

学 位 論 文 要 旨

題 目 Characterization of 308L Stainless Steel Coatings Fabricated by Laser Cladding
(レーザークラッド法により作製した 308L ステンレス鋼の特性評価)

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Laser hot wire cladding (LHWC) has proven to be a very efficient laser cladding manufacturing process with the advantages of fast deposition speed, high material utilization, and no environmental pollution. 308L stainless steel is widely used in petroleum, natural gas, shipbuilding, mining, and other fields owing to its excellent mechanical properties and corrosion resistance. Most current research on LHWC technology to prepare stainless steel coatings mainly focuses on optimizing the process parameters during the preparation process. Although there have been studies on the microstructure and mechanical properties, few studies have been conducted on the microstructure and performance of the matrix and the HAZ. There is also a lack of systematic research on the bonding properties of heterogeneous materials in laser cladding processes.

However, in practical applications, the substrate and cladding layer are applied as a whole, so it is not enough to study only the cladding layer, especially when the substrate and the cladding layer are different materials. The combination of the substrate and the cladding layer is also very important. To comprehensively analyze the laser welding process, it is needed to study not only the cladding layer but also the bonding process of the matrix and the cladding layer. It is necessary to characterize the microstructure and properties of each region separately, including the matrix, HAZ, and the cladding layer. These regions are then combined to completely characterize the microstructure evolution and mechanical properties of the products prepared using LHWC technology.

Multi-layer 308L stainless steel samples were prepared using the LHWC technique in this study. To comprehensively evaluate the samples, OM, EBSD, and other characterization techniques were used to determine the microstructure and crystal orientation of the whole sample section. The microstructure evolution of the matrix, HAZ, and the cladding layer, as well as the mechanical properties such as hardness and tensile properties of the multi-layer sample, were studied in detail. The solidification process was simulated in combination with numerical simulation techniques to determine the solidification mode of 308L stainless steel coating. In addition, the connection between microstructure and mechanical properties was explored, revealing the microstructure evolution law during the LHWC process. This study provides the theoretical basis for the 308L stainless steel coating application.

The conclusions of this thesis are summarized as follows:

- 1) The surface of the 308L stainless steel coating sample prepared by LHWC technology under appropriate process parameters was smooth. The height of the HAZ was 1.58mm. The height of the cladding layer was 11.84mm. The metallurgical bonding between the substrate and the cladding layer was good, proving the stability and reliability of the LHWC process. The 308L cladding layer consists mainly of dendritic austenite and columnar austenite, with δ -ferrite (content: 9%) distributed between the austenite grains. Equiaxed crystals are generated in the central region, and most of the columnar dendritic morphology in the edge region is located along the structural direction. There is a dilution zone

consisting of single austenite near the interface of the cladding layer. Carbon migration and low Cr content in the interface region are the main reasons for creating the dilution zone. From the bottom of the first layer to the top of the third layer, the grain morphology showed periodic changes. Inside each layer, columnar dendrites grew along the structural direction. The crystal morphologies of the coating from the bottom to the top was plane crystal, columnar dendritic, and equiaxed grain. Both FA mode and AF mode exist in the cladding layer, and FA mode is the primary solidification mode. The coexistence of FA mode and AF mode is caused by the cladding layer's different cooling rates and element segregation during solidification.

- 2) The interior of the cladding layer was mainly composed of columnar austenite grains that grew along the structural direction. 60% of the grains had a size larger than $19.7\mu\text{m}$, and the preferred orientation of the crystals in the cladding layer was evident. The matrix and the HAZ were refined equiaxed grains, with more than 60% concentrated below $16.2\mu\text{m}$, and the crystal orientations were randomly distributed without obviously preferred orientations. A large number of LAGBs were gathered near the fusion line of the HAZ and each cladding layer, which increased the strength macroscopically.
- 3) The microstructure of the HAZ region consists mainly of ferrite and tempered bainite. Slatted martensite produced by recrystallization can be observed in the part near the interface, and the presence of martensite can be inferred both from the Schaeffler diagram and the EBSD data; The element migration at the interface not only enhances the transformation of martensite but also leads to a smaller grain size of HAZ. No martensite was found in the substrate far away from the interface.
- 4) The HAZ of the sample had the highest hardness, while the matrix had the lowest hardness. The hardness was higher in the layer-to-layer fusion zone, and then gradually decreased with the increase of the cladding height inside each layer. The elongation of the cladding layer (44.8%) was higher than that of the fusion zone (32.1%) and matrix (20.4%). The tensile strength of the fusion zone was the highest, which was 585MPa. From the dimples in the sample section, it could be concluded that the fracture form of the sample from the matrix to the cladding layer was ductile fracture. Using the Hall-Petch relationship to establish the correlation between the material's microstructure (grain size) and mechanical properties (yield strength). The CRSS law proves the relationship between texture and yield behavior of metal materials, thus proving the influence of microstructure on mechanical properties.
- 5) The thermal cycle curves of specific regions and temperature changes during solidification were obtained. The results showed that the heat was mainly transferred downward by heat conduction during the cooling of the cladding layer. The cooling rate was different at different locations, and the temperature of the edge area dropped faster, in other words, the cooling rate was faster, resulting in different solidified structures. By combining the simulated temperature field with the experimental microstructure, it could be seen that the temperature gradient at the edge of the coating was the largest, consequently, the coating edge area is

dominated by columnar crystals. From the edge to the center, the temperature gradient became smaller and smaller and gradually reached the boundary of CET; the microstructure gradually turned to be dominated by equiaxed crystals. In addition, the equiaxed crystals were concentrated in the center of the cladding layer, the preferred orientation of crystals was weak, and the grain size was larger. In contrast, the edge region with more columnar crystals had the stronger selective orientation but the smaller crystal size.