

**EVALUATION OF MICROSTRUCTURE AND MICRO-HARDNESS OF 410L SS COATINGS
FABRICATED USING LASER ASSISTED COLD SPRAYING: PROCESS DEVELOPMENT****T. Mathebula^{1*}, M. Tlotleng¹, K. Malabi¹, S. Pityana¹ & S. Camagu²**

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ABSTRACT

Automotive, marine, power generation, petrochemical and mining industries experience problems which results in huge financial constraints due to damage of the engineering components. Sometimes the components are exposed to aggressive, corrosive, contaminating and erosive environments which accelerate the degradation of these components. Surface coatings are generally used to protect and prolong the lifetime of the parts. Laser Assisted Cold Spray (LACS) is a relatively new surface coating process which can be used to protect surfaces of engineering components against these aggressive environments.

LACS is a hybrid process that combines the supersonic powder stream with laser heating of the deposition zone. In this process, the deposited particles and the substrate are not melted by the laser beam, but heated to just below the melting. Since no melting is involved, it is referred to "Laser Assisted Cold Spraying".

LACS technique is an emerging mainstream process; which means there are gaps in the knowledge base relating to LACS-dependent applications. This paper will focus on the microstructural evolution, mechanical deformation, the correlation between functional properties and process parameters necessary for the development of required LACS coatings. This paper will provide the basis on which research will follow-on-research that will lead to the development of high-productivity LACS coatings for identified industrial applications. The investigation of the effect of varying experimental parameters such as laser power, laser travel speed and powder feed rate on coating deposition efficiency, microstructure evolution and micro-hardness of the deposited coatings, will be discussed.

INTRODUCTION

Surface treatment of metals, particularly in refurbishing worn metal parts instead of replacing them, has gained momentum and significant recognition in numerous industries [1,2]. Different surface treatment methods can be applied to most functioning worn out metal components at lower cost and in shorter periods of time to combat the problems faced by industries that can result in huge financial implications when damaged parts need to be replaced. The need to develop suitable, easily processable and cost effective coating fabrication techniques arises [1].

Surface coating systems are suggested for the application of corrosion and wear resistance to either successfully produce good mechanical properties and/or reinstate their surface integrity to endure in their service environments [3]. Until recently, long-established and thermal methodologies have been employed for the deposition of coatings for surface repair [1-3]. Traditional methods such as electroplating and chemical vapour deposition (CVD) are relatively sluggish, costly and are coupled with low deposition rates; while thermal spraying systems like vacuum plasma spray (PS), laser cladding (LC) and high velocity oxygen flame (HVOF) encounter challenges such as thermal distortion, occurrence of high residual stresses, formation of undesirable intermetallic phases, poor mechanical properties as well as the necessity of expensive high purity inert working environments to prevent oxidation [1,3].

The use of lasers has gained significant acceptance in various industries as a tool to repair defects of components without destroying the targeted surface and changing the microstructure of the target area. Olakanmi *et al.* [1,2] have extensively explained that the use of different laser based methods have come to the aid of industries, in which high value components such as moulds and dies cannot be refurbished by conventional methods [2, 3]. In order to enhance the surface properties of components coating techniques need to conform to certain expectations; as summarised below [3]:

1. There should be excellent metallurgical bonding with little or no porosity between the coating and the base material which will impart good mechanical (hardness, ductility, fatigue/shear strength, as well as corrosion/wear resistance), thermal and impact resistant properties;
2. Thicker coatings will ensure extended life services of components, and
3. There should be compatibility of thermo-physical properties of the coating and substrate.

To achieve best coating qualities the process has to be optimised by appropriately adjusting gas pressures and temperatures with respect to the material to be sprayed, powder size range and the type of nozzle used [5]. Unfortunately, CS is only economically viable for limited applications because of its high operating costs and its suitability to a limited range of materials [2].

LACS was introduced to address the problems associated with CS in which LACS can accommodate the deposition of a wider range of materials using nitrogen gas while eliminating the need for gas heating; which in fact reduces operating costs as compared to traditional CS processes, but it is yet to be fully developed into an industrial method [2]. In LACS, building up of a coating can be achieved at half the impact velocity used in CS [1, 2]. In LACS, the laser is a heat source and is used to heat up the powder particles and the targeted substrate area to temperatures between 30 and 70% of their melting point; making it easier for the particles to deform which in turn results in high deposition rates [1, 2].

