HARDFACING USING SUPERSONIC LASER DEPOSTION OF STELLITE-6
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Abstract

The capability of manufacturing coatings is of central importance in engineering design. Many components require nowadays the application of additional layers, to enhance mechanical properties and protect against hostile environments. Supersonic Laser Deposition (SLD) is a novel coating method, based upon Cold Spray (CS) principles. In this technique the deposition velocities can be significantly lower than those required for effective bonding in CS applications. The addition of laser heat energy permits a change in the thermodynamic experience of impacting particles, thereby offering a greater opportunity for metallurgical bonding at lower velocities compared to the CS process technology. The work reported in this paper demonstrates the ability of the SLD process to deliver hard facing materials to engineering surfaces. Stellite-6 has been deposited on low carbon steel tubes over a range of process parameters, determining the appropriate target power and traverse speeds for coating deposition. Coating properties and parameters were examined to determine the main properties, micro-structure and processing cost. Their morphology was studied through optical microscopy, SEM and X-Ray Diffraction. The results have shown that SLD is capable of depositing Stellite-6, with enhanced properties compared to laser clad counterparts.

Keywords: SLD, Cold Spray, supersonic, laser, metal, deposition.

Introduction

The current industrial demand of high quality complex engineering structures often requires the use of enhanced materials for the manufacturing of each single component. In many applications specific properties are only required locally, therefore achievable though the formation of coating layers.

For the formation of metallic type layers, High Velocity-Oxygen Fuel (HVOF) and Laser Cladding (LC) [1,2] are the most employed industrial technologies. Each method is different in working mechanism, however they have all in common the melting of the feedstock material, and a relatively high working temperature at the deposition site. Melting of the feedstock material often results in extensive oxidization, change of microstructure and in the formation of unwanted brittle phases during the re-solidification process. Also, when working temperatures are too high, distortion and cracking of the substrate material can occur. Such conditions are becoming increasingly unacceptable when associated to the current industrial demand of producing high quality components, and cost-efficient at the same time.

An alternative method to heating is a solid-state deposition process, known as Cold Spray (CS) [3]. In this technology the feedstock material (in the form of powder) is not melted, but accelerated at supersonic velocity by a carrier gas, therefore enabled to generate high energy impacts when colliding against a substrate surface. Each material is characterized by a minimum velocity to achieve deposition [4]. As a consequence, the use of helium in large flow rates with gas-heating are unavoidable conditions for the formation of high quality coatings made out of strong and wear-resistant materials such as WC-Co [5,6].

This paper presents experimental results related to the deposition of a C-Co-Cr hard-facing alloy (commercial name is Stellite-6) onto steel tubes substrates, with an innovative process under development at the University of Cambridge and known as Supersonic Laser Deposition (SLD). This process has the potential to overcome the disadvantages of CS, and has already been successfully applied to the deposition of Ti onto steel [7]. In this technique, the effect of using nitrogen as carrier gas (low particles velocity) is compensated by the implementation of a laser source to illuminate the coating location. Optimum process parameters are presented, alongside with a coating analysis.

The SLD Process

The SLD technology evolves from a successful preliminary process study by Bray et al. [8,9], who investigated the effect of substrate softening on coating formation through the application of 1kW laser source.

The SLD process is similar in working mechanisms to CS, its schematics are shown in Figure 1. Metal powder delivered from a high pressure feeder (Praxair 1264HP) is accelerated up to supersonic velocity through a carrier gas (nitrogen), within a converging-diverging nozzle. The maximum allowable nozzle inlet pressure is 30bar in the current system, giving a particle impact velocity within the 400-550m/s range, depending on size and type of material. Threshold levels can be further increased by the use of a gas-heater (CGT kinetics3000) to increase the gas temperature in the nozzle inlet, i.e. its exit velocity.

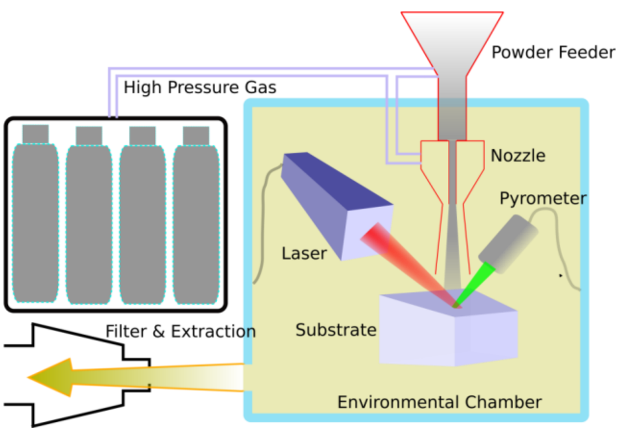

Figure 1: SLD process schematics.

