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Additive manufacturing of compositionally gradient metal-ceramic structures: Stainless steel to vanadium carbide

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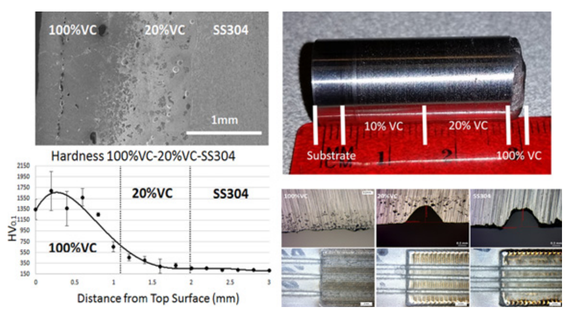
HIGHLIGHTS

- Direct additive manufacturing of compositionally gradient metal-ceramic structures
- Using LENS, SS304 to vanadium carbide structures were processed
- 100% vanadium carbide layer showed very high hardness and wear resistance

GRAPHICAL ABSTRACT



Additive Manufacturing of Compositionally Gradient Metal-Ceramic Structures: Stainless Steel to Vanadium Carbide

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ABSTRACT

Processing of hard, refractory ceramic coatings in a metal matrix is challenging due to various factors including delamination or cracking due to large material property differences at the interphase, and non-uniform distribution due to improper mixing. These issues can be reduced or even eliminated if the coating had a gradual change in material properties from the surface to the inside. Additive manufacturing is now being looked at to accomplish compositional control beyond the ability to produce net shape parts for repair as well as adding functionality. In this study, laser engineered net shaping (LENS™) was used to manufacture compositionally gradient structures of vanadium carbide (VC) and stainless steel 304 (SS304). Compositions ranging from 5 to 100 wt% of VC were mixed with SS304. The internal stress from the carbides significantly increased the hardness and wear resistance of the coatings. The 100%VC outer layer increased the hardness by 1450 HV and lowered the wear rate by 95% compared to SS304 substrate.

1. Introduction

Processing of ultra-high temperature ceramic coatings to metal is challenging. They are generally limited to techniques that have little to no flexibility in composition control or on-demand design changes [1]. These processes generally possess the ability to apply fully ceramic coating with little or no transition between the coating and the substrate. Such approaches create challenges such as increased probability of cracking, delamination, and stress fracture at high temperature due to large mismatch in coefficient of thermal expansion (CTE) [2]. In many cases, if a gradual change in material properties could be achieved, the likelihood of these types of failures could be decreased significantly [3]. If compositional variations can be controlled, coating material property can also be tailored locally. Laser engineered net shaping (LENS™) has now been looked at for manufacturing metal matrix composites

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with varying compositions apart from controlling size and shape based on a computer aided design (CAD) file. In this work, we have processed parts with varying compositions from 100% metal to a 100% ceramic in one operation to reduce the likelihood of failures from material property mismatch issues. Such an approach can also be used towards repair of parts with added functionality.

Surface modification is a common approach to enhance wear resistance. One of the main benefits of this method is that inexpensive materials can be used for the bulk of the part while more expensive ones are only used in small portions to improve surface properties [4]. Over the years, many hard, high modulus materials have been researched for use as coatings to be applied to components for increased wear resistance [4–9]. VC coatings have been used in the past to protect tools from damage, improve mechanical properties, lengthen service life, and increase corrosion resistance [10,11]. VC is an incredibly hard refractory ceramic that has excellent wear resistance, high elastic modulus (400 GPa) and melting temperature, and good strength retention even at high temperature [11]. VC has shown to increase protective properties when added to steel either as a coating or as a reinforcement phase in metal matrix composites (MMC) [10,11]. VC can be used to make a protective coating on steels in a few different ways. VC can diffuse into the grains and strengthen the lattice by substitution [12,13]. It can also be added as a precipitate and be dispersed in the steel making the coating an MMC [14]. These precipitates cause internal stress and increase both hardness and strength. Carbides can also be directly deposited on the surface to make a 100%VC coating to improve wear resistance.

VC and other vanadium compound coatings primarily have been applied using various reactive deposition methods [10,15]. These methods have proven to make very hard coatings with impressive properties of high hardness and good adhesion. There are some issues though. CVD requires high processing temperatures, while PVD needs expensive equipment and generally results in a weaker coating due to limited diffusion [15]. These coatings are also limited by diffusion and only yield coatings with a small depth and limited coating thickness [16]. This means there is very little depth of material that needs to be removed before the bulk material is exposed, and the part is just as vulnerable to damage as it would be without the coating. It would be ideal to have a coating with a larger depth and a gradual change in material properties to reduce the chance of cracking or delamination.

