

## Research on influence of typical microstructure characteristics of Ni base single crystal on creep rupture and deformation analysis of turbo blade

CAO Juan, WANG Yan-rong, SHI Duo-qi

(School of Jet Propulsion,  
Beijing University of Aeronautics and Astronautics, Beijing 100191, China)

**Abstract:** Considering the influence of typical microstructure characteristics on creep performance, a series of UM-F single crystal alloys which had similar element components but different microstructures were used to analyze the relationship between creep life and microstructure characteristics of Ni base single crystal. Three main factors were proposed: misfit, volume fraction of precipitate and maximum matrix channel width. The Microstate parameter  $Y_{\text{micro}}$  was established to estimate the deformation state of the materials. The linear relationship between the initial value of microstate parameter  $Y_0$  and creep life under a certain temperature/load was affirmed. By analyzing the high temperature region of turbo blade using the material parameters of DD3, the creep deformation and the life prediction of the critical points of blade were obtained and the result closed to the test.

**Key words:** Ni base single crystal; typical microstructure characteristics; microstate parameter; creep life evaluation; creep analysis of turbo blade

**CLC number:** V231.91

**Document code:** A

Turbo blade of Ni base single crystal has been used in the aero-engine for nearly 30 years at home and abroad. The elements and the technologies of the single crystal material are being improved continuously in order to increase the potential of creep strength in high temperature application. These improvements lead to the difference of typical microstructure characteristics of Ni base single crystal from the first generation to the fourth or fifth generation. Numerous experiment results showed that the creep performance of the single crystal changed when the microstructure states different.

The typical microstructure characteristics of single crystal include shape, size and misfit of  $\gamma/\gamma'$  dual-phase in general. Research on the shape of  $\gamma/\gamma'$  is mainly about the initial shape of  $\gamma'$  precipitate which could be cubic, strip, spherical, papilionaceous and so on through dif-

ferent heat treatments<sup>[1]</sup>. Most of the test and simulation results proved that the initial cubic shape of  $\gamma'$  corresponds to a good performance of material<sup>[2-7]</sup>.

Research on the best initial size of  $\gamma/\gamma'$  dual-phase and its evolvement is a main aspect. Caron P and Harris et al.<sup>[8]</sup> considered  $0.45\ \mu\text{m}$  ( $\gamma'$  volume fraction 70%) as the best size for CMSX-2/CMSX-4 under which the creep strength was best. Nathal<sup>[2]</sup> thought the best size of  $\gamma'$  changed with the value of misfit, and the influence of  $\gamma'$  size on creep would be more if the absolute value of misfit was higher. In addition, research on the evolvement of  $\gamma'$  thickness and  $\gamma$  channel width are many. The test results of Link T et al.<sup>[9-11]</sup> on SRR 99 showed that the thickness of  $\gamma/\gamma'$  dual-phase was increased with the creep strain and the process was given in quantity, especially the value of matrix channel

width which was considered having big influence on creep rate. Another tests on CMSX-4 in high temperature verified the important effect of  $\gamma$  channel width as well<sup>[12-15]</sup>. Research on misfit, one focus on the relationship between misfit sign and the direction of rafting, the others on the effect of the absolute value of misfit on creep that high absolute value may be corresponding to a good creep performance<sup>[16-20]</sup>.

A series of Ni base single crystal with similar alloy elements but different initial microstructure states were analyzed to study the influence of alloy's initial microstructure on the creep performance of the materials. Three microstructure parameters were picked up to establish the

microstate parameter  $Y_{\text{micro}}$  and the linear relationship between initial value of microstate parameter and creep life were obtained. The creep life of turbo blade with the material parameters of DD3 was analyzed using this method and the life prediction about the critical points was close to the test.

## 1 Influence of typical microstructure characteristics on creep

The value of microstructure parameters and creep life under a certain temperature/load of a series UM-F Ni base single crystal and the first generation single crystal alloy MK-4<sup>[21]</sup> are given in Table 1 and 2.

**Table 1 Initial microstructure parameters and creep life of MK-4 and UM-F series alloys**

| Parameters                                  | Material      |            |                             |            |
|---------------------------------------------|---------------|------------|-----------------------------|------------|
|                                             | MK-4          | UM-F9      | UM-F18                      | UM-F11     |
| Misfit                                      | -0.002        | 0          | 0.001                       | 0          |
| Rafting                                     | Plate rafting | No rafting | Rod rafting                 | No rafting |
| Size of precipitate edge/nm                 | 430           | 350        | 350                         | 350        |
| Matrix channel width/nm                     | 80            | 82         | 80                          | 85         |
| Volume fraction of precipitate              | 0.6           | 0.53       | 0.54                        | 0.52       |
| Shape of precipitate                        | Cubic         | Spherical  | Between cubic and spherical | Spherical  |
| Initial value of microstate parameter $Y_0$ | -1.5          | 0          | 0.675                       | 0          |
| Creep life/h(1 223 K/290 MPa)               | 275           | 50         | 74                          | 125        |

**Table 2 Initial microstructure parameters and creep life of UM-F series alloys**

| Parameters                                  | Material      |               |               |
|---------------------------------------------|---------------|---------------|---------------|
|                                             | UM-F22        | UM-F20        | UM-F30        |
| Misfit                                      | -0.001        | <-0.003       | -0.003        |
| Rafting                                     | Plate rafting | Plate rafting | Plate rafting |
| Size of precipitate edge/nm                 | 430           | 600           | 450           |
| Matrix channel width/nm                     | 70            | 92            | 60            |
| Volume fraction of precipitate              | 0.62          | 0.65          | 0.68          |
| Shape of precipitate                        | Cubic         | Cubic         | Cubic         |
| Initial value of microstate parameter $Y_0$ | -0.8857       | -2.11956      | -3.4          |
| Creep life/h(1 223 K/290 MPa)               | 347           | 493           | 869           |

