

Solid-State Manufacturing of Tungsten Deposits onto Molybdenum Substrates with Supersonic Laser Deposition

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Abstract

Near fully dense tungsten coatings onto molybdenum substrates have been demonstrated using the Supersonic Laser Deposition (SLD) process. This is a characteristic that is not readily achievable with refractory materials. The tensile strength of the tungsten deposited coatings, 724MPa, is comparable to that of wrought tungsten with no evidence of melting or substrate grain growth. The results have shown that SLD is able to deposit tungsten with unique interface bonding and desirable properties as opposed to other deposition processes for refractory materials.

Keywords: coating, laser deposition, bending test, powder consolidation, cold spray, tungsten.

1. Introduction

Tungsten is a refractory metal which is fairly ductile in its purest state but it becomes brittle when contaminant levels are similar to those found in commercially available powder. The

melting temperature of 3410 °C is the highest of all metals. The density of tungsten is typically 19.3g/cm³ at 20 °C, while the room temperature tensile strength has a range of 690 - 3450MPa [1]. Its applications include filaments for light bulbs, emitters and targets for X-ray tubes.

When used as target material for generating X-rays, an electron beam impinges on the target. After some period of time, the tungsten target is compromised due to the electron beam interaction with the material. This may include even “mud cracking” defects on the electron beam race track. Targets are typically discarded after service hours of use and with the occurrence of undesirable defects. The targets are typically discarded because there has not been a means to refurbish them such that they could be continued to be used.

The development of a practical method for the deposition of tungsten would allow X-ray targets to be repaired rather than discarded. Currently the options available for the deposition of tungsten are limited. One established method is through chemical vapour deposition (CVD) using WF₆ as a precursor. Although this technique has been used for the manufacture of X ray targets [2], the low deposition rate of 100-300µm per hour limits its practical use in this application.

Deposition of tungsten via the consolidation of micron scale powder has been reported using selective laser melting (SLM) and Cold Spray (CS) [3,4]. Although deposition has been achieved with SLM, work reported details deposits which are either alloyed to allow full density to be achieved [5], or porous with densities not exceeding 82% [3].

The deposition of W-Ni-Fe powders using CS has been reported [4]. When tungsten powder was used, coatings of less than 10µm thickness were produced despite using

powder feed rates comparable to those used in the deposition of $\sim 50\mu\text{m}$ W-Ni-Fe coatings, suggesting that build rate is very low.

Supersonic Laser Deposition (SLD) has evolved from Laser Cold Spray (LCS) [6], and it is a process under development at the University of Cambridge. In this technique, which is similar in working mechanisms to conventional CS, the effect of using nitrogen as a carrier gas (reduced particle velocity) is compensated by the implementation by an infrared ($1.064\mu\text{m}$ wavelength) laser source to illuminate the coating zone so as to facilitate deposition.

In this paper, the application of SLD to the deposition of tungsten coatings is discussed while the suitability of the deposits for use as X-ray targets is assessed via density measurements and mechanical characterization.

2. Deposition Process

The SLD system schematics are shown in Figure 1. Metal powder delivered from a high pressure feeder (Praxair 1264HP) is accelerated up to supersonic velocity through a nitrogen carrier gas within a converging-diverging nozzle. The maximum allowable nozzle inlet pressure is 3MPa in the current system which provides a particle impact velocity in the 400-550m/s range depending on the size and type of material.

As Figure 1 shows, the deposition zone is illuminated by a laser beam (IPG fiber laser, with maximum power of 4kW). This is to soften the substrate material (not for melting) to enable the coating formation without the necessity of accelerating powders up to full threshold CS velocities. It has been shown that it is possible to achieve the deposition of high strength materials (such as stellite-6 and titanium) in a cost-efficient manner, therefore

with nitrogen as the carrier gas [7,8]. The nitrogen gas supply is from MCP's (Manifold Cylinders Pallet). During processing, it is removed from the working chamber through an extraction system.

