

Supersonic Laser Deposition of Self-Lubricating Coatings

Andrew COCKBURN^{a,1}, Nicholas SOANE^b, Martin SPARKES^a and William O'Neill^a

^a*Laserfusion Technologies Ltd, Suite 1, Unit A1 Tectonic Place, Holyport Road, Maidenhead, Berkshire, SL6 2YE, UK*

^b*Institute for Manufacturing, University of Cambridge, 17 Charles Babbage Road, CB3 0FS, UK*

Abstract. Supersonic Laser Deposition (SLD) is a coating and fabrication process combining cold spray (CS) with laser heating of the deposition zone. Laser heating increases deformation on impact, improving bonding for a given particle velocity, eliminating the need to use helium while retaining the advantages of CS; solid-state deposition, low oxidation and high build rate (≤ 10 kg/hr). Although solid lubricants offer advantages over liquid lubrication, remaining effective over a wide range of operating temperatures and loads, while simplifying sealing, their use is limited by current application methods. SLD enables the deposition of metallic coatings which incorporate solid lubricants into metallic coatings, onto a range of substrates. This paper details the powders and conditions used to deposit nickel/graphite using SLD, and the structure and tribological properties of the coatings produced. Co-efficients of friction below 0.14 were demonstrated for nickel/graphite coatings on aluminium substrates.

Keywords. Supersonic Laser Deposition, Solid Lubricant, Metallic Coating.

1. Introduction

Friction and wear present a major engineering challenge. Oil and grease satisfy most requirements but do not perform well under all conditions. When loads and temperatures are high, or atmospheric pressure is low, liquid lubricants are unsuitable.

Typical solid lubricants include graphite, molybdenum disulphide (MoS_2), hexagonal boron nitride (hBN), and polytetrafluoroethylene (PTFE). Sintered composite materials produced via powder metallurgy can remain self-lubricating under extreme conditions [1]. The fraction of lubricant necessary is dependent on the load and matrix but typically varies between 6 and 20 vol% when using graphite as the lubricant [2].

While composites exhibit low friction and good wear resistance, they are manufactured as discrete blocks. Depositing coatings directly onto components is desirable [3] and has seen attention of authors using processes such as plasma spray [4], [5], high velocity oxy-fuel spraying [6], and laser cladding [7]. In these processes, solid lubricants are degraded by the temperatures experienced during deposition and co-efficients of friction (CoF) comparable with sintered composites have not been achieved.

The low temperatures the feedstock is exposed to in CS make it an attractive option for the deposition of solid lubricants. CS has been tested with both hBN [8] and MoS_2 [9]

¹ Corresponding Author. andrew@laserfusiontech.com

with little success. Only mixtures containing ≤ 5 vol% lubricant have been shown to form coatings, while friction and wear performance have not improved.

Metal coated lubricant particles show more promise. Huang et al[10] deposited nickel coated graphite (NCG) with aluminium powder. The CoF for the composite coating was lower than aluminium. However, after 10 minutes of testing, the CoF of the composite coating increased from 0.16 to 0.22 suggesting a lack of durability over time.

Segall et al[11] reasoned that a minimum metal cladding thickness is required for lubricant particles to survive spraying. Nickel coated hBN powders were produced an Ni fraction of up to 68 vol% to aid lubricant capture. The CoF for the coatings produced was improved to 0.2, approximately half of the value recorded for pure nickel.

Supersonic Laser Deposition (SLD) is a hybrid coating and fabrication process in which a supersonic powder stream similar to that found in found in Cold Spray (CS) impinges on a substrate which is simultaneously heated with a laser. SLD retains the advantages of CS: solid-state deposition, high build rate (≤ 10 kg hr^{-1}), while reducing the costs arising from the use of extensive gas heating and large volumes of helium[12], and allowing the range of materials deposited to expand to higher strength materials[13], [14].

In SLD, the softened substrate allows particle velocity to be reduced, the powder undergoes less deformation on impact while the temperatures experienced are below those found in cladding or plasma spray. SLD is an ideal candidate to deliver and embed solid lubricants in hard metal matrices, forming durable, self-lubricating coatings.

In this paper, the ability of SLD to deposit lubricating coatings onto both aluminium and titanium substrates is examined. The deposition behavior of coated and uncoated lubricant particles are compared, and the tribological performance of selected coatings is characterized.

