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RESTORATION AND THERMAL STABILITY INVESTIGATION OF INTERMETLLIC PHASE IN EXPOSED NICKEL BASE SUPERALLOY UDIMET 500 TURBINE BLADES

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Preliminary Note - Prethodno priopćenje

The Udimet 500 nickel base superalloy blade exposed for 50000 hours in land base gas turbine working conditions faced the structure degradation. Six different heat treatments procedures have been applied (the blades were exposed at 900 °C and 1000 °C for different periods with maximum hold of 2500 hours) to rejuvenate the degraded structure. Metallographic work was performed, generally, aging at both temperatures modify the gamma prime size, morphology and distribution characteristics substantially. The volume fraction of secondary gamma prime decreased with increasing aging time.

Key words: *nickel base superalloy, microstructure, heat treatment (HT), blade structure degradation*

Istraživanje oporavka i termičke stabilnosti intermetalne faze nikljove super legure Udimet 500 pri dugotrajnoj uporabi lopatice turbina. Lopatice plinskih turbina nikljove super legure Udimet 500 tijekom uporabe 50000 sati izložene su uvjetima koji izazivaju strukturnu degradaciju. Šest različitih postupka toplinske obradbe je istraživano (lopatice izložene temperaturama 900 °C i 1000 °C pri različitim vremenima, maksimalno 2500 sati) za obnavljanje degradirane structure. Metalografska istraživanja su pokazala općenito da starenje pri obje temperature modificira primarno gama zrno, morfologiju i raspodjelu karakterističnih supstanci. Volumen frakcije sekundarnog gama zrna smanjuje se porastom vremena starenja.

Ključne riječi: *nikljova super legura, mikrostruktura, toplinska obradba (TO), degradacija strukture lopatice*

INTRODUCTION

Nickel base superalloys are structural materials, which are employed at high temperature and resisting variable thermomechanical loading. The microstructure and mechanical properties can be related to their chemical composition and heat treatment process. The most frequently used heat treatment, at which solution treatment is followed by a single or a double aging sequence, secures gamma prime precipitation within the grains interior, and as well discrete carbides $M_{23}C_6$ grain boundary carbides, to increase creep resistance [1]. The proper chemical composition of alloy and heat treated microstructure can provide stability of present phases, and consequently adequate high strength and good ductility even after long-term thermal exposure.

The mechanical behavior of nickel base superalloys is very strongly related to the alloy microstructures. The superalloy microstructures continually change with time at the elevated temperatures. In heat treated alloys, the gamma prime particles are arranged in a structure, which results in an optimum balance of tensile, fatigue, and creep properties [2]. A number of previous research works had been carried out to investigate these microstructure-mechanical properties relationships [3 - 5].

The use of these materials is very expensive and requires for the safety and economic reason a repair process providing the re-establishment of the initial properties in exposed parts after long term of using [6]. The heat-treatment processes for nickel-base superalloys continue in upgrading optimizing the mechanical and physical properties [7 - 9]. This makes the selection of heat treatment parameters increasingly challenging.

Udimet 500 is a gamma prime precipitation-strengthened nickel base superalloy which is 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 precipitation strengthening of ordered $L1_2$ intermetallic Ni_3 (Al, Ti) gamma prime phase.

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The size, distribution and the morphology of gamma prime precipitate can be modified by aging temperature. Both, single and double aging treatment procedures are utilized at heat treatment of this alloy.

The aim of this study is to determine the most suitable and practicable repair condition in exposed turbine blades. In first step the sequence of rejuvenation heat treatments of long-term exposed gas turbine blades were performed. Then the stability of structure received after blade rejuvenation was evaluated at two annealing temperatures with exposure time varying.

MATERIAL AND EXPERIMENTAL PROCEDURE

The experimental material for structural analysis were as-cast blades from nickel base superalloy Udimet 500 exposed 50000 hour in service, operated by Electricity Generating of Thailand (EGAT). The he chemical composition of the nickel base superalloy was as follows (in wt. %): 18% Cr, 17% Co, 3% Ti, 3% Al, 4% Mo, 0,1% C, 2% Fe, and balance nickel (53 %).

