EFFECT OF RE-HEAT-TREATMENTS ON MICROSTRUCTURES IN CAST NICKEL-BASE SUPERALLOY TURBINE BLADE, UDIMET 500

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VPLYV OPÄTOVNÉHO TEPELNÉHO SPRACOVANIA NA MIKROŠTRUKTÚRU ODLIEVANEJ TURBÍNOVEJ LOPATKY Z NIKLOVEJ SUPERZLIATINY UDIMET 500

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Abstrakt

Cieľom tohto príspev ku je štúdium obnovy mikroštruktúry superzliatiny po jej dlhodobej expozícii na prevádzkovej teplote využitím jednoduchého opätovného tepelného spracovania. Mikroštruktúra odlievanej polykryštalickej niklovej superzliatiny Udimet 500, ktorá bola predtým dlhodobo prevádzkovaná (50000 hodín) spoločnosťou Electricity Generating Authority of Thailand (EGAT) bola študovaná riadkovacou elektrónovou mikroskopiou po rozdielnych spôsoboch opätovného tepelného spracovania. V príspevku bol študovaný a analyzovaný vplyv rozdielnych podmienok rozpúšťacieho žíhania a starnutia v niklovej superzliatine na proces rozpúšťania a precipitácie spevňujúcej fázy γ'. Bolo zistené, že mikroštruktúra dlhodobo exponovanej vzorky môže byť takmer úplne uzdravená opätovným rozpúšťacím žíhaním, za ktorým nasledoval dvojstupňový proces starnutia. Počas procesu rozpúšťacieho žíhania boli hrubé karbidy a precipitáty fázy γ' čiastočne rozpustené v matrici materiálu. Následne boli vzorky spracované sériou procesov starnutia, čo malo za následok nerovnomernú precipitáciu častíc fázy γ', tie však boli rovnomernejšie distribuované, než bolo pozorované v mikroštruktúre dlhodobo exponovanej vzorky. Vo všeobecnosti, dobrú žiarupevnosť mnohých superzliatin na báze niklu je možné očakávať v dôsledku vysokého objemového podielu malých precipitátov spevňujúcej fázy γ′ ($Ni_3(Al,Ti)$) v matrici materiálu. Hoci taktiež bolo zistené, že vyššia teplota rozpúšťacieho žíhania mala za následok menší objemový podiel hrubých precipitátov γ' a taktiež ich väčšiu heterogenitu než nižšia teplota. Nadôvažok, dlhší čas výdrže v druhom stupni starnutia mal nepriaznivý vplyv na mikroštruktúrne charakteristiky, čo sa prejavilo v menšej hustote veľmi jemných precipitátov častíc γ', ktoré sa následne opätovne rozpustili v matrici materiálu.

Abstract

This work has an aim to refurbish the microstructure of superalloy after long-term service at elevated temperature by simple re-heat treatment. The microstructures of cast polycrystalline nickel base superalloy, Udimet 500, operated by Electricity Generating Authority of Thailand (EGAT) for long-term services (50000 hours) were investigated by scanning electron microscopy (SEM) after different re-heat-treatment conditions. The influence of various solution and aging heat treatments on the dissolution and precipitation behaviors of γ' in the nickel base superalloy was studied and analyzed. It was found that microstructure of the exposed specimen after long-term service could be nearly recovered by a re-solution treatment followed by two-step aging treatments. During solution treatment, the coarse carbides and gamma prime precipitates were partially dissolved into the matrix. Then specimens were heat treated through series of aging resulting in uniformly dispersed precipitation of gamma prime particles, which is more uniform than those in the long-term exposed microstructure. Generally, good high-temperature strength in most nickel-base superalloys could be expected from the presence of a high volume fraction of small precipitates of the γ′-phase ($Ni_3(Al,Ti)$). However, it was also found that the higher solution annealing temperature resulted in less volume fraction of coarse gamma prime precipitates and less homogeneous in microstructure than the lower one. Furthermore, the longer secondary aging time results in negative effect on microstructure due to the less density of very fine γ' precipitated particles, which were re-dissolved again.

