**Laser and GTAW torch processing of Fe-Cr-B coatings on steel:**

**I- melt features**

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**ABSTRACT**

A comparison of a coating of Fe-Cr-B alloy powder processed on a plain carbon steel by surface melting using either laser or gas tungsten arc welding (GTAW) torch was made**.** The alloy powder was injected in laser melted surface, while the preplaced powder was melted using the GTAW technique.The topography of the GTAW tracks showed a relatively smooth surface, but the laser track surface was very rough. Because of high energy input, the GTAW method produced very wide and deep tracks with a high dilution compared to those of the laser tracks. Pores and fine cracks were seen in laser tracks; the cracks were elongated across the track width and some of them propagated down to the melt depth. The GTAW track produced at a low energy was free from any cracking, but a centerline crack was present when processed at a high energy input.

**Keywords:** Steel; Coating; Laser; GTAW torch; Topography; Depth; Dilution; Defects.

1. **INTRODUCTION**

Laser cladding uses a high energy input to produce a hard surface layer by melting the reinforcing material and the part of the substrate. This is known to provide improved wear and corrosion resistance compared to the untreated substrate. 1  Surface treatment using the laser technique involves a high cost of equipment and is relatively uneconomical due to the low processing speed, 2-4 which may make this technique unfavourable for total surface coating. An alternative, gas tungsten arc welding (GTAW) has been found to be adequate for modifying the surface layer of the base metal,5-9  but this method generates a large geometric dilution. Xu et al.10 reported that following coating a SUS403 stainless steel base metal with a Co-based alloy powder, the dilutions for the diode laser cladded samples were 4 and 7% when using output powers of 500 and 600 W, respectively. On the other hand, GTAW processed samples produced dilutions of 41 and 46% with heat inputs of 12~15 kJ/cm (100 and 120 A). In other work, Rakesh Paul et al.,11 studying the microstructure of a 1.2 mm thick sheet of stabilized 17 -wt% Cr stainless steel, observed columnar grains growing from the resolidified melt front to meet the axial grains at the centerline after both GTAW and CO2 laser melting. Using a 40CrMnMo7(1.2311) tool steel as the base metal and filler wire, Vedani 12 found that the hardened layer produced on a Nd-YAG laser melted sample was 300 µm in thickness, while it was 10 times deeper for the GTAW track. In two of these studies, stainless steel surfaces were modified either with or without adding Co-based alloy powder, while in the third case, a tool steel substrate was used employing a tool steel powder. The present paper is the first which compares Fe-Cr-B powder on plain carbon steel for both laser and GTAW surface engineering.

Fe-Cr-B SHS 7170 powder is known to be highly effective for surface protection against wear and corrosion.13, 14 The development of this alloy has concentrated entirely on a multi-component Fe-based amorphous alloy containing boron and /or carbon. Moreover, the nano-scale microstructure of ~100 nm in diameter, of the SHS 7170 gas atomized powder, is reported to provide a unique combination of high hardness and toughness, giving its strength 10 times that of conventional steel15, and these properties were associated with processing by HVOF spray coating, laser cladding and Laser Engineered Net Shaping (LENS) to produce coatings or components without losing feedstock’s partial amorphous structure. A limited amount of work has been reported previously on the use of this alloy powder for hard surface coatings. 16-18 The motivation for the work reported here was to compare the quality of coating produced on the substrate by melting preplaced SHS 7170 alloy powder surface under a conventional GTAW torch to that processed by powder injection on a laser melted surface. This paper describes the variation in surface topography, melt feature, dilution and defect of the coating layers processed using these methods. Part11 will discuss the hardness and related microstructure developed by the two surface engineering techniques.