2. Experiments

3 mm thick 6082-T6 aluminium and grade 2 titanium were selected as substrates. Substrates were ground using 320 grit SiC paper before being washed in ethanol.

Nickel, graphite and NCG powders were used in this study. Spherical nickel powder with a D50 of 25 μm was supplied by Sandvik Osprey Ltd. Irregular graphite powder specified as 95% < 53 μm , was supplied by Innoxia Ltd. Nickel coated graphite, supplied by Oerlikon Metco, consisted of irregular graphite flakes coated in 3-4 μm thick nickel shells to give a graphite fraction of 41 vol% and a particle size range of 30-90 μm . Micrographs showing polished cross sections of the three powder types are shown in figure 1.

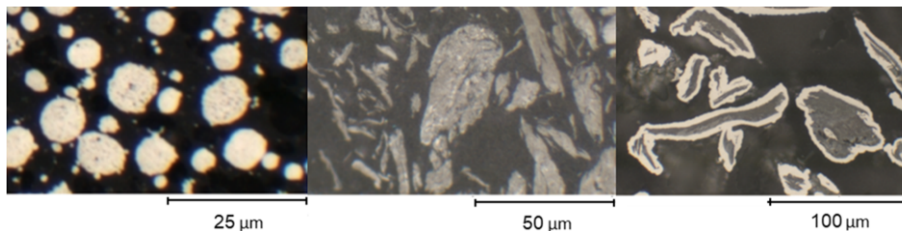


Figure 1. Cross sections of nickel (left), graphite (centre) and nickel coated graphite (NCG) (right) powders.

The SLD equipment used in this study, figure 2, consists of an in-house developed cold spray system which operates with 30 bar, 500°C nitrogen gas, and a linear de Laval

nozzle. Substrate heating is provided by an IPG photonics 4 kW, 1070 nm wavelength fibre laser operating out of focus to produce a 6 mm spot on the substrate. Deposition temperature is monitored using an IMPAC IGAR 12-LO infra-red pyrometer. This can control laser power through a PID loop allowing a consistent temperature to be maintained during deposition.

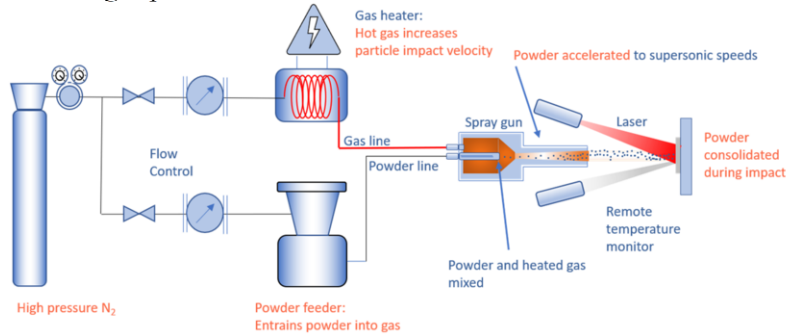


Figure 2. Schematic of SLD system

Single lines were deposited using parameters given in table 1. These were examined to determine the most promising feedstock compositions and deposition parameters to carry forward to produce coatings for wear testing.

Table 1. Parameters for deposition trials

Substrate	Lubricant powder	Graphite (vol%)	Gas pressure (bar)	Gas Temp (°C)	Traverse rate (mms ⁻¹)	Laser power (W)
Al 6082	Graphite+NCG	0-41	30	500	40-100	0-1500
Ti Gd2	Graphite+NCG	0-41	30	500	40-100	0-1200

Deposits were sectioned using a Struers Secotom-10 saw, mounted using an Opal 400 hot press (ATA GmbH), polished using a Saphir 550 metallographic polishing machine (ATA GmbH) and examined using an Olympus BX51 optical microscope. Aquinto A4i image analysis software, was used to measure track cross sectional area, porosity and graphite content.

Pin-on-disc friction and wear tests were completed according to ASTM-G99 at ESR Technology Ltd. A EN13 hardened steel pin 50 mm radius was applied to the rotating samples with a 20 N load, wear track diameters of 18-23 mm, rotation rates of 50-150 RPM and test durations of 30 to 125 minutes were employed in testing. The pin was replaced between each test. Samples were scanned using a 3D WLI non-contacting profilometer calculate the volume of material removed and therefore the specific wear rate.