As Figure 1 shows, the deposition zone is illuminated by a laser beam (4kW fiber laser - IPG). This is to soften the substrate material (not for melting), to enable the coating formation without the necessity of accelerating powders up to CS velocity. It has been shown that is possible to achieve the deposition of high strength materials in a cost-efficient manner, therefore with nitrogen as the carrier gas. The nitrogen gas supply is from MCP's (Multiple Cylinders Pallet). After processing, it is removed from the working chamber through an extraction system.

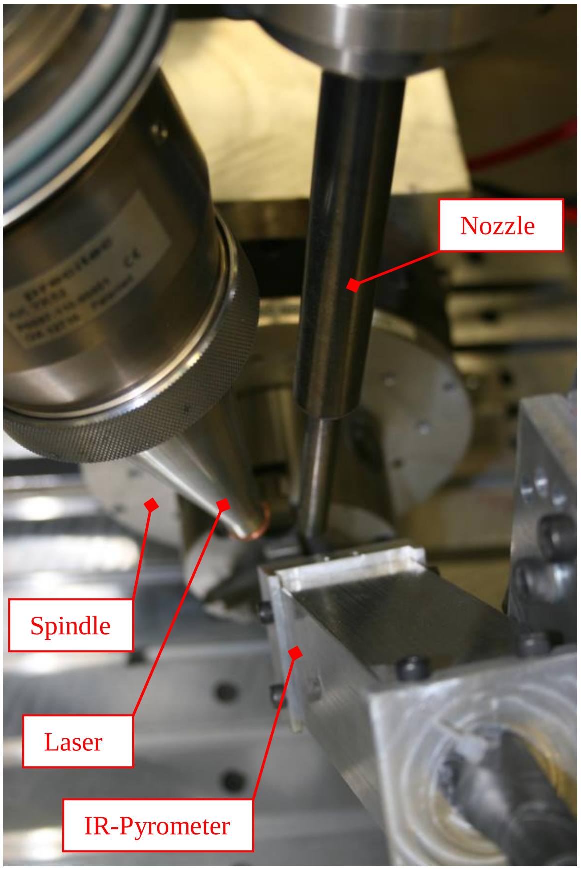

Figure 2: SLD processing working zone.

Figure 2 shows the process working zone, and the space arrangement of the main components: laser head, supersonic nozzle, IR-Pyrometer and spindle. The IR-Pyrometer is used to monitor the temperature on a spot of the coating, and to maintain it at a set value through a PID closed loop control with the laser. The spindle is implemented in the system, to allow for the coating of tubes.

SLD of Stellite-6

Stellite-6 Properties and Applications

Stellite-6 cobalt base alloys consist of complex carbides in an alloy matrix. Its chemical composition is show in Table 1. They are resistant to wear, galling and corrosion and retain these properties at high temperatures, due mainly to the inherent characteristics of the hard carbide phase dispersed in a Co-Cr alloy matrix. It is regarded as the industry standard for general purpose wear resistance applications, against many forms of mechanical and chemical degradation over a wide temperature range (retains a reasonable level of hardness up to 500°C). It has also good resistance to impact and cavitation erosion. Stellite-6 is suited to a variety of hard facing processes and can be turned with carbide tooling. Uses include valve seats and gates, pump shafts and bearings, erosion shields, rolling couples and for the repair of steam turbines blades.

Co	Cr	C	W	Ni, Fe, Si, Mn, Mo	Hardness	Melt Range
base	28.5	1.2	4.6	< 2	380-490HV	1285-1410 ^{0}C

Table 1: Stellite-6 chemical composition (wt%), hardness and melting temperature [10].

The application of coatings of this metal with CS may be possible, however only with helium and gas heating. Alternative techniques industrially implemented are Laser Cladding or Laser Melt Injection of solid powder. Laser Cladding requires a melt pool on the substrate into which material is fed. This melt pool is kept to a small size to ensure a metallurgical bond is developed between the substrate and the layer. This gives a low rate of deposition (<0.9Kg/h) and requires the feedstock material to be fully melted in order to obtain a dense deposit. Laser Melt Injection of solid powdered feedstock into a melt pool generated by a laser beam is another method. As soon as the laser beam passes by, the melt pool rapidly re-solidifies, trapping the particles in place. Welding of Stellite-6 requires the material to be fully melted and re-solidified. As a consequence, the potential advantage of SLD is that the powder can be applied without forming a melt pool, retaining the properties of the pre-processed materials.