Keywords: Microstructural Refurbishment, Rejuvenation, Re-Heat-Treatment, Superalloys, Lifetime Extension, U-500

1. Introduction

Nickel base superalloys are used within the industrial gas turbine (IGT) engine leading to the need of the high temperature path components. These materials can be exposed to very severe operating conditions where high tensile strength, good fatigue and creep resistance as well as oxidation and hot corrosion resistances are required. A range of nickel base superalloys, from dilute, solid solution strengthened alloys to the highly alloyed precipitation hardened materials are available for high temperature loading performance and environmental resistance. For optimal performance, high pressure/high temperature turbine blades are generally made of nickel base superalloys. Due to the mechanical properties are related to the microstructures. Therefore, many previous research works [1 - 6] had been carried out to investigate these relationships of microstructure-mechanical properties.

However, the use of these expensive materials requires a repair process providing the re-establishment of the initial properties and the original microstructure of the long-term used or damaged parts for the economic reason. The heat-treatment processes for nickel-base superalloys continue to change in order to optimize for numerous mechanical and physical properties [7 - 13]. This allows making the selection of heat treatment parameters increasingly challenging. The heat treatment processes for precipitation-strengthened nickel base superalloys are very complicated even they have been developed for some decades. Heat-treating of nickel-base superalloys can involve solution-heat-treating cycles, stabilizing cycles, and aging cycles. Each thermal cycle was developed and designed for very specific metallurgical structure operation and control. Each heat treatment is heated to a single and uniform temperature.

Udimet 500 is a γ' precipitation-strengthened nickel base superalloy, widely used as turbine blades in hot sections of gas turbine engines due to its outstanding strength properties at high temperature as well as excellent hot corrosion resistance. Udimet 500 contains substantial amount of Al and Ti together about 6 wt.%, which provides enough precipitation strengthening of ordered $L1_2$ intermetallic $Ni_3(Al, Ti)$ γ' phase. The size distribution and the type of γ' precipitate are affected by aging temperature. Usually, selection of a single aging temperature may result in obtaining optimal amounts of multiple precipitating phases. Alternatively, a double-aging treatment, which produces different sizes and types of precipitate at different temperatures, may be utilized. Aging treatments usually are sequentially lower.

2. Material and Experimental Procedure

The cast nickel base superalloy in this study was U-500, with the following composition (by wt.%): 18 % Cr, 17 % Co, 3 % Ti, 3 % Al, 4 % Mo, 0.1 % C, 2 % Fe and the balance is nickel (53 %). About 1 cm^2 rectangular plates were cut from the most severe degradation zone of turbine blades. The plates were given different heat treatment conditions including solution treatment, primary and secondary precipitate aging treatments in vacuum furnace, see experimental heat treatment details in Table 1. Heat-treated plates were cross sectioned in order to observe microstructure comparing to those of parallel grinded and polished surface of turbine blades. All sectioned samples were polished using standard metallographic techniques and were subsequently etched in marble etchant, which has chemical composition as following 10 g $CuSO_4$, 50 ml HCl and 50 ml H_2O. The microstructures of heat-treated samples were study by scanning electron microscope with secondary electron mode and Image Analyzer.

Table 1 Heat treatment conditions applied to long-term exposed U-500

No.	**Solution treatment**	**Primary precipitate aging**	**Secondary precipitate aging**
1 ∗	1150°C/ 4 hrs. (AC)	1080°C/ 4 hrs. (AC)	760°C/ 16 hrs. (AC)
2	1150°C/ 4 hrs. (AC)	1080°C/ 4 hrs. (AC)	760°C/ 24 hrs. (AC)
3	1150°C/ 4 hrs. (AC)	1080°C/ 4 hrs. (AC)	800°C/ 16 hrs. (AC)
4	1150°C/ 4 hrs. (AC)	1080°C/ 4 hrs. (AC)	800°C/ 24 hrs. (AC)
5	1150°C/ 4 hrs. (AC)	1080°C/ 4 hrs. (AC)	840°C/ 16 hrs. (AC)
6	1150°C/ 4 hrs. (AC)	1080°C/ 4 hrs. (AC)	840°C/ 24 hrs. (AC)

