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EXPERIMENTAL INVESTIGATION of DOUBLE AGING HEAT TREATMENT of INCONEL 718 MONOBLOCK GAS TURBINE DISC IN A SALT BATH

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ABSTRACT

The heat treatment of Inconel 718 (In718) monoblock gas turbine discs are mainly done by vacuum furnaces. Despite the vacuum furnaces allow to make a clean and reliable heat treatment, its operation costs affects the final product's cost. In this work, as an alternative to the vacuum furnaces, the double aging heat treatment of In718 disc in a salt bath was investigated. The appropriate temperature for high and low temperature salt bath was identified in order to achieve necessary cooling rates of 125°C/min and 120°C/min for a 400 kg workpiece. It is shown that the heat treatment could be done when the high and low temperature salt baths temperatures are equal to 300°C. It is also found that the heat transfer coefficient for simulation could be taken as 650 $W/m^2.K$ regardless to the salt bath temperature.

Keywords: *Salt Bath, Aging, Heat Transfer Coefficient, Superalloy, Simulation*

INCONEL 718 MONOBLOK GAZ TÜRBİN DİSKİNİN TUZ BANYOSUNDA ÇİFT YAŞLANDIRMA ISIL İŞLEMİNİN DENEYSEL İNCELENMESİ

ÖZET

Inconel 718 (In718) monoblok gaz türbini disklerinin ısıl işlemi esas olarak vakum fırınları ile yapılmaktadır. Vakum fırınları temiz ve güvenilir bir ısıl işlem yapılmasına izin verse de; işletme maliyetleri nihai ürünün maliyetini etkilemektedir. Bu çalışmada, vakumlu fırınlara alternatif olarak In718 diskinin tuz banyosunda çift yaşlandırma ısıl işlemi incelenmiştir. 400 kg'lık bir iş parçası için gerekli olan 125°C/dk ve 120°C/dk soğutma hızlarını elde etmek için yüksek ve düşük sıcaklıklı tuz banyosu için uygun sıcaklık belirlenmiştir. Isıl işlemin, yüksek ve düşük sıcaklıklı tuz banyoları sıcaklıkları 300°C'ye eşit olduğunda yapılabileceği gösterilmiştir. Simülasyon için ısı transfer katsayısının tuz banyosu sıcaklığından bağımsız olarak 650 $W/m^2.K$ alınabileceği de bulunmuştur.

Anahtar Kelimeler: *Tuz banyosu, Yaşlandırma, Isı Transfer Katsayısı, Süper Alaşım, Simülasyon*

1. Introduction

In the aerospace industry, system components require high temperature and pressure resistance throughout their service life. The thermo-physical properties and creep-rupture properties of the components are highly dependent on the microstructure of the alloy [1]. Selection of the heat treatment method is important to ensure precise control of fines and homogeneous microstructure [2]. The term "superalloy" was first used after World War II. Superalloys are materials containing high amounts of

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chromium, low amounts of tungsten, molybdenum, aluminium and titanium, based on iron, cobalt or nickel. The most important feature of superalloys is their resistance to high pressure and temperatures. It has superior tensile and friction resistance at extreme conditions. Superalloy materials are used in nuclear reactors, submarines and ships, aircraft, gas turbines, space vehicles, thermal power plants, rocket engines and many more [3]. Among from them, In718 is the most preferred superalloy in the aviation industry [4].

The term "superalloy" was first used after World War II. Superalloys are materials containing high amounts of chromium, low amounts of tungsten, molybdenum, aluminium and titanium, based on iron, cobalt or nickel. The most important feature of superalloys is their resistance to high pressure and temperatures. It has superior tensile and friction resistance at extreme conditions. Superalloy materials are used in nuclear reactors, submarines and ships, aircraft, gas turbines, space vehicles, thermal power plants, rocket engines and many more [3]. Among from them, In718 is the most preferred superalloy in the aviation industry [4].

