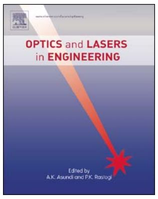
Optics and Lasers in Engineering 88 (2017) 139–152

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

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



Online monitoring of thermo-cycles and its correlation with microstructure in laser cladding of nickel based super alloy

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ARTICLE INFO

Article history:
Received 19 April 2016
Received in revised form
20 July 2016
Accepted 14 August 2016

Keywords:
Laser cladding
Online monitoring
Thermo-cycles
IR pyrometer

ABSTRACT

Laser cladding, basically a weld deposition technique, is finding applications in many areas including surface coatings, refurbishment of worn out components and generation of functionally graded components owing to its various advantages over conventional methods like TIG, PTA etc. One of the essential requirements to adopt this technique in industrial manufacturing is to fulfil the increasing demand on product quality which could be controlled through online process monitoring and correlating the signals with the mechanical and metallurgical properties. Rapid thermo-cycle i.e. the fast heating and cooling rates involved in this process affect above properties of the deposited layer to a great extent. Therefore, the current study aims to monitor the thermo-cycles online, understand its variation with process parameters and its effect on different quality aspects of the clad layer, like microstructure, elemental segregations and mechanical properties. The effect of process parameters on clad track geometry is also studied which helps in their judicious selection to deposit a predefined thickness of coating. In this study Inconel 718, a nickel based super alloy is used as a clad material and AISI 304 austenitic steel as a substrate material. The thermo-cycles during the cladding process were recorded using a single spot monochromatic pyrometer. The heating and cooling rates were estimated from the recorded thermo-cycles and its effects on microstructures were characterised using SEM and XRD analyses. Slow thermo-cycles resulted in severe elemental segregations favouring Laves phase formation and increased γ matrix size which is found to be detrimental to the mechanical properties. Slow cooling also resulted in termination of epitaxial growth, forming equiaxed grains near the surface, which is not preferred for single crystal growth. Heat treatment is carried out and the effect of slow cooling and the increased γ matrix size on dissolution of segregated elements in metal matrix is studied.

1. Introduction

Laser cladding is a deposition technique in which metal powder or wire is fused to a base material using high energy laser beam as a heat source. The process offers the potential to deposit new materials with required mechanical and physical properties onto different low value substrates with minimum dilution, heat effect zone, distortion and good bond strength. Fast cooling rates by self-quenching attainable in laser cladding process give rise to extremely refined microstructure, leading to improved mechanical properties. Laser cladding finds its applications in aerospace, nuclear, rail, oil rig, mining industries etc. for repairing as well as direct generation of functional components [1–3].

Based on the application and method of powder feeding, this processes is called by several names like selective laser sintering (SLS) or direct metal laser sintering (DMLS), laser engineered net shaping (LENS), laser metal forming (LMF), laser additive manufacturing (LAM) etc [2,4]. SLS or DMLS uses pre-placed powder technique wherein a thin layer of powder is placed on a part building table, scanned by a laser beam in selected areas and the table is displaced down and a new layer is placed. The process is repeated till the final component is built up [5]. Furthermore, pre-placed powder technique is largely used in the field of laser surface coatings to study the metallurgical properties of different materials upon irradiating with laser beam, optimum mixing ratio of metal powders and ceramic particles to obtain a defect-free coating with enhanced surface properties like wear resistance, corrosion resistance etc [6,7].

Control of final characteristics of deposited clad track like geometry which includes clad height, width and contact angle, percentage of dilution, surface roughness, microstructure and mechanical properties requires a good understanding of the relationship among these characteristics, processes parameters and

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http://dx.doi.org/10.1016/j.optlaseng.2016.08.005
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thermal history of molten pool during cladding. Furthermore, application of this process in industry requires proper monitoring system to diagnose the process online. Laser cladding involves more than 19 process parameters [8] which include laser beam power, scan speed, beam spot diameter, powder layer thickness, powder mass flow rate, carrier and shielding gas pressure, powder particle size and shape, standoff distance, thermal conductivity of powder and substrate, hatch spacing, percentage of overlapping, interlayer ideal time, operating environment, geometric dimensions of the substrate etc. To a greater extent these process parameters are machine or system dependent which include the nozzle design (number of outlets, powder exit angle etc), type of laser system integrated, it is operating wavelength and beam intensity distribution etc. Thus, the monitoring system or the parameter should be such, which is independent of the system, can capture and provide all the necessary information to assess the metallurgical and mechanical properties of the deposited layer or component. Thermal history of the molten pool is one such parameter which is an outcome of the combination of many of the above critical process parameters and affects the mechanical and metallurgical properties of the deposited component. Therefore, monitoring the molten pool temperature and thermal history can facilitate in real-time non-destructive evaluation of the process.

