CREEP BEHAVIOR OF MAGNESIUM

MICROALLOYED WROUGHT SUPERALLOYS

Peili Ma, Ying Yuan, Zengyong Zhong

Central Iron and Steel Research Institute
Beijing, PR China

Abstract

By adding minor amount of magnesium to the wrought superalloys, the rupture life and ductility are considerably improved, the steady stage of creep, and especially the tertiary stage of creep are prolonged, and the steady creep rate is decreased at low strain rates. It is found that magnesium segregates to grain boundaries and interfaces, and also exists in matrix, γ' phase and carbides. The magnesium causes the change in interfacial energy and enhances the cohesion of the grain boundaries and of the interfaces. Magnesium can spheroidize the carbides in the grain boundaries, purify the grain boundaries and decreases the vacancy concentration in the alloys. In order to clarify the mechanism of these effects, detailed studies have been made.

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G. Maurer, S. Antolovich and C. Lund
The Metallurgical Society, 1988

Introduction

Magnesium had been seldom utilized as a microalloying element in commercial alloys although the studies of the effects of it on the superalloys could be found in the literatures. Over the years, a series of studies have been carried out by Chinese materials scientists and the application of magnesium has being introduced into commercial wrought superalloys. The results of the studies indicated that minor amount of magnesium would favor the properties of superalloys, especially considerably improve the rupture life, rupture ductility, high-temperature tensile ductility, notch sensivity and hot workability. Some studies of the mechanisms of these effects have also been done.

In this work, a systematic investigation about the effects of magnesium on the creep and creep rupture behaviors in wrought superalloys was carried out and the mechanism was investigated.

Experimental Procedures

In the present work, two differently alloyed wrought superalloys were used for study. Alloy A (GH33), simply alloyed, has the similar composition to Nimonic 80A and approximately 8wt-% γ'phase. Alloy B (GH220), complexly alloyed, contains molybdenum and tungsten, etc, as strengtheners and approximately 45 wt-% γ'phase. It can operate at 900℃. The compositions of these two alloys are listed in table 1.

Table I. Compositions of the Alloys (wt,%)

Alloy	C	Cr	Co	W	Mo	Al	Ti	V	B
A (GH33)	0.02	20	--	—	—	0.7	2.5	—	0.007
B (GH220)	0.06	10	15	5.5	5.5	4.3	2.5	0.3	0.008

The contents of magnesium were investigated to be 0.0003%, 0.006%, 0.013% and 0.030% for alloy A, and 0.0003%, 0.007%, 0.0125% and 0.028% for alloy B.

Rupture life, elongation and creep curves under various stresses were measured. Fracture characteristics and the microstructures of the tested specimens were studied by metalloscope, SEM and TEM, etc.

The concentration of magnesium in the phases was determined by means of electroextraction and chemical analysis. The lattice constant of γ'phase and carbides were determined by Nonus II Guinier camera. Tests of grain boundary sliding during creep was taken in a vacuum creep-testing equipment. Vacancy activation energy of the alloys was calculated from the values of electrical-resistivity.

Experimental Results

1. Stress Rupture Properties

The effect of magnesium on the rupture life is shown in fig.1. It shows clearly that minor amount of magnesium can increase the rupture life, particularly for alloy A. Excessive amount of magnesium, however, decreases the rupture life. The elongation is also significantly improved with enhancing of the rupture life. Similar results have come out for some other superalloys. It should be noted that the optimal content of magnesium varies in different alloys.

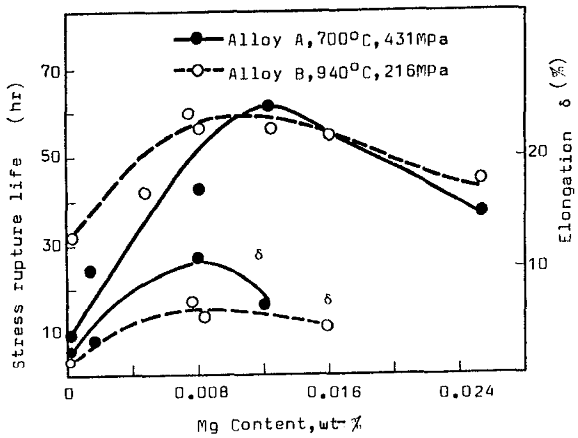


Fig.1 Effect of Mg-Content on the Stress-Rupture Properties

2. Creep Behavior

Fig.2 shows the effect of magnesium on creep behavior. Proper amount of magnesium lengthens the duration of second stage of creep and especially the tertiary stage, thereby the creep rupture life is enhanced and the total creep strain increases.