Inconel 718 (In718) features face-centered cubic (fcc), body-centered cubic (bcc), hexagonal closed-pack (hcp), and body-centered quadrangular (bct) crystallographic lattices. These are made of austenitic fcc matrix γ (gamma phase), as well as secondary phases: gamma prime γ' face ordered $Ni_3(Al, Ti)$; gamma double prime γ'' bct ordered Ni_3Nb; eta (η) hexagonal ordered Ni_3Ti; delta (δ) orthorhombic Ni_3Nb intermetallic compounds and other topologically closed-packed structures such as μ and Laves phases [5]. Alloys include bcc transition metals such as Nb, Cr and Ta for these phases. The microstructural properties of superalloys are improved using heat treatment techniques. As the solution annealing process, which is the first part in the heat treatment of precipitation hardening alloys, recrystallization, homogenization and dissolution of the phases in the fcc matrix structure, dissolving the carbides at the grain boundaries and grain growth, high creep-rupture resistance are expected [6].

For several applications, Ni-based superalloys are emphasized as solution annealed and precipitation hardened. The Inconel grades of the Ni-based superalloys are hardened with the precipitation of the gamma prime and carbides as a secondary phase inside the metal matrix [7]. The quenching process after solution treating done in the air for a single crystal superalloy and that can be taken a lot of time when air is used as a quenching agent. As a solution for shortening this period, vacuum furnaces are chosen by using pressurized argon or nitrogen; but the process cost is very high. However, vacuum furnaces with high pressure gas quenching (HPGQ) has a limited application area when considering the workpiece thickness. The HPGQ effectiveness is reduced when the workpiece thickness getting higher. Thus much more pressure is needed in order to cool the workpiece homogeneously. This is economically not possible in such cases where the thickness is above the critical limit for HPGQ. Thus another alternative cooling medium is needed for thicker workpieces. Strength can be increased by precipitation of additional amounts of secondary phases from the supersaturated matrix developed by solution treatment with aging processes. In the In718 heat treatment, which is generally double-aged, the tank is brought back to the aging temperature after quenching, and this causes large energy losses and the use of extra equipment (such as water quench tank and tempering furnace). As a consequence, salt bath is an emerging alternative when considering energy efficiency and high process costs to the vacuum furnaces. With the use of a high temperature salt bath, both the cooling rates expected from the quenching process can be achieved and there is no need for secondary and tertiary temper heating [4]. In this respect, the developed system has a more compact structure and provides energy savings. For this process the critical cooling rates of the material between 1150°C to 950°C and 950°C to 750°C are determined as 125°C/min and 120°C/min, respectively [1].

The heat treatment studies for In718 mainly focused to identify the phase precipitation on behalf of the metallurgical aspect. Nearly none of them quantified the heat transfer during the process. On the other hand, the cooling rate curves are belong to the laboratory scale experimental setup. In this work, the double aging heat treatment of In718 monoblock gas turbine disc in a salt bath was investigated in a industrial scale heat treatment facility. In this context, the appropriate salt bath temperature for high and low temperature salt bath was identified in order to achieve necessary cooling rates of 125°C/min and 120°C/min for a 400 kg workpiece. 300°C, 400°C and 500°C salt bath temperatures were considered for experiments. On the other hand, simulations were performed to find the heat transfer coefficient during aging processes.

2. Material and Method

2.1. Workpiece

The massive workpiece used in this research has a hollow disc shape as shown in Figure 1. The geometry of the workpiece is prepared by considering the high pressure gas turbine rotor disc which mass equal to 400 kg. It has 800 mm outer and 107 mm inner diameter with changing thickness from 106 mm to 165 mm. In order to measure the temperature homogeneity during heat treatment, two N-type thermocouples (TC) were located on the workpiece. The locations of the TC1 and TC2 were chosen by considering the thickest and thinnest cross section position of the core which is illustrated on Figure 1 by detail B and C.

