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A Study on Welding Characteristics of Laser Beam Coatings by Fe-Based Bulk Metallic Glass

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Abstract

In this study, the mechanical properties and microstructure of a surface hardenings coating layers formed by laser cladding using bulk metallic glass (BMG) wire as a filler, have been evaluated. The fabricated powder shape as a filler metal was observed as sphericalness, which is suitable for laser welding. X-ray diffraction analysis observed that the powder was fully amorphous. The mechanical properties were measured by tensile strength tests and micro-hardness tests, whereas the microstructure and grain structure were analyzed by using a field emission scanning electron microscope and transmission electron microscope. Surface coating was carried out by laser cladding and gas tungsten arc welding (GTAW) processes. The tensile strengths of the laser-clad and GTAW coatings were determined to be 2.0 and 1.7 GPa, respectively. The tensile strength and micro-hardness of the laser-clad coating were about 15% and 14.3% higher, respectively, than those of the GTAW coating. Additionally, the laser-clad coating showed finer grains and fewer dendrites due to reduced dendrite distribution. The BMG layer was composed of a mixture of α-Fe and amorphous phases.

Keywords: *Gas tungsten arc welding, Laser cladding, Bulk metallic glass, Amorphous, Surface hardening coating*

1. Introduction

Owing to rapid increase in the number of laser applications and the reduced cost of laser systems, material processing using lasers has become increasingly important in various industries. The laser technology is widely used for various purposes such as welding, cutting, and surface hardening in many industries including automobile, aerospace, power generation, oceanic, and defense. In recent years, it has received much attention because of its vast potential in material processing in areas such as metal coating, expensive component repair, prototyping, and even small-scale production [1-2]. As a processing method involving a high-density heat source, the laser processing technology has the advantage of minimal heat input for surface treatment, which results in a minimal heat affected zone and limited heat distortion [3-5]. Laser cladding is a processing technique in which two materials are fused by means of a laser beam, wherein a filler metal is added to the surface of the unreinforced matrix alloy (substrate) to endow the alloy with desired properties such as wear resistance, corrosion resistance, and heat resistance [6-7]. High-density energy is focused for localized heating, as a result of which the temperature of the heated zone of the specimen can be controlled very effectively. It is a welding technique that requires small heat input and yields superior joining properties. Therefore, it features the best properties of conventional thermal spray coating and thin-film coating.

In this paper, the laser cladding technique and gas tungsten arc welding (GTAW) surface coating technique, which is currently applied to various power generation equipment, are compared and analyzed by evaluating the mechanical and microstructural

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properties of coatings fabricated by the two methods. In the case of laser cladding, bulk metallic glass (BMG) wire has been used as the filler metal.

2. Materials and Experimental Method

2.1. Materials

The substrate used in this study was STS316L, which is widely used as a material for gas turbines, high-temperature bearings, hinges, and water tube boilers in modern power generation facilities. The filler metal was BMG wire (Fe-Cr-Mn-Mo-Si-B).

Table 1 shows the chemical composition and mechanical properties of the substrate (STS316L) and filler metal (BMG).

Table 1. Chemical Composition and Mechanical Properties of the Substrate and Filler Metal

(a) Chemical Compositions

Material (wt. %)	Cr	Ni	Mo	Mn	Si	B	C	Fe
Substrate	16.0-18.0	12.0-15.0	2.0-3.0	-	-	-	≤ 0.03	bal.
Filler	220-28.0	-	1.0-3.0	1.0-3.0	1.0-3.0	2.0-4.0	1.5-3.5	bal.

(b) Mechanical Properties

Material	Yield strength (N/mm^2)	Tensile strength (N/mm^2)	Elongation (%)	Hardness (Hv)
Substrate	≥ 175	≥7480	≥748	≤7480
Filler	≥ 2000	-	≥00	≥000e

2.2. Experimental Methods

The laser cladding device used in this study was LDF 2.500-150 procured from LASERLINE Co. (Germany). The wavelength of the high-power diode laser is 910-940 nm, and the maximum power is 2.5 kW. TIG STAR 350A produced by Panasonic Co. (Japan) was used as the welding apparatus for GTAW, and the inert gas argon was used as the shielding gas in the experiments. The processing conditions for the laser cladding and GTAW processes are shown in Table 2.