At first, the relationship between the sign of misfit and the rafting type is consistent with the former conclusion. The material MK-4, UM-F22, UM-F20 and UM-F30 with negative misfit have the plate rafting. The material UM-F9 and UM-F11 with the misfit of zero have no rafting and the material UM-F18 with the misfit of positive has the rod rafting. At the same time, from the shape of precipitate it can be found that the cubic  $\gamma'$  corresponded to a high absolute value of misfit, but the misfit value near zero show the spherical precipitate. Therefore, if the  $\gamma'$  precipitate prefer to be cubic and then enhance the strengthening effect, the high absolute value of misfit is necessary in addition to the high  $\gamma'$  volume fraction.

Second, creep life of material MK-4, UM-F22, UM-F20 and UM-F30 are longer than UM-F9, UM-F18 and UM-F11 under the same condition. By observing the different of these two group of alloys' microstructure characteristics, we can obtained: (1) the group of alloys with longer creep life have the misfit of negative and take place rafting of plate; (2) this group have the relatively bigger volume fraction of precipitate and have the cubic shape of  $\gamma'$ ; (3) the size of the precipitate edge about this group are larger than 400 nm with the relatively narrow channel width of matrix. Therefore, we can conclude that the large enough misfit absolute value and precipitate volume fraction with narrow channel width are the precondition of having a good creep life. In the group with longer creep life, alloy UM-F30 has the best creep performance where creep life is two times more than that of MK-4. But these two alloys have the similar misfit value and precipitate edge size except the 1/4 narrower channel width of UM-F30 than MK-4. Hence, with large enough misfit absolute value and precipitate volume fraction, the less narrow channel width of matrix corresponds to a longer creep life.

Use the dislocation creep and rafting model before<sup>[22-23]</sup> to simulate the creep of these alloys. The parameters needed are seen in Table 3 and

4. The elastic constants come from Ref. [21]. Through combination the microstructure evolution picture of transmission electron microscopy (TEM) given in the Ref. [21] with the conclusion we obtained about the creep rafting of single crystal at high temperature before, hypothesis the rafting finish time of all these alloys are 50 h and obtained the parameters of rafting process  $n$  and  $k$ . Then, the creep tertiary time can be obtained using the test creep curves of the alloys and the value of parameters  $a$ ,  $b$  and  $k_t$  can be calculated. The remainder items can be obtained using the method as the same as before. It is not difficult to find out in the Table 3 and 4 that most value of parameters about the creep model of these alloys are the same, it means these group of alloys have a strong comparison.

The simulation results compared with the test results are show in Fig. 1. Using the creep model parameters and the value of microstructure characteristics above can make the calculated results well consistent with the test curves. Hence, it can be concluded that the difference of these typical microstructure characteristics of the alloys effect creep life much.

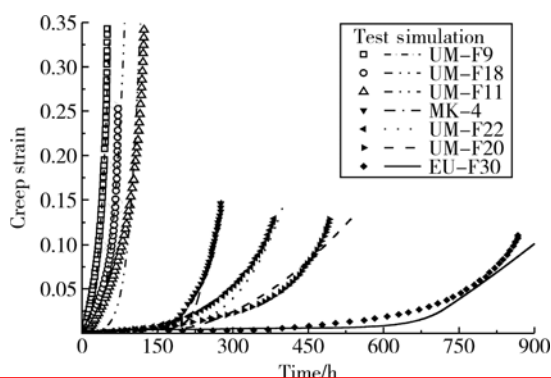


Fig. 1 Creep curves of MK-4 and UM-F series alloys under 1223 K/290 MPa

## 2 Definition of microstate parameter

Based on the analysis and simulation results above, three microstructure characteristics which effecting the creep much are chosen to define the microstate parameter  $Y_{\text{micro}}$

$$Y_{\text{micro}} = A \frac{\delta V_{\gamma'}}{\max(h_1, h_2, h_3)} \quad (1)$$

