Effects of Solution Heat Treatment on Laves Phase and Corrosion Behaviors in Selective Laser Melted Inconel 718 Alloy

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Abstract. Effect of solution heat treatment on microstructure and electrochemical corrosion behaviors were investigated for the selective laser melted (SLM) Inconel 718 superalloy. Electrochemical results showed that solution treatment Inconel 718 has lower corrosion current density and bigger radius of the capacitive loop than as-deposited Inconel 718, means that the solution heat treated Inconel 718 has superior corrosion resistance than as-printed Inconel 718. Microstructure studies suggested that Nb-rich Laves phase widely distributed in the as-deposited Inconel 718 matrix, unlike less Laves phase is existed in annealed Inconel 718. The superior corrosion resistance of the solution heat treatment Inconel 718 could be elucidated by the removed Laves phase.

1. Introduction

Inconel 718 is a precipitation hardened nickel based superalloy, widely used in aerospace industry, nuclear and oil/gas applications [1, 2]. The slowly precipitation process of Inconel 718 make it suitable to selective laser melting (SLM) technology [3]. Compared with conventional processing method such as forging and casting, the SLM process could easily manufacture components with complex shapes and high dimensional accuracy [4]. Meanwhile, the SLM technology also has some defaults such as the γ/γ′ strength phase precipitation is inhibited during the process and high thermal stresses exited in the matrix, which is known for degrading material properties [5]. Therefore, the post heat treatment is required for SLM fabricated Inconel 718 to improve mechanical property or just release residual stress. There are numerous work has been reported aimed at clarifying the effects of heat treatment on microstructure and mechanical property, while the corrosion resistance study were limited [6, 7]. And the detailed mechanisms behind the heat treatment effect on corrosion resistance yet remain unclear. As the components made of Inconel 718 are mainly served in a strongly corrosion environment [8, 9], the corrosion resistance property is need to be given enough attention.

In this works, the solution heat treatment effect on the corrosion resistance of SLM-Inconel 718 has been investigated. The electrochemical measurements of electrochemical impedance spectroscopy (EIS) and Tafel polarization test were used to evaluate the corrosion resistance of SLM-Inconel 718.
superalloy [10, 11]. The relationships between the corrosion behaviors and the Laves phase evolution were also analyzed.

2. Experiment
The Inconel 718 superalloy has been fabricated by SLM, the elemental composition is Fe 18.50, Cr 18.00, Nb 5.30, Mo 3.00, Ti 0.95, Al 0.50, C 0.020, B 0.003, Ni Balance (wt. %). The process was executed under protective atmosphere of high purity argon with a beam spot size of 180μm and maximum power of 100W. The heat treatment process is 980℃ keeping 1h followed by air cooling (HT980). For microstructure observation, the samples were ground and fine polished to 0.5μm under silica suspension, and etched using Kalling’s 2 reagent.

For the electrochemical test, both heat treated and non-heat treated specimens were tested in 3.5wt. % NaCl solutions at room temperature. The SLM-fabricated Inconel 718 had a texture microstructure, and only its vertical sections (VS) with an area of 0.5cm² worked as the measured surface. The specimens were mechanically ground with a series of abrasive papers to 1000 grit, degreased with alcohol, and ultrasonically rinsed with distilled water. A platinum sheet and a saturated calomel electrode (SCE) were used as the counter electrode and reference electrode, respectively. Anodic polarization curves were obtained at a scan rate of 3mV/s. Electrochemical impedance spectroscopy (EIS) was performed with an AC amplitude of 10mV at OCP within 10⁵Hz to 10⁻²Hz frequency range.

