

Metal matrix composite laser metal deposition for ballistic application

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Abstract. The armour development industry uses ceramic tiles to provide effective ballistic protection to critical areas of military vehicles. The ceramic tiles are generally attached to a ductile backing material by means of an adhesive, which often incorporates defects that are undesirable for ballistic protection. Laser cladding provides a more efficient approach for applying a ceramic material onto a ductile backing through metallurgically bonding the materials. A 3kW, IPG fiber laser system was used to manufacture test coupons to investigate the process parameters for the laser metal deposition of a tungsten carbide (chemical formula WC) metal matrix material onto an Armox 500 backing material. Results show that good fusion to the base material with limited solidification cracking can be achieved. Vickers microhardness and sound velocity results showed satisfactory results for a ballistic application.

1. Introduction

Ceramic materials offer excellent mechanical properties for ballistic applications, such as high modulus of elasticity, high hardness, high compressive strength, wear resistance and light weight [1, 2]. The primary drawback of ceramics is that they have fairly poor crack resistance, and hence they are used in combination with a ductile backing material [3]. The main purpose of the ceramic is to fragment the bullet and reduce its penetrability, whilst the purpose of the ductile backing is to absorb the kinetic energy of the bullet by plastic deformation [4, 5]. The ceramic material is conventionally bonded to the backing material by an adhesive, which may compromise the ballistic performance of the assembled component [6].

Laser metal deposition (LMD) or Laser Cladding (LC) is a process whereby material is deposited onto a substrate by essentially melting particles of the material to be deposited and the substrate with a high energy laser beam [7]. The process is a high energy, low heat input process with extremely fast cooling rates in excess of 2000° C/s. Due to the fast cooling rates, the deposited layer forms unique microstructures, e.g. extremely fine structures, which results in high hardness accompanied with high toughness [8]. The process also results in strong metallurgical bonding to the substrate, hence offering a more efficient approach that addresses the limitations of ceramic bonding by adhesive layers [7]. The main objective of this investigation is to address the limitations of bonding a ceramic material to Armox 500 by using a LMD process.



2. Experimental Procedure

A 3 kW IPG multi-mode Ytterbium fiber laser with a feeding fiber of 200 μm was used for the generation of all test coupons. A Precitec cladding head was used to give a beam spot diameter of 2 mm and 4 mm on the workpiece. WC metal matrix powder was deposited and melted onto Armax 500 substrate coupons that were milled clean and wiped with acetone. The argon carrier gas flow rate was kept constant at 2 l/min and a shielding gas flow rate of 10 l/min was also maintained.

Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) evaluation of the powder used for the laser metal deposition process was performed to ensure that the powder is suitable for the process. SEM and EDS analysis was obtained using a JEOL 610 LV plus microscope.

A metallurgical evaluation was conducted by taking cross-sections through the clad layers and observing the samples using an optical microscope. A Vickers micro-hardness analysis was performed with a Zwick Roell Indentec using a 500g load and dwell time of 10 seconds, 10 indentations were performed for each sample set. Sound velocity measurements were conducted using standard non-destructive evaluation (ultrasonic testing) equipment. Initially a powder investigation was conducted to identify the powder most suitable for the laser cladding of WC with different matrix compositions onto Armax 500. The preliminary experimental parameters for the respective powders are shown in table 1.

Table 1. Experimental parameters for identifying suitable powder.

WC Powder	Spot Size (mm)	Heat Input (kJ/m)	Powder flow rate (g/min)
Powder 1 (Co, Cr Matrix)	2	180	5.3
Powder 2 (Ni Matrix)	4	180	11.4
Powder 3 (Ni, Cr Matrix)	4	180	9.7

The parameters used to generate test coupons with the identified powder are listed in table 2. The laser beam spot diameter used was 4mm.

Table 2. Experimental Parameters of identified powder.

Sample No.	Laser Power (W)	Scanning Velocity (m/s)	Line Energy (kJ/m)
C1	2000	0.010	200
C2	1500	0.010	150
C3	1200	0.010	120
C4	1800	0.017	108
C5	1500	0.017	90
C6	1200	0.017	72
C7	1800	0.010	180
C8	2200	0.010	220
C9	2500	0.010	250

3. Results and Discussion

3.1. Powder Characterization

SEM analysis of the WC powders, with varying host matrix compositions, was performed to assess the morphology and particle size of the powders. The micrographs were obtained using back-scattered electron (BSE) mode to distinguish between the WC particles and the host matrix particles. The micrographs of the respective powders are shown in figure 1. Powder 1 has uniformly distributed particles which were composed of WC, Co and Cr. For powders 2 and 3 the WC particles are dispersed within the matrix particles. The lighter particles represent the WC particles, whilst the darker particles show the Nickel based matrix particles.