Table 3 Elastic and creep model parameters of MK-4 and UM-F series alloys

| Parameters                             | Material |         |         |         |
|----------------------------------------|----------|---------|---------|---------|
|                                        | MK-4     | UM-F9   | UM-F18  | UM-F11  |
| Temperature/K                          | 1 223    | 1 223   | 1 223   | 1 223   |
| $C_{11}$ /MPa                          | 187 200  | 187 200 | 187 200 | 187 200 |
| $C_{12}$ /MPa                          | 123 000  | 123 000 | 123 000 | 123 000 |
| $C'_{11}$ /MPa                         | 168 200  | 168 200 | 168 200 | 168 200 |
| $C'_{12}$ /MPa                         | 110 400  | 110 400 | 110 400 | 110 400 |
| $C_{44}$ /MPa                          | 33 600   | 33 600  | 33 600  | 33 600  |
| $C'_{44}$ /MPa                         |          |         |         |         |
| Burgers/nm                             | 0.25     | 0.25    | 0.25    | 0.25    |
| Misfit                                 | −0.002   | 0       | 0.001   | 0       |
| Size of precipitate edge/nm            | 430      | 350     | 350     | 350     |
| Matrix channel width/nm                | 80       | 82      | 80      | 85      |
| Volume fraction of precipitate         | 0.6      | 0.53    | 0.54    | 0.52    |
| $\alpha$                               | 0.2      | 0.2     | 0.2     | 0.2     |
| $\beta/10^{-9}$                        | 2.2      | 2.2     | 2.2     | 2.2     |
| $\rho_b$                               | 0.01     | 0.01    | 0.01    | 0.01    |
| $u_b^{\text{filling}}/10^{-3}$ (nm/s)  | 0.5      | 5.0     | 5.0     | 0.9     |
| $V^{\text{filling}}(b^3)$              | 46.8     | 46.8    | 46.8    | 46.8    |
| $D/10^{-5}$ (nm/s • MPa)               | 1.85     | 1.85    | 1.85    | 1.85    |
| $\theta$                               | 0        | 0       | 0       | 0       |
| $u_b^{\text{shear}}/10^{-6}$ (nm/s)    | 1.51     | 8.51    | 8.51    | 1.51    |
| $V^{\text{shear}}(b^3)$                | 48.6     | 48.6    | 48.6    | 48.6    |
| $E^{\text{spb}}/(\text{J}/\text{m}^2)$ | 0.066 4  | 0.066 4 | 0.066 4 | 0.066 4 |
| $\varphi$                              | 0        | 0       | 0       | 0       |
| $(q/\sqrt{2}L_k)/10^{-2}$ eV           | 1.56     | 1.56    | 1.56    | 1.56    |
| $u_b^{\text{back}}/10^{-5}$ (nm/s)     | 1.0      | 1.0     | 1.0     | 1.0     |
| $n$                                    | 1.456    | 1.456   | 1.456   | 1.456   |
| $k/10^{-8}$                            | 4.3      | 4.3     | 4.3     | 4.3     |
| $a$                                    | 195.697  | 43.296  | 43.296  | 43.296  |
| $b$                                    | −9.65    | −1.81   | −1.81   | −1.81   |
| $k_t/10^{-6}$                          | 4.82     | 4.82    | 4.82    | 4.82    |

Table 4 Elastic and creep model parameters of UM-F series alloys

| Parameters                             | Material |         |         |
|----------------------------------------|----------|---------|---------|
|                                        | UM-F22   | UM-F20  | UM-F30  |
| Temperature/K                          | 1 223    | 1 223   | 1 223   |
| $C_{11}$ /MPa                          | 187 200  | 187 200 | 187 200 |
| $C_{12}$ /MPa                          | 123 000  | 123 000 | 123 000 |
| $C'_{11}$ /MPa                         | 168 200  | 168 200 | 168 200 |
| $C'_{12}$ /MPa                         | 110 400  | 110 400 | 110 400 |
| $C_{44}$ /MPa                          | 33 600   | 33 600  | 33 600  |
| $C'_{44}$ /MPa                         |          |         |         |
| Burgers/nm                             | 0.25     | 0.25    | 0.25    |
| Misfit                                 | -0.001   | <-0.003 | -0.003  |
| Size of precipitate edge/nm            | 430      | 600     | 450     |
| Matrix channel width/nm                | 70       | 92      | 60      |
| Volume fraction of precipitate         | 0.62     | 0.65    | 0.68    |
| $\alpha$                               | 0.2      | 0.2     | 0.2     |
| $\beta/10^{-9}$                        | 2.2      | 2.2     | 2.2     |
| $\rho_0$                               | 0.01     | 0.01    | 0.01    |
| $v_0^{\text{filling}}/10^{-4}$ (nm/s)  | 5.0      | 5.0     | 5.0     |
| $V^{\text{filling}}(b^3)$              | 46.8     | 46.8    | 46.8    |
| $D/10^{-5}$ (nm/s • MPa)               | 1.85     | 1.85    | 1.85    |
| $\theta$                               | 0        | 0       | 0       |
| $v_0^{\text{shear}}/10^{-6}$ (nm/s)    | 1.51     | 0.451   | 0.451   |
| $V^{\text{shear}}(b^3)$                | 48.6     | 48.6    | 48.6    |
| $E^{\text{npb}}/(\text{J}/\text{m}^2)$ | 0.066 4  | 0.066 4 | 0.066 4 |
| $\varphi$                              | 0        | 0       | 0       |
| $(q/\sqrt{2}L_k)/10^{-2}$ eV           | 1.56     | 1.56    | 1.56    |
| $v_0^{\text{back}}/10^{-5}$ (nm/s)     | 1.0      | 1.0     | 1.0     |
| $n$                                    | 1.456    | 1.456   | 1.456   |
| $k/10^{-8}$                            | 4.3      | 4.3     | 4.3     |
| $a$                                    | 195.697  | 195.697 | 253.4   |
| $b$                                    | -9.65    | -9.65   | -12.63  |
| $k_t/10^{-6}$                          | 4.82     | 4.82    | 4.82    |

In the formula,  $A=1.0 \times 10^{-4} \text{ m}$  is a parameter,  $\delta$  is the value of misfit,  $V_{\gamma'}$  is the volume fraction of  $\gamma'$ ,  $\max(h_1, h_2, h_3)$  is the maximum value of matrix channel width. In general, the misfit value and  $\gamma'$  volume fraction change little at a certain temperature, but the channel width of  $\gamma$  will become thicker as the increase of creep strain, hence, the absolute value of Microstate parameter will decrease during the creep deformation.

The initial value of microstate parameter  $Y_0$  can be obtained when the misfit,  $\gamma'$  volume fraction and matrix channel width all take its initial value  $\delta_0$ ,  $V_{\gamma'}^0$  and  $h_0$

$$Y_0 = A \frac{\delta_0 V_{\gamma'}^0}{h_0} \quad (2)$$

If we know the initial value of these three parameters about an alloy at a certain condition, the creep life of the alloy at this condition will be evaluated through the value of  $Y_0$ . The solid points show in Fig. 2 are the  $Y_0$  vs creep life of the alloys above under the same temperature/

load. The values are indicated in Table 1 and 2. It can be found out that the relationship between  $Y_0$  and creep life is linear nearly.

