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Microstructural characteristics of the built up layer of a precipitation hardened nickel based superalloy by electrospark deposition

M. Ebrahimnia [a], F. Malek Ghaini [a,*], Y.J. Xie [b], H. Shahverdi [a]

[a] Department of Materials Science and Engineering, Tarbiat Modares University, P.O. Box 14115-111, Tehran, Iran
[b] State Key Laboratory for Corrosion and Protection, Institute of Metal Research, Chinese Academy of Sciences, Shenyang 110016, China

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ABSTRACT

Buildup of precipitation hardened nickel base superalloys by electro spark deposition due to the low heat input of the process has many attractions. Characterization of the microstructure of the ESD built up layer of IN738LC over an as-cast base metal is accomplished in this work. The grain structure and solidification texture of the coating are investigated by orientation imaging microscopy (OIM), optical and scanning electron microscopy. It is shown that the deposited layer is formed mainly through epitaxial nucleation and growth on the base metal structure while discontinuities acting as nucleation sites produce fine grains with independent orientations. It is shown that such independent grains can have a significant role in improving the integrity of the ESD built up layer, since they can act as crack arrest sites and make the coating more resistant to the propagation of liquation and solidification fissures. Moreover, it is found that nanosized γ' precipitates exist in the coating indicating the high tendency of γ' for precipitation even in the extremely high cooling rates involved in the ESD process. Hardness measurements indicated a higher hardness for the built up layer which is attributable to the finer microstructure of the coating.

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1. Introduction

Electrospark deposition has many applications in rebuilding and coating conductive materials. Because of its very low heat input, it is ideal for rebuilding metals which are susceptible to heat affected zone (HAZ) cracking like nickel based superalloys [1–3]. Nickel based superalloys e.g. IN738LC have many applications in aerospace industries due to their excellent high temperature mechanical properties [4]. An exceptional combination of high-temperature strength and oxidation resistance is exhibited by the IN738LC, which has a γ' precipitation-strengthened nickel-based superalloy. It has been widely used in today's heavy-duty gas turbines for hot gas path components such as blades, vanes and heat shields, as previously reported by Hays [5].

IN738LC can encounter several obstacles when being welded with conventional fusion welding processes e.g. laser and GTAW [6,7]. Liquation cracks and solidification cracks are two main defects when welding or cladding this alloy with a filler metal with the same composition as the base metal.

Liquation of γ' particles, γ-γ' eutectic, MC carbides and Ni–Zr–B constituents in grain boundaries of HAZ, are responsible for liquation cracks in IN738LC [8,9]. Although there were many attempts to eliminate the liquation cracks in this alloy, few have been found to be effective regarding this issue [10–12].

Electrospark deposition of NiCoCrAlYTa alloy on directionally solidified nickel-based superalloy with 8 mm thickness shows high potential of using Ni base filler alloy for rebuilding industrial components [13]. However, because of hot cracking susceptibility of precipitation hardened alloys, most filler metals for electrospark deposition were designed with lower mechanical properties than those of the base metal. In a recent study by the author it was shown that IN738LC can be built up by electro spark deposition (ESD) process using a similar filler metal and then subjected to pulsed laser fusion processing to improve the integrity of the ESD deposited layer [1]. It was found that the ESD material has more resistance to liquation and solidification cracking than the cast base metal. ESD deposits consist of individual splats which are connected together by metallurgical bonding due to the partial melting of electrode and substrate. In this process, a round conductive electrode is electrically charged (positive pole) and is rotated closely relative to a stationary conductive substrate (negative pole), resulting in intimate contacts and discharges. Because of short duration high-current electrical pulses, sparking occurs between electrode and substrate. As a result of sparking, multiple small molten splats form and get detached from the electrode, then contact the surface and deposit on top of each other [14]. The mechanism of coating in this process has been the subject of a number of previous researches [15–21].

The objective of the current investigation is characterizing the microstructure of the ESD built up layer IN738LC over an as-cast

* Corresponding author. Tel.: +98 21828844388; fax: +98 2182884390.
E-mail addresses: ebrahimniya.m@gmail.com (M. Ebrahimnia), fmalek@modares.ac.ir (F. Malek Ghaini), yjxie@imr.ac.cn (Y.J. Xie), Shahverdi@modares.ac.ir (H. Shahverdi).

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component in order to establish the metallurgical features that can contribute to its improved resistance to liquation and solidification cracking.

2. Materials and methods

As-cast Inconel 738LC was used with the following chemical composition (wt.%): C 0.10, Cr 15.73, Co 8.38 W 3.02, Mo 2.16, Nb 0.70, Fe 0.12, Al 3.4, Ti 3.45, Ta 1.80, Zr 0.04, B 0.01, Ni balanced. Electrodes were cut from the same casting in the form of a round pillar with 4 mm diameter and 5 cm in length by electrical discharge machining (EDM)-wire cut machine.

Electro spark deposition of IN738LC was accomplished using an ESD machine developed at Tarbiat Modares University. The base metal was $100 \times 50 \times 5$ mm^3 rectangular plates machined from the as-received cast billets. In order to help the operator locating the rotating electrode on the target, a rectangle 10 mm × 10 mm with 0.5 mm depth was machined out from the base plate. ESD deposition was performed using a hand held gun with a co-axis argon shield gas with a flow rate of 15 L/min. Initially a number of tests were performed to establish a suitable ESD process window. The selected process parameters were: electrode rotation speed 2500 rpm, voltage 100 V, pulse frequency 250 Hz, and duty cycle 2.4%.