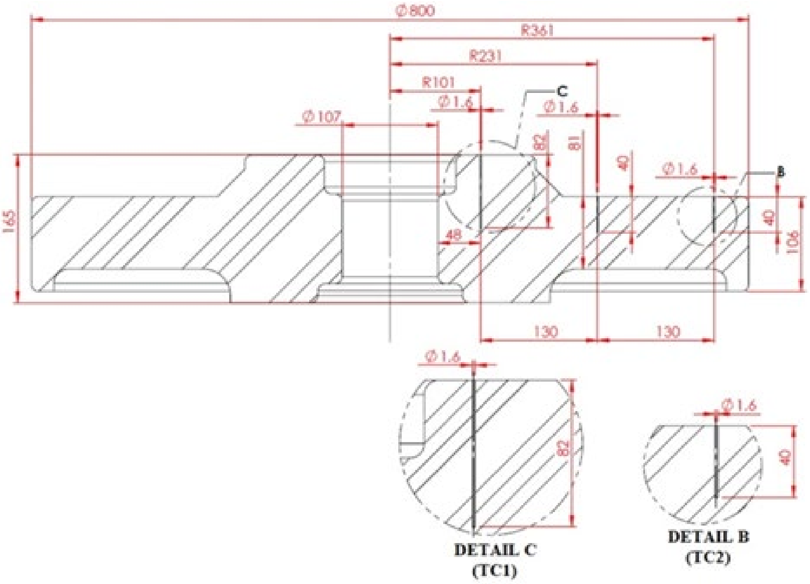


Figure 1. Test sample and thermocouple locations

2.2. Salt Bath Facility

The double aging heat treatment of the In718 alloy was conducted by a salt bath facility which was manufactured by Sistem Teknik Industrial Furnaces with the serial number BF-EH-A-100907-08 as shown in Figure 2. The explanation of the components of the facility is given as follows;

1: Annealing Furnace: Used to heat the workpiece under atmospheric pressure from room temperature to 1150°C. The heating power and useful dimensions of the annealing furnace are 200 kW and width: 1000 mm, height: 700 mm, length: 900 mm, respectively.

2: High Temperature Salt Bath: Used to quench the workpiece under atmospheric pressure from 1150°C to 950°C. The heating power and useful dimensions of the high temperature salt bath is 400 kW and diameter: 1800 mm, height: 1700 mm, respectively. The high temperature salt bath was agitated with two circulators.

3: Low Temperature Salt Bath: Used to quench the workpiece under atmospheric pressure from 950°C to 750°C. The heating power and useful dimensions of the low temperature salt bath is 180 kW and width: 1300 mm, height: 1700 mm, length: 1800 mm, respectively. The high temperature salt bath was agitated with one circulator.

4: Spare Salt Bath: Used to store the molten salt during maintenance of the high and low temperature salt bath. The heating power and useful dimensions of the spare salt bath is 90 kW and diameter: 1800 mm, height: 2300 mm, respectively.

5: Rinsing Tank: Used to eliminate the contaminated alt particles from the workpiece. The useful dimensions of the rinsing tank are width: 2000 mm, height: 1800 mm, length: 2000 mm.

6: Manipulator: Used to transport the workpiece to the desired location. The maximum load capacity and minimum linear movement velocity of the manipulator is 1000 kg and 0.2 m/s.

7: Salt Recovery Unit: Used to regain the dissolved salt from the rinsing tank.