3. Results & Discussion

Track cross sectional area increased with laser power for all feedstock compositions, figure 3. Pure nickel and the 17 vol% graphite Ni/NCG feedstocks deposited when cold sprayed. Other compositions required a threshold power to be exceeded before deposition occurred. While Ni/graphite mixtures did not match the build rate, of nickel alone, 17 vol% graphite Ni/NCG feedstock resulted in track areas approximately 100%

greater than uncoated graphite for the same composition. This suggests that the nickel shells are effective in aiding deposition and bonding.

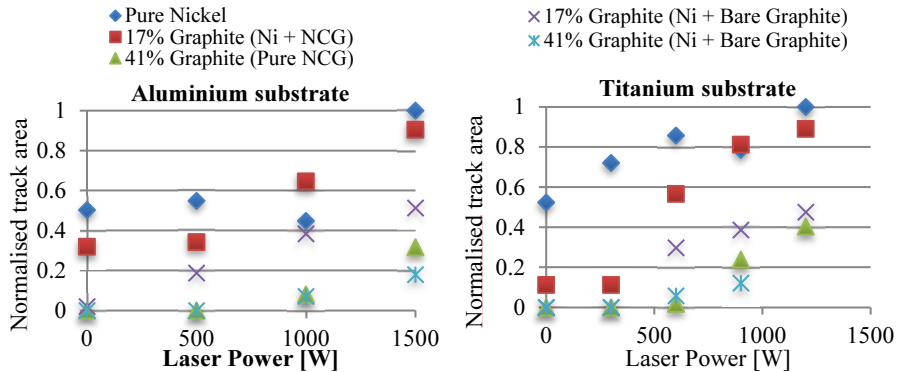


Figure 3. Track cross sectional area as a function of laser power for a range of feedstock compositions on both aluminium and titanium substrates at a traverse rate of 60 mms^{-1}

Cross sections of representative deposits, figure 4, show that although the nickel/graphite mixture has deposited, it does not contain visible graphite and is unlikely to provide improved tribological properties over nickel alone.

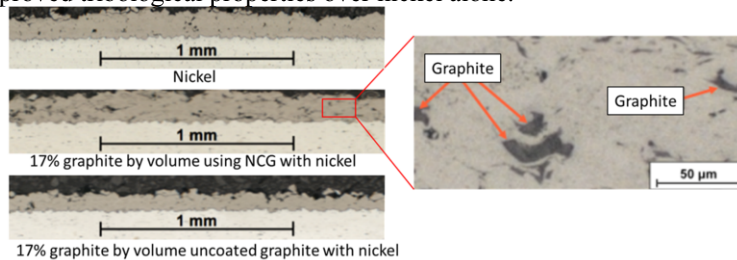


Figure 4. Cross-sections of single lines deposited from nickel, nickel + NCG, and nickel + graphite on aluminium using 1500 W. Only the nickel + NCG coating contained significant graphite

Graphite content and porosity, for a given feedstock composition, improved with deposition site temperature, figure 5. Graphite content was greater for tracks deposited on aluminium substrates reaching a maximum of 17.4 vol%. Given this finding, coatings for wear testing were deposited onto aluminium using 500°C , 30 bar nitrogen gas, a traverse rate of 40 mms^{-1} , track separation of 3 mm and a laser powder of 1500 W. The composition and porosity of the coatings produced are detailed in table 2. In each case the graphite content reduced when going from single tracks to overlapping deposits suggesting that the deposition of each overlapping track has led to preferential erosion of the graphite content of the preceding track. Despite this, the 30 vol% graphite feedstock resulted in a coating whose lubricant content lies in the 6-20 vol% range for effective lubrication described in the literature.