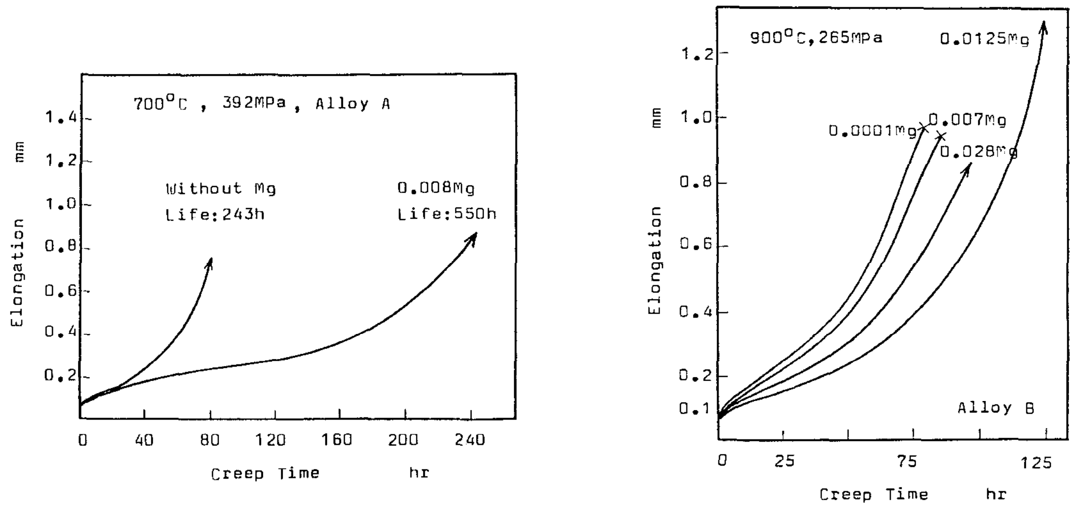


Fig.2 Creep Curves of Alloy A and B with various Mg-Addition

The experimental results of the effect of magnesium on the steady creep rate (fig. 3, 4 and 5) show that minor amount of magnesium could