The directed energy deposition technique utilized in LENS™ has many advantages compared to those coating techniques. It has a fast processing speed, parameters can be accurately controlled, and can process complex shapes with compositional gradients [17]. It has been shown that VC coatings can be applied using Nd:YAG laser [13,14,17,18]. Out of these studies, though, none tried to make a compositionally gradient structure varying composition from 100% metal to 100% ceramic. It was hypothesized that LENS™ would be a viable process to manufacture compositionally gradient structures of VC and SS304. The scientific objective of this research was to understand the influence of compositional variation on physical, mechanical, and wear resistance VC-SS304 compositionally gradient structures. It is envisioned that such an approach may open up possibilities of processing parts via additive manufacturing in which not only the shape and size are controlled, but also the properties at different locations can be tailored based on application needs.

2. Materials and methods

2.1. LENS™ processing

VC powder was purchased from American Elements® with 99% purity and a particle size of −100/+270 mesh. 304/304L (SS304) powder was bought from Carpenter® with a powder size of −140/+325 mesh. The composition of the powder is listed in Table 1. SS304 and VC powders were mixed in proportions of 0%, 5%, 10%, and 20%wt.VC. Powders were weighed and mixed on a ball mill for 1 h to ensure thorough mixing and homogeneity. For the rest of this paper, coatings will be referred to by their respective VC content. Coatings were deposited on SS304 substrates. Hot rolled SS304 substrates were purchased from Penn Stainless Products and its constituent elements are also listed in Table 1.

Table 1
Chemical compositions of materials used (wt%).

	C	Cr	Ni	P	Si	Mn	S	N
304/304 L plate	0.022	18.15	8.05	0.033	0.44	1.72	0.0003	0.07
304/30 L powder	0.03	18 to 20	8 to 12	0.045	1	2	0.030	–

Coatings were made using a LENS 750 (Optomec Inc., Albuquerque, NM), which is shown in Fig. 1. LENS operates by having powder deposited under a focused Nd:YAG laser using argon transport. The powder flows at the focal point of the laser where it is melted and solidified on the substrate. The base plate moves in X and Y directions, while the head moves in the *Z*-direction. Build parameters are listed in Table 2. These parameters were used for all coatings apart from the 100%VC. This was done to keep consistency between the coatings, and only study how the addition of carbides changed the properties. However, the 100%VC samples were made differently because VC has a very high melting temperature (2810 °C) [11]. All samples were made in argon gas environment with chamber oxygen level below 30 ppm.

For each sample, two layers were deposited in a 10.7 mm × 14.7 mm rectangle with one contour. The only exception to this was the 100%VC, which was deposited twice on top of a 20%VC sample to make a gradient coating. For each composition, a sample was also made with an additional laser pass (1LP). This meant after the second layer was deposited, the powder feeder was shut off and the laser was run over the sample again at the same speed and power as it was built. This was done to further densify the surface of the coating and has shown in the past to increase the hardness of SS410 [19]. A sample was also made with a laser pass on each layer to see if that helped densify the coating. Also, to show proof of being able to make a gradient filling on a broken part, a 12 mm diameter cylinder was built with twenty layers of 10%VC, twenty layers of 20%VC, and five layers of 100%VC. All build parameters remained the same for the respective coatings of the cylinder.

2.2. Physical characterization

The microstructures were analyzed by grinding and polishing the top surface. Silicon carbide paper was used successively with 120, 300, 600 and 1000 grit sandpapers. Samples were then polished on a felt

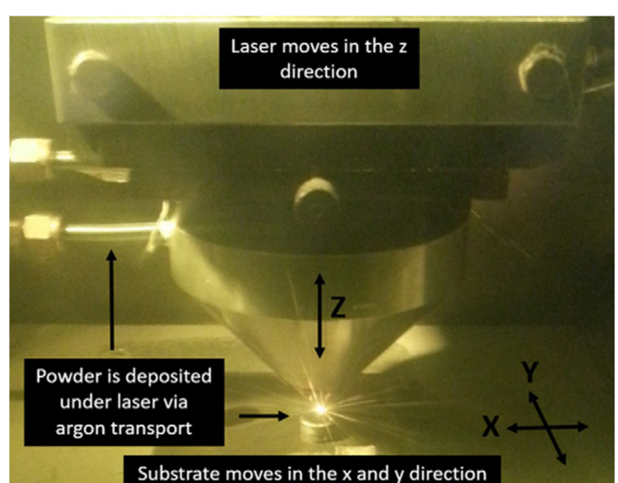

Fig. 1. Laser Engineering Net Shaping (LENS) – a directed energy deposition based additive manufacturing process.