During deposition, using LACS, the particle strength and softening of the deposition site are reduced simultaneously by controlling five main variants; laser power, laser beam irradiation and powder spray gun spot alignment, stand-off distance, laser beam traverse speed and powder flow rate [1, 2]. Results of LACS deposited coatings with 410 L stainless steel powder on 304 stainless steel base material are presented here to show process

optimization on the coating deposition by varying the above mentioned parameters for enhancement of the particle to substrate, and particle to particle bonding mechanism where micro-scale porosity within the coating and interphase are eliminated.

INVESTIGATION METHODOLOGY

Powder Feedstock and Base Material

In this work, gas atomised 410L stainless steel powder (supplied by TLS TECHNIK GmbH, with a particle size distribution of +45-90 microns) having a near spherical morphology was used. 304L stainless steel base material with dimensions of 100 mm x 50 mm x 5 mm was used. The surfaces of the base material were grit blasted for a rougher surface to improve adhesion of the coating during deposition.

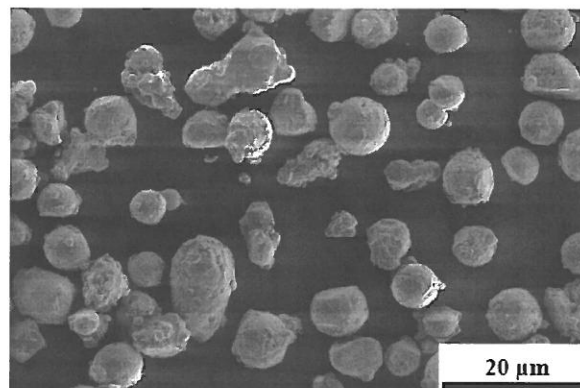


Figure 1: Morphology of 410L powder particles used for this study

LACS Set-Up

Figure 2 illustrates the LACS equipment set up used in this study which was located at the Laser Materials Processing laboratories at the Council of Scientific and Industrial Research (CSIR), Pretoria, South Africa. The equipment included a 4.4 kW Nd:YAG (ROFIN SINAR DY 044) laser system of 1.06 μm wavelength and a gas flow rate set at 30 bar. The converging-diverging (de Laval) DLV-180 nozzle employed for spraying the 410L powder was mounted on a KUKA robot. A 600 microns optical fibre delivered the laser beam through a beam shaping module consisting of a 200 mm focal length collimator and a Precitec YW50 unit.

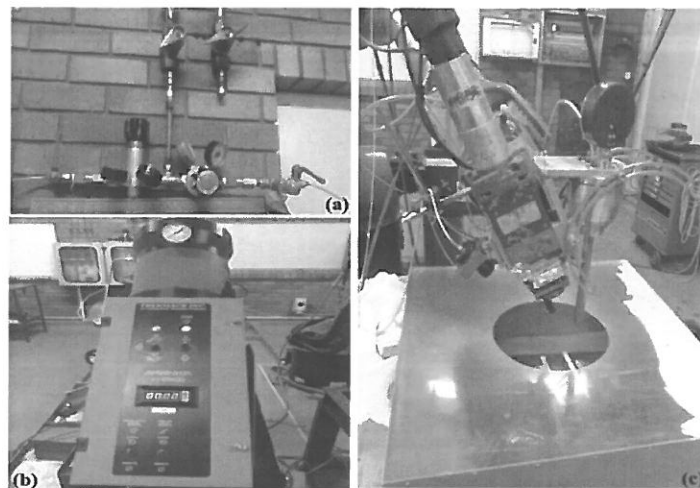


Figure 2: LACS experimental set-up [2]

LACS Experimental Procedure

410L powder particles were propelled with high pressure nitrogen (N₂) gas which was sent through the converging-diverging nozzle, both directed towards the substrate at 30 bar via the powder feeder; where the particles were mixed with the gas. Typically a high pressure gauge and a high flow measurements regulator are essential to safely control and operate the set-up. The laser beam was directed at an angle of 27° to the surface normal. Laser powder was varied between 1.0 to 1.2 kW with the gas pressure kept steady at 30 bar; powder feed rate was varied between 20-30 rpm; transverse speed was varied between 2.5 to 10 mm/s while keeping the stand-off distance at 50 mm.