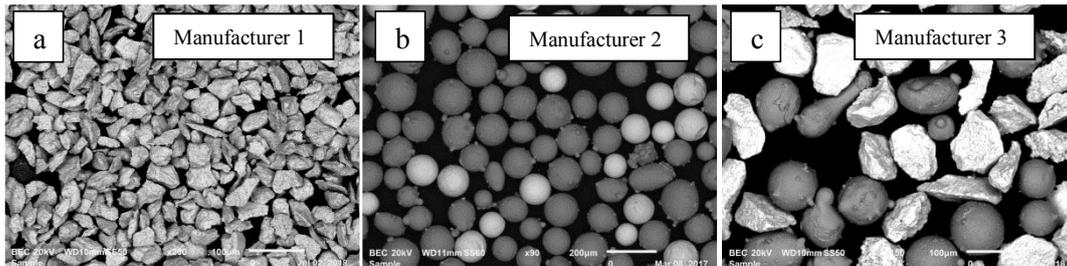


Figure 1. SEM micrographs of a) Powder 1, b) Powder 2, and c) Powder 3.

These results were confirmed by EDS analysis. From figure 1 it is evident that all the powders have different particle morphologies and different host matrices. The results of EDS analysis of the various powders is shown in table 3.

Table 3. Chemical Composition of the powders.

Powder	Main Elements
Powder 1	WC, Co, Cr
Powder 2	WC, Ni, Fe, Si
Powder 3	WC, Ni, Cr, Co, Fe

3.2. Metallurgical Evaluation

A Metallurgical evaluation was conducted by taking cross-sections through the clad layers and observing the samples with an optical microscope and SEM. Evaluation of the sample generated using a 2mm laser beam spot diameter showed that all of the WC particles were melted and that the clad layer that formed had multiple cracks and exhibited lack of fusion to the base metal. The result obtained using a 2mm beam spot diameter is undesirable for the proposed application, since the main objective was to metallurgically bond the ceramic composite to the ArmoX substrate while maintaining the WC particles distributed in the matrix. A 2mm beam spot diameter resulted in a high energy density which caused dissolution of the WC particles in the melt pool. The dissolution of these particles resulted in the formation of secondary phases which consequently resulted in an increase in the sensitivity to cracking [9].

Figure 2 show the micrographs of the samples generated using powders 2 and 3 respectively. The laser spot size was increased to 4mm, in order to reduce the energy density with the aim of limiting the cracking of the clad layers as well as minimizing the dissolution of the WC particles in the matrix.

In figure 2(a) the darker round spherical particles represent the suspended WC particles, similarly, the round light spherical particles shown in the clad layer of powder 3 represents the WC particles. Evidently the distribution of WC particles suspended within the host matrix is much greater for powder 2 than for powder 3.

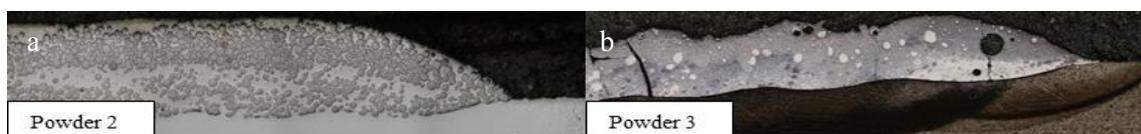


Figure 2. Optical micrograph of the cross section of the test coupon generated using (a) powder 2 and (b) powder 3.

The test coupon generated using powder 3 also shows the presence of cracking in the clad layer, which may be caused by the presence of the chromium (Cr) in the matrix. The Cr increases the precipitation of hard phases in the material, resulting in a more brittle structure, thereby increasing the material’s susceptibility to cracking [9, 10]. In addition, the presence of Cr in the powder increases the WC dissolution, as observed by Liyanage et.al [11]. Another factor to consider is the formation of brittle chromium carbide precipitates within the matrix since chromium has a high affinity for carbide formation. The cracking observed is undesirable for ballistic applications since any discontinuity or free surface in the material results in the reflection of an impacting pulse as a tensile wave. If the reflected tensile wave’s magnitude is larger than the tensile fracture strength of the material it will fracture [12].

Based on the results, especially the powder morphology, powder 2 appeared to be more suitable for the LMD process and the desired application. The LMD process parameters shown in table 2 were used to generate the test coupons. The resulting single clad layer heights and line energy values are provided in table 4.

Table 4. Summary of the effect of line energy (heat input) on clad layer thickness.

