# TEM STUDY ON MICROSTRUCTURE BEHAVIOR OF ALLOY 718 AFTER LONG TIME EXPOSURE AT HIGH TEMPERATURES

Jianxin Dong, Xishan Xie, Zhichao Xu, Shouhua Zhang
Department of Materials Science and Engineering
University of Science and Technology Beijing, Beijing 100083, China

## Mengzhe Chen

Beijing Laboratory of Electron Microscopy, Chinese Academy of Sciences Beijing 100080, China

John. F. Radavich School of Materials Engineering, Purdue University West Lafayette, IN 47907, USA

#### Abstract

An Alloy 718 gas turbine disk with 28,000 hours service life was investigated by means of transmission electron microscopy (TEM) in details. Complicated microstructure behavior was observed directly on firtree part with a wide—range temperature gradient. Besides  $\delta$  phase formation,  $\gamma''$ ,  $\gamma'$  and  $\delta$  coarsening and solution were observed. The softening mechanisms of Alloy 718 at high temperatures have been discussed. One of the important softening processes is the  $\gamma''$  to  $\delta$  transformation. Detail TEM study has shown that the nucleation of  $\delta$  phase occurs at the stacking faults within  $\gamma''$  precipitates. However, a transformation sequence from  $\gamma''$  to  $\delta$  phase promotes to form  $\delta$  plates. Furthermore, crystallography of  $\gamma''$  to  $\delta$  transformation and a conceptual transformation model is proposed for further understanding the transformation mechanism.

Superalloys 718, 625, 706 and Various Derivatives Edited by E.A. Loria The Minerals, Metals & Materials Society, 1994

### Introduction

Many land based gas turbine disks currently in operation have been exposed up to 30, 000 hours. Some investigators have documented the long time aging stability of Alloy  $718^{(1-3)}$  and found that it still has adequate strength and ductility after several ten thousand service hours at temperatures up to  $650^{\circ}$ C. A previous work  $^{(3)}$  on microstructure analysis of Alloy 718 disk by scanning electron microscopy (SEM) after long time service was studied. However, it is scarcely studied in detail about the effect of long time exposure with stresses at high temperatures on microstructure of Alloy 718 by means of transmission electron microscopy (TEM). In current study emphasis is placed on TEM observation of a temperature range up to  $650^{\circ}$ C.

The transformation of metastable ordered BCT phase  $\gamma'' - Ni_3$  (NbTiAl) (DO<sub>22</sub> structure) to the equilibrium phase  $\delta - Ni_3Nb$  (DO<sub>a</sub> structure) has been discussed in previous papers<sup>(4-7)</sup>. The nucleation of intragranular  $\delta$  phase appears to be connected with the occurrence of stacking faults in  $\gamma''$  phase<sup>(9)</sup>. However, the further study of the  $\gamma'' \rightarrow \delta$  transformation has not been reported in detail. The present paper will concentrate on the  $\gamma'' \rightarrow \delta$  transformation mechanism and on the basis of experimental results, a conceptual model is proposed for the transformation of  $\gamma'' \rightarrow \delta$  phase.

#### Materials and Methods

An Alloy 718 gas turbine disk with service life of 28,000 hours and exposed to temperatures possibly up to  $650\,^{\circ}$ C was made available for this study. There exists a temperature gradient from the web to top of the firtree part of disk. Therefore, it is valuable and suitable for study on microstructure behavior after long time stressed exposure at different temperatures. The following areas were selected for direct observation by TEM: the top part of the firtree, 5mm away from the top, 10mm away from the top and finally the web part. The samples to be studied by TEM were thinned by dual jet electropolishing in solution of  $10\,^{\circ}/_{0}HClO_{4}+CH_{3}CH_{2}OH+C_{4}H_{10}O$  at  $-20\,^{\circ}$ C.

