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Composition monitoring using plasma diagnostics during direct metal deposition (DMD) process

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ABSTRACT

The monitoring and controlling of the composition during laser additive manufacturing processes have attracted considerable attention since uniform composition is essential to maintain superior material properties of the fabricated part. In this study, the composition monitoring using plasma diagnostics is successfully carried out during direct metal deposition (DMD) process. Optical emission spectroscopy (OES) is employed to observe the Ni-base superalloy plasma generated during the DMD process. Composition prediction by line intensity ratios and plasma temperature is compared, and their monitoring performance is discussed.

Ni-I/Cr-I line ratios almost linearly increase with increasing Ni composition. However, the plasma temperature decreases with the Ni composition. It is also observed that bright and high temperature plasma is produced at relatively high Cr concentration (i.e., low Ni concentration) because of the low boiling point and preferential oxidation of the Cr.

The regression line of the line ratio data shows the better prediction of the Ni composition than that of the plasma temperature data. It is suggested that using the plasma temperature as a monitoring tool may not be suitable due to the non-linear characteristics and low sensitivity shown in the plasma temperature data. The regression line of the Ni-I (352.45 nm)/Cr-I (399.11 nm) line ratio gives the most accurate prediction compared with the regression lines for other combinations of Ni-I and Cr-I lines. The predicted Ni composition error by the Ni-I (352.45 nm)/Cr-I (399.11 nm) line ratio ranges from 0.02% to 4.5% (average 1.6%), which shows that using the line ratio for monitoring of the composition is quite reasonable. The method to predict Ni composition is also validated through the DMD experiment using as-received Inconel 718 powder with a certified Ni concentration of 50.9% (in atomic percentage). Average prediction for the Ni composition is 51.8% (error 1.6%) when the Ni-I (352.45 nm)/Cr-I (399.11 nm) line ratio is used.

1. Introduction

Direct metal deposition (DMD) is one of the laser additive manufacturing technologies that attract a great attention from many industries. It is essentially similar with laser cladding technology in that powdered metals are dropped on the substrate, and they are melted and deposited on it by a laser beam under an inert atmosphere. However, the DMD could fabricate near-net shape components by integrating the laser cladding technology with computer aided design (CAD) data, sensors and feedback control systems [1–10]. The potential of the DMD process in manufacturing industry is growing more and more. The direct fabrication of molds and dies and the repair of these parts as well as coatings of metallic parts for improvement of surface properties are mostly well known application [11–13]. Various applications for surgical instrument, aerospace and military industry have been also explored [14].

As described above, the DMD technology is a very attractive manufacturing process which is applicable to from surface coatings to complex three dimensional metallic parts in a one-step process. However, like other laser aided manufacturing processes, intrinsic instabilities due to complex laser-matter interaction always exist in the DMD process too. Theses instabilities can come from various sources such as non-uniform powder feed rate, laser power or laser-plasma interaction. The interaction between a shielding gas and melt pool also could be a source of the instability. The instabilities can affect composition and microstructure of the deposits, which in turn can change material properties of the deposits. Uniform elemental composition is important to maintain superior

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material properties in the deposited part. Therefore, the monitoring and controlling of the composition in deposits during the DMD process are highly required.

The plasma produced during laser-material interaction is the part that must be studied in all laser assisted manufacturing processes because a portion of laser beam energy is absorbed by plasmas, which can affect processes. In the DMD process, a certain portion of powders is bound to evaporate when the temperature of the melt pool exceeds a boiling temperature of the material, and this causes material loss of the melt pool during the deposition. The plasma formed from these evaporated materials including atoms, ions and electrons. They are closely related with the elemental composition of the melt pool. Therefore, the compositional information of the deposits could be estimated through the observation of the plasma.

Many studies associated with plasma diagnostics in laser material processing have been reported. Most of them are for laser ablation [15–21], welding [22–25] and drilling [26,27] that require high power density of the laser beam (>10^6 W/cm^2) for either removing or joining the material. Kumar [15] reported the effect of background gas on plasma during the laser ablation of the copper using optical emission spectroscopy (OES). According to results of the study, the intensity of emission lines increased in presence of a background gas (argon and neon gas) since the plasma was confined to a small region by collision between the background gas and plasma. Sibillano [22] studied the plasma diagnostics of the laser welding process. In this study, a spectrometer only collected emission lights from the top of the keyhole. Plasma temperature during the welding process decreased with laser power and penetration depth since deeper penetration by higher laser power shifted the hottest core of the plasma to the lower position in the keyhole. The plasma diagnostics using OES was also reported for laser drilling [27]. Temporal histories of the plasma parameters including emission line intensity, electron temperature, and number density were examined in relation to drilling depths. It was found that they had an inverse proportional relationship with the drilling depth because of the reduction of material removal and the downward movement of plasma core.