1. **EXPERIMENTAL**

The substrate used in this study was 60x40x6 mm mild steel (BS08015). The laser experimental work was conducted at the Department of Mechanical, Materials and Manufacturing Engineering, Nottingham University in United Kingdom, while the GTAW work was conducted at the Department of Manufacturing and Materials Engineering, International Islamic University Malaysia (IIUM), both techniques using typical processing conditions. The SHS 7170 gas atomized powder was used as the reinforcing material to produce single tracks on the substrate surface. According to the manufacturer, the chemical composition of the powder is 18-22Cr, 3.9-7Mo, 5-6.5W, 2-4.9Mn, 0.3-1.9Si, 3-4B, and <0.4C (all in -wt%) with a nominal size in the range of 15 to 53 µm. A coaxial YLR-2000 ytterbium fiber laser with a wavelength at 1070 nm and a single phase GTAW machine type TIG165 were used to produce the coated samples under different processing conditions which are given in Tables 1 and 2, respectively. Metallographic specimens from the track vertical cross sections were prepared using a standard technique and polished cross sections were etched with acidic ferric chloride solution (25 g of FeCl3, 25 ml of HCl, and 100 ml of distilled water). The track width, total depth (melt depth + clad height), melt depth/penetration, clad height and heat affected zone (HAZ) were measured from the features revealed on the etched cross section under the optical microscope. Dilution of the processed samples was measured using an expression taken from the literature. 18, 19 It should be noted that dilution in this work refers to a change in clad dimensions, as distinct from when the term is associated with welding, which refers to changes in chemical composition.

A JEOL JSM 5600 scanning electron microscope was used to examine defects in the processed tracks. The heat inputs for the laser and GTAW processing were calculated using standard expressions from literature 18, 20, 21 The calculated energy input values for this work are given in Tables 1 and 2.

1. **RESULTS AND DISCUSSION**
   1. **Surface Topography**

Laser processing at 125 J/mm created a small melt pool with rough surface (Fig. 1a), while at 188 J/mm, a greater melt pool of wider track dimension was created (Fig. 1b). Sudden freezing of the melts resulted in of some blown powder adhering to the melt surface and consequently the tracks became rough and dull. Surface rippling marks occurred on all the GTAW tracks. The 1008 J/mm track had a relatively low dilution viscous melt, forming fewer ripples (Fig. 1c), while the 1296 J/mm track produced more melt fluidity which created fine ripples both in radial and traverse directions (Fig. 1d). Ripples were reported previously in both laser and GTAW processed composite coatings.20, 22-24

* 1. **Melt Geometry**

The data collated in Table 3 show that laser coated tracks produced smaller melt regions, associated with small heat affected zones (HAZ), compared to those of the GTAW tracks. With the same laser power (P) and beam diameter (D), the energy input (E = P/vD)18 is dependent on speed (v). So, at a slower scanning speed of 400 mm/min associated with the 188 J/mm track, more powder was blown on to a unit area compared to that of the 125 J/mm track processed at a higher speed of 600 mm/min. Compared to that of the 125 J/mm track, the greater powder mass in the 188 J/mm track experienced a longer interaction time for heating in the attenuated laser beam zone before being incorporated into the melt pool. For this reason the 188 J/mm track produced a greater total depth and width, with reduced penetration depth and dilution, compared to the 125 J/mm track. As seen in Table 3, the clad height is greater for the 188 J/mm track than for the 125 J/mm track. This signifies that at higher energy input, a greater proportion of the powder melted, but a smaller fraction was incorporated into the melt. At a faster speed associated with low energy input, a smaller amount of powder for heating in the attenuation zone was delivered, so a greater proportion of the beam energy remained to irradiate the substrate surface generating a deeper melt pool of 0.32 mm (Table 3). On the other hand, the greater volume of powder delivered in the 188 J/mm track absorbed more energy during their flight through the laser beam, leaving a smaller proportion of energy to heat the substrate surface. These conditions produced a shallow melt depth of 0.23 mm together with high clad height. Similar observations have been reported previously.25 In this work, after increasing the energy input from 125 to 188 J/mm, the width of laser track increased from 1.19 to 1.80 mm as did the HAZ, (Table 3). This was due to the longer time required by the high energy melted track to dissipate a greater amount of heat through the steel substrate.

GTAW tracks developed relatively large melt features with a very small clad height. The melt dimensions were smaller for the 1008 J/mm track than those processed at 1296 J/mm (Table 3). The reduction of melt size and HAZ with a decrease of energy input has also been recorded previously.23, 24, 26 Processing at a higher energy input generated a melt with a high temperature, requiring a longer time for the heat to dissipate. This resulted in a greater HAZ with the 1296 J/mm track compared to that processed at the lower energy. Also, the 1296 J/mm GTAW track created a melt thickness three times deeper and twice as wide as that of the 188 J/mm laser track (Table 3), showing that a larger melt pool can be attained by the low cost GTAW technique when compared with the more expensive laser processing technique.