SLD has the potential to overcome the disadvantages of other deposition processes for tungsten, especially CS and SLM, since the process allows the impact site to be heated to above the ductile brittle transition temperature of tungsten while avoiding the need to melt the material so as to produce bonding.

The coatings used in this study consisted of 19 μ m average (D_{50}) diameter tungsten powder deposited onto molybdenum substrates. Coatings for mechanical assessment were deposited using a gas pressure of 3MPa, laser power of 4kW, a substrate traverse rate of 10mm/s, and a carrier gas inlet temperature of 500 $^{\circ}$ C. The nozzle used in this case had a restriction cross sectional diameter of 2.7 mm, with a total length of 200mm. Deposition temperature could not be recorded for the deposition of tungsten as it took place at a temperature outside the range of the SLD system's IR pyrometer. Coatings were produced by overlapping adjacent tracks of tungsten and depositing multiple layers until the required coating thickness was achieved. Two layers were sufficient so as to achieve the deposition of an overall coating thickness of approximately 0.4mm.

3. Coating Structure

Metallographic examination of the SLD tungsten deposit, Figure 2(a), showed that there is no melting of the tungsten powder feed stock. The coating was chemically etched so as to reveal its structure. Typical tungsten particle sizes in the feed stock can be observed in the consolidated coating with two grains highlighted at ~5.6 μ m and 14.7 μ m. The coating

appears to be essentially porosity free with no melting of the tungsten feedstock evident. In addition, no melting, grain growth, or any other micro-structural changes to include the formation of Heat Affected Zones (HAZ) are observed in the molybdenum substrate, as shown in Figure 2(b).

The density of the SLD tungsten deposit, measured using the Archimedes method (density balance), was 18.3g/cm^3 which falls within the specification range of $18.3\text{-}18.7\text{g/cm}^3$ for what would be required if the technique was to be used for a X-ray target refurbishment operation [9]. This deposit density result is approximately 95% of the density of wrought tungsten (19.3 g/cm^3). There is certainly some headroom for further improvements on the SLD tungsten deposit density through a more detailed study of process parameters.

4. Mechanical Behaviour

To address the room temperature tensile strength of the SLD tungsten deposit, a 3-point bend test was conducted. A 3-point bending test coupon was wire EDM cut out of the deposit. The nominal dimensions of the test coupon were 30mm length, 1mm thickness and 2mm width. Figure 3 shows a schematic of the 3-bend test configuration. It shows that the support span, L , that is 20mm long.

Figure 4 shows the experimental loading characteristic of the specimen before it failed. The failure load was measured to be 53.5N. The tensile strength of the of the SLD tungsten deposit can be calculated using the bending stress relationship, shown in Equation 1. In the formula, P is the failure load in the load-deflection curve (53.5N), L is the support span (20mm), b is the width of the test beam (2.02mm) and d is the thickness of the test beam (1.05mm). The calculated stress at the outer surface at midpoint, σ_f , equals to 724MPa.

$$\sigma_f = \frac{3PL}{2bd^2} \quad (1)$$

Although the tungsten was deposited being powder the feedstock material, the tensile strength was within the range of the tensile strength for wrought tungsten (values range is reported in [1]). The deposition characteristics, microstructure and mechanical behaviour of SLD deposited tungsten suggests that it may provide a viable route for the refurbishment of tungsten X-ray targets.

5. 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 to be possible without the necessity of accelerating metal powder up to their full critical velocity. SLD was applied to the coating of a molybdenum substrate with a tungsten deposit. This resulted in a tungsten deposit that exhibited strength and density properties that were very similar to that of wrought tungsten properties. Most importantly, there were no thermal effect resulting in no deposit-substrate melting at the interface, no tungsten feed stock melting and no molybdenum substrate grain growth. SLD was proven a viable technology, potentially capable of being employed for the repair of X-Ray targets, and able to overcome disadvantages of current methods.

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Figure 1: SLD process schematics.

Figure 2: (a) Tungsten deposit image after chemical etching. (b) Substrate (molybdenum) micro-structure.

Figure 3: 3-point bend test schematic.

Figure 4: Failure load graph for 3-point bending test.