1.1. Background

Several researchers developed analytical and numerical models to estimate the effect of process parameters on the surface temperature and to predict the extent of heat effected zone. Fang et al. [9] developed a three dimensional finite element model to estimate the temperature distribution and cooling rate surrounding the molten pool, and correlated it with the heat effect zone in laser cladding process. Lie et al. [10] developed a three dimensional model to simulate high power laser cladding of TiC/NiCrBSiC composite coating on Ti6Al4V alloys and could predict the temperature distribution, shape and size of the molten pool and the heat affected zone using the model. Tahmasbi et al. [11] also carried out FEM modelling to study the effect of layer number on the temperature distribution in a vertical build up of IN-738 layers. All the above analytical and numerical models are focused on predicting the clad geometry, heat effected zone and surface temperature with respect to the process parameters. Summing up the published results, the analytical models could help in understanding the process and the effect of process parameters on temperature distribution. However, the temperature history predicted from these models fail to capture some of the important events like shift in phase transformation point upon addition of foreign materials, melt pool and solidification shelf lifetime which controls the microstructure and mechanical properties of the clad layer and vaporisation from the clad surface. This is because, all the above studies consider the effect of latent heat of fusion and Marangoni flow by modifying the specific heat capacity and thermal conductivity, and neglect any chance of vaporisation because of which surface temperature predicted in many cases is near 4000 °C which in real case is not possible. Thus, online monitoring system which can record all the above mentioned events is of significant importance.

Since many coupled physical events takes place in a very short period of time during laser cladding, involving a wide temperature range, small processing zone, sharp temperature gradients i.e. fast heating and cooling rates (10^4–10^6 K/s), it requires a non-contact type temperature measuring system, not affected by laser radiation and having short signal acquisition time [12]. Feasibility studies on the application of pyrometer in online monitoring and control in laser machining have been carried out by several researchers [12–16]. Ignatiev et al. [13,14] developed a two wavelength pyrometer, demonstrated that the measurement within a spectral band free from spectral lines of irradiated material provides accurate monitoring of brightness temperature. In case of 1-spot pyrometers the temperature signal may fluctuate from the mean value in the range of several hundred degrees which may be due to the spikes of free-running laser pulse, plume dynamics, and melt hydrodynamics, etc. Doubenskaia et al. [15,16] studied the variation in brightness temperature profile with laser beam power, pulse shape and powder feed rate. Bi et al. [17] applied different measuring systems like photodiode, pyrometer and CCD camera to detect the IR radiation from processing zone and studied the effect of process parameters on temperature signal. Temperature signal detected with photodiode arranged coaxially with the cladding nozzle increased with increase of powder feed rate up to certain extent and became constant. However, pyrometer signals showed a decreasing trend with increase of powder feed rate, similar to the results of Doubenskaia et al. [16]. Bi et al. also developed a cladding head integrated with different sensors like contact thermometers, photodiodes and CCD cameras to monitor the process and simultaneously the condition of various optical components incorporated in the head [18]. In multilayer thin wall deposition, the heat conduction mechanism transforms from 3D to 2D as the number of layers increases, resulting in heat accumulation and inhomogeneous wall thickness. Further, absence of material at the edges to conduct the heat results in edge build up as well as shrinkage of the wall. The authors further extended their work in which laser beam power was varied during the process with change in IR-temperature signal from a pre-set value using a PID controller based closed loop control system [19]. Pavlov et al. [20] studied the effect of scan speed and composition of MMC's on brightness temperature signal. It was observed that with the increase of TiC content in metal matrix, the brightness temperature increased which was attributed to the shift of critical phase transitions point, optical and thermal properties. Also, the TiC content resulted in decreasing the height of multi layer deposition. Presence of MMC's like TiC on the surface of clad acts as a thermal barrier and also has high melting point. This results in increase of surface temperature, decrease in temperature gradients and melt pool size and thus powder catchment efficiency [21]. Emamian et al. [22] estimated the variation in surface temperatures using a 3D model during deposition of multiple tracks at a particular distance from one other. They observed that compared to the first track the later ones were less prone to micro-cracks due to the relatively lower thermal stresses as a result of slow cooling rates owing to substrate heating caused by previously deposited tracks. The temperature variation along multiple tracks could also influence the dimension and shape of clad layers as they depend on the surface tension between the solid-liquid-gas which is dictated by the melt pool lifetime and the surface temperature of substrate as well as the melt pool. Yu et al. [23] studied the effect of process parameters viz. laser beam power, scan speed and powder mass flow rate on melt pool lifetime and its effect on spreading of molten pool on substrate surface. They used a two wavelength pyrometer to detect the temperature signal and found that in case of multilayer deposition, the melt pool lifetime increases with increase of layer number, decreasing the dimensional accuracy.

All the above studies are focused on the application of various detection sensors and techniques, their industrial feasibility and effect of process parameters on the clad geometry and detected signal in laser cladding process. However, the ultimate mechanical properties of components fabricated by laser cladding process depend on the thermal-history-dependent microstructure. Therefore, it is vital to understand the changes in thermo-cycles with various input parameters and their effect on the resulting microstructures and mechanical properties.