* 1. **Dimensional Dilution**

The coatings formed in this work were mostly by alloying rather than cladding. The dilutions were found to be 41 and 63 % for laser tracks processed at 188 and 125 J/mm, while they were 87 and 95 % with GTAW tracks processed at 1008 and 1296 J/mm, respectively. The energy used in laser processing was very small, which melted more of the injected powder than the substrate. So the dilution was low relative to that found for the GTAW track (Table 3). However, Sun et al.25 reported dilutions of 50 to 85% when Stellite 6 was cladded on stainless steel using a laser pulse energy between 14 and 25 J/pulse. The factors that influence the dilution on laser samples are the substrate thermal conductivity, substrate temperature, powder flow rate, process speed and input power.27 By comparison, the GTAW tracks produced a greater melt depth with an increased dilution.

**Defects**

In general, the GTAW tracks produced fewer defects compared to the laser tracks. Pores and cracks were seen in laser tracks and these defects increased when processed at 188 J/mm (Figs. 2a and 2b). No such cracks were seen with the GTAW track processed at 1008 J/mm, although a pore was visible (Fig. 2c). However, a solidification crack was present in the 1296 J/mm track (Fig. 2d). Pores were reported to form due to gas entrapment during fast freezing of the melt20, 23, 24. Viscous melts generally entrap more gas. This explains why the 1008 J/mm GTAW (Fig. 2c) and 188 J/mm laser tracks (Fig. 2b) contain pores. The long solidification time of a high temperature melt, generated by the high energy input, allowed time for dissolved gas to escape. Therefore pores were not seen in the 1296 J/mm coating track (Fig. 2d). Large volume powder additions generate a low fluidity melt resulting in more gas entrapment on solidification. This explains why the low dilution (41%) 188 J/mm laser track has more pores compared to the 63% dilution laser track processed at 125 J/mm (Figs. 2a and 2b).

Since the number and size of the pores is related to the binder volume 20, 24,a reduction in the binder volume incorporated in the powder prior to pre-placement is likely to lower or eliminate pores, but diminish the adhesion of the powder. This may cause the powder to be blown away by the shielding gas during melting process, reducing the powder content in the melt track. The present observation suggests that either increasing the energy input or reducing the powder addition can generate a high temperature melt, which prolongs the solidification time, allowing time for entrapped gases to escape from the melt. Under these conditions, however, the low dimensional dilution state is inevitable sacrificed, since more melting of the substrate is believed to occur.

Cracks are a major concern in laser coating. In Fig. 2b, the crack extends from surface to the melt interface and micro cracks were seen near the fusion line (Fig. 3). These can form both at high and low temperatures.25 Whether cracks occur after solidification or during the cooling period depends on the planar tensile residual stress in the resolidified melt layer and its toughness. Cracks initiate when the strain generated due to the residual stress in the layer is higher than the plasticity of the coating. The residual stress is related to cooling rate, which depends on the melt volume and the temperature, while the toughness of a melt layer depends on its composition and microstructure, and related to the dilution. Therefore, cracks initiated at both high and low temperatures may be eliminated by reducing the cooling rate and minimizing the dilution 25.

The GTAW track processed at 1296 J/mm had a long solidification period, which was responsible for the development of microsegregation at the center of the melt pool, resulting in cracking at the grain boundaries (centerline cracking) along the glazing direction (Figs. 1d and 2d); the crack propagated down to the fusion line. On the other hand, the track processed with the low energy input of 1008 J/mm solidified faster, creating little microsegregation. This is presumed to have prevented cracking in this track, see Figs. 1c and 2c. It can be envisaged that with GTAW technique, minimizing the dilution using low energy melting may help to reduce or eliminate cracking.

