Influences of Soaking Time in Hot Isostatic Pressing on Strength of Inconel 718 Superalloy

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Hot Isostatic Pressing (HIP) is widely used in the casting industry to remove the internal porosity generated during the casting process. It combines higher pressure and temperature to produce materials and parts with substantially better properties than those by other methods. This results in improved strength, ductility and fatigue life of castings. The aim of this paper is to discuss the methods and to find a suitable soaking time of HIP for Inconel 718 superalloy castings. In this study, the HIP temperature was maintained at 1453 K, pressure was kept 175 MPa and three different soaking time are 2, 3 and 4 h. The experiment results show that HIP treatment at 1453 K under the pressure of 175 MPa for 4 h for Inconel 718 superalloy is the optimum condition. It can decrease the porosity of Inconel 718 superalloy castings. In this study, it can reduce porosity about 86% after HIP treatment. For the tension test at a fast strain rate (0.001 s⁻¹) that it increased the tensile strength by 31% at room temperature, 27% at 813 K, and 24% at 923 K. While at a very slow strain rate (0.0001 s⁻¹), it increased the tensile strength by 24% at room temperature and 20% at 813 K. For a 3-point bending test, it showed that the optimum soaking time of HIP procedure could enhance the bending strength by 38% at room temperature and 26% at 813 K.

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1. Introduction

HIP process applies heat and pressure within an enclosed vessel to consolidate or densify materials such as castings. It is a common method in the industry to improve strength and durability of the parts and remove voids from castings. HIP can be applied to a wide range of metals, alloy and ceramics. Functions of HIP processes include defect healing of castings, removal of internal porosity, diffusion bonding of dissimilar materials, improvement in property scatter and mechanical properties. Its major application is for eliminating casting defects.1–4) The development of HIP processing for superalloys started in the 1970’s when there was a need for improved materials in the hot sections of gas turbine engines. Inconel 718 superalloy is a niobium-modified nickel-base superalloy that is used widely in gas turbine and related high temperature of aerospace applications.5,6) Inconel 718 superalloy is a precipitation hardenable, nickel-based superalloy that has high strength at room temperature and excellent creep as well as fatigue strengths at high temperatures. It used in gas turbines, rocket motors, spacecraft, nuclear reactors, pumps and tooling. The alloy consist of several phases in the matrix including δ, γ’, γ” and NbC. However Inconel 718 is a nickel-rich alloy strengthened by order body centered tetragonal (BCT) precipitates, γ’.7–9)

In this experiment, the effects of different soaking time of HIP treatments on Inconel 718 superalloy and their influential parameters of HIP process were performed. The parameters of HIP process used including three different soaking times: 2, 3 and 4 h. Beside, the HIP temperature was maintained at 1453 K, and pressure was kept at 175 MPa. After HIP treatment, all the specimens were subjected to the following heat treatment: solution treated was performed at 1253 K for 1 h followed by N2 cooling, aged at 993 K for 8 h, furnace cooling (330 K/h) to 893 K, soaking for 8 h, and then air cooling to room temperature.10–12) The solution-treating and age-hardening were performed in a commercial German SCHMETZ vacuum furnace. Tension and bending tests of mechanical properties for Inconel 718 superalloy castings were conducted at room temperature as well as at a high temperature. The fracture surfaces of the tensile specimens were examined using SEM, X-ray diffraction, and porosity and microstructure inspection to evaluate the effects of different soaking time of HIP treatments on Inconel 718 superalloy.

2. Experimental

Inconel 718 nickel-based superalloys are defined as those alloys that have nickel as the major constituent, with a significant amount of chromium. This alloy may contain niobium, molybdenum, aluminium and titanium as major alloy additions. In this study, the chemical composition (mass%) of the HIP treated for Inconel 718 superalloy is as follows: 52.89% Ni, 17.3% Cr, 3.52% Mo, 5.26% Nb, 0.52% Al, 0.83% Ti, 19.36% Fe, 0.05% Mn, 0.07% C, 0.01% V, 0.08% W and 0.011% Co. The Inconel 718 superalloy casting was prepared by Vacuum Induction Melting (VIM) process. After melting, the alloy was solidified into square plate castings. All the specimens of tension and bending test were obtained from the castings by Wire Electronic Discharge Machining (WEDM) treatment. The specimen sizes of the tension and bending test are illustrated schematically in Fig. 1. For the tension and bending test, a SHIMADZU universal material test machine with a maximum load of 25 tons was used.