Coatings Manufacturing and Properties

The SLD process was used to produce Stellite-6 coatings on low carbon steel substrates, in the form of tubes. The tubes measured 50mm external diameter, with a wall thickness of 3mm. Spherical Stellite-6 powder, -45 μm size, was used. The spraying process was carried out with nitrogen at 30bar inlet pressure, heated up to a temperature of 500°C to maximise the gas jet speed at the exit of the nozzle. The supersonic nozzle employed for the experiments had a restriction cross-section diameter of 2.7mm, and an overall length of 200mm.

The coating process was investigated with a selection of processing parameters, in order to identify the optimum conditions. The laser power was changed at each trial, within the range 1.2-3kW, and tested at different substrate Transverse Speeds (TS), i.e. the linear velocity on the outer circumference of the tube. The effect of process powder feed rate on deposition characteristics was also investigated.

Figure 3: Typical Stellite-6 coating track cross-section on steel by SLD.

Figure 3 shows a cross-section, obtained with the optical microscope, of a typical Stellite-6 single track produced with SLD. The figure suggests the deposit is characterized by a relatively low porosity level and a negligible heat-affected zone on the substrate. Erosion or cracking of the steel substrate and coating had not occurred.

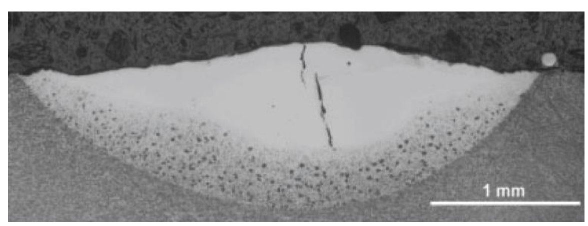

Figure 4: Stellite-6 coating track cross-section by Laser Cladding [11].

In contrast, Figure 4 shows the cross-section of a Stellite-6 coating produced by Laser Cladding, therefore with complete melting of the feedstock material [11]. The heat-affected zone is large in this case, approaching 1mm in depth. In such condition distortion of the work-piece is most likely to occur. Also, cracking of the coating can take place, due to high stresses which can form through differential contraction, following the clad formation. Being a solid-state deposition process, SLD has the potential to overcome to these difficulties and disadvantages.

Single tracks can be simply overlapped to form a wider coating as the micrograph cross-section in Figure 5 shows. No cracks were observed in both substrate and coating.

Figure 5: Wide Stellite-6 coating on steel.

It was possible to efficiently deposit Stellite-6 at TS levels as high as 40mm/s, for a coating build rate of approximately 2.2Kg/h, using 3kW laser power. In such processing conditions, the porosity of the deposited layer was measured (optically) to be <1%, while the micro-hardness approached the level of 610HV, therefore higher than the material in the bulk form as from Table 1. The adhesion strength of the coating was also measured, through the execution of a pull-off experiment. The test gave values in the excess of 62.4MPa, confirming excellent bonding with the substrate despite no melting having occurred during the process.

Coatings Micro-Structural Analysis

Figure 6 shows a micrograph cross-section (optical microscope) of a chemically etched Stellite-6 coating. The deposit was manufactured on a steel tube substrate again with 3kW laser power, and TS of 40mm/s. The figure clearly shows that particles are plastically deformed as a result of the high energy impacts on the substrate surface. Such behavior is also typical in CS. As particles boundaries are clearly visible, it can be confirmed that no melting of the coating had occurred during the coating process. Within each deformed particle in Figure 6, it is possible to observe the grain structure and its overall size, measuring less than 1 μm in most locations. Fine grain sizes have been associated with improved wear resistance, so this structure may provide a performance advantage in the final coating.

The grain of the Stellite-6 deposit is more clearly visualized in the etched SEM pictures shown in Figure 7. It was possible to highlight the location of the carbide phases, more resistant to the corrosive action of the etchant acid. Figure 8 confirms the size is relatively small, in the 200 nm range.