### Results and Discussions

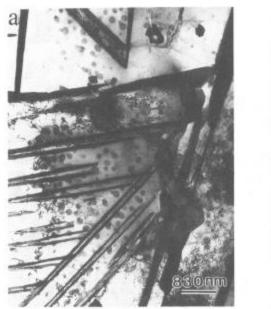
It should be noted from Figure 1 that a large number of  $\delta$  plates are observed and large  $\gamma'$  spheroids are found in the top area of firtree, where all

the  $\gamma''$  precipitates have dissolved because of long time exposure at high temperature ( $\approx 650\,^\circ\text{C}$ ). The microstructure in this area is totally different from Alloy 718 as standard heat treatment condition. The microstructure of the web part as showing in Figure 3, the main strengthened phase  $\gamma''$  still remains in finer sizes. However in comparison with the structure in the area 5mm away from the top of firtree as Figure 2 shows extensive coarsening of  $\gamma''$  and  $\gamma'$  phase. Therefore, it is suggested that the strengthening effect degradation of Alloy 718 is attributed to the coarsening of separately precipitated strengthening phases  $\gamma''$  and  $\gamma'$ , especially further formation of larger  $\delta$  plates as shown in Figure 1 because of the long time exposure at higher temperatures.

Complicated microstructure behaviour has been demonstrated in the area of  $10 \mathrm{mm}$  away from the top of firtree. Because of the existence of great temperature gradient, Figure 4 shows the co—existence of large  $\delta$  plates, coarsened  $\gamma''$  phase and  $\gamma'$  particles. Detail analyses show the interaction of dislocations with  $\gamma''$  phase (as arrow A indicated) and the interfacial dislocations at  $\delta$  plates (as arrow B indicated). It is interested that the serious interaction of dislocation with large  $\gamma''$  phase can be often observed in this area because of the stress imposed effect on long time exposure as shown in Figure 5. Meanwhile, the special careful dark—field illumination at higher magnification demonstrates that the existence of stacking faults directly in  $\gamma''$  phase as arrow indicated in Figure 6 (g=  $\{1\ 1/2\ 0\}$ ) after interaction with dislocations. However, in this area sometimes the multiple shearing and fragmentation of sheared  $\gamma''$  particle slices can be also observed (see Figure 7).

On the experimental facts of detail TEM observation it confirms that the  $\gamma'' \rightarrow \delta$  transformation is accelerated by the stress effect, and further observation will concentrate on the dislocation interaction with  $\gamma''$  precipitates.

Indeed, the nucleation of  $\delta$  phase often occurs at the stacking faults lying on the close packed planes within  $\gamma''$  precipitates during aging at temperatures below the  $\gamma''$  solvus<sup>[8]</sup>. Figure 8 shows the stacking faults formation within  $\gamma''$  phase, by using the reflection of  $g=(110)_{\delta}$ , Figure 8 (a) reveals the bright contrast pattern of stacking faults as indicated arrows A, B, which is corresponding to arrows A, B in Figure 8 (b), respectively. However, it is emphasized in Figure 9 that along the direction of the angle of 70 degree with one of  $\gamma''$  variants, the result of moving dislocations interaction with  $\gamma''$  particles conduces to the stacking faults formation within each  $\gamma''$ 



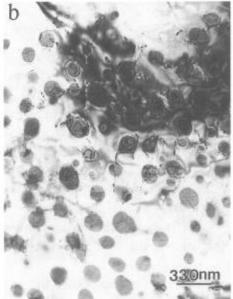


Figure 1 - TEM images at the top part of firtree showing large  $\delta$  plates and  $\gamma'$  particles (a), and  $\gamma'$  particles at higher magnification (b)

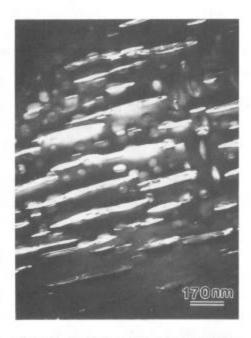


Figure 2 - TEM images in the area of 5mm away from the top of firtree showing coarsened \gamma'', and \gamma' particles (dark field)