3. Results

As is shown in Fig. 1.a, the as-print Inconel 718 microstructure exhibits distinctive segregation pattern of scan laser pool and high density dendrites. The dendrite structures revealed very high speed of cooling rates during the SLM process. Columnar grains have been observed carried a large amount of dendrites growing along the build direction and cross several successive layers. This growth behavior of columnar microstructure is generated owing to the high thermal gradient in the scan laser pool during the SLM process [12]. After the solution heat treatment (HT980), the optical microscope images exhibited columnar grains with disappeared scan laser pool and decreased dendritic segregation levels compared with as-printed state as seen in Fig. 1.b.
Figure 2. SEM image showing the Laves phase precipitation and dendritic segregation in a) as-printed, b) heat treated Inconel 718 fabricated by SLM.

Microstructures of the as-printed and annealed Inconel 718 are shown in Fig. 2. The dendritic growth result in typical segregation patterns for the heavy elements of Nb and Mo. The columnar dendrites and Nb-rich Laves phase is observed in Fig. 2.a. It is evident that the Laves phase is located in the inter-dendritic zones while the γ matrix is located in dendritic trunk. It is worth mention that Laves phase is widely distributed in the matrix and covered a certain area. Besides, the atomic compositions of the Laves phase is \((\text{Ni,Cr,Fe})_2(\text{Nb,Mo,Ti})\) and have a higher corrosion potential than γ matrix \([7, 13]\). The 980°C solution heat treatment (HT980) microstructure under SEM, the majority of metastable Laves particles were dissolved, reduced the micro-segregation degree in SLM-Inconel 718, as seen in Fig. 2.b. However, the residual Laves phase occur on γ matrix, revealed the γ matrix has not been completely homogenized.

Figure 3. Tafel Polarization curves of the SLM-fabricated Inconel 718 a) as-printed, b) heat treated state on the vertical -planes in 3.5wt. % NaCl solution.

The Tafel polarization curves of the as-printed and annealed Inconel 718 in 3.5wt. % NaCl solution are shown in Fig. 3.a. The corrosion potential of as-printed state (-0.29V) was higher slightly than that of annealed state (-0.30V). Furthermore, the corrosion current for annealed state (0.177μA·cm\(^{-2}\)) is lower than that of as-print Inconel 718 (0.187μA·cm\(^{-2}\)), indicating that the annealed Inconel 718 has a lower corrosion rate than as-print Inconel 718. The EIS result reflects a more significant difference before and after solution heat treatment, as seen as Fig. 3.b. The HT980 treated Inconel 718 has a larger capacitance radius than that of as-printed Inconel 718.

4. Discussion
The Laves phase micro-segregation can increase corrosion potential. The corrosion potential of solution treated Inconel 718 (-0.3V) is more negative than that of as-printed state (-0.29V), caused by
the lower corrosion potential of γ phase than secondary phases and the 980°C solution dissolved most of secondary phases on γ matrix. The Laves phase also increased corrosion current density and reduced corrosion resistance. The Laves phase that existed in inter-dendritic regions relay on its higher corrosion potential than γ phase would induce dendritic regions more sensitive to corrosion [7]. Company with the 980°C solution heat treatment removed Laves phase segregation, the corrosion induce effect of Laves phase to γ matrix was disappeared. As a result, the corrosion current density decreased from 0.187μA·cm² to 0.177μA·cm². According to Faraday's law the lower corrosion current density for annealed state revealed superior corrosion resistance. The electrochemical impedance spectroscopy (EIS) result is well consist with the Tafel polarization test. For electrochemical impedance spectroscopy (EIS) result, the high and medium frequency range of capacitive arcs is generally used to estimate the kinetic process of corrosion [11]. It is obvious that the 980°C solution treatment state has a bigger radius of the capacitive loop, revealed better corrosion resistance than as-printed Inconel 718 [14].

5. Conclusion
The widely distributed Laves phase can increase corrosion potential, furthermore, increase corrosion current density and reduced corrosion resistance. The solution treatment dissolved most of Laves phase which effectively eliminates the corrosion induced effect of Laves phase, resulting in the improved corrosion resistance for selective laser melted Inconel 718.

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