In order to verify the linear relationship between  $Y_0$  and creep life under the same condition, another three commercial single crystals' typical microstructure characteristics are given in Table 5 as well as its  $Y_0$  value and creep life under 1313 K/137 MPa<sup>[24]</sup>. The hollow points in Fig. 2 denote these three alloys. They are revealing the approximate linear relationship too.

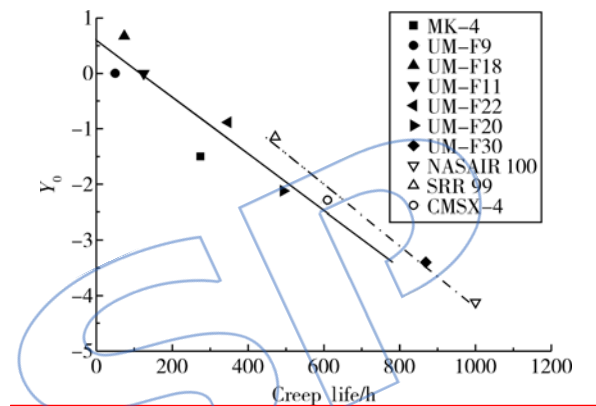


Fig. 2 Relationship between  $Y_0$  and creep life

Table 5 Initial microstructure parameters and creep life of three commercial single crystal alloys

| Parameters                                  | Material      |               |               |
|---------------------------------------------|---------------|---------------|---------------|
|                                             | NASAIR 100    | SRR 99        | CMSX-4        |
| Misfit                                      | -0.0036       | -0.0015       | -0.0018       |
| Size of precipitate edge/nm                 | 330           | 450           | 430           |
| Matrix channel width/nm                     | 55            | 80            | 80            |
| Volume fraction of precipitate              | 0.63          | 0.61          | 0.68          |
| Rafting                                     | Plate rafting | Plate rafting | Plate rafting |
| Initial value of microstate parameter $Y_0$ | -4.12         | -1.1475       | -2.29         |
| Creep life/h(1313 K/137 MPa)                | 1000          | 472           | 610           |

The solid and hollow points are under different conditions, respectively. We use the method of least square to fit the linear relationship between  $Y_0$  and creep life

$$t_{\text{creep}} = \psi Y_0 + \zeta \quad (3)$$

Use the MK-4 and UM-F series alloys as the sample to calculate the parameter  $\psi = -195.699$ ,  $\zeta = 116.863$ , and the linear correlation coefficient  $r = 0.915$ . Use the other three commercial alloys as the sample then obtained

the  $\psi = -180.938$ ,  $\zeta = 238.187$  and  $r = 0.982$ . The lines fitted which draw in real and broken are shown in Fig. 2, respectively. Through the line the creep life under a certain condition can be evaluated if the initial value of microstate parameter is known.

### 3 Creep analysis of DD3 turbo blade

Adopt the elastic module, Poisson ratio,

heat conductivity and line-expand coefficient of DD3 at  $[001]$  direction<sup>[25]</sup> to a structure of turbo blade. The temperature distributions of the blade are given in Fig. 3. It can be seen that the

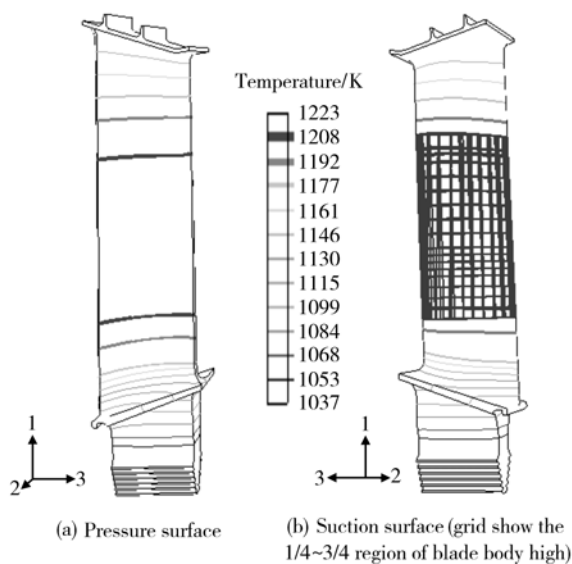


Fig. 3 Temperature state of DD3 turbo blade

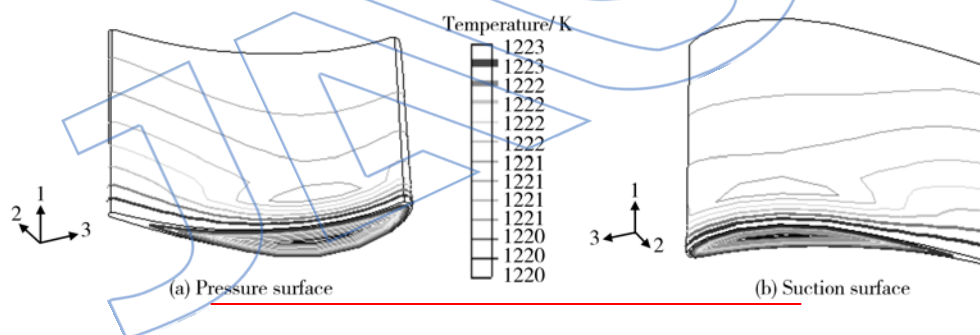


Fig. 4 High temperature region of DD3 turbo blade

Fig. 5 shows the radial creep distribution of high temperature region at different creep time. The maximum creep strain reveals on the suction surface near to the blade root where stress is big. From the figure it can be seen that the maximum radial strain is 0.028 when the creep time are 5 h, and it increase to 0.075 at 10 h and 0.18 at 15 h, the strain rate become much bigger at the remaining creep time. At the same time, the distribution region of the maximum strain is more concentrate on one point. We choose three nodes 1222, 1210 and 1204 on the blade indicated in Fig. 5 (a) as the object and draw the change of some parameters during creep

highest temperature on the blade is 1 223 K and mainly in the region of 1/4~3/4 blade body high.