Sample No.	Line Energy, kJ/m	Clad layer height, μm
C1	200	388.2
C2	150	275.2
C3	120	203.5
C4	108	230.4
C5	90	197.2
C6	72	176.0
C7	180	387.8
C8	220	517.8
C9	250	593.9

The appearance of the clad layers produced is shown in the micrographs of figure 3. From figure 3 it is evident that good fusion was achieved between the clad layers and the Armox 500 substrates for the test coupons. This is a favourable outcome since it shows that the process may be used to eliminate the use of adhesives for the purpose of armour applications.

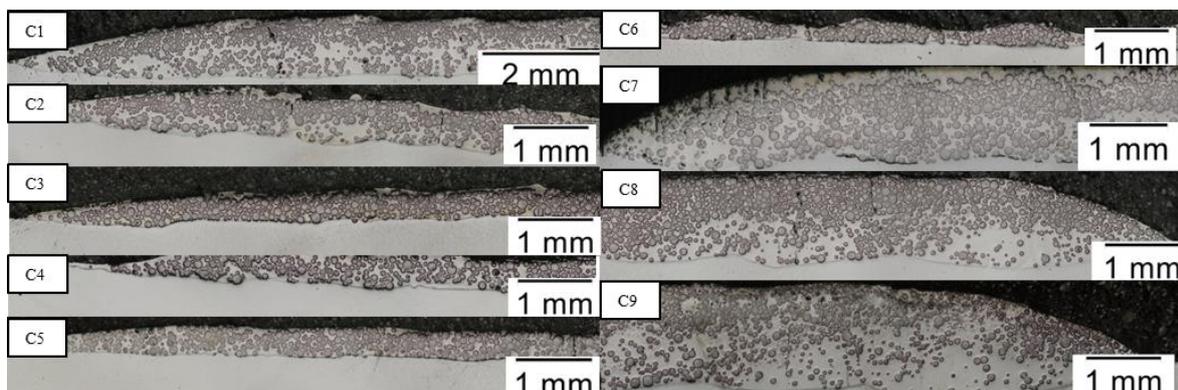


Figure 3. Optical micrographs of the cross section of the test coupons generated using powder 2.

Cracking becomes more prevalent with line energies greater than 180 kJ/which may be attributed to the increase in the WC dissolution which in turn increases the cracking sensitivity of the material [11]. Optimised parameters are those that result in good fusion, minimum WC particle dissolution, no clad layer cracking as well as minimum melt-in (dilution) into the base metal.

3.3. SEM analysis

Sample C7 was selected for SEM and EDS analysis since it produced a clad layer without cracking, together with good fusion and dispersion of WC particles in the host matrix. Figure 4 shows the SEM micrograph of the structure of the matrix and the suspended WC particles. The WC particles are suspended in a dendritic matrix. The dendritic phases are formed as a result of the rapid solidification during the laser metal deposition process. Similar results have been observed by Cheng et. al [13]. The EDS analysis confirms that the spherical particles consist of WC, whilst the dendritic matrix is composed of Ni, Si and Fe, with an increase in the concentration of Fe closer to the fusion line due to the dilution of the Armox 500 substrate.

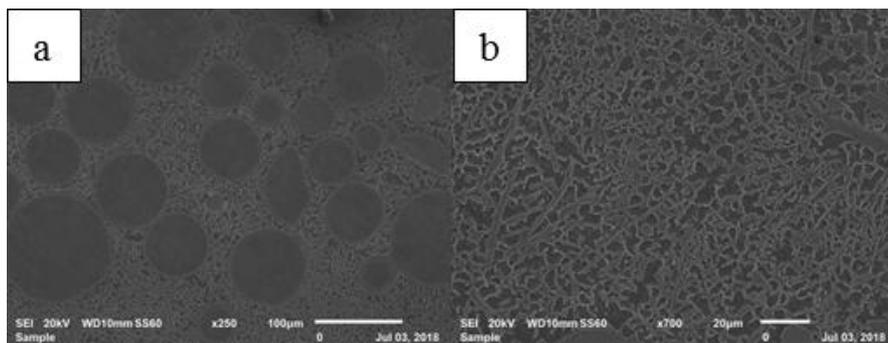


Figure 4. SEM micrograph of a) the WC particles suspended in the matrix, and b) the microstructure of the matrix.

The formation of dendritic microstructures as a result of rapid solidification has been known to increase the mechanical properties of materials [14]. The tempered martensitic microstructures have however been identified as the most suitable phases that provide the highest level of strength in armour steels. In addition, it possesses increased ductility and toughness, crucial for enhancing impact energy and strength [15].