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In earlier study, the effects of the temperature and pressure parameters of HIP on Inconel 718 superalloy were discussed. Four different HIP temperatures were used, including 1423, 1448, 1453 and 1478 K. Four different HIP pressures were used, including 100, 150, 175, 200 MPa. It showed that optimum HIP temperature and pressure for Inconel 718 superalloy were 1453 K and 175 MPa, respectively. This paper will continue to discuss the effects of the soaking time of HIP on Inconel 718 superalloy casting. The HIP temperature was maintained at 1453 K, pressure was kept at 175 MPa and three different HIP soaking time were used: 2, 3 and 4 h. HIP equipment was from Flow Autoclave Pressure System, Inc. This commercial HIP equipment provided with an Uniform Rapid Cooling (URC) system that offers decreased cycle time, higher productivity and combined solution heat treating. The uniform rapid cooling rate can reach up to 290 K/min.

After HIP treatment, the solution and ageing treatment on Inconel 718 superalloy casting are needed. Because the Inconel 718 superalloy has a composite structure of austenite matrix and precipitated \(\gamma'\) and \(\gamma''\) phases produced by the heat treatment. The strengthening phase in the alloy is the metastable body centered tetragonal Ni\(_3\)Nb, \(\gamma''\). The creep phenomenon can’t be ignored in the condition of HIP and heat treatment. The mechanical properties depend on the morphology, size and contents of \(\delta\), \(\gamma'\) and \(\gamma''\) phases in Inconel 718 superalloy.\(^{13-19}\) In this experiment, the test specimens of Inconel 718 superalloy after HIP treatment were placed in a vacuum furnace and then solutionized at 1253 K for 1 h soaking followed by \(\mathrm{N}_2\) rapid cooling, aged at 993 K for 8 h, furnace cooling (330 K/h) to 893 K, soaking for 8 h, and finally air cooling to room temperature.\(^{12,16}\)

### 3. Results and Discussion

Inconel 718 superalloy is a face-centered cubic (FCC) austenite matrix strengthened by precipitation of order intermetallic or carbide precipitates. Both of \(\gamma''\) and \(\gamma'\) phases are found in alloy, but \(\gamma''\) is the predominant strengthening agent.\(^{17-19}\) HIP process is always used to close pores and flaws by plastic flow. Figure 2 shows the amount of porosity for Inconel 718 superalloy as a function of the soaking time of HIP treatment. The porosity was reduced proportionally to the soaking time of HIP treatment. In this study, it can reduce porosity about 78% at 2 h, 84% at 3 h and 86% after HIP treatment for 4 h. Because the Inconel 718 superalloy was used vacuum melting in production, it is hard to avoid the segregation, porosity and non-uniformity of the microstructure generated during solidification. These defects will degrade the mechanical properties of the superalloy.\(^{18-21}\)

The optical micrograph of the as-heat treated Inconel 718 superalloy after solutionized and aged treatment is shown in Fig. 3(a). It contains a severe segregation and casting microstructure, which was hard to remove from the casting structure. Beside, there are a few porosities existing on the microstructure of Inconel 718 superalloy casting. HIP process can densify the castings and improve strength, ductility and fatigue life of materials with significantly less variation from lot to lot. Figures 3(b), (c) and (d) shows the optical micrograph of Inconel 718 superalloy through the different soaking time by HIP treatment. The casting microstructure has obviously improvement. Comparison the average grain size of as-heat treated specimens and after HIP treatment for 4 h, it showed that the average grain size is 92\(\mu\)m for as-heat treated and 75\(\mu\)m for optimum HIP treatment. They show the grain sizes are uniform and the segregated structure is improved after HIP treatment. The slender needle d precipitation and twin microstructure were disappeared in the grain boundary.