Fig. 4 shows the 1/4~1/2 region of the blade body high in which have the highest even homogeneous temperature field and relatively big stresses. The temperature difference in this region is only 3 K and temperature on the surface is higher than in the middle of the blade. Because of the small temperature difference in this region, we can see it as the homogeneous temperature region and use the creep parameters of DD3 at 1223 K<sup>[23]</sup> to analyze the creep deformation of this region.

Blade rotational speed is 12 640 r/min and the displacement constraints on the surfaces of tenon tooth and end face are given. The creep parameters of DD 3 at 1223 K are adopted in high temperature region of the blade body show as the grid part of Fig. 3 (b). The initial time step is 0.01 s and the maximum time step is 10 s.

deformation in order to analyze the process.

Fig. 6 shows the radical stress-strain curves and Mises stress-strain curves about three nodes. We can see the radical stresses of the nodes increase rapidly at the very beginning from 0 to about 325 MPa, then decrease gradually to about 250 MPa and keep stable. Compared with the radical stresses, the Mises stresses increase to the more higher peak stress which nears to 380 MPa, then after decrease to 250~300 MPa the stresses increase again.

Fig. 7 shows the creep of three nodes in three directions, respectively. We can see the shape of the creep curves are very similar to the

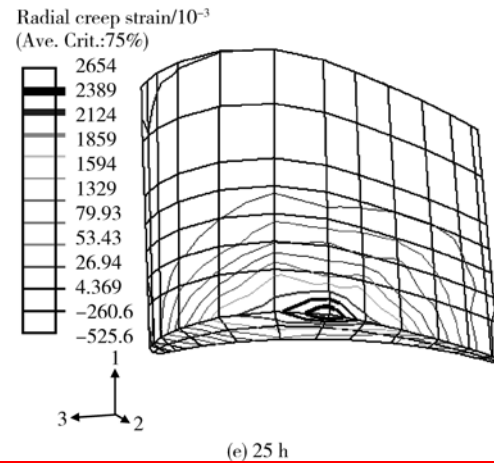
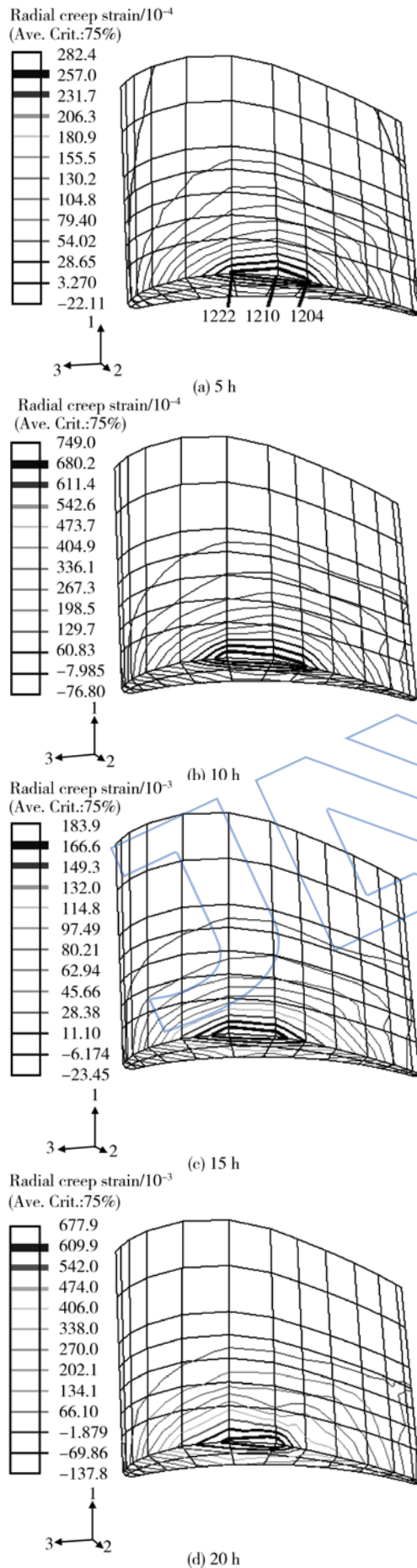


Fig. 5 Radial creep distribution in high temperature region at different creep times