Table 2. Graphite and porosity in nickel and nickel/NCG coatings

Sample	Porosity in single track	Porosity in coating	Graphite in single track	Graphite in coating
Nickel	1.1%	0.9%	0%	0%
17 vol% graphite	1.5%	6.32%	4.1%	3.1%
30 vol% graphite	6.3%	2.5%	17.4%	13.3%

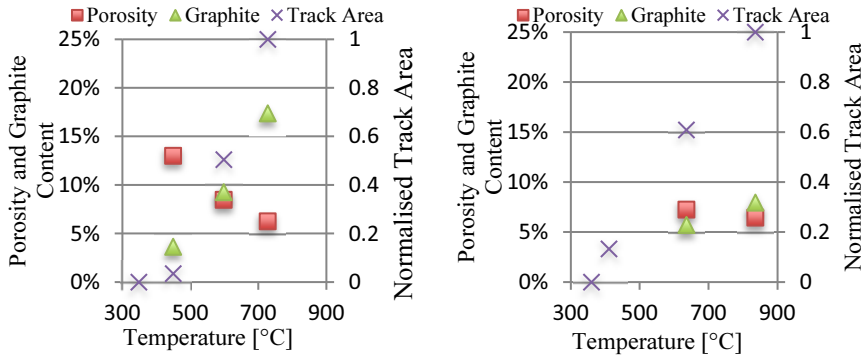


Figure 5. Track area, porosity and graphite content as a function of temperature on aluminium (left) and titanium (right) substrates for the Ni/NCG feedstock containing 30 vol% graphite.

Pin-on-disc testing was carried out on Ni/NCG coatings containing 0, 3.1 and 13.3 vol% graphite with at least three tests carried out for each composition to test consistency. Samples were tested as deposited as surface contamination from finishing may influence test results.

Due to limitations of the test equipment, retaining the selected rotation speed for the three coatings types proved impossible. The high friction exhibited by the pure nickel coatings exceeded the load rating of the tribometer, requiring a reduction in rpm to complete testing. This was accounted for by normalizing run length, allowing results to be compared directly.

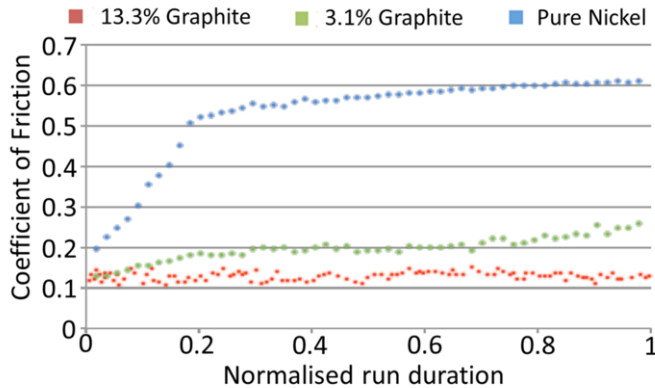


Figure 6. Reduced data showing coefficient of friction against time.

Typical results for each composition are compared in figure 6. After bedding in, the CoF for the nickel coating rose to approach the literature value for nickel against steel (0.64). The Ni/NCG coatings both exhibited reduced friction but only the 13.3 vol% coating maintained a consistent CoF (0.13) throughout the test. This is lower and more consistent than the values reported for cold sprayed Al/NCG [10] and comparable with sintered bronze/graphite bearings.

Table 3 summarizes friction wear data. Although CoF was consistent between samples, wear rate showed significant variability. Nickel and Ni/13.3 vol% graphite coatings have comparable wear rates, outperforming the 3.1 vol% graphite and the wear rates reported for aluminium substrates[4].

Table 3. Summary of wear test results.

Graphite content in powder	Graphite content	Average Coefficient of Friction	Average Wear Rate (m ³ /Nm)
0%	0%	0.54 ± 0.08	9.0 ± 6.4 × 10 ⁻¹⁴
17%	3.1%	0.18 ± 0.01	24 ± 9.7 × 10 ⁻¹⁴
30%	13.3%	0.13 ± 0.00	16.3 ± 5.5 × 10 ⁻¹⁴

4. Conclusions

SLD can successfully deposit nickel/graphite composites on to aluminium and titanium substrates when nickel coated graphite powder is used as the source of graphite.

For a given feedstock composition, deposit dimensions and graphite content increase with laser power and deposition site temperature.

Ni/graphite coatings can be produced with graphite contents in the range 6-20 vol% identified in the literature as providing effective lubrication.

Coatings containing 13.3 vol% graphite have low and consistent coefficients of friction, 0.13. This value is comparable to sintered composites, while offering an improvement over metal/solid lubricant coatings reported in the literature.

The wear rate of the coatings is variable but is comparable with SLD nickel coatings and better than that reported for aluminium.

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