The substrate (STS316L) was prepared in accordance with the ASTM E08 standard for tensile testing, as shown in Figure 1. The 19.5 mm diameter rod was surface-coating welded. The post-weld diameter was 22 mm and after polishing, the diameter was 20 mm. The shape and penetration depth of the surface coating as well as its external appearance were observed, compared, and analyzed for each processing parameter, in areas of the coating surface where there were no defects such as pores or cracks.

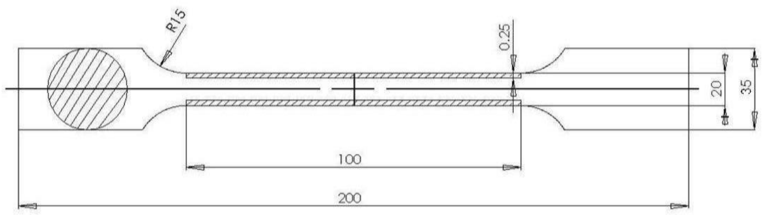


Figure 1. Specimens for Tensile Strength Measurements

Table 2. Processing Conditions for Laser Cladding and GTAW

Condition	GTAW	Laser cladding
Position	Flat	Flat
Current (A)	60	-
Power (W)	-	800.0
Wavelength (nm)	-	910-940
Shielding gas	Ar 100%	-
Lathe feed rate (mm/rev)	3	3
Spindle rotational speed (rpm)	10	10
Wire feed rate (mm/min)	200	220

3. Results and Discussion

3.1. Amorphous Alloy Powder

For laser welding alloy powder, a powder size of 20–70 ㎛ is most widely used. This is because when the powder size is less than 1 ㎛, liquidity is very low and agglomeration occurs, thereby making powder transportation difficult and when the powder size is over 100 ㎛, surface energy is very small thereby causing a difficulty in obtaining products with uniform properties. Thus, when a laser welding alloy powder is fabricated, size control is one of the most important factors. The gas atomizing method used in this study is a process that can control powder size, and is highly regarded as a suitable fabrication method for laser welding powders. Figure 2 shows the shape of the Fe-based alloy powder fabricated using a gas atomizer. The fabricated powder shape was revealed as spherical, which is suitable for laser welding because of good liquidity. X-ray diffraction analysis revealed that the powder was fully amorphous, showing typical broad amorphous peak, as shown in Figure 3.