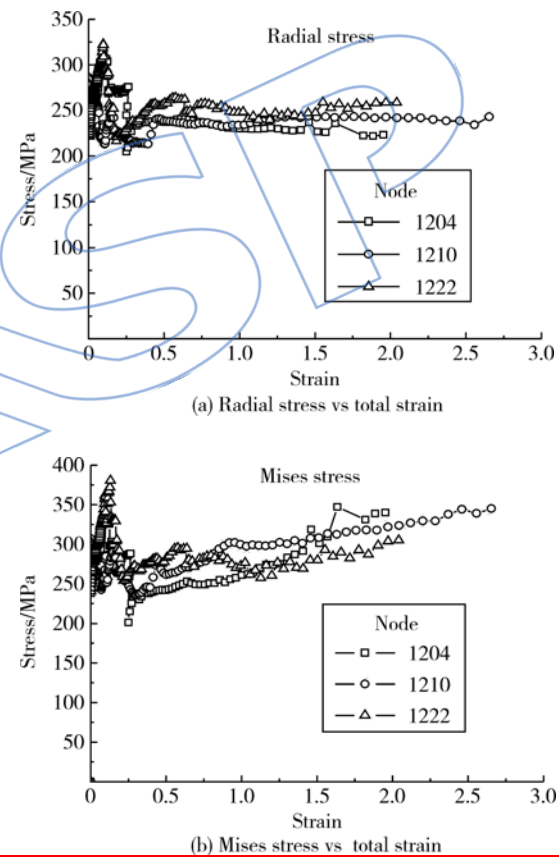


Fig. 6 Stress-strain curve of three nodes

test ones in Ref. [23] which have no first and stable phase obviously and the creep rate keep increasing. At the same time, radical creep strain is the largest, hoop strain takes the second place and the axial strain minimum. Node 1204 exhibits decrease of creep strain at three directions near 18h maybe relate to its position on the blade.

Fig. 8 shows the evolution of cell dimen-

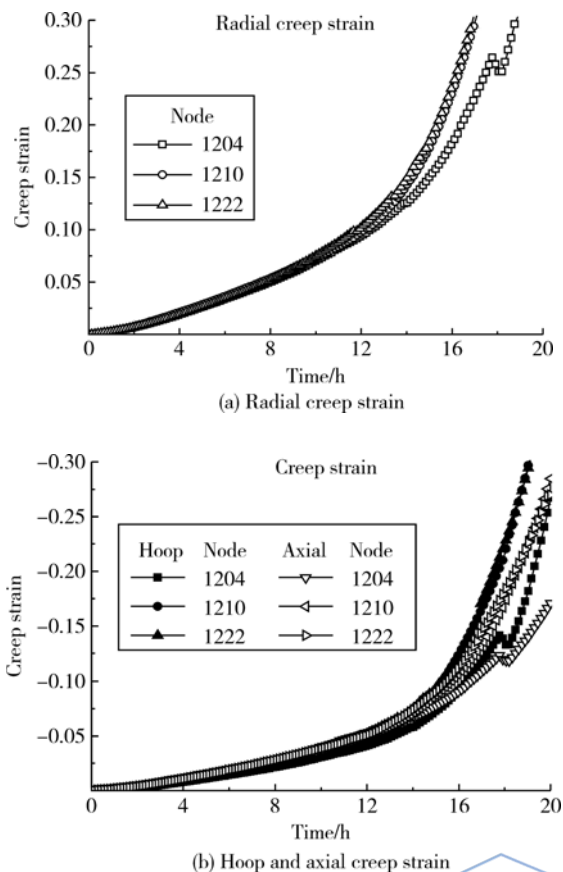


Fig. 7 Creep of three directions at three nodes

sions at two nodes.  $L_1$ ,  $L_2$  and  $L_3$  denote the sizes of precipitate edges at three directions. At the beginning,  $L_2$  and  $L_3$  have the increase trend but  $L_1$  keep stable. After 10 h of creep, one of  $L_2$  and  $L_3$  is continue increasing but the other one become decrease.  $h_1$ ,  $h_2$  and  $h_3$  denote the channel widths of matrix at three directions. During creep deformation one of the vertical channel and the horizontal channel widths have the increasing trend too, but the other vertical channel is becoming much more narrowing. The Ref. [23] gave the formulas about these evolutions in detail. Thus, we can see that the microstructure has the trend of plate rafting at the beginning, but after 10 h's creep, only one of the directions perpendicular to the load is continuing rafting with the decrease of channel width at this direction. Therefore, the plate rafting happened when the creep strain less than 0.05, and the rafting type changed with the increase of the creep strain. This phenomenon is different from the situation under uniaxial load.

We also see from the Fig. 8 that the changing of the dimensions at the same direction of the two nodes is different which means different positions on the blade body have different microstructure evolution processes.

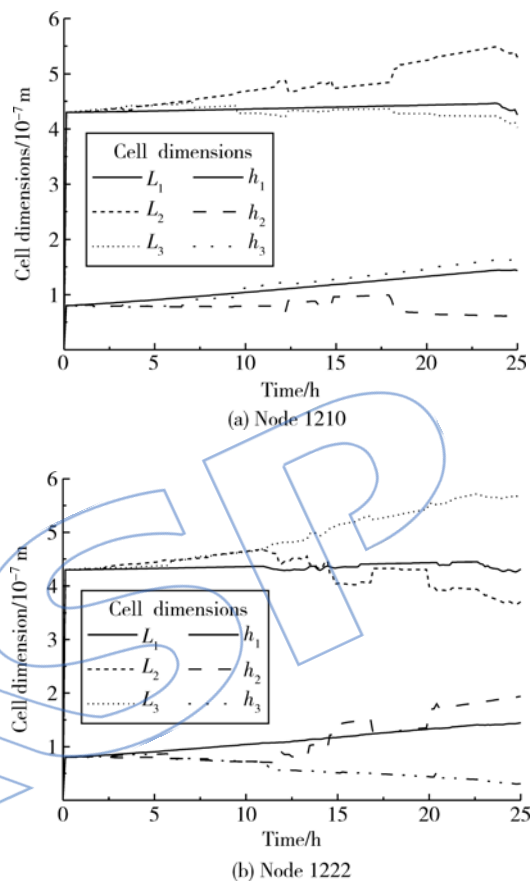


Fig. 8 Microstructure dimensions' evolution at different nodes

Fig. 9 shows the change of the microstate parameter  $Y_{\text{micro}}$  with creep time at three nodes. The initial value of  $Y_{\text{micro}}$  is  $-0.75$ . With the increasing value of maximum channel width during creep, the absolute value of  $Y_{\text{micro}}$  become smaller. From Fig. 9 we can see the change of  $Y_{\text{micro}}$  with creep time present linear nearly at these three nodes. During 10~20 h they are different in which node 1210 change fastest and 1222 take the second place. This relationship may give us a way of using the value of  $Y_{\text{micro}}$  to predict the residual creep life at the critical points of the blade body. The analysis above also shows that node 1210 possess the largest creep strain and destroys most. These two conclusions indicate  $Y_{\text{micro}}$  can characterize the damage of the material