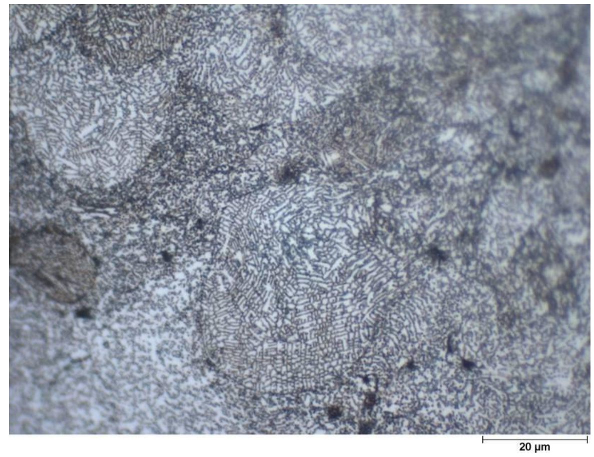

Figure 6: Etched Stellite-6 coating track cross-section (optical microscope).

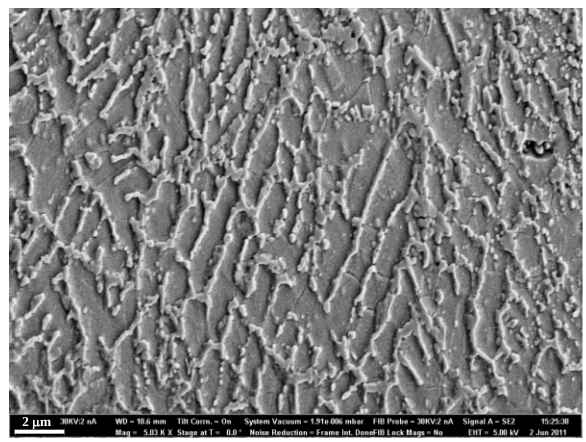

Figure 7: Etched Stellite-6 coating cross-section image within a single particle (SEM).

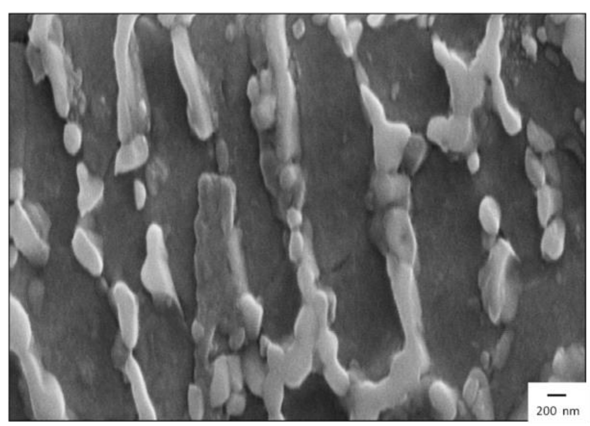

Figure 8: Etched Stellite-6 coating cross-section image (close up) within a single particle (SEM).

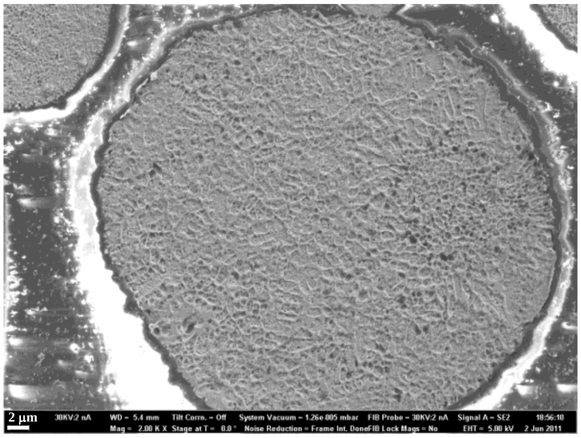

Figure 9: Etched single Stellite-6 particle cross-section prior to the spraying process (SEM).

Figure 9 shows a SEM image of a single Stellite-6 particle, prior to the spraying process. The grain structure is visible and very similar in size to the coating in Figure 7, confirming and excellent level of material structural integrity and preservation from the prior to the post-processing configuration.

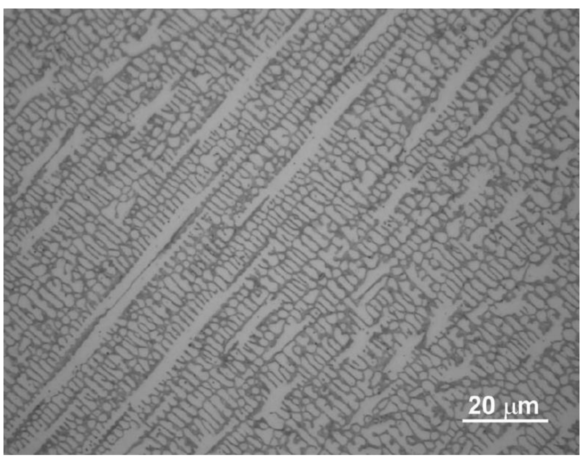

Figure 10: Stellite-6 coating by Laser Cladding, grain structure visualisation [12].