The plates of about 1 cm^2 were cut from the most severe degradation zone of leading edge of the turbine blades. The specimens were heat treated according to heat treatment conditions including solution treatment and two step aging in vacuum furnace. The rejuvenation heat treatments performed are stated in Table 1.

Table 1. **Heat treatment conditions applied to long term exposed Udimet 500 alloy**

Tablica 1. **Uvjeti toplinske obradbe primjenjenih za dugotrajno tretiranje legure Udimet 500**

No.	Solution treatment	Primary aging	Secondary aging
1*	1150 °C / 4 h / **	1080 °C / 4 h / **	760 °C / 16 h / **
2	1150 °C / 4 h / **	1080 °C / 4 h / **	760 °C / 24 h / **
3	1150 °C / 4 h / **	1080 °C / 4 h / **	760 °C / 16 h / **
4	1150 °C / 4 h / **	1080 °C / 4 h / **	760 °C / 24 h / **
5	1150 °C / 4 h / **	1080 °C / 4 h / **	760 °C / 16 h / **
6	1150 °C / 4 h / **	1080 °C / 4 h / **	760 °C / 24 h / **
* Standard heat treatment procedure, ** Air cool			

The treated specimens were then aged at temperatures of 900 °C and 1000 °C for 500, 1000, 1500, 2000, and/or 2500 hours in order to evaluate the coarsening behavior of gamma prime particles. All sectioned samples after thermal treatments were prepared by standard metallographic techniques and subsequently etched in Marble etchant. The microstructure characteristics of thermally exposed samples were observed by scanning electron microscope using secondary electron mode and image analyzer to define the gamma prime precipitate characteristics. The size and volume fraction of the gamma prime precipitates were determined.

EXPERIMENTAL RESULTS AND DISCUSSION

The microstructure of exposed blade

The microstructure of cast Udimet 500 superalloy generally consists of extensive precipitation of ordered L1$_2$ γ' intermetallic phase within dendrite core and in the interdendritic region. Carbides predominantly $M_{23}C_6$ type deposited along grain boundaries and MC type in vicinity of eutectic islands, which form during ingot solidification, are usually present in as-cast structure. Microsegregation during ingot solidification causes the formation of non-equilibrium gamma γ - gamma prime γ' eutectic.

Scanning electron microscopy micrograph of the degraded blade structure, obtained from transverse sections of the exposed blade, is shown in Figure 1. Due to long term operation service of the blades the changes the bimodal gamma prime precipitates are apparent. The morphology, size, distribution characteristics and volume fraction, of the both precipitates, the primary and secondary gamma primes, are degraded. The morphology of coarse and finer precipitates exhibits also morphological instability. The formerly cuboidal precipitates became irregular in shape and small gamma prime distribution is not uniform. The changes of the grain boundary carbides were observed as well. The local coarsening of $Cr_{23}C_6$ carbides deposited along grain boundaries and their shape modification was found. During exposure they can dissolve or agglomerate, resulting in variation of amount ads morphology. Frequently in vicinity of coarse carbides and/or carbide residues the pores were found. The reason for their appearance is either creep process or local incipient melting. The degree of degradation, as measured by the gamma prime particle size, is directionally proportional to time and temperature of exposure.

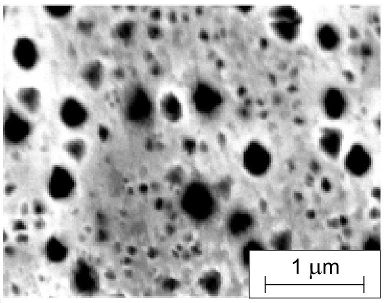

Figure 1. **SEM micrograph of long term exposed gas turbine blade**

Slika 1. **SEM mikrostruktura lopatice parne turbine poslije dugotrajne uporabe**

The blade microstructure shows significant degradation in service comparing to the microstructure of the root section. In virgin as-cast structure of the blade the primary gamma prime particle size was about 0,4 µm and secondary gamma prime precipitate size was about 0,1 µm. The primary gamma prime particles have grown larger changing round shape morphology and the secondary gamma prime coarsened and modification of their distribution was observed. It is expected that these structure changes modify the high temperature creep resistance of the blade materials. Applying a refurbishment treatment appears as less expensive alternative to extend the blade life time. In order to recover microstructure in exposed blade the effective heat treatment process should be found to obtain the structure of similar characteristics like in the virgin blade.