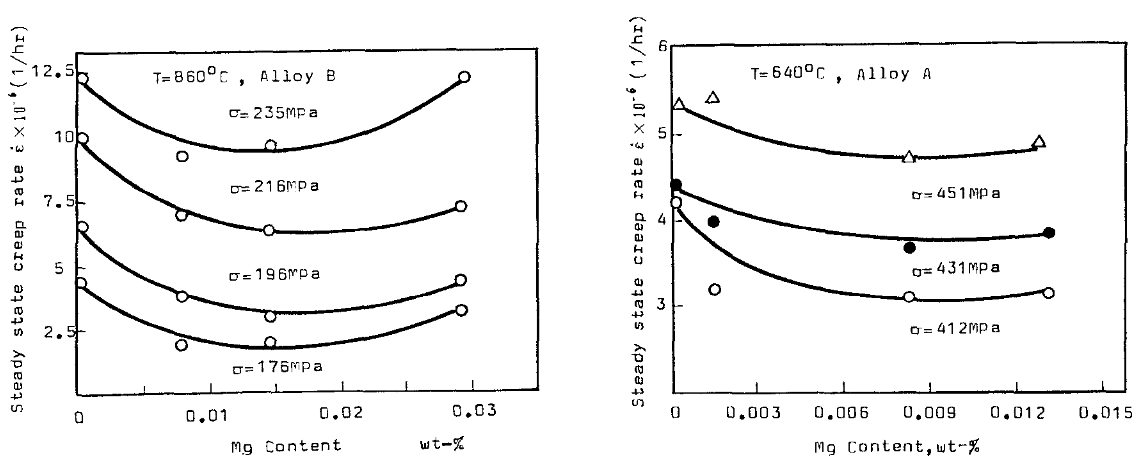


Fig.3, 4 Influence of Mg on the Steady-State Creep Rate decrease the rate of steady state creep at low creep rate($\dot{\varepsilon} < 10^{-5}$ mm·mm^{-1}·hr^{-1}) At the strain rate greater than a critical value($\dot{\varepsilon} > 10^{-5}$ mm·mm^{-1}·hr^{-1}), the effect of magnesium vanishes, i.e. the effect on the steady creep is present only within the range of low strain rate.

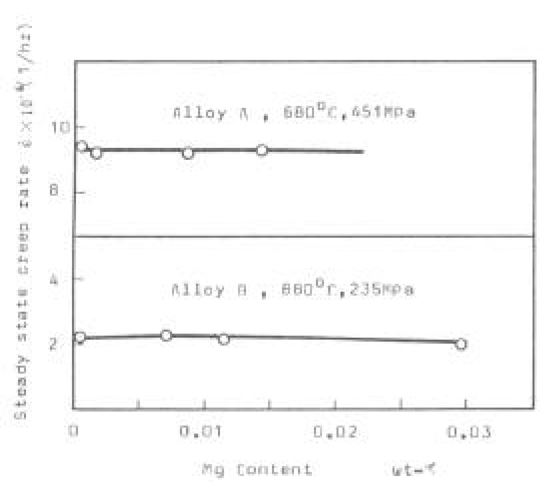
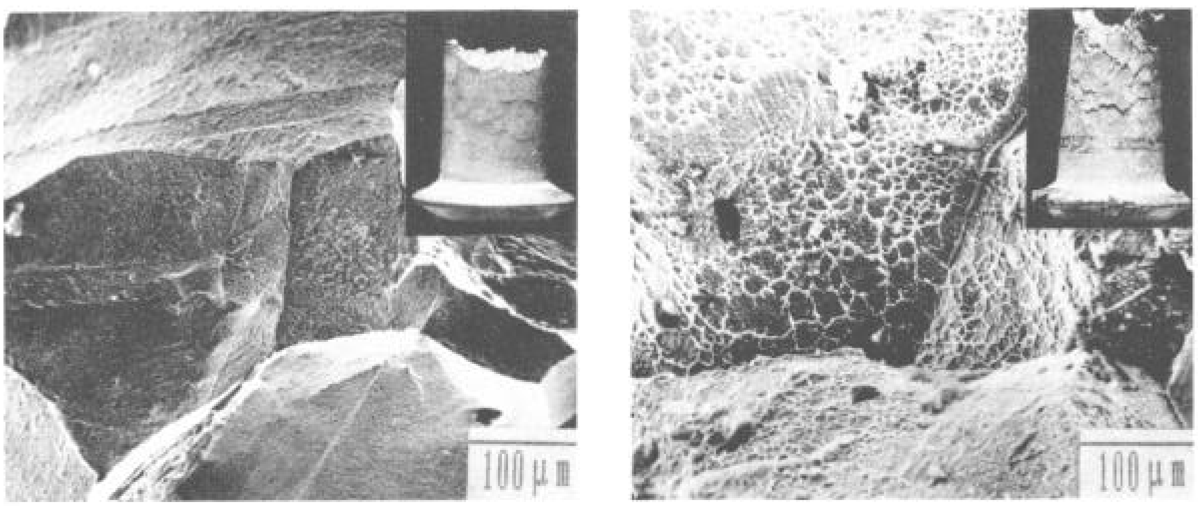


Fig.5 Influence of Mg on the Steady-State Creep Rate

3. <u>Fracture Characteristics</u>

The fractured specimens of alloy A were studied. The specimens without Mg-addition show smooth surface, no necking and insignificant local deformation near fracture place. The fracture surface exhibites intergranular brittle rupture (fig. 6a). The specimens that contained magnesium, however, show many micro-cracks on the surface and obvious necking down. Ductile intergranular rupture is yielded at the fracture surface (fig. 6b).