A number of samples were taken for metallographic characterization of the as deposited electrospark buildup layer of Inconel 738LC. For electron microscopy characterization, the specimens were etched electrolytically in 5% oxalic acid solution at 6 V for 5 s. For electroetching of the IN738LC metallographic samples, they were connected to the positive pole and a piece of stainless steel sheet was connected to the negative pole of a direct current power source.

An EPMA-1610 (Shimadzu, Japan) electron probe microanalyzer (EPMA) was used to analyze the chemical composition of ESD coating. The EPMA was operated at an accelerating voltage of 15 kV and a beam size of 1 μm and beam current of 10 nA for optimal spatial resolution for chemical composition analysis of deposited layer. Elemental map was acquired according to the elemental composition at an area of 15 μm × 15 μm with time of 2 h.

The orientation imaging microscopy (OIM) technique based on electron backscattered diffraction (EBSD) was used as an efficient method to study complicated microstructures formed during solidification after ESD processing. For observing the grain structure of ESD layer and its association with base metal grain structure, EBSD analysis was used. For this purpose, the samples were subjected to the standard metallographic preparation procedure starting with grinding on SiC grit papers (up to 2000), followed by polishing in diamond particle suspension (3 and 2.5 and 1 lm size) and then electropolishing in (HNO_3 30% + 70% ethanol vol.%) solution At 25 V for 3 s. This procedure resulted in good EBSD signal from the electrospark deposited layer and the substrate. TSL backscatter diffraction system installed inside a Philips XL 30 scanning electron microscope was used to collect OIM data. EBSD data and grain orientation measurements were obtained by TSL OIM Collection 5 and analyzed by TSL 5.31 OIM analysis software. The samples were mounted in the scanning electron microscope such that their surface normal was at 70° to the electron beam direction. The orientation of the crystal lattice at each predetermined sample surface point was then automatically determined in a sample coordinate system. Typical OIM scan in this experiment consists of 118745 points. Grain boundary lines presented in this work were constructed electronically using the criterion that a grain boundary between two points exists when the crystal misorientation angle between these two points exceeds 5°. Scanning was done with 1 μm step size.

Vickers microhardness measurement was carried out using a Leco LM 247AT microhardness machine. A hardness profile was carried out on the ESD layer from top of the layer toward the base metal/ESD layer interface. The load of microhardness measurement was set at 300 g and 15 s dwell time. TESCAN electron microscope and Carl Zeiss field emission electron microscope were used for microstructural study.

3. Results and discussion

Fig. 1-a shows an optical image of the ESD coating deposited on the IN738LC base metal (BM). ESD zone (ESDZ) has a thickness about 500 μm and consists of many tiny splats which were deposited subsequently to form a thick coating. Fig. 1-b shows the interface area with higher magnification. The different solidification products in the as cast base metal are labeled to help show different elemental segregations between as cast and ESD coating. Arrows show different constituents in the base metal microstructure mainly in the grain boundaries of the base metal like γ-γ′eutectic, MC carbides and terminal solidification products adjacent to the ESD zone which are the results of heavy elemental segregation in the as-cast base metal.

It is worth mentioning that the cooling rate in the ESD process is about 10^5 K s^{-1} which is much higher than that in the conventional fusion welding processes [1]. Because of the extreme cooling rate involved, there is no heavy elemental segregation in this process and this results in the prevention of formation of grain boundary terminal solidification constituents, which are the sources of liquation cracking in the cast alloy [1].

Electron probe microanalysis (EPMA) results also confirmed that there is very little elemental segregation in the ESD layer. Fig. 2 shows

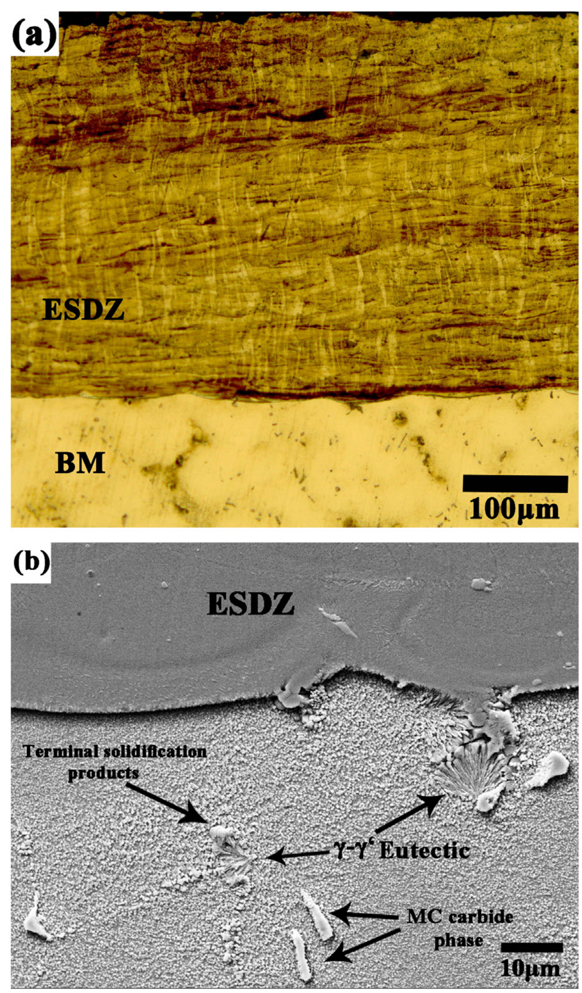

Fig. 1. Microstructure of ESD zone (ESDZ) and base metal (BM). a) 500 μm thickness ESD coating on the IN738LC base metal, b) arrows show different constituents in base metal microstructure mainly in the grain boundaries of base metal like γ-γ′eutectic, MC carbides and terminal solidification products adjacent to the ESDZ.

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