The microstructure of heat treated alloy

According to the previous works, repeating the standard heat treatment sequence with aim to recover degraded microstructure of nickel base superalloy Incomel 738 exposed blade does not always work efficiently [10]. The structure and properties were not fully recovered. In this experimental, for the Udimet 500 exposed blade, the six different heat treatment schedules which were used are stated in Table 1. The formation of new microstructure in exposed blade was modified through solutioning and double aging. To restrict the number of parameters, which can modify the gamma prime characteristics in time of treatment, the only temperature of second aging was gradually increasing and hold time was extended in individual schedules. The microstructure of blade obtained after the standard heat treatment is presented in Figure 2. Resulting gamma prime precipitates are of duplex size. Comparing this restored structure with that one observed in exposed blade the progress in structure restoration is evident. Under these heat treatment condition, the alloy exhibits bimodal morphology of gamma prime precipitates. The coarse gamma primes, which precipitated during the primary aging process at higher temperature, possess the round shape and they are accidentally distributed in gamma matrix. The quite higher temperature of prime aging modified also the size and volume fraction of these coarser gamma primes. The secondary gamma primes, which precipitated at lower aging temperature of 760 °C are fine size and uniformly distributed in gamma matrix.

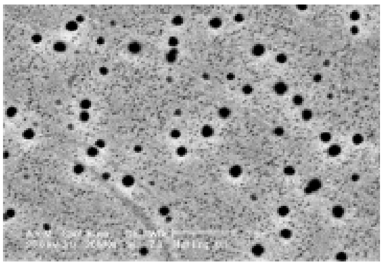

Figure 2. **SEM micrograph of U 500 alloy microstructure after standard treatment**

Slika 2. **SEM mikrosnimak legure U 500 poslije standardnog tretmana**

With increasing aging temperature and holding time, the morphological characteristics and distribution of bimodal gamma prime precipitates have not changed evidently. The gamma morphology is very quite similar to that of the standard heat treatment. Performing all treatments, the both gamma primes, fine and/or coarser, which precipitated in matrix at different aging temperatures, exhibit the round shape, regardless the temperature of the secondary aging was increasing when comparison with the standard heat treatment schedule for Udimet 500, (see Table 1.). The representative microstructures for two different temperatures of the secondary aging and the same holding time are presented in Figure 3. and Figure 4. The precipitation characteristics, received at individual heat treatment conditions, do not display expressive differences in gamma prime morphology and distribution with increasing aging temperature and extending hold time. Analyzing the results obtained at this rejuvenation experiment, the modification of the temperature and hold time at the secondary aging stage did not show the substantial difference considering the gamma prime morphology and distribution.

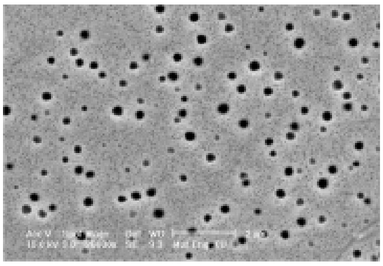

Figure 3. **SEM micrograph of gamma prime morphologies received after HT schedule No. 4**

Slika 3. **SEM mikrosnimak gama primarne morfologije dobivene poslije TO po postupku br. 4**

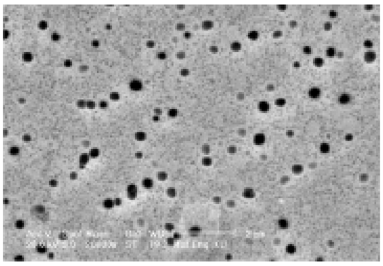

Figure 4. **SEM micrograph of gamma prime morphologies received after HT schedule No. 6**