Sample Analysis

Various coating thicknesses were produced using the experimental condition listed above. Each sample was then cross-sectioned, and the coating-substrate interphase and microstructure of each were examined by optical microscopy (OM) Olympus BX51M. The thickness of the coatings was quantitatively measured using image analysis of the optical micrographs. The micro-hardness was measured using a Vickers' hardness tester (Matsuzawa Seiko) with a load of 0.3 N and a dwelling time of 10 seconds. The effects of the variable parameters on the quality characteristics of the coatings were then studied.

RESULTS

Effects of Laser Power, Transverse Speed and Powder Flow Rate on the Deposition Efficiency of LACS Deposited Coatings

Deposition efficiency of LACS fabricated 410L coatings at various laser powers, transverse speeds and powder flow rates are hereby evaluated in respect to the layer thickness of the coatings. Table 1 and Figure 3 show the relationship between LACS 410 deposited coatings' layer thickness at various process parameters.

Table 1: Data from the LACS deposition experiments

Layer thickness of Coatings (µm)									
Transverse Speed (mm/s)	Powder Flow Rate								
	20 rpm			25 rpm			30 rpm		
	Laser Power (W)								
	1200	1100	1000	1200	1100	1000	1200	1100	1000
2.5	1670.4	1299.2	912.7	1600.0	1515.5	1089.3	1526.3	1442.6	1185.3
5.0	1112.3	943.4	547.8	1168.7	862.7	459.5	1128.9	830.7	647.9
10.0	552.9	417.3	216.3	611.8	341.8	158.7	592.6	362.2	217.6

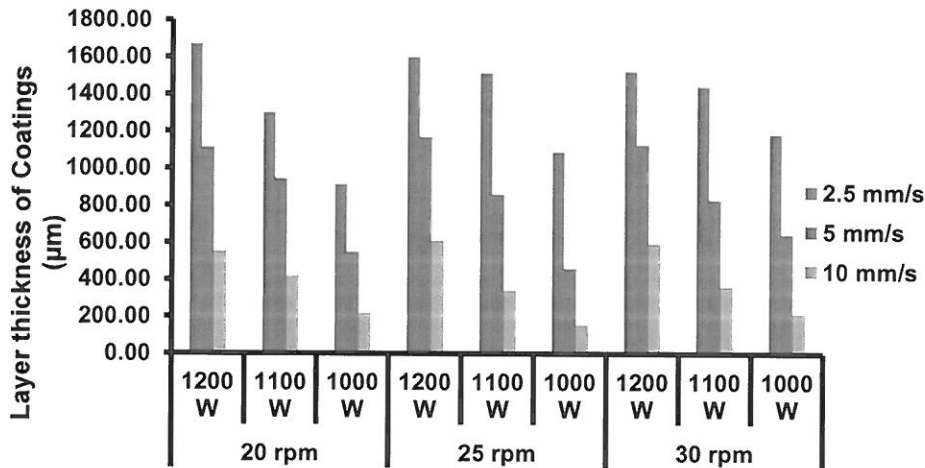


Figure 3: Relationship between LACS deposited 410L layer thickness of coatings and powder flow rate, laser power and transverse speed

Figure 3 shows that the layer thickness of the coatings does vary for the different laser powers and also the used powder flow rate and transverse speed. The layer thickness of the coatings for different laser powers the 20 rpm, 25 rpm and 30 rpm samples show a general slight decrease of about 70 µm in the layer thickness of the coatings which is a trend for the various laser powers at the various powder flow rates.

An observation of the macrostructures, Figures 4, 5 and 6 show that different travel speeds produced significantly varied layer thickness coating for the various process parameters investigated. Figure 6 reveals that the travel speed of 10.0 mm/s, regardless of set laser power and powder flow rate, resulted in thin, discontinuous coating tracks being produced (see Figure 6 d). The layer thickness of the coatings produced with the same transverse speed and laser power was relatively similar regardless of the powder flow rate used. It is clear, from the graph Figure 3, that the layer thickness of the deposited coatings increased as the applied laser power was increased. This observation is substantiated by the measurements of the coating thickness presented in Table 2. The results also show that the slower the travel speed the thickness of the coating increases from about 200 µm at 10.0 mm/s to about 1000 µm at 2.5 mm/s; this is relevant for all the powder flow rates.