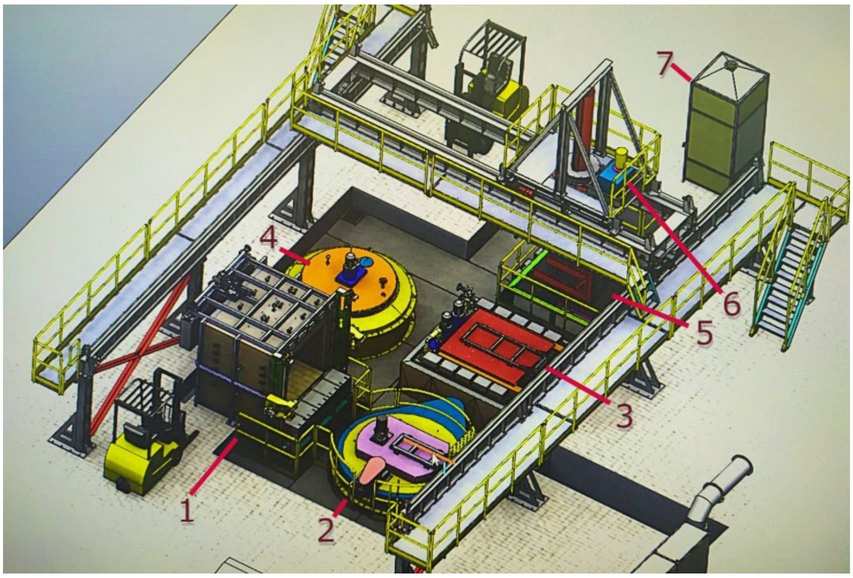


Figure 2. Experimental facility

2.3. Experimental Procedure

In the experiments, the double aging heat treatment was done by following the heat treatment recipe is given at Figure 3. According to the recipe, the workpiece was heated in the annealing furnace in order to perform solution annealing process from room temperature (25°C) to the 1150°C. After that, for the first aging process, the workpiece was delivered to the high temperature salt bath via manipulator in order to reduce the workpiece temperature from 1150°C to 950°C with 125°C/min ramp. Then the workpiece was delivered to the low temperature salt bath via manipulator, in order to reduce the workpiece temperature from 950°C to 750°C with 120°C/min ramp. The schematic representation of the recipe is given at Figure 4. The TTT (Time-Temperature-Transformation) diagram shows the first step allows precipitation of Ni_3Nb inside the γ phase. Then additional 1 hour is done to get γ'-γ'' strengthening phase [8]. In order to ignore the heat losses to the surrounding atmosphere, the manipulator transportation time kept between 5-10 second. In the experiments, HEF Durferrit GS-230 salt was used in the both high and low temperature salt bath. GS-230 salt is used for quenching and tempering applications above 300°C and the salt properties are given in Table 1.

Table 1. GS-230 Salt Properties

Property	**Value**	**Unit**
Working Temperature Range	270-600	°C
Melting Temperature	250	°C
Bulk Density	1700	kg/m^3
Heat Capacity at Constant Pressure	1510	J/kg.K
Thermal Conductivity	8.65	W/m.K

In order to determine the appropriate salt temperature to catch the necessary cooling rate at the high and low temperature salt bath, the temperature of the both salt baths are changed from 300°C to 500°C with 100°C increment. The temperature values were recorded by Hioki LR8400-20 type data logger.

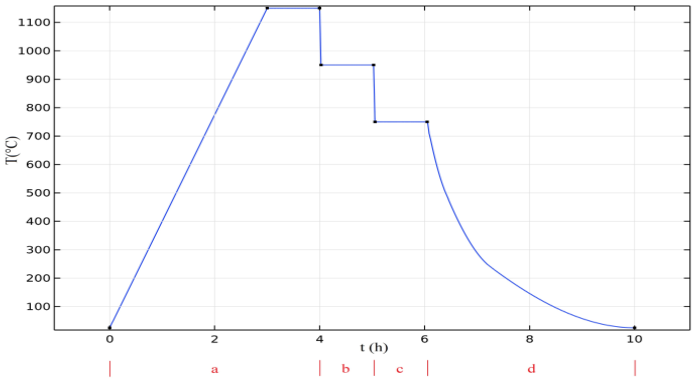


Figure 3. Heat treatment recipe, a) Annealing Furnace, b) High temperature Salt Bath, c) Low Temperature Salt Bath, d) Air