1. **CONCLUSIONS**

In a study which compared nano-size Fe-Cr-B powder coatings on plain carbon steel processed by laser and by GTAW surface engineering methods, it has been found that:

* The laser tracks produced a dull rough surface with adherence of injected particles, while the GTAW tracks were smooth and shiny containing rippling marks.
* GTAW processing created more than 1 mm thickness coating layer but dimensional dilution was over 85%. By comparison, laser processed coating thickness was less than 50% of the GTAW track, with a reduced dilution. GTAW tracks produced a greater geometric size coating compared to the laser processed tracks.
* More pores and cracks were seen in laser tracks than in GTAW tracks. The GTAW track processed at 1008 J/mm was free from any cracks.

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**Table 1: Laser processing conditions.**

|  |  |  |
| --- | --- | --- |
| **Sample 1** | **Heat input: 125 J/mm; Speed: 600 mm/min** | |
| **Sample 2** | **Heat input: 188 J/mm; Speed: 400 mm/min** | |
| Power (Output power)  Laser waveform  Power feed nozzle angle  Shielding gas (Argon)  Offset distance  Spot size  Powder feed rate/Blown  Carrier gas  Etching solution | | 1200 W  1070 nm  0 degree  10 L//min  7.24 mm  0.96 mm  6 g/min  10 L/min  HCl+HNO3+Glycerol at 1:3:3 |

**Table 2: GTAW processing conditions.**

|  |  |  |  |
| --- | --- | --- | --- |
| **Sample 3** | | **Heat input: 1008 J/mm; Current: 70 A** | |
| **Sample 4** | | **Heat input: 1296 J/mm; Current: 90 A** | |
| Voltage  Travelling speed  Powder application  Powder amount  Shielding gas (Argon)  GTAW electrode  Offset distance  Etching solution | | 30 V  1 mm/s  Preplaced using PVA binder  0.5 mg/mm2  20 L//min  Ø2.4 mm thoriated tungsten  1 mm  Nital |

**Table 3: Melt configuration from the processed tracks (1 and 2 laser; 3 and 4 GTAW).**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Track**  **(Sample)** | **Energy**  **J/mm** | **Total depth**  **mm** | **Clad height mm** | **Width**  **mm** | **HAZ**  **mm** | **Melt depth**  **mm** | **Dilution**  **%** |
| 1 | 125 | 0.51 | 0.19 | 1.19 | 0.22 | 0.32 | 63 |
| 2 | 188 | 0.56 | 0.33 | 1.80 | 0.30 | 0.23 | 41 |
| 3 | 1008 | 1.30 | 0.17 | 3.10 | 0.85 | 1.13 | 87 |
| 4 | 1296 | 1.80 | 0.09 | 3.88 | 0.88 | 1.72 | 95 |

|  |  |
| --- | --- |
| New Picture (63)  **500 µm**  a | New Picture (64)  **500 µm**  b |
| New Picture (65)  **600 µm**  c | New Picture (66)  **600 µm**  **Crack**  d |
| Fig. 1: Surface topographies of laser samples glazed at: (a) 188 J/mm, (b) 125 J/mm and GTAW samples glazed at: (c) 1008 J/mm, (d) 1296 J/mm. | |

|  |  |
| --- | --- |
| Description: New Picture (69)  **Pore**  **200µm**  a | Description: New Picture (70)  **300µm**  **Crack**  **Pore**  **i**  b |
| Description: New Picture (67)  **500µm**  **Pore**  c | Description: New Picture (68)  **500µm**  **Crack**  d |
| Fig. 2: Melt cross sections of laser coating tracks processed at (a) 125 J/mm, (b) 188 J/mm and GTAW coating tracks processed at (c) 1008 J/mm, (d) 1296 J/mm. | |

|  |
| --- |
| New Picture (71)  Crack  Pore  Interface |
| **Fig. 3: Microcracks are present near the fusion line of track in Fig. 2b (i).** |

**List of Figure Captions:**

* **Fig. 1: Surface topographies of laser samples glazed at: (a) 188 J/mm, (b) 125 J/mm and GTAW samples glazed at: (c) 1008 J/mm, (d) 1296 J/mm.**
* Fig. 2: Melt cross sections of laser coating tracks processed at (a) 125 J/mm, (b) 188 J/mm and GTAW coating tracks processed at (c) 1008 J/mm, (d) 1296 J/mm.
* Fig. 3: Microcracks are present near the fusion line of track in Fig. 2b (i).