



The tensile deformation behavior of laser repaired Inconel 718 with a non-uniform microstructure

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ABSTRACT

Laser repairing technology, based on laser additive manufacturing technology, has been used in repairing damaged components for saving time and economic cost. Due to the existence of laser deposited zone, the microstructure and mechanical properties of laser repaired (LRed) components are different from original wrought parts. In this paper, the tensile deformation behavior of LRed Inconel 718 was compared with that of wrought Inconel 718 by using digital image correlation (DIC) method. The microstructure and the failure mechanism of LRed Inconel 718 were also investigated. The results showed that the LRed Inconel 718 sample could be divided into two parts: laser deposited zone (LDZ) and substrate zone (SZ). The laser deposited zone consisted of columnar dendrite growing epitaxially along the deposition direction, where the γ'' phases gathered around the interdendritic Laves phases. However, the microstructure of the substrate zone was equiaxed grain with the uniform distribution of δ and γ'' phases. It means that the microstructure of the LRed Inconel 718 was non-uniform. The deformation compatibility of the LRed Inconel 718 was inferior to that of the wrought Inconel 718 because of the existence of the Laves phases and the heterogeneous distribution of the γ'' phases. As a result, strain concentrated in the laser deposited zone resulting in that most plastic deformation was clustered in this region. The hard and brittle Laves phases slipped and broke up into smaller parts due to local stress concentration. Microscopic holes formed at the interface of the Laves phases and the γ matrix and combined together to cause the fracture of the LRed Inconel 718.

1. Introduction

Inconel 718 is one of the most common nickel-base superalloys which has been widely used in gas turbine disks, rocket motors, aircraft engines, nuclear reactors, pumps and blisks due to its good weldability, excellent creep resistance, high yield strength and high fatigue strength at elevated temperature [1–3]. However, for integral-structure parts such as blisks, mis-machining damage during manufacturing process and foreign object damage in service are occasionally happened, which bring huge losses of economy and time. Laser Repairing (LR) technology, which is based on Laser Additive Manufacturing (LAM) technology, has been considerable to be used in restoring both geometrical and mechanical properties of the damaged components.

Recent years, the microstructure and mechanical properties of

Inconel 718 fabricated by using LAM technology have become hot research topics [3–11]. Liu studied the influences of atmosphere [4], laser scanning path [5], recrystallization [6], residual stress [7], overlap rate [8] and intermediate heat treatment [9] on the microstructure and mechanical properties of Laser Additive Manufactured (LAMED) Inconel 718 in detail. Ma [3] investigated the effect of energy input on the microstructural architectures, dendritic morphology and precipitated phases of LAMED Inconel 718. Zhao [10] studied the effect of powder type on the microstructure and tensile property of LAMED Inconel 718 and found that the typical microstructures of LAMED Inconel 718 superalloy fabricated with different powders were columnar dendrites which grow epitaxially from the substrate.

Unlike the LAMED samples, the repairing of damaged components will reference to different microstructure, especially in the interface

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areas. Ming [11] indicated that the microstructure of substrate zone (SZ) was equiaxed grain while that of laser deposited zone (LDZ) was columnar crystal in Laser Repaired (LRed) Inconel 718. But he did not figure out the influence of such non-uniform microstructure on the mechanical properties. Tabernero [12] investigated the evaluation of the mechanical properties of LRed Inconel 718, but he did not connect this with non-uniform microstructure as well. Qi [13] found that the ductility of the direct-aged LRed Inconel 718 was reduced due to Laves particles that remain at the interdendritic region. Thus, although there are already a lot of researches about LAM Inconel 718, the investigation about the deformation and failure behavior of LRed Inconel 718 with non-uniform microstructure is still scarce. Similarly, there is still no consideration about the influence of the non-uniform microstructure on mechanical property of the partly repaired Inconel 718 samples by LAM.

Digital image correlation (DIC) is an effective and practical optical metrology technique which has been widely used in experimental mechanics fields, due to the advantages of easy operation, non-contact, full field optical measurement, high accuracy, high computational efficiency and so on [14–16]. For example, Yang [14] investigated the damage of granite under uniaxial tension by using DIC method; Zhu [17] studied the measurement of true stress-strain curves and the evolution of plastic zone of low carbon steel under uniaxial tension using DIC technology; and Saranath [18] investigated the mechanical behaviors of different zones in electron beam welded Ti-6Al-4V alloy by using DIC technique. Nevertheless, there is no researcher using this technology to investigate the deformation behavior of LRed Inconel 718 to author's knowledge. Besides, the technique can offer an easy and accurate method to analyze local properties for LRed Inconel 718 with a non-uniform microstructure. This can help us get better understand of deformation behavior of LRed Inconel 718.

In this paper, compared with wrought Inconel 718 samples with uniform microstructure, the tensile deformation behavior of LRed Inconel 718 with non-uniform microstructure was investigated by using DIC technique. In addition, the failure mechanism of LRed Inconel 718 was also studied by fractographic analysis as well. The consequences can help us get better knowledge of LAM technology on repairing damaged components.