to some extent. Then, we choose a row of nodes on the suction surface of the blade high temperature region and draw the line of  $Y_{\text{micro}}$ . The stresses of these nodes from underside to upside show in Fig. 10 are decreased in turn. We can see from the line of Fig. 11 that the absolute

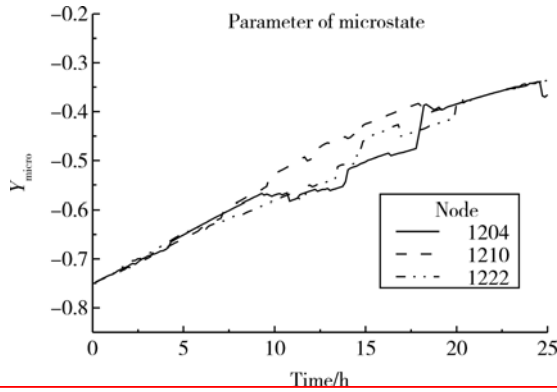


Fig. 9  $Y_{\text{micro}}$  change with creep time at three nodes

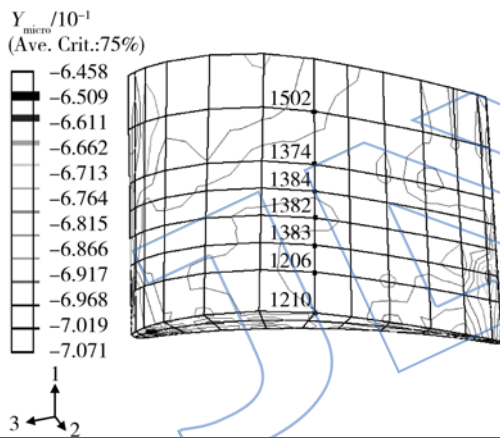


Fig. 10  $Y_{\text{micro}}$  distribution of blade high temperature region

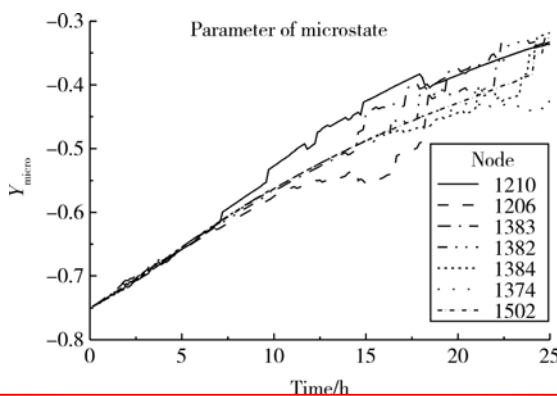


Fig. 11  $Y_{\text{micro}}$  change with creep time at a series nodes on suction surface

value of  $Y_{\text{micro}}$  at node 1210 decrease fastest, node 1206 and 1383 take the second place, and node 1384, 1374 and 1502 change slow relatively. Thus, the nodes which have large stresses reveal the rapid decrease of absolute value of  $Y_{\text{micro}}$ .

From Fig. 9 we can obtain the initial value of microstate parameter  $Y_0 = -0.75$ , then the creep life of DD3 under 1 223 K/290 MPa can be calculated using the formula (3). The predict creep life is about 263 h which is close to the test result 250 h that reference given<sup>[25]</sup>. Therefore, the initial value of microstate parameter has the ability of predicting the creep life of single crystal turbo blade under a certain condition to some extent.

## 4 Conclusion

A series of Ni base single crystals with similar alloy elements but different initial microstructure states were analyzed to study the influence of alloy's initial microstructure on the creep performance of the materials. Three microstructure parameters: misfit, precipitate volume fraction and matrix channel width were showed to have evident influence on creep life. In order to enhance the strengthening effect of the precipitate, the shape of which should be cubic and the large enough misfit and  $\gamma'$  volume fraction are necessary as well as the narrow matrix channel width. Thus, the microstate parameter was defined and the linear relationship between initial value of  $Y_{\text{micro}}$  and creep life were obtained to predict the creep life of single crystal under a certain temperature/load.

Using the creep model parameters of DD 3 under 1 223 K to analyze the turbo blade and chose the 1/4~1/2 region of blade body as object to implement the creep calculation. Aiming at three nodes which had the largest strains and drawing the change of stresses, strains and microstructures evolution. A row of nodes were takeout to show the relationship between microstate parameter and creep damage and verified the damage characterization ability of  $Y_{\text{micro}}$ . At last, used the linear formula of  $Y_0$  and creep life

to predict the life of blade at high temperature region and the result near to the test.