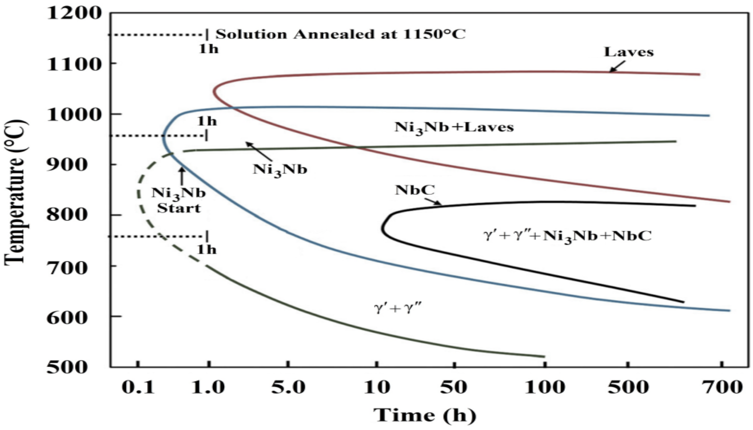


Figure 4. Illustration of designed heat treatment process on In718 TTT diagram

2.4. Simulation Procedure

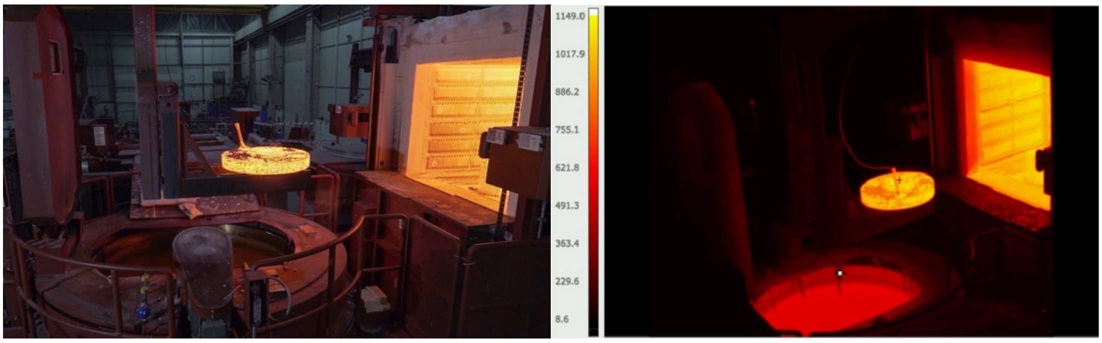
The simulations were conducted by considering the changing salt bath temperatures via Comsol Multiphysics. The main purpose of the simulations is to determine the heat transfer coefficients. In the simulations, the hollow disk geometry was imported to the model firstly, and then the arbitrary heat transfer coefficients found in the literature was defined on the exterior boundaries of the geometry [4].

The model was investigated under transient study. It was thought that the properties of salt which were given in Table 1 are temperature independent. However, for the In718 workpiece, the pre-determined temperature dependent properties inside the program were chosen. In order to identify the real heat transfer coefficient the inverse method presented on the literature and the experimental temperature values were used [2].

3. Results and Discussion

In this study, double aging heat treatment of monoblock gas turbine disc made of In718 in a molten salt bath was investigated experimentally. Simulations were done to identify the heat transfer coefficient during aging of the workpiece. In this section, it was shown that the aging process could be done in a molten salt bath with appropriate bath temperature.

Figure 5 shows the transportation of the workpiece from annealing furnace to the high temperature salt bath via manipulator. The real and thermal images were taken from the same position for the salt bath temperature 500°C. The emissivity of the thermal camera was set to 0.8 by considering the In718 workpiece. With this value, the maximum temperature on the workpiece was identified with red plus symbol and the corresponding temperature value was measured as 1149°C. It was also observed that the temperature homogeneity on the workpiece without considering the removable oxide layer is quite uniform.