Slika 4. **SEM mikrostruktura gama primarne morfologije poslije TO po postupku br. 6**

Effect of thermal exposure on gamma prime precipitates characteristics

Two different temperatures of 900 °C and 1000 °C and various hold times were selected for investigation of thermal stability of gamma primes in rejuvenated blades. It was observed that annealing at 900 °C already resulted in fast coarsening of duplex size gamma prime received in initially heat treated blade samples. Extending the holding time and increasing temperature the gamma prime size increases. Considering the mechanism of gamma prime coarsening, in first step some of the gamma prime dissolves in to matrix (less stable) and by enriching the gamma matrix with elements, which contributes to precipitate growth (Al, Ti), the more stable gamma primes grow larger. We do not expect that at this annealing temperature the gamma prime would initially precipitate in gamma matrix and then to grow.

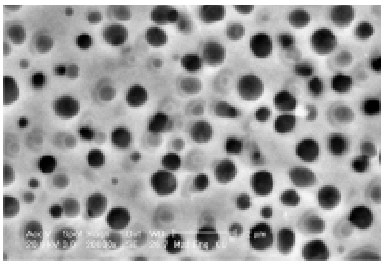

Figure 5. **Microstructure of gamma prime exposed to 900 °C for 2000 h. Dissolving effect of precipitates in gamma matrix**

Slika 5. **Mikrostruktura primarne gama strukture tretirane na 900 °C pri 2000 sati. Efekt otapanja precipitata u gama matriksu**

The dissolution process of gamma prime precipitates at temperature of 900 °C is clearly seen for in Figure 5. The coarsening process of gamma prime is more effective as hold time increases, and consequently the heterogeneity in gamma prime size is then more distinctive for all schedules of heat treatments, Figure 6.

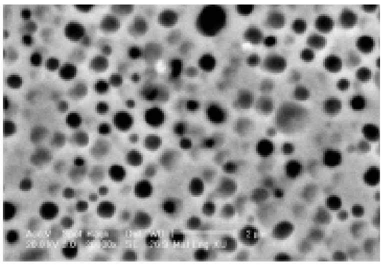

Figure 6. **The gamma prime heterogenity of size observed after 2500 h of annealing at 900 °C**

Slika 6. **Primarna gama heterogenost primjećena nakon 2500 sati žarenja na 900 °C**

Heating at increased temperature of 1000 °C resulted in more drastic coarsening of gamma prime particles for all hold times. The process of gamma prime coarsening was observed already after of 500 h of thermal exposure. The gamma prime coarsened into round shape at the beginning of the process, Figure 7. When blade was exposed to longer holds of 2000 h the gamma prime possesses the mixed morphology of quasicuboidal shape, like is displayed in Figure 8. From the results of metalography analysis can be concluded that there was not observed a substantial influence of the prior conducted heat treatment on thermal stability of duplex gamma prime precipitate regarding the heat treatment schedule applied. The statistical results concerning the change of gamma prime size in dependence of the applied thermal treatment and conducting long term annealing are shown in Figure 9. These results have been obtained from measurements of the gamma prime size which was modified by condition of the heat treatment schedules (Table 1.) and by different holding times at annealing temperature of 900 °C and 1000 °C. From the dependences is clearly seen that there is continuous gamma prime size increase as holding time increases for both annealing temperature. Consequently the results suggest that for Udimet 500 superalloy, exposed in land base gas turbine, already at lower exposure temperature of 900 °C the gamma prime instability in blades exposed at the first stage of high pressure gas turbine can be relevant. Analyzing the results on the effect of annealing process, there was not observed the substantial difference, considering the prior two step aging, on gamma prime coarsening behavior in individual