## Reference:

- [1] Muller L, Glatzel U, Feller-Kniepmeier M. Modeling thermal misfit stresses in nickel-base superalloys containing high volume fraction of  $\gamma'$  phase[J]. *Acta Metallurgica et Materialia*, 1992, 40(6): 1321-1327.
- [2] Nathal M V. Effect of initial gamma prime size on the elevated temperature creep properties of single crystal nickel base superalloys[J]. *Metallurgical and Materials Transaction A*, 1987, 18(11): 1961-1970.
- [3] Tinga T, Geers M G D, Brekelmans W A M. micro-mechanical model of a single crystal nickel-based superalloy [R]. Hamburg: 25th International Congress of the Aeronautical Sciences, 2006.
- [4] Tien J K, Copley S M. The effect of uniaxial stress on the periodic morphology of coherent gamma prime precipitates in nickel-base superalloy crystals [J]. *Metallurgical and Materials Transaction B*, 1971, 2(1): 215-219.
- [5] Nathal M V, Mackay R A, Miner R V. Influence of precipitate morphology on intermediate temperature creep properties of a nickel-base superalloy single crystal[J]. *Metallurgical and Materials Transaction A*, 1989, 20(1): 133-141.
- [6] Nathal M V, Ebert L J. Elevated temperature creep-rupture behavior of the single crystal nickel-base superalloy NASAIR 100[J]. *Metallurgical and Materials Transaction A*, 1985, 16(3): 427-439.
- [7] Sakaguchi M, Okazaki M. Hybrid composite model for high-temperature fatigue life prediction in single crystal Ni-based superalloy [R]. Nagaoka: 6th Japan-China Bilateral Symposium on High Temperature Strength of Materials, 2007: 107-112.
- [8] REN Yinglei. Microstructure evolution and mechanical performance at high temperature of a Ni base single crystal [D]. Shenyang: Graduate School Institute of Metal Research Chinese Academy of Sciences, 2002. (in Chinese)
- [9] Link T, Epishin A, Bruckner U. Increase of misfit during creep of superalloys and its correlation with deformation [J]. *Acta Materialia*, 2000, 48(8): 1981-1994.
- [10] Epishin A, Link T, Bruckner U. Kinetics of the topological inversion of the  $\gamma/\gamma'$  microstructure during creep of a nickel-based superalloy [J]. *Acta Materialia*, 2001, 49(19): 4017-4023.
- [11] Epishin A, Link T, Portella P D. Evolution of the  $\gamma/\gamma'$  microstructure during high-temperature creep of a nickel-base superalloy [J]. *Acta Materialia*, 2000, 48(16): 4169-4177.
- [12] Peng Z, Glatzel U, Link T. Change of phase morphologies during creep of CMSX-4 at 1253K [J]. *Scripta Materialia*, 1996, 34(2): 221-226.
- [13] Fedelich B, Künecke G, Epishin A. Constitutive modelling of creep degradation due to rafting in single-crystalline Ni-base superalloys [J]. *Materials Science and Engineering A*, 2009, 510-511(15): 273-277.
- [14] Epishin A, Link T, Klingelhöffer H. New technique for characterization of microstructural degradation under creep: application to the nickel-base superalloy CMSX-4 [J]. *Materials Science and Engineering A*, 2009, 510-511(15): 262-265.
- [15] Matan N, Cox D C, Rae C M F, et al. On the kinetics of rafting in CMSX-4 superalloy single crystals [J]. *Acta Materialia*, 1999, 47(7): 2031-2045.
- [16] Conley J G, Fine M E, Weertman J R. Effect of lattice disregistry variation on the late stage phase transformation behavior of precipitates in Ni-Al-Mo alloys [J]. *Acta Materialia*, 1989, 37(4): 1251-1263.
- [17] Zhang J X, Wang J C, Harada H, et al. The effect of lattice misfit on the dislocation motion in superalloys during high-temperature low-stress creep [J]. *Acta Materialia*, 2005, 53(17): 4623-4633.
- [18] Muller L, Link T, Feller-Kniepmeier M. Temperature dependence of the thermal lattice mismatch in a single crystal nickel-base superalloy measured by neutron diffraction [J]. *Acta Metallurgica et Materialia*, 1992, 26(6): 1297-1302.
- [19] Biermann H, Strehler M, Mughrabi H. High-temperature X-ray measurements of the lattice mismatch of creep-deformed monocrystals of the nickel-base superalloy SRR99 [J]. *Scripta Metallurgica et Materialia*, 1995, 32(9): 1405-1410.
- [20] Royer A, Jacques A, Bastie P, et al. The evolution of the lattice parameter mismatch of nickel based superalloy: an in situ study during creep deformation [J]. *Materials Science and Engineering A*, 2001, 319-321: 800-804.
- [21] Rowland L J. Creep and microstructural stability of ruthenium-containing nickel-base single crystal superalloys [D]. Ann Arbor, USA: University of Michigan, 2005.
- [22] CAO Juan, WANG Yanrong, SHI Duoqi. Slip model for the plastic behavior of Ni base single crystal based on dual-phase microstructure cell [J]. *Journal of Aerospace Power*, 2009, 24(7): 1537-1543. (in Chinese)
- [23] CAO Juan, WANG Yanrong, SHI Duoqi. Rafting creep model of Ni base single crystal at high temperature based on microstructure cell [J]. *Journal of Aerospace Power*, 2009, 24(8): 1691-1698. (in Chinese)
- [24] Chen Q Z, Knowles D M. Mechanism of  $\langle 112 \rangle/3$  slip initiation and anisotropy of  $\gamma'$  phase in CMSX-4 during creep at 750 °C and 750 MPa [J]. *Materials Science and Engineering A*, 2003, 356(1-2): 352-367.
- [25] Editorial Committee of Chinese Aviation Material Manual Book. Chinese aviation material manual book Vol. 2: deforming and Ni based superalloys [M]. Beijing: Standards Press of China, 2002. (in Chinese)