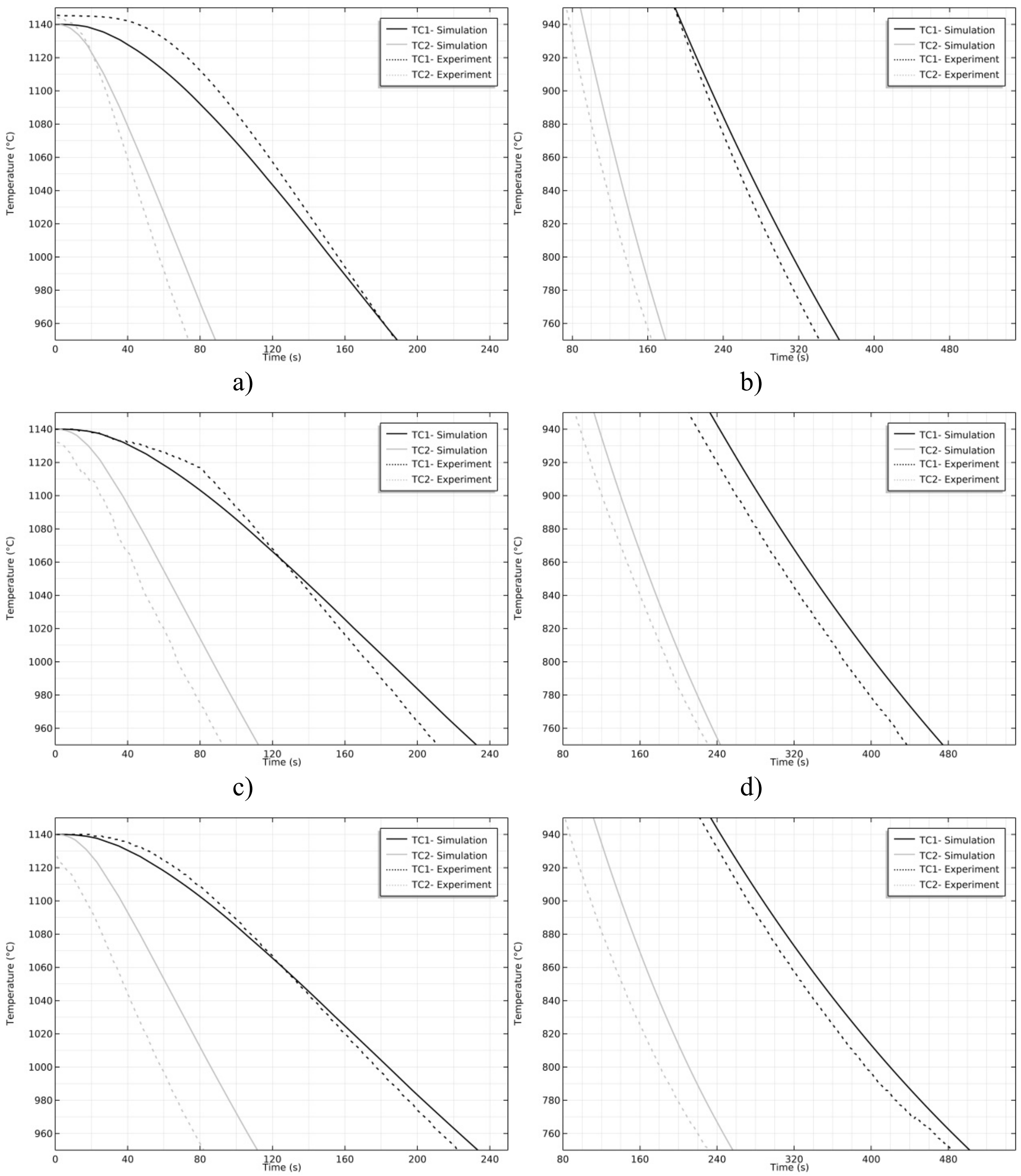


a) b)