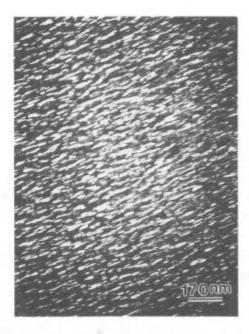


Figure 3 - Dark field TEM micrograph at the web part showing finer precipitates in comparison with that of 5mm away from the top of the firtree (Figure2)

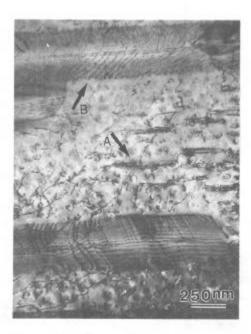


Figure 4 - The co-existence of large δ plates, γ" and γ' phase and the interaction of dislocations with γ" phase and interfacial dislocations at δ phase

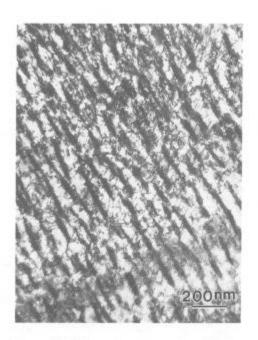


Figure 5 - The serious interaction of dislocations with \( \gamma'' \) phase



Figure 6 - The stacking faults within γ" phase in detail as arrow indicated

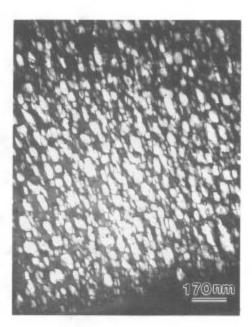


Figure 7 - The fragmentation of  $\gamma^{\prime\prime}$  in the area of 10mm away from the top of firtree





Figure 8 - TEM images showing the stacking faults formation within  $\gamma''$  phase (a) in the same area after a slight tilt (b)

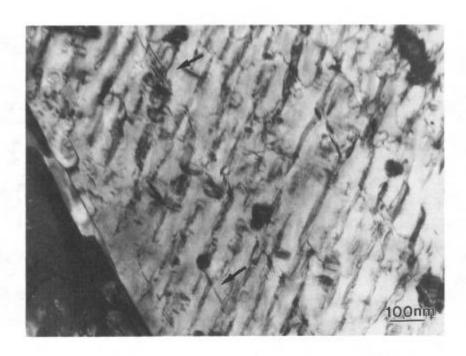


Figure 9 - The interaction of dislocations with  $\gamma''$  along a straight line (as arrows indicated)



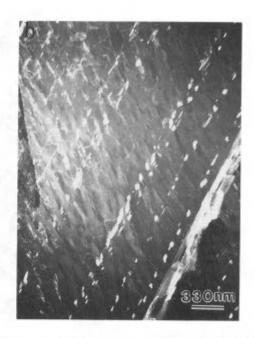


Figure 10 - TEM micrograph of the array of " points" (stacking faults in  $\gamma$ " ) (a) bright-field image (b) dark-field,  $g=(110)_{\delta}$ 

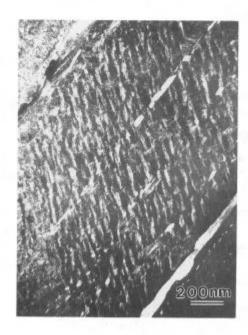


Figure 11 - The array of " points" (stacking faults in γ") after a slight tilting



Figure 12 - The co-existence of the array of "points" (stacking faults in  $\gamma$ ") and formed  $\delta$  plates