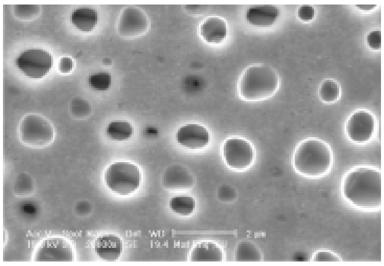

Figure 7. **SEM micrograph of gamma prime thermally at 1000 °C for 1000 hours**

Slika 7. **SEM mikrosnimak primarne gama strukture grijane na 1000 °C pri 1000 sati**

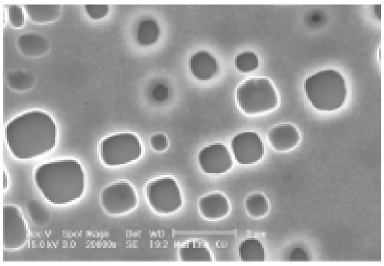

Figure 8. **SEM micrograh of gamma prime having quasicuboidal morphology at 1000 °C for 2000 hours**

Slika 8. **SEM mikrosnimak primarne gama strukture koja ima kvazi kuboidalnu morfologiju na 1000 °C pri 2000 sati**

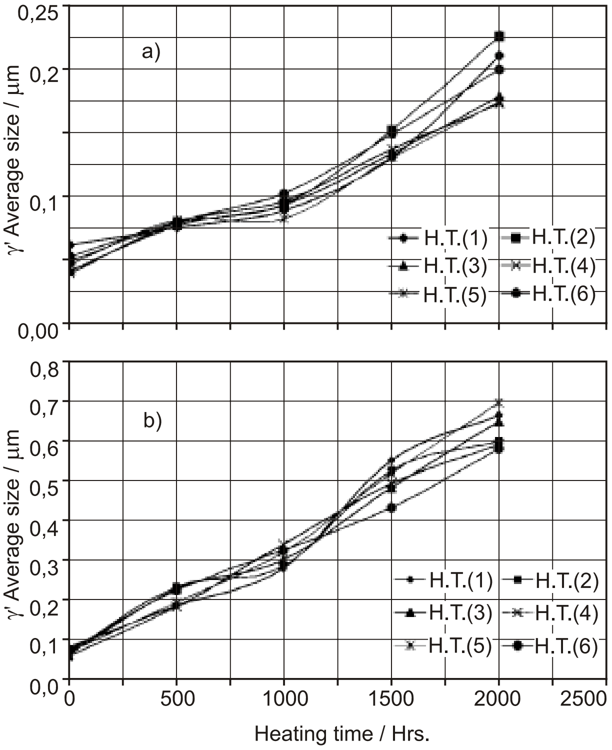

Figure 9. **The relationship between heating time and coarsening characteristics of gamma prime resulting from annealing at: a) 900 °C and b) 1000 °C**

Slika 9. **Ovisnost između vremena zagrijavanja i karakteristika ogrubljivanja primarne gama strukture kao rezultat zagrijavanja: a) 900 °C i b) 1000 °C** structures. Concerning the evaluation of alloy thermal stability for applied conditions it could be concluded that all obtained microstructures after annealing was not to show any beneficial characteristic providing a guarantee for long term exposure at high temperatures. In all annealed specimens the results showed the continuous gamma prime coarsening was more detrimental with increasing exposure time for both temperatures. It is only natural that higher temperature accelerated the gamma primes morphology changes in larger extent.

CONCLUSIONS

The experimental was carried out with an aim to evaluate the structural degradation of the turbine blades cast from Rudiment 500 nickel base super alloy, prior long term exposed in land base gas turbine. The extent of microstructure degradation was evaluated. The series of rejuvenation heat treatments were conducted with aim to recover gamma prime characteristics. The evolution of gamma prime morphology, size and distribution at solution and two steps aging treatment has been investigated. With increasing temperature and hold time at the second aging the morphological changes of primary gamma prime appeared at the highest temperature applied. The thermal stability of restored gamma prime precipitates in blades, which exhibits duplex size after rejuvenation treatment, has been then tested at two different annealing temperatures for the different holding time. The gamma prime morphology changes and reduction of volume fraction was observed at both annealing temperatures. The higher annealing temperature of 1000 °C promoted formation of gamma prime instability.

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