Figure 4 is the scanning electron micrographs of Inconel 718 superalloy before and after different HIP soaking time treatments. Figure 4(a) shows the grain boundary is not obvious. In Fig. 4(b) the needle d precipitation emerged on the grain boundary and MC carbide is distributed on the matrix.\(^{22-24}\) Increasing the soaking time of HIP treated seems to decrease the \(\delta\) phase precipitation. And it will have the clearly grain boundary and grain size are appropriate as
shown in Fig. 4(c). For HIP treatment for 4 h, more NbC and \(\gamma''\) precipitation exist on the grain boundary, as shown in Fig. 4(d). Increasing the soaking time of HIP will enhance the effects of NbC and precipitation-strength \(\gamma''\) phases. The lump MC carbides appear in the grain-boundaries is helpful for stress rupture life. And they can effectually prevent the grain-boundaries sliding.

Figure 5(a) represents the XRD patterns of Inconel 718 before HIP treatment. The primary NbC formed during solidification are large and stable. The X-ray diffraction pattern were identified as the NbC(111), \(\gamma(111)\), \(\gamma(200)\) and \(\gamma(220)\) phases. Here only the austenite \(\gamma\) phase can be detect
and the $\gamma'$ and $\gamma''$ were absent. It was found that increased the soaking time of HIP treatment, the counts of intensity will increase, especially for the soaking time is 4 h. The Figs. 5(b)(c)(d) shows the XRD patterns of Inconel 718 after HIP treatment for 2, 3 and 4 h. The XRD patterns were identified as the NbC(111), $\gamma(111)$, $\gamma(200)$ and $\gamma(220)$. All the intensities of XRD patterns are larger than those of as-heat-treated. And the NbC(200), $\delta(201)$ and $\delta(020)$ are shown in XRD pattern after different HIP soaking time treatment.

Figure 6 shows the tensile strength measured at room temperature, 813 and 923 K for Inconel 718 after HIP treatment at different soaking time. And the strain rate of 0.001 s$^{-1}$ is used. In this study, both of the tensile strength and elongation of Inconel 718 superalloy increase proportionally to the soaking time of HIP treatment. Increase the soaking time of HIP treated, the tensile strength and elongation are rapidly to rise up. Because extended the soaking time of HIP treatment is helpful to eliminate the porosities of Inconel 718 superalloy. Increasing the soaking time of HIP will enhance the effects of NbC and precipitation-strength $\gamma''$ phases. The optimum tensile strength and elongation appeared for 4 h soaking time of HIP treated Inconel 718 superalloy. It can increase the tensile strength by 31% at room temperature, 27% at 813 K, and 24% at 923 K. The elongation of Inconel 718 superalloy also can increases about 100% at room temperature and 130% at 813 K and 60% at 923 K after tension tests.

The hardness of as-heat treated Inconel 718 superalloy after solution and aged treatments is 36.3 HRC. After HIP treatment for 2 h, the hardness of Inconel 718 superalloy can reach 42.2 HRC. And 43.2 HRC for 3 h, 43.7 HRC for 4 h HIP treated. The hardness increasing of Inconel 718 superalloy castings is proportional to the HIP soaking time. Even after tension test at the temperatures of 813 and 923 K, the hardness of HIP-ed sample is almost the same, it is slowly to decrease the hardness after high temperature tension test. In this experiment, after 813 K tension test (strain rate = 0.001 s$^{-1}$), the hardness of Inconel 718 superalloy is 42.1 HRC for 2 h, 43.0 HRC for 3 h, and 43.2 HRC for 4 h HIP treated. And after 923 K tension test, the hardness of Inconel 718 superalloy is 41.0 HRC for 2 h, 42.9 HRC for 3 h, and 43.0 HRC for 4 h HIP treated. It shows that the HIP treatment was helpful to enhance the strength and hardness for Inconel 718 superalloy casting at high temperature situation.