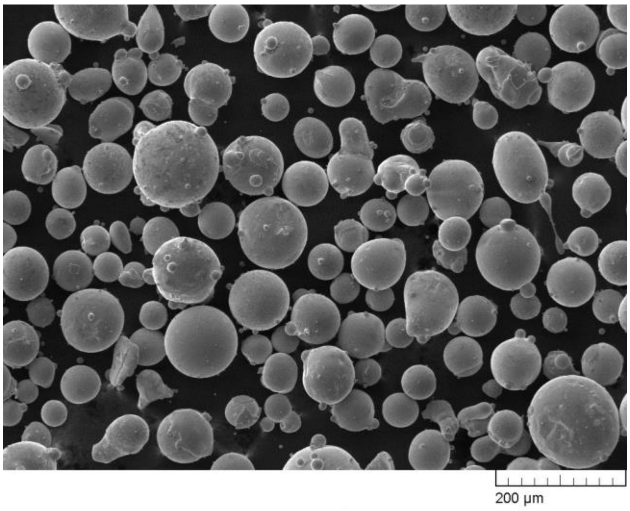


Figure 2. Shape of the Fe-Based Alloy Powder Fabricated

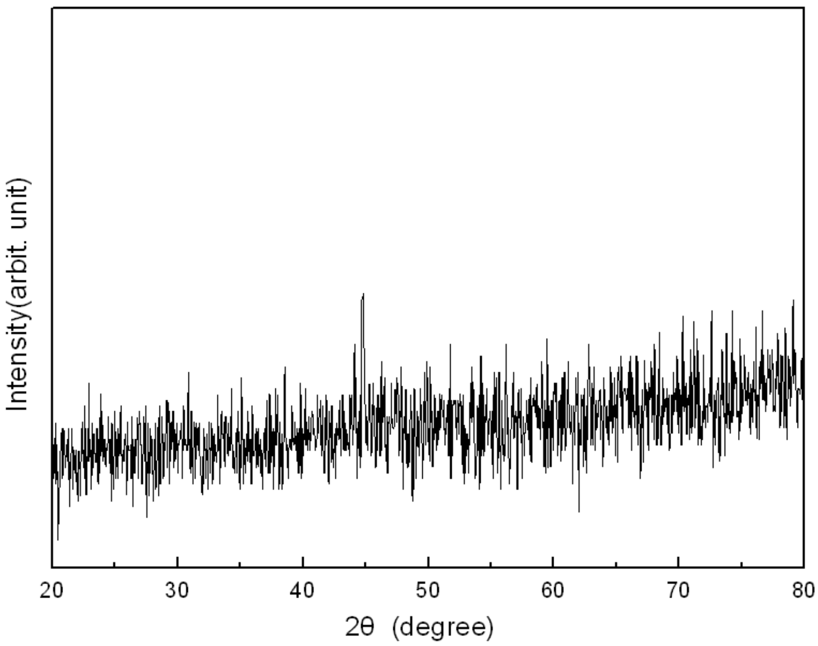


Figure 3. Peak of Fe-Based Alloy Powder Fabricated

3.2. Mechanical Properties

Tensile test measurements of the STS316L substrate revealed a cup-cone fracture, which is a type of ductile fracture on the fracture plane. The substrate also showed torn fibers. The tensile fracture planes of the laser-clad and GTAW coatings showed brittle fracture, whereas the fracture plane of the substrates showed ductile slant fracture. Laser cladding yielded thicker and wider dimples, which is also a type of ductile fracture, compared to GTAW, in the midsection of the rod. This is thought to be due to the lower deformation of the coating at the interface during the laser cladding process.

As shown in Figure 4, the yield strengths of the STS316L substrate and GTAW and laser cladding coated specimens were 292.1, 360.7, and 378.9 MPa, respectively, whereas the tensile strengths were 591.8, 534.8, and 568.9 MPa, respectively. Therefore, the tensile strength of the substrate (STS316L) was 9.63% and 3.86% higher than those of the GTAW and laser cladding coated specimens, respectively. However, the yield strengths of the GTAW and laser cladding coated specimens were higher than that of the substrate (STS316L) by 19.02% and 22.91%, respectively.

Generally, the yield strength is a more important mechanical property than tensile strength for metals used in structural products. This is because elastic deformation does not affect the appearance of the product, whereas plastic deformation changes the size or appearance of the product, decreasing its value. The yield strength of the coating can be calculated using Eq. (1), which is shown below.

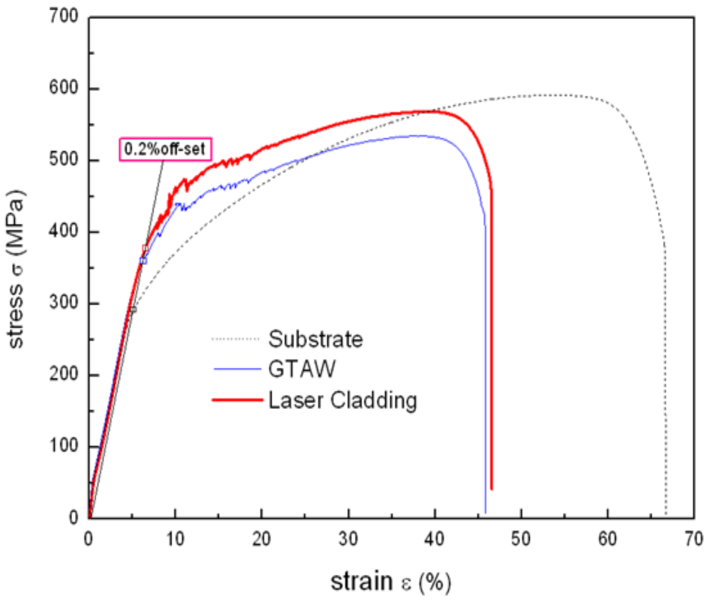


Figure 4. Strain-Stress Curves with the Coating Processes

$$\sigma_{Total} = \sum^{n}\left(\sigma_n \times \frac{A_n}{A_{Total}}\right) \quad (1)$$

$$\sigma_{Total} = \sigma_1 \times \frac{A_1}{A_{Total}} + \sigma_2 \times \frac{A_2}{A_{Total}} + \sigma_3 \frac{A_3}{A_{Total}}$$

$$\sigma_{Coating} = \frac{A_{Total}}{A_{Coating}}\left(\sigma_{Total} - \sigma_{Substrate} \times \frac{\sigma_{Substrate}}{\sigma_{Total}}\right)$$

Where σ is the yield strength and A is the cross-sectional area. Generally, the yield strength of Fe-BMG has been reported to be about 2 GPa [8-9]. Based on the above equation, the yield strengths of laser cladding and GTAW coated specimens were about 2.0 and 1.7 GPa, respectively. The yield strength of the laser-clad specimen was similar to that of amorphous Fe, which indicates that the laser cladding process does not reduce the yield strength of the coating.