Figure 5. Transportation of the hollow disk, a) real image, b) thermal image

The time-temperature curves of the first and second aging process were given at Figure 6. The first aging process covers the temperature range between 1150°C-950°C in a high temperature salt bath, while the second aging process covers 950°C-750°C in a low temperature salt bath as described in the material and method section. As could be seen in the figure, the workpiece had lost 10°C for each trial while transportation from annealing furnace to the high temperature salt bath. However, this value is so small when considering the workpiece outlet temperature, so it can be ignored. The transportation of the workpiece took 10 s and 12 s from the annealing furnace to the high temperature salt bath and high temperature salt bath to the low temperature salt bath, respectively. In this context, one can say that the workpiece heat loss to the atmosphere equals 1°C/s. The whole aging process is done in 240 s and 500 s in the high and low temperature salt bath, respectively, which is competitive to the vacuum furnace performance [9]. The cooling characteristics of the workpiece under different salt bath temperatures were also changed for both high and low temperature salt baths. It is interesting to note that the cooling characteristic of the workpiece for 400°C and 500°C nearly the same between the 1150°C-950°C, however the main difference had occurred between the 950°C-750°C. The time-temperature curves implied that the relative difference between TC1 and TC2 were reduced when the salt temperature increased. The main reason for this situation is that the relative temperature difference reduces when the salt bath temperature increases and this causes a low heat loss during aging process. Thus, the relative temperature difference of the thicker and thinner section reduces. As a result of this process, the fastest cooling curves were obtained for 300°C salt bath temperature.

On the other hand, in the simulations, 1140°C was considered as an initial temperature value of the workpiece. 650 W/m^{2}K heat transfer coefficient was considered without taking into account the salt bath temperature for all simulation. This value also stays in the limits for the salt bath quenching heat transfer coefficients as described in the literature [9].These initial and boundary condition caused a good match with the experimental data. However, it was observed that the relative difference between the experimental and simulation temperature values for TC2 is higher than TC1. By knowing that the TC1 was measured the thicker cross section of the workpiece, it may cause rapid heating behavior for the thinner cross section which measured by TC2. It should be also note that the relative error between experimental and simulation were decreased when the salt bath temperature decreased.



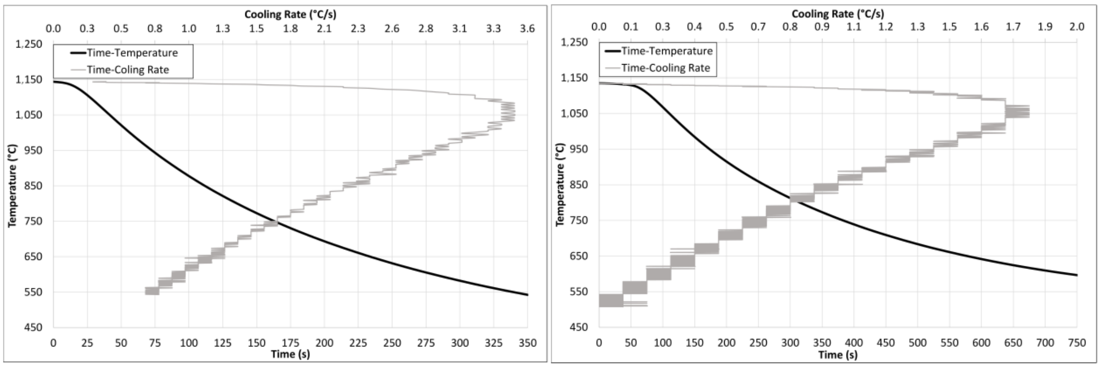
a) b)

c) d)

e) f)

Figure 6. Time-temperature curves of workpiece for 300°C salt bath temperature a) 1150°C-950°C range, b) 950°C-750°C range; for 400°C salt bath temperature c) 1150°C-950°C range, d) 950°C-750°C range; for 500°C salt bath temperature e) 1150°C-950°C range, f) 950°C-750°C range