∗ Standard Heat-Treatment condition

3. Experimental Results and Discussion

3.1 The microstructure of as-received alloy

The microstructure of as-cast alloy generally consists of extensive precipitation of ordered $L1_2$ γ’ intermetallic phase within dendrite core and in the interdendritic region. Carbides predominantly MC type, and γ-γ’ eutectic which form during ingot solidification are found in smaller volume fraction locating along the interdendritic region as well, according to works. SEM micrographs, obtained from the transverse sections at about mid blade height of the airfoil, are shown in Fig. 1. The chromium carbide ($M_{23}C_6$) and agglomerated gamma prime and secondary gamma prime particles can be seen. Coalescence of the primary and secondary gamma prime particles seems to occur resulting in larger and rounded particles in order to reduce the internal energy in the material. The degree of degradation, as measured by the gamma prime particle size, increases with exposed time and service temperature. In this study, however, the primary gamma prime particle size was about 0.4 μm and secondary gamma prime particle size was about 0.15 μm. The airfoil microstructure shows significant degradation in service. The primary gamma prime particles have spheroidized and secondary gamma prime coarsened in the airfoil samples. This type of microstructure morphology is theoretically expected to have low efficiency to block dislocation movements during loading at high temperatures resulting in lower creep resistance. Therefore, it is needed to recover microstructure to the same as or similar to the original one by simple re-heat-treatment processes.

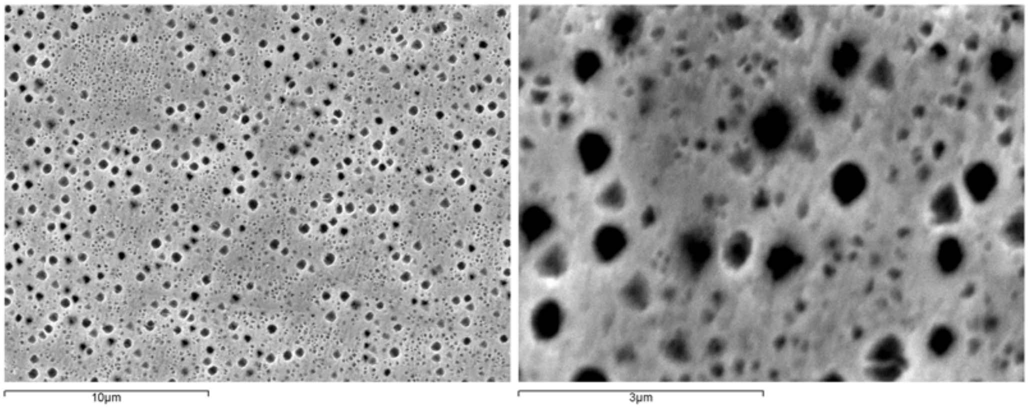


Fig.1 As-received microstructure after long-term service: Low magnification (left) and high magnification (right) showing very fine gamma prime particles among coarse gamma prime particles

3.2 The microstructure of heat-treated alloy

According to the previous works [14 - 17], repeating the standard heat treatment sequence does not always work well. The structure and properties were not fully recovered by this refurbishment treatment applied to these U-500 blades. It is reported that the microstructure was only partially recovered by such simple re-heat treatment. However, when re-heat treatment condition, according to No. 1 (standard heat treatment), was applied to long-term exposed specimen in this study, the microstructure consisting of non-uniform dispersion of gamma prime precipitates are found with low volume fraction. Both sizes of γ' precipitate particles are uniform and similar in size and shape, Fig. 2 (left). This type of microstructure is previously expected and theoretically desired as the most optimized microstructure, which could provide good mechanical properties in some degree at elevated temperatures, especially, for both short-term strength at elevated temperature and high creep resistance.