The plasma study for the laser additive manufacturing processes such as DMD or laser cladding process is very limited because of the difficulty in observation of the weak plasma generated by a relatively low power density beam (10^3–10^5 W/cm^2). Tewari [28] observed the plasma produced during laser cladding using OES method to correlate spectral data with elemental compositions in clads. Emission line intensities and their ratios for Nb and Hf atoms and Al ions were used to estimate a relative composition of the species in plasma. The quantitative correlations between line intensity ratios (Nb-I/Al-II and Nb-I/Hf-I) and the Nb concentration in clads were also obtained for different laser powers. It was shown that Nb-I/Al-II and Nb-I/Hf-I ratios linearly increase with increase in the concentration of Nb in the clad. Song et al. studied for the prediction of the real-time Cr composition during the DMD of the pure Cr and H13 tool steel material using OES [29]. In this study, alloyed H13 tool steel powders and high purity Cr powders are mechanically premixed to make different Cr composition in clads. Spectroscopic data including emission line intensity ratios (Cr-I/Fe-I), plasma temperature and electron number density were obtained for the DMD experiments using the powders with various Cr compositions, and they were correlated each other. According to results, the predicted Cr concentration using a line intensity ratio calibration curve was more accurate than that from both plasma temperature and electron number density calibration curve. The smallest error in the Cr concentrations predicted by the line intensity ratio calibration curve was 0.96% (in average). An accurate and robust method to improve the composition prediction performance of the DMD process was proposed [30]. In this study, Ti-Al binary metal powders were deposited onto Ti substrates by a fiber laser and the spectral signal of plasma plume during the process was collected by OES. In order to predict the Al concentration in deposits, a mathematical algorithm called support vector regression (SVR) method using spectroscopic parameters as inputs was adopted. The results from the study showed that more accurate prediction for the Al concentration was obtained when both line intensity ratio and line intensity were used as inputs than only line intensity ratio was considered. The SVR method proposed in this study also proved that accurate and universal operating parameter independent prediction was possible for varying operating condition during the process.

As described above, plasmas produced during laser material processing have been widely studied for various materials and processes. However, only a few studies have been reported for the plasma diagnostics of the laser additive process so far. In addition, no research has reported the observation of the Ni-base superalloy plasma during the DMD process. In this study, the spectroscopic data of the Ni-base superalloy plasma generated during the DMD process is analyzed in relation to the Ni composition in deposits for the first time. Composition prediction by line intensity ratios and plasma temperature is compared, and their monitoring performance is discussed. There is a well-known composition analysis technique called laser induced breakdown spectroscopy (LIBS) [31,32] which is also based on plasma diagnostics. This technique is able to give a fast and convenient method of composition analysis. However, the application of the LIBS is only confined to the surface analysis of materials. The method proposed in this study can provide not only surface composition but also internal composition of materials through the real-time monitoring of the plasma during the process. It is also expected that the plasma diagnostics from this study could be possibly used in the field of plasma-based deposition [33,34] and etching [35] processes for monitoring and controlling of the important physical and chemical properties.

2. Experimental details

A 6 kW CO_2 laser (TRUMP Inc.) with a focused beam diameter of 0.5 mm is used as a heat source to deposit material. A laser beam is focused via a copper turning mirror and gold coated focusing mirror. The laser is incorporated into an Allen-Bradley 3-axis CNC machine for precise control of the relative position between the laser beam and substrate. For DMD experiments, powders with five different Ni compositions are made by mechanical mixing of a gas-atomized Ni-base superalloy (Inconel 718) powder (−125/+45 mesh size) and high purity Cr powder (200 mesh size, 99%). After the DMD experiments, the final Ni compositions of the powders are confirmed through an energy dispersive spectrometer (EDS)

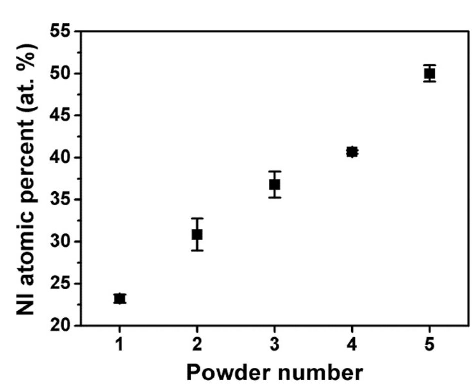

Fig. 1. Ni composition in the DMD layers deposited with five different powders (composition is measured with EDS).