Microstructure of LACS deposited 410L Coatings

Depending on the application and requirements provided by a customer, the layer thickness of the coatings will be determined. However, for the purpose of this study results will be presented for coatings with a layer thickness above 500 µm. The optimised coatings were taken for microstructural analysis since there were transitional features for all the coatings, Figure 4. No distinct differences in the cross-section of the macrostructure could be identified as evident by the absence of porosity, cracks and un-bonded particles. Additionally, it can be seen that the bottom portion of the coating is noted to be denser than the top regions of the coatings (Fig. 4). A study of Figure 6 reveals that the macrostructure of the coatings produced with the faster transverse speed showed the densest microstructure. Moreover, the bonding between the coating and substrate appears to be strong and coherent as no porosity or cracks could be found at the interphase. There also was not distinct difference visible in the microstructure of the coatings with different laser powers used; laser power only influenced the layer thickness of the coatings.

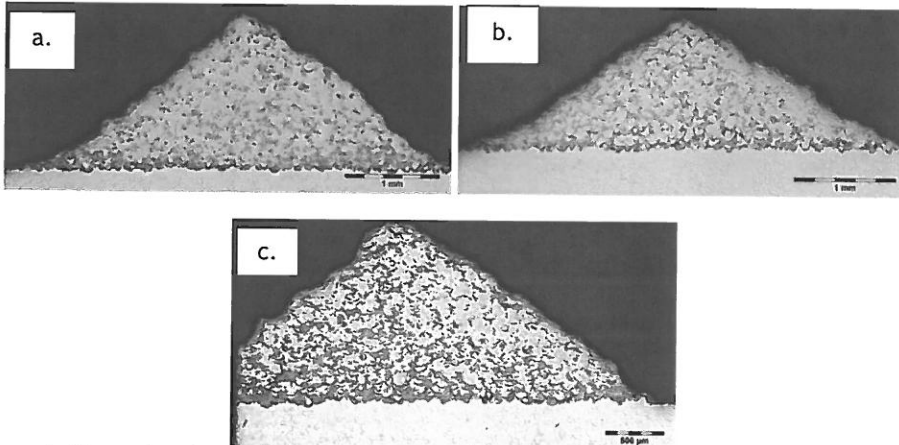


Figure 4: Macrostructure of the coatings produced at 2.5 mm/s, 1200 W with a. 20 rpm, b. 25 rpm and c. 30 rpm

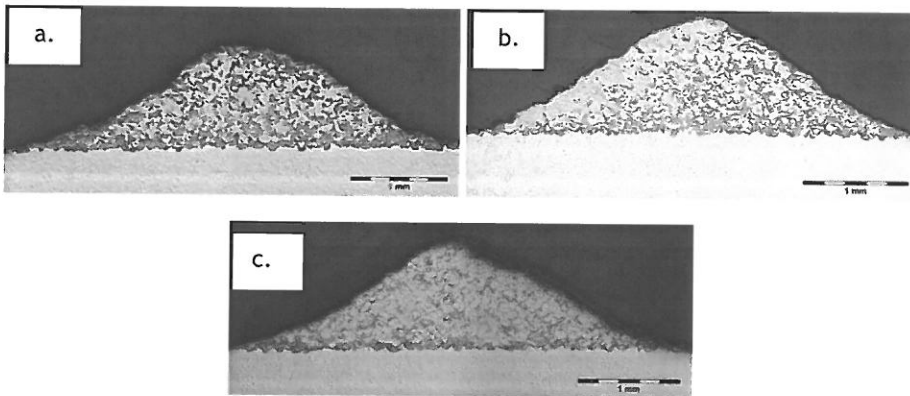


Figure 5: Macrostructure of the coatings produced at 5.0 mm/s, 1200 W with a. 20 rpm, b. 25 rpm and c. 30 rpm