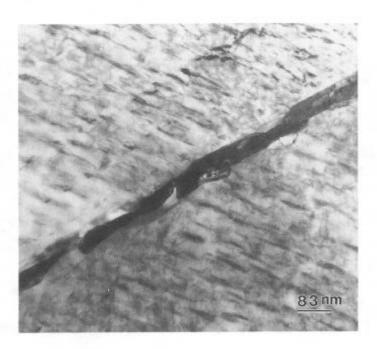


Figure 13 - TEM image at higher magnification clearly shows the initial formation of δ plate

particles, where these faults are almost along a straight line direction. Using the reflection of  $g=(110)_{6}$ , Figure 10 shows the array of "points" in bright—field image (Figure 10a) and dark—field image both (Figure 10b). Actually, this array of "points" are a series of the stacking faults directly formed within  $\gamma$ " phase. Figure 11 apparently shows the array of "points" (stacking faults) and the initial  $\delta$  plates formation at careful observation after a slight tilting. Figure 12 clearly reveals the co—existence of the array of stacking faults within  $\gamma$ " phase and already formed  $\delta$  plates. Figure 13 indicates in more detail a  $\delta$  plate at initial formation condition.

The crystallographic relationship between stacking fault within  $\gamma''$  phase and  $\delta$  habit plane in  $\gamma$ —matrix can be expresses as:

stacking faults (in 
$$\gamma''$$
)  $\delta$  habit plane (in  $\gamma$ -matrix) (112) $\gamma''$  (010) $\delta$ 

Some representative relationships on basis of tracing analysis method are illustratively shown in Figure 14. On the fact of the detail microstructural analyses and further crystallographic calculation, a conceptual model for  $\gamma'' \rightarrow \delta$  transformation is proposed as shown in Figure 15. At the initial stage, moving dislocations interact with  $\gamma''$  and result in the formation of stacking faults within  $\gamma''$  as shown in Figure 15 (a), consequently, these stacking faults grow into  $\gamma$ —matrix (see Figure 15b), and turn on further transformation to form  $\delta$  plate by the linking of allinged small  $\delta$  particles (see Figure 15c, d).

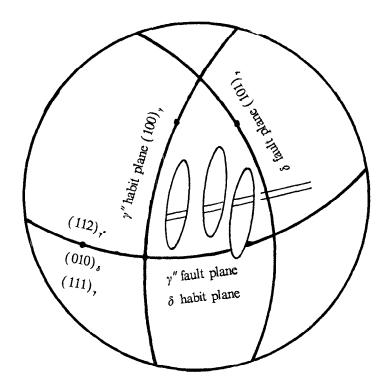


Figure 14 - The stereogram illustrating the crystallographic relationship of  $\gamma''$  and  $\delta$  phase

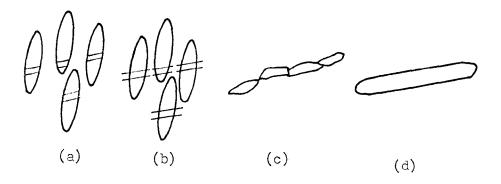


Figure 15 - Schematic model of  $\gamma''$   $\longrightarrow\!\!\delta$  transformation

## **Conclusions**

A sample of firtree cut from a trubine disk after 28, 000 hours long time service has been studied in detail as a series of samples after long time stress aging at different temperatures, and the following conclusions can be drawn:

- 1) The degradation of strengthening effect of Alloy 718 after long time stress aging is attributed to the coarsening of separately precipitated strengthening phases of  $\gamma''$  and  $\gamma'$ , and especially, the phase transformation of  $\gamma''$  to stable  $\delta$  phase.
- 2) A proposed model of stress induced  $\gamma'' \rightarrow \delta$  phase transformation can be-expressed as following sequence:
  - $\gamma'' \rightarrow$ stacking faults formation in  $\gamma''$ 
    - $\rightarrow \delta$  nucleation
    - $\rightarrow \delta$  growth into  $\gamma$ —matrix
    - $\rightarrow$  linkage of small  $\delta$  particles
    - $\rightarrow \delta$  plate formation

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