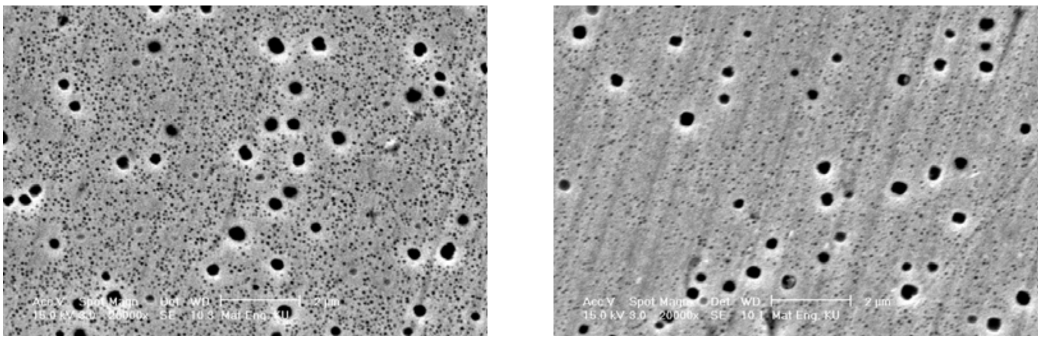


Fig.2 After heat treatment at 760°C/ 16 hrs. (AC), left; and 760°C/ 24 hrs. (AC), right

According to heat treatment of program No. 2 (Fig. 2 (right)), It was found that the morphology is very similar to that of the standard heat-treated one, which consists of bimodal morphology. Secondary precipitate aging at 760°C for 24 hours resulted in precipitation of gamma prime γ', which its volume fraction is seem to be less than that of the microstructure according to program No. 1. After secondary precipitate aging, elements needed to form γ' precipitates would diffuse into the former gamma prime precipitates more causing the slightly coarsening of the precipitates during secondary aging. Such kind of microstructure could probably provide rupture and/or creep resistance in some degree. As it is already well known that creep strength of alloys by γ' precipitation is a function of γ' particle size. It could be concluded that the longer time secondary aging at temperature of 760°C should not produced any significant difference in morphology. However, it could be also observed that the microstructure according to program No. 1 consists of more secondary precipitated γ' particles in very fine size than that of program No. 2.

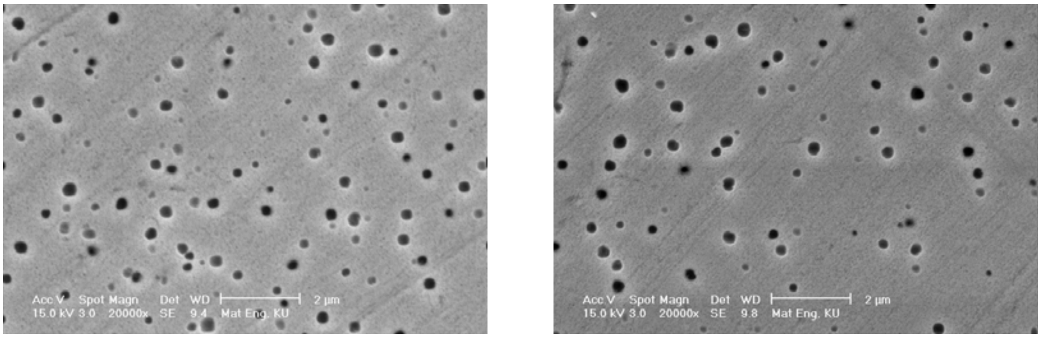
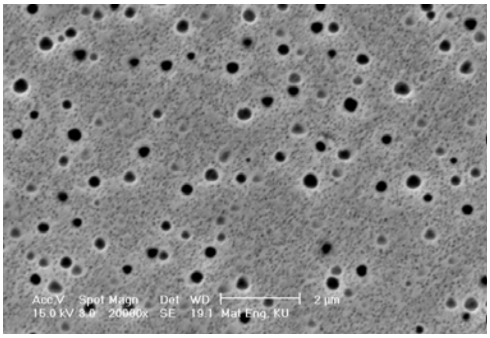


