre laser polishing of SLM parts was undertaken to achieve a smooth surface profile, through the control of laser process parameters and analysis of melt pool dynamics. Melt pool dynamics significantly influence the surface profile, hence this investigation focuses on understanding the effects of melt pool dynamics on surface topology and roughness. Along with experimental results, a three-dimensional computational fluid dynamic (CFD) model was developed to study the effect of laser polishing parameters on melt pool dynamics and surface topology. Temperature field, velocity field and melt pool geometry were modelled for various scanning parameters. The calculated melt pool geometry and surface conditions were compared with experimental results obtained under similar parameters, in order to explain the findings.

2. Material and methods

The base materials used in this study were SLM manufactured Ti–6Al–4V components of size $40 \times 10 \text{x} 5\ \text{mm}^3$ produced at 45° build angle, and supplied by 3T RPD Ltd. Ti–6Al–4V samples were used as the test material due its challenges with laser processes, including its susceptibility to rapid oxidisation [14,15] and stress cracking [16] However the fundamental results discussed in this paper are applicable to most metals and alloys. The chemical composition of the base material used in the study is given in Table 1. The average surface roughness of the base material is around 10.2 µm.

The experimental setup, shown schematically in Fig. 1, was used to perform the laser polishing experiment, and to determine the process window that will give the best surface morphology. Laser polishing was performed using a continuous wave fibre laser at 1070–1090 nm wavelength, with a maximum power output of 200 W. A co-axial nozzle assembly with an exit diameter of 2.5 mm and a 120 mm focal length lens was used to focus the beam to the work piece surface. The distance between the nozzle and workpiece was maintained at 5 mm so as to achieve the required beam size of 0.5 mm. Argon gas (99%) was used to protect the melt pool from oxidization. Initial trial shows optimal shielding of the melt pool at a gas pressure of 1.0 bar and mass flow rate of 8 l/min. Samples were irradiated in a horizontal position with the vertical beam interaction at room temperature. The workpiece was held on a numerically controlled *X–Y–Z* stage set. For each parameter set, three sets of samples were produced to eliminate the effect of systematic errors.

The energy density delivered to the work piece plays a major role [17] in the thermal cycle, fluid dynamics, microstructure and consequent surface profile, and is controlled by changing the input power and scanning speed [18]. Pre-experimental trials were used to assess the range of feasible polishing parameters, with the objective of obtaining uniform laser polishing track.

The metallographic samples were prepared according to ASTM E3-11 standard and then etched with Kalling's reagent to reveal the microstructure. Surface morphology and cross-sectional microscopic characteristics of the laser polished samples were examined by Keyence digital microscope. More detailed examination of the surface morphology was undertaken by scanning electron microscopy (SEM), where, a Hitachi S-3400N operating in secondary electron mode, equipped with an energy dispersive X-ray spectroscopy (EDX) detector, was employed. A MahrSurf surface profiler was used to measure the surface roughness and a Buehler micro-hardness tester was used to measure the hardness.

Table 1
Chemical compositions for Ti–6Al–4V used in the study (wt%).

Al	V	O	N	C	H	Fe	Ti
5.5-6.75	3.5-4.5	0.2	0.05	0.08	0.015	0.30	Bal.

3. Numerical modelling methodology

The CFD analysis was performed to model the physical phenomena in the laser polishing, heat transfer and fluid flow and was performed using finite volume based code, FLUENT. The mathematical model used in this work was based on the Navier–Stokes equations with the Reynolds method of averaging the time-dependent equations (RANS). The governing equations [19] were composed of the conservation of mass, conservation of momentum, and conservation of energy, which are given by Eqs. (1)–(3):

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \vec{v}) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho v) + \nabla(\rho \vec{v}\vec{v}) = -\nabla p + \mu \nabla^2 v + S_w \tag{2}$$

where ρ is the density, t is the time, $\vec{v}$ is the melt pool velocity in respective directions, p is the pressure force, μ is the viscosity and S_w is the momentum sink.

The energy equation is written in terms of the sensible enthalpy. An appropriate formulation of the latent heat function plays a pivotal role in ensuring that the results from the energy equation are consistent with phase-change considerations.

$$\frac{\partial}{\partial t}(\rho H) + \nabla(\rho \vec{v} H) = \nabla(k \nabla T) + S \tag{3}$$

where H is enthalpy, k is the thermal conductivity, T is the temperature and S is the volumetric heat source. Enthalpy of the material is computed as the sum of sensible enthalpy (h) and latent heat (ΔH).

$$H = h + \Delta H \tag{4}$$

$$h = h_{ref} + \int_{T_{ref}}^{T} C_p dT \tag{5}$$

where h_{ref} is the reference enthalpy, T_{ref} is the reference temperature and C_p is the specific heat at constant pressure. Latent heat content (H) can be written in terms of latent heat of the material (L).

$$\Delta H = \beta L \tag{6}$$

where β is the liquid fraction, which is defined as

$$\beta = \begin{Bmatrix} 1 & T > T_1 \\ (T - T_s)/(T_1 - T_s) & T_s \le T \le T_1 \\ 0 & T < T_s \end{Bmatrix} \tag{7}$$

where T_l is the liquids temperature and T_s is the solidus temperature. The values of β, ranges between 0 and 1, defining the extent of melting. The mushy zone is treated as a porous medium in momentum equations. A momentum sink is added to the momentum equation (Eq. (2)) to extinguish velocities in the solid region. The momentum sink (S_w) due to reduced porosity in the mushy zone can be written as

$$S_w = \frac{(1-\beta)^2}{(\beta^3 + \xi)} A_m(w) \tag{8}$$

where ξ is a small number (0.001) to avoid division by zero and A_m is the mushy zone constant.

Heat loss due to convection and radiation was considered over