2. Materials and experimental procedures

The substrate was 42 mm×24 mm×10 mm (length×width×height) wrought Inconel 718 alloy with a nominal chemical composition (wt%) of Mo 3.06, Nb 4.95, Cr 19.49, Ni 51.82, Al 0.61, Ti 0.95, and Fe balance. The surface of the substrate was polished to remove oxide skin by abrasive paper and cleaned with acetone before LAM process. The Plasma-Rotating Electrode Process (PREP) Inconel 718 spherical powder with a nominal chemical composition (wt%) of Mo 3.18, Nb 4.91, Cr 19.68, Ni 51.75, Al 0.63, Ti 0.97 and Fe balance were employed as the deposition material. The diameters of these PREP powders were 100–150 μm . Before LAM experiment, the powders were dried in a vacuum oven at 120 $^{\circ}\text{C} \pm 10^{\circ}\text{C}$ for 2 h.

The experiments were performed on the LSF-III B laser additive manufacturing system established by State Key Laboratory of Solidification Processing with the parameters listed in Table 1. This

Table 1
The parameters of LAM process.

Laser power (kW)	Scanning velocity (mm/s)	Laser spot diameter (mm)	Increment of Z axis (mm)	Power feeder rate (g/min)	Overlaps (%)
1.5–2.0	8–10	2	0.3–0.4	5	50

system consists of a 4 kW continuous wave CO_2 laser with the wavelength of 10.6 μm , a five-axis numerical control working table, an inert atmosphere processing chamber (oxygen content ≤ 50 ppm), a powder feeder with a coaxial nozzle and an adjustable automatic feeding device with high precision (typed DPSF-2), etc. The LRed Inconel 718 samples in which the volume fraction of the laser deposited zone are set to 50% are shown in Fig. 1(a) and (b). It can also be seen that the wrought substrate was put on the bottom and the laser repairing direction was upwards from the wrought substrate. The laser scanning direction was cross direction raster scanning as shown in Fig. (a). The green plane stood for the interface between the laser deposited zone and the wrought substrate. Direct age heat treatment (DA, 720 $^{\circ}\text{C} \times 8$ h/furnace cooling to 620 $^{\circ}\text{C} \times 8$ h/air cooling) was used for all the samples in case that the solution heat treatment would deteriorate the wrought substrate. Microstructural investigations were performed by optical microscope (OM) and scanning electron microscopy (SEM) after etched with an etching solution of 50 ml $\text{HCl} + 10$ ml $\text{HNO}_3 + 2$ ml $\text{HF} + 38$ ml H_2O . Uniaxial tensile test was carried out at room temperature by using a test machine typed INSTRON 3382. The tensile tests were conducted with a constant displacement rate of 2.5 mm/min. Fracture analysis was carried out by SEM and the deformation structure was observed by TEM (transmission electron microscope).

Digital image correlation (DIC) technology was used to obtain information of strain evolution of the specimen during tensile test (Fig. 2). Prior to tensile test, the full gage length of each specimen was sprayed with a randomized speckle pattern. Two high speed cameras integrated with data acquisition system were placed longitudinally and facing the full gage length to capture specimen images. During tensile test, the images were acquired at the rate of 10 fps (frames per second) and analyzed by using DIC software to get strain field distribution. The correlation algorithm used to evaluate the strain field is based on principle of tracking the movements of patterns within the images by comparing photographs of deformed specimens with that of an initial configuration [19].

3. Experimental results

3.1. Microstructure analysis

Typical microstructure of the direct-aged (DA) LRed Inconel 718 sample is featured in Fig. 3. Based on different microstructural characteristics, the specimen could be divided into two parts: laser deposited zone (LDZ) and substrate zone (SZ). Columnar dendrites grow epitaxially along the deposition direction in the LDZ. However, the microstructure of the SZ was equiaxed grain as shown in Fig. 3(a). Both zones combined together metallurgically.

During LAM process, most of the heat is dissipated through the substrate and the already deposited part as can be seen in Fig. 4. Vector Q_h represents the heat flux through the horizontal previously deposited zone due to the movement of the laser and vector Q_v represents the heat flux through the vertical previously deposited zone and the wrought substrate. In addition, vector Q_y represents another horizontal heat flux due to the heat dissipation through adjacent previously deposited zone. But it will be ignored in this paper because it is very small compared with Q_h and Q_v [3]. Q represents the actual heat flux direction. In this study, due to the small dimension (24 mm×10 mm) of the interface (the green plane in Fig. 1(a)), the heat is easy to accumulate and the heat loss is much lower in the horizontal direction compared with that in the vertical direction. That is to say, the value of Q_h is much smaller than that of Q_v . Therefore, the direction of vector Q is approximately parallel to the deposition direction. As a result, the directional columnar dendrite grows epitaxially from the bottom up based on the solidification theory [3,5]. The average primary dendrite spacing was about 10 μm due to the rapid solidification process in LAM [10]. Meanwhile, a large number of precipitates were observed in the

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