Fig.3 After heat treatment at 800°C/ 16 hrs. (AC), left; and 800°C/ 24 hrs. (AC), right

In Figures 3 (left and right), the microstructures after heat treatment according to programs No. 3 and 4 show the more uniform dispersion of coarse gamma prime precipitates. The gamma precipitates are in rounded or nearly cubic shape at the proper size. Effect of secondary precipitate aging at 800°C for both 16 and 24 hours resulted in more uniform precipitation of coarse gamma prime particles including higher volume fraction after secondary aging comparing to the heat-treated microstructure of programs No. 1 and 2, which have lower amount of primary precipitate particles, which were aged at 760°C.

It should be noted that such higher temperature of primary aging might provide the more uniform precipitation of coarse γ' particles as occurring in the case of the lower temperature. The sufficient high temperature of secondary aging at 800°C could be considered as a carbide stabilization heat treatment. However, it was also found that the diameter sizes of very fine gamma prime particles are difficult to be observed and appear in much smaller than those obtained from heat treatment programs No. 1 and 2.

According to the results of programs No. 5 and No. 6, it should be noted that the higher secondary aging temperature could somehow influence the final microstructures comparing to those of programs No. 3 and No. 4, see Figs. 4 (left and right). In both cases, it was found that microstructures are more homogeneous consisting of both higher volume fraction coarse γ' precipitate dispersion and volume fraction of very fine gamma prime precipitates than those of programs No. 3 and No. 4. It should be noted that at higher secondary aging temperatures of 840°C for both 16 and 24 hours, γ' forming elements would diffuse more from the matrix to form the coarse γ' particles than aging at lower temperatures of 760°C and 800°C for both 16 and 24 hours, resulting in the precipitation of more stable and coarser of fine γ' particles during final aging.



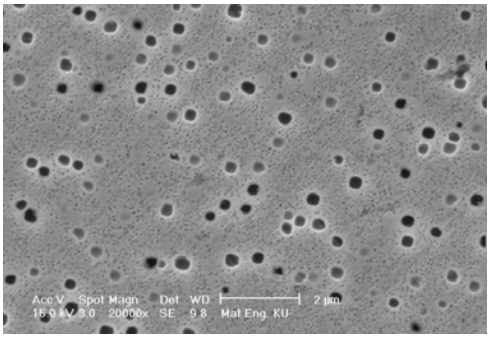


Fig.4 After heat treatment at 840°C/ 16 hrs. (AC), left; and 840°C/ 24 hrs. (AC), right

Comparing the effect of secondary aging time on both programs (No. 5 and No. 6), it was found that the shorter aging time (16 hours) provided the more precipitations of very fine γ' particles. This should result in higher tensile and fatigue strength at high temperatures comparing to those from other programs [18, 19]. Too long final aging time should result in lower density of very fine γ' precipitation where very fine γ' particles might re-dissolve continuously into the matrix and/or agglomerate with the adjacent coarse γ' particles. The summary of both primary and secondary γ' particle sizes are shown in Table 2.

Table 2 Gamma prime particle size after heat treatments

Heat treatment program	Average primary γ' particle size (μm)	Average secondary γ' particle size (μm)
1	0.28	0.12
2	0.29	0.11
3	0.27	0.08
4	0.26	0.07
5	0.27	0.09
6	0.28	0.07

4. Conclusions

1. After various re-heat treatment conditions, the microstructures according to the programs No. 1 and No. 5 seems to be the optimized microstructures for both short-time tensile and fatigue properties at elevated temperatures, as well as creep rupture properties where re-heat-treated microstructure of program No. 1 consists of lower volume fraction of coarse γ' particles and bigger size of very fine γ' particles comparing to the another one.
2. The longer secondary aging time results in the negative effect on microstructure due to the less density of very fine γ' precipitated particles, which were re-dissolved again.

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