Figure 5 shows the measured micro-hardness values of the substrate (STS316L), GTAW, and laser cladding coated specimens. As shown in the figure, the micro-hardness values of the substrate (STS316), GTAW coating and laser-clad layer were Hv 170.5±14, 718.1± 21.9, and 821.1±17, respectively.

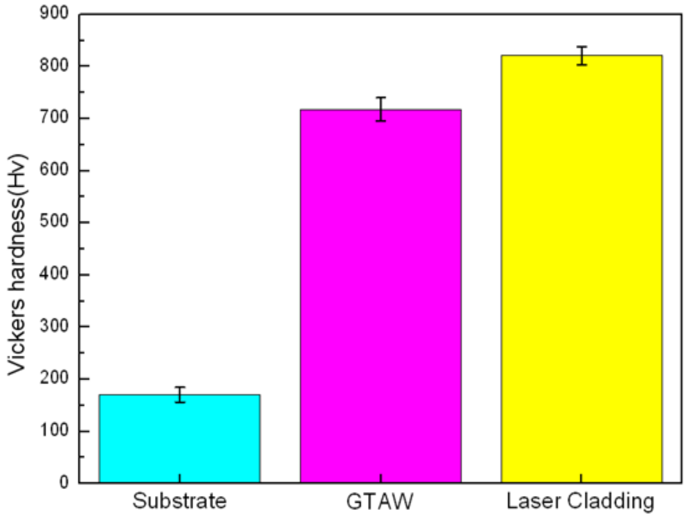
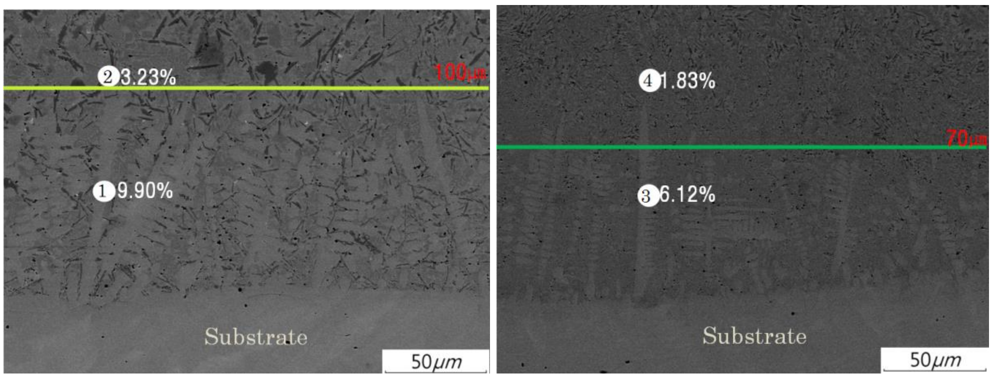


Figure 5. Micro-Hardness of the Coatings Produced by the Two Welding Processes

3.2. Microstructural Evaluation

Figure 6 shows micrographs of the GTAW and laser-clad coatings, observed using a high-resolution scanning electron microscope. The dendrite microstructures grew to distances of about 100 and 70 ㎛ from the substrate/coating interface to the inside of the coatings in the GTAW and laser cladding specimens, respectively. As shown in the figure, the laser-clad coatings exhibited smaller and denser grains than the GTAW coatings, as well as reduced distribution of tree-branch shaped dendrites, which are formed as a result of the compositional difference between the part that solidifies first and the part that solidifies later, when the molten alloy starts to solidify.