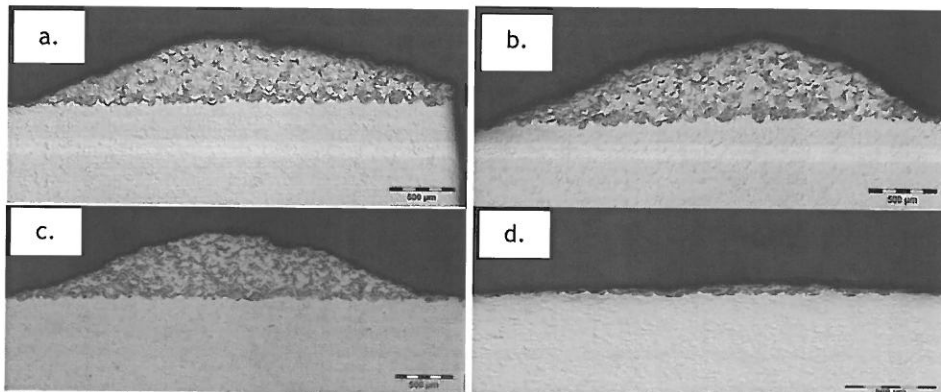


Figure 6: Macrostructure of the coatings produced at 10.0 mm/s, 1200 W with a. 20 rpm, b. 25 rpm, c. 30 rpm and d. 1000W at 25 rpm

The microstructure of the LACS deposited 410L coatings consists of a two-phase microstructure made up of un-tempered martensite (dark phase) and δ -ferrite (grey phase), Figure 7.

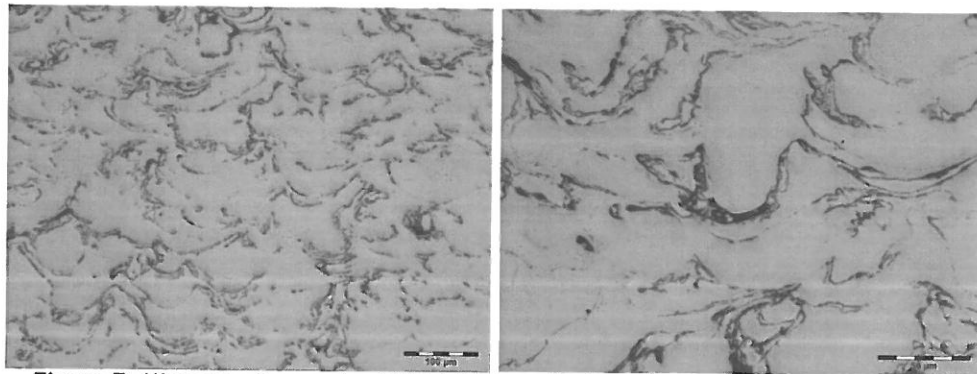


Figure 7: Microstructures of a 410 LACS deposited coatings taken at 20 X and 50 X magnifications

Micro-Hardness

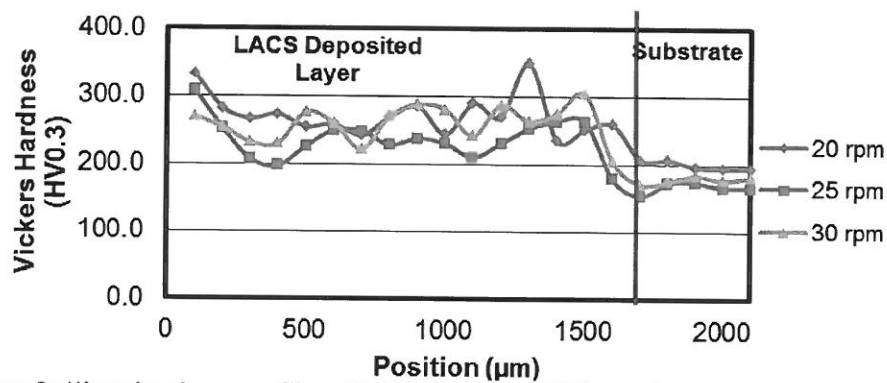


Figure 8: Micro-hardness profiles of LACS deposited 410L coatings at 20, 25 and 30 rpm for 1200 W with 2.5mm/s transverse speed.

Analysis of the micro-hardness results obtained for LACS processed 410L coated samples at 20, 25 and 30 rpm for 1200 W with 2.5, 5.0 and 10.0 mm/s transverse speeds is presented in Figure 8 above. In Figure 9, it can be seen that the indent in the dark phase (~39 µm diagonals) is distinctively smaller than the indent produced in the grey phase (~44µm diagonals).