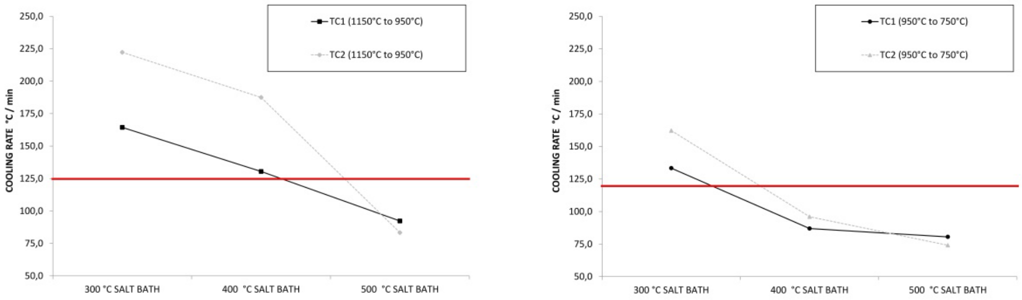
The total cooling rate curves for 300°C salt bath temperature is given at Figure 7. From the figure, nor the film boiling stage and nor the convection stage is not observed. This is an interesting finding for salt bath aging process. It is well known that the maximum heat transfer is occurred in the bubble boiling phase [9]. Regarding to the curves of Figure 7, it could be said that the whole process happened in the bubble boiling phase and the heat transfer coefficient had maximum value during the whole aging process. On the other hand, the maximum cooling rates of the thicker and thinner section was gathered as 3.4°C/s and 1.67 °C/s, respectively. This result showed that the thicker section requires process time nearly two times more than the thinner section.



a) b)

Figure 7. Total cooling rate curves of workpiece for 300°C salt bath temperature, a) For TC1, b) For TC2

Figure 8 represents the averaged cooling rates for different salt bath temperatures. The red straight line shows the necessary cooling rate values for the high and low temperature salt bath. According to the figure, it is observed that 500°C salt bath temperature is not enough to reach the demanding cooling rates for both high and low temperature salt bath. On the other hand, 400°C salt bath temperature is sufficient for high temperature salt bath but not for low temperature salt bath. The optimum operating conditions were achieved for 300°C salt bath temperature.



a) b)

Figure 8. Cooling rate of workpiece between a) 1150°C-950°C range, b) 950°C-750°C range

The high temperature salt bath temperature rise in each trial was obtained as 9.5°C, 10.8°C and 12.0°C for 500°C, 400°C and 300°C, respectively. Considering the 400 kg load and the maximum operation temperature of the GS-230 salt as a 600°C, it could be said that the aging application didn't increased too much load for the continuous process. However, for further processing, the production speed and the workpiece mass should be kept in mind in order to keep the salt bath temperature in a safe range.

4. Conclusion

In this work, the double aging heat treatment of In718 monoblock gas turbine disc was investigated by considering the heat transfer analysis. The outcomes from the experimental and numerical study can be summarized as follows:

- Double aging heat treatment process of monoblock gas turbine discs could be done in a salt bath with considerable heat transfer competitiveness as in HPGQ.
- The cooling rate decreases with increasing salt bath temperature.
- The temperature stability during and after quenching in a salt bath is quite reliable.
- The quenching inside the salt bath does not include film boiling and convection stage. The process occurs only with bubble boiling stage.
- At the same time, the cooling rate of the thicker cross section of the workpiece has two times lower than the thinner cross section.
- The salt bath temperature should be below 500°C in order to get the first metallurgical change for Ni_3Nb with 125°C/min.
- Similarly, to precipitate the γ'-γ'' phases with 120°C/min, the salt bath temperature should be below 400°C.
- The heat transfer coefficient for simulation or first estimation by hand calculation could be taken as 650 $W/m^2.K$ regardless to the salt bath temperature.

In the future studies, the metallurgical changes after double aging heat treatment process will be focused.

Conflict Of Interest

The authors declare that they have no conflict of interest

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