3.4. Vickers Micro-hardness results

The Vickers micro-hardness of the particles and the metal matrix were evaluated to obtain an overview of the overall Vickers hardness profile of the clad material using the rule of mixtures (ROM), given that the composite layer consists of 60% WC particles and 40% metal matrix. A table with the average Vickers micro-hardness of the particles, metal matrix and the composite clad layer hardness is provided in table 5.

The Vickers hardness of the ceramic WC particles is significantly higher than that of the metallic matrix. This is expected since ceramics are characterized by high hardness [2]. The hardness of the matrix appears to have a linear relationship with an increase in process heat input (line energy), as shown in figure 5.

The linear relationship observed in figure 5 is attributed to the increased WC dissolution in the metal matrix with increasing heat input. The increased dissolution results in the formation of hard phases in the metal matrix, thereby increasing the overall Vickers micro-hardness of the metal matrix

[16, 17]. No relationship between the ceramic particle hardness and the heat input was observed since the particles are not changing phase during processing, i.e. melting.

Table 5. Average Vickers Micro-hardness results of the particles, metal matrix and composite clad layers based on the rule of mixtures.

Sample No.	Ave. Particle Hardness (HV)	Ave. Matrix Hardness (HV)	Composite Hardness (HV)
C1	2492 ± 375	642 ± 122	1752 ± 230
C2	2646 ± 313	595 ± 84	1826 ± 191
C3	2570 ± 391	578 ± 56	1773 ± 236
C4	2246 ± 432	548 ± 53	1567 ± 260
C5	2388 ± 728	549 ± 36	1652 ± 437
C6	2579 ± 176	587 ± 86	1782 ± 111
C7	2390 ± 862	614 ± 58	1680 ± 518
C8	2678 ± 104	642 ± 150	1864 ± 87
C9	2446 ± 358	694 ± 57	1745 ± 216

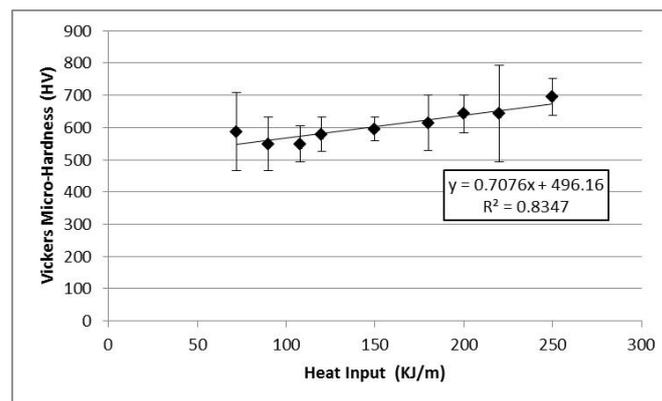


Figure 5. Graph illustrating the linear relationship between hardness of the metal matrix and heat input of the process.

The main purpose of the ceramic material in composite armour systems is to fragment the incident projectile, therefore a higher hardness can assist in increasing the abrasion of the incident projectile. Although increased hardness is useful, it should be mentioned that this may result in increased brittleness, which in turn results in an increased susceptibility to tensile cracking [18, 19]. It is envisaged that the softer metal matrix will assist in the absorption of additional kinetic energy from fragments of the projectile, whilst simultaneously providing some tensile strength to the composite material.

3.5. Sound Velocity Measurements

When a material is subjected to impact, the impact is propagated through the material as a wave pulse at a certain speed. Thus it translates to a finite time whereby the material is affected by the total applied impact. The speed, c_l of the wave is given by:

$$c_l = \left(\frac{E}{\rho}\right)^{\frac{1}{2}} \quad (1)$$

E and ρ represent the Young's Modulus and the density of the material respectively in which the wave pulse propagates [12]. The sound velocity is proportional to the energy dissipation capacity of the material, thus an increased sound velocity corresponds to increased ballistic performance [20].

The sound velocity of the clad layer was measured to be 6100 m/s. These results are comparable to the sound velocities of the ceramic materials that are currently in use by the armour industry [21].

4. Concluding remarks

The powder selection and laser cladding parameters most suitable for ballistic applications have been investigated. Results show that the powder with a Ni matrix produces clad layers with minimal cracking, even particle distribution, and good fusion to the base material. This indicates that the laser metal deposition process may be used to deposit (metallurgically bond) ceramic particles to ductile ArmoX backing material.

Analysis of the micrographs reveals that crack sensitivity increases as a function of heat input, and the corresponding metallic matrix forms dendritic microstructures. Vickers micro-hardness results show that the ceramic WC particles have a higher hardness than the softer metallic matrix. Additionally, sound velocity measurements show that the laser cladding process is suitable for producing materials for composite armour.

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5. References

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