(a) GTAW (b) Laser Cladding

Figure 6. Microstructure of the Coatings Produced by GTAW and Laser Cladding

Quantitative analysis of the dendrite microstructure and needle-like structure of the GTAW coating revealed Ni contents of 9.90% and 3.23%, respectively, in the two layers. On the other hand, quantitative analysis of the dendrite microstructure and needle-like structure of the laser-clad coating showed that the Ni contents were 6.12% and 1.83%, respectively, as shown in Table 3. The STS316L mill sheet purchased from Posco had about 12-15% Ni content. However, the filler metal (BMG) developed in our study did not contain Ni. This shows that the surface of the substrate (STS316L) was melted more into the coating by the arc discharge-based GTAW process with high heat input compared to the laser cladding process, which uses a lower input heat and heats locally. Therefore, the dendrite microstructure can be considered to be a result of the melting and solidification of the substrate (STS316L). This melting/solidification process results in the formation of a substrate/BMG composite material, which greatly contributes to increased adhesive strength [10-11].

Table 3. Results of Quantitative Analysis (in wt. %)

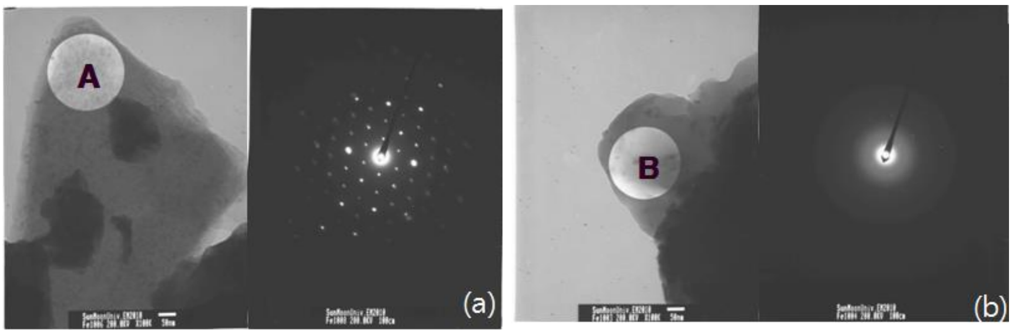
(a) GTAW

	C	Si	Cr	Fe	Ni	Mo	Mn
(1)	4.01	0.30	15.68	67.15	9.90	1.81	1.15
(2)	5.66	0.44	24.69	62.50	3.23	1.91	1.57

(b) Laser Cladding

	C	Si	Cr	Fe	Ni	Mo	Mn
(3)	4.16	1.55	12.68	74.03	6.12	0.37	1.09
(4)	6.15	0.13	31.59	56.17	1.83	2.53	1.59

Figure 7 shows micrographs of the BMG coating as observed with a transmission electron microscope (TEM). The selected area diffraction (SAD) pattern for part A is shown as a spot in Figure 5(a); this part is composed of the αthe crystal phase. On the other hand, part B is amorphous, as shown in the SAD pattern in Figure 5(b). Therefore, as revealed by the TEM analysis, the BMG layer was composed of a mixture of α-Fe and amorphous phases.



(a) α-Fe Crystal Phase (b) Amorphous

Figure 7. TEM Images of the Coating Layer

4. Conclusions

The STS316L substrate was coated using a laser cladding process with a laser cladding apparatus and BMG wire as the filler. The following conclusions were obtained from the results of the study.

1) In the case of the laser-clad coating, the substrate (STS316L) exhibited a 22.9% increase in yield strength, which is 3.89% higher than that achieved by GTAW processing. Therefore, the yield strength of the coating alone was about 15% higher by laser cladding than by GTAW processing.

2) The micro-hardness of the laser-clad coating was about Hv 100 (14.3%) higher than

that of the GTAW-processed coating.

3) The GTAW and laser cladding processes produced substrate/BMG composite layers that were about 100 and 70 ㎛ in thickness, respectively. Laser cladding resulted in smaller and denser grains in the coating compared to GTAW processing. In addition, the former process exhibited reduced distribution of dendrites compared to the latter process.

4) The BMG coating was composed of a mixture of α Fe and amorphous phases.

Bulk Metallic Glasses alloy has a characteristic of high-hardness and strength. However, it has a weak crack and impact resistance because of the brittle is too high. Laser cladding process supplements the corrosion and wear resistance of BMG's characteristic. It is a new technique without cracks and defects. So far, there is no case study by laser cladding technique using BMG as a filler metal. The heat input is low, as well as the joining characteristic is superior, we consider that is new joining technique with only superior characteristic of the existing thermal spray and thin film coating.

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