For comparison, Figure 10 shows the grain structure of a laser clad Stellite-6 coating. Similar dendrites in comparison to SLD are observed, however the overall size is considerably larger and reported to be approximately 1.1 µm [12].

A major drawback of metal deposition techniques based upon the complete or partial melting of the feedstock material and substrate, is the formation of undesired phases in the solidification process. An X-Ray Diffraction (XRD) analysis was therefore carried out in both Stellite-6 powder and SLD coating, to examine the potential difference between the two. Results are plotted in Figure 11.

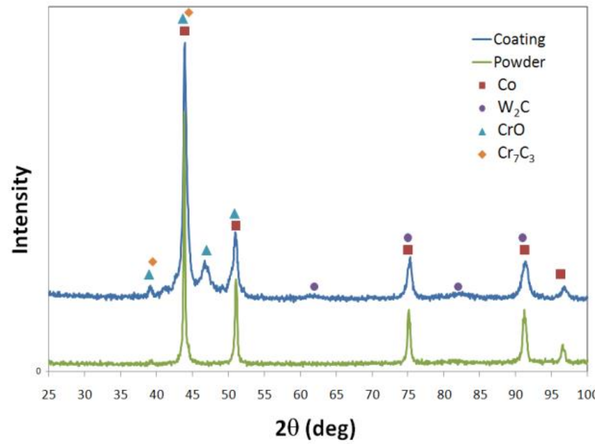

Figure 11: X-Ray Diffraction (XRD) analysis on Stellite-6 powder and coating.

Corresponding peaks to specific phases have given very similar outcomes between the powder and coating, confirming this type of material is likely to retain its original structure when SLD processed. However, some differences were observed, as an additional phase appears in the coating, but not in the powder. This seems to correspond to the CrO phase, however a more detailed analysis is necessary to confirm this result.

Processing Cost Analysis

It was possible to produce Stellite-6 coatings on steel tubes with SLD at a variety of processing conditions. In all cases, very similar micro-structural properties were observed. It is therefore evident the most favorable conditions are directly related to the lowest processing cost. A cost analysis was therefore carried out, to identity the most economical set of parameters.

Elements of the procedure that incur substantial cost include the energy requirement for the laser, the material cost for the powder and gas, and the energy required to heat the gas up to 500°C. The gas heater works at 15.5kW to generate the requested temperature. An average energy cost of £0.12/kWh was assumed, while Stelllite-6 powder is charged at the cost of £46/kg. The average nitrogen gas consumption at 500°C through the processing nozzle approaches 1000slpm, which translates into a total charge of approximately 20£/h.

With such rates the SLD total cost processing window was calculated in relation to the amount of material deposited, and estimated to be within the range 1905£/Kg – 442£/Kg. It was acknowledged that the use of a higher laser power (3kW) and TS (40mm/s) are associated to a minimum in total running cost. It must be considered that industrial volumes may substantially reduce this.

The majority of the cost is associated to the powder usage and its waste. As an example, for an ideal 100% efficient experiment, i.e. the entire powder flow rate from the nozzle is assumed to deposit, the relative cost of the most economical run would not be 442£/Kg, but approximately 50£/Kg instead. For this reason effort is currently being placed in researching possible solutions aimed at a substantial increase of powder deposition efficiency.

Conclusions

The Supersonic Laser Deposition (SLD) process was introduced. This coating technique is similar in working principles to Cold Spray (CS), however deposition is demonstrated possible without the necessity of accelerating metal particles up to their full critical velocity. SLD was applied to the hard-facing of low carbon steel tubes with Stellite-6. It was possible to achieve deposition within a variety of working parameters. A processing cost analysis within the optimum deposition window had concluded the optimum conditions are when laser power and Transverse Speed (TS) are the highest used in this investigation, therefore 3kW and 40mm/s respectively. Stellite-6 coatings by SLD had shown a crack-free structure, low porosity and excellent bond strength with the substrate. This was achieved without melting the feedstock material, or causing permanent damage and distortion to the substrate such as in Laser Cladding. The coatings grain size was measured to be sub-micron (200 nm), giving the potential for a much improved wear resistance.

Acknowledgments

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