When the strain rate of tension test change to very slowly (0.0001 s$^{-1}$), the results of the tension test for Inconel 718 superalloy at 298 and 813 K were shown in Fig. 7. They can increase the tensile strength by 24% at room temperature and 20% at 813 K. The elongation is increase 48% at room temperature and 282% at 813 K. Both of the tensile strength and elongation of Inconel 718 superalloy are similarly increase proportional to the soaking time of HIP treatment. After a long time of 813 K tension test, the hardness of Inconel 718 superalloy is still kept 42.2 HRC for 2 h, 42.6 HRC for 3 h, and 43.0 HRC for 4 h HIP treated.

The rupture ductility is improved marginally after HIP treatment. Figure 8 shows the fracture surfaces of as-heat treated specimens and after HIP treatment for 4 h at room temperature.
temperature with different strain rate. Figures 8(a) and (c) represent the brittle fracture microstructure before HIP treatment. They showed the brittle intergranular failure mode. Figures 8(b) and (d) represent the dimpled rupture of Inconel 718 superalloy by 1453 K, 175 MPa, 4 h HIP treatment. In Fig. 8(d), it shows the very fine dimpled rupture in the interior of the grains at very slowly strain rate. It indicated a ductile transgranular failure mode.\textsuperscript{13,14} Figure 9 shows the
fracture surfaces of as-heat treated and 1453 K, 175 MPa, 4 h HIP treatment at 813 K with different strain rate. For as-heat treated specimens, the micropore take place at high temperature and cause the decrease of tensile strength showed in Figs. 9(a) and (c). For the HIP treatment for 4 h, the fine dimpled rupture transform to more coarse and ductile rupture was showed in Figs. 9(b) and (d). Comparison the Figs. 10(a) and (b), in Fig. 10(a) shows the micropore appear in the grain boundaries and become more brittle at 923 K tensile tested. For the optimum HIP treated, Fig. 10(b) shows the ductile rupture of Inconel 718 superalloy specimens.

Figure 11 shows the schematic diagram of the 3-point bending test. The $R_{bh} = 3FLk/2bh^2$ and $K = \text{chamfer correction factor (normally 1.00~1.02)}$ for the 3-point bending test. The bending rate was kept at 0.005 s\(^{-1}\). This test results are shown in Fig. 12. Increase the soaking time of HIP treated, the bending strength at room temperature and 813 K are proportional to the soaking time. It indicates that the specimen subjected to HIP treatment for 4 h has the best bending strength at room temperature and at a higher temperature conditions. It can increase bending strength by 38% at room temperature, and 26% at 813 K.

4. Conclusion

(1) The experimental results show that 4 h of HIP treatment for Inconel 718 superalloy was optimum. It can improve the porosity, elongation and segregation of Inconel 718 superalloy than 2 or 3 h of HIP treatment. Meanwhile, it can more strengthen the tensile and bending properties.

(2) The rupture ductility was improved marginally after 4 h of HIP treatment. At a fast strain rate (0.001 s\(^{-1}\)), the optimum HIP treatment can increase the tensile strength by 31% at room temperature, 27% at 813 K, and 24% at 923 K. When the strain rate was reduced (0.0001 s\(^{-1}\)), it can increase the tensile strength by 24% at room temperature and 20% at 813 K.

(3) The optimum HIP treatment can improve the porosity of Inconel 718 superalloy casting. In this study, it can reduce porosity about 86% and after 4 h of HIP treatment.

(4) Increasing the soaking time of HIP will enhance the effects of NbC and precipitation-strength $\gamma''$ phases. Meanwhile the slender needle $\delta$ precipitation and twin microstructure were disappeared in the grain boundary.

(5) For the 3-point bending test, it showed that the optimum soaking time of HIP procedure could enhance the bending strength of Inconel 718 superalloy casting about 38% at room temperature and 26% at 813 K.

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REFERENCES