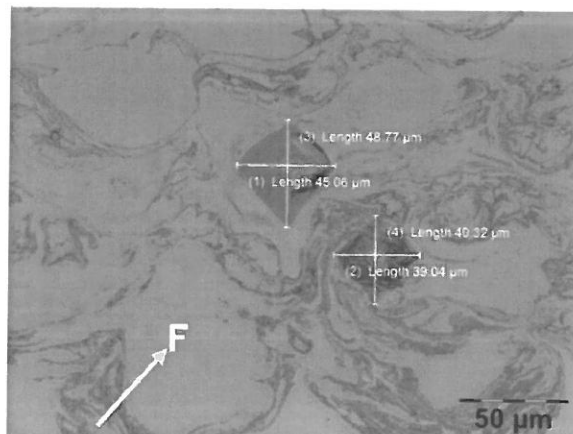


Figure 9: Microstructure of LACS deposited 410L coating showing micro-hardness indents.

DISCUSSION OF RESULTS

Deposition Efficiency of LACS Deposited 410L Coatings

Examination of the laser beam interaction with the 410L powder stream being propelled by cold N₂ gas under high pressure indicates that the laser beam heats up the powder-gas combination. This then resulted in an increase in temperature as well as high kinetic energy of the powder-gas combination in comparison to the cold state as used in CS, without the laser irradiation. An increase in the temperature of the particles of 410L powder during spraying translates to reduction of their atomic bond energy which then results in particle softening as their yield strength is reduced [1].

In addition, the laser irradiation also has a softening effect on the deposition site on the substrate due to heat conduction which in return makes it easier for the 410L particles to impact, deform and get embedded into the target area [1, 2]. Increased coating layer thickness reported in this study with the increase of laser power (Fig. 2) could be attributed to the fact that the 410L particles and the substrate's surface became more softened with increased laser power. This also points out the fact that the slower the transverse speed the longer the interaction time between the deposited powder and the laser beam; which allows more powder to be deposited resulting in higher or denser layer thicknesses of the coatings. Therefore, the increased softening of the deposited powder and deposition site on the substrate enhanced the embedding of the particles; this is found to be independent of powder flow rate but influenced by transverse speed. This outcome is similar to the findings by Olakanmi *et al.*, [1] who deposited Al-12wt% Si by means of LACS.

Microstructure of LACS Deposited 410L Coatings

Results obtained from the microstructural analysis of LACS deposited 410L coatings were defect free with deposition of appropriate layer thicknesses achieved by the selection of appropriate processing parameters. The two phases present in the microstructure of the 410L coatings are identified to be un-tempered martensite (dark phase) and delta-ferrite (grey phase). Considering the microstructure of the 410L (Fig. 8), it may be deduced that the interaction of the particles resulted in shearing. This phenomenon is believed to be responsible for the existence of the two-phase microstructure of the coatings. This suggests that the super-saturation of the delta-ferrite transformed to un-tempered martensite during rapid solidification of the localized particle boundaries formed by the particles impacting on the deposition site. In addition, these phases are noted to have existed in all the microstructures irrespective of the applied laser power during the LACS deposition of 410L coatings.

The microstructure shown in Fig. 8 is a typical structure from the LACS deposition of 410L powder feedstock. However, the coatings produced at higher transverse speeds are noted to contain more of the dark phase as compared to the presence of more delta-ferrite in the coatings obtained from slower transverse speeds (Fig. 4 to Fig. 6). Although the already softened 410L particles remain solid during flight, upon reaching the deposition site because they encounter high temperatures coupled with high velocities, lead to their deformation by flattening (see regions F in Fig. 8). It is evident from Fig. 6 that the applied laser power together with the powder flow rate, when increased from 20 to 30 rpm, could have weakened the 410L particles further, thereby making it easier for them to be embedded onto the substrate.

Micro-Hardness

Varied values of hardness were obtained for the coatings produced with evidence that the dark phase is harder (~280 HV) than the grey phase (~220 HV). The non-uniformity in the micro-hardness of the coatings is not due to porosity or cracking but solely due to the presence of two phases.

CONCLUSION

The thickness of the LACS deposited 410L coatings increased with increased laser power. The coatings also increased with decreasing transverse speed for constant laser power and powder flow rate settings. Laser power and transverse speed influence the inter-particle bonding of the microstructure. Shearing as well as thermal softening of the particles occurs when depositing the coatings. Although all the coatings were free from porosity and cracks, this study draws attention to the importance of choosing appropriate parameters in depositing 410L coatings with strong adhesion to the deposition site when using the LACS method. Parameters used in this study have provided a process window for further work. Meanwhile, a detailed experimental study using the Taguchi method to design experiments will be undertaken to understand the role of other LACS process parameters in the development and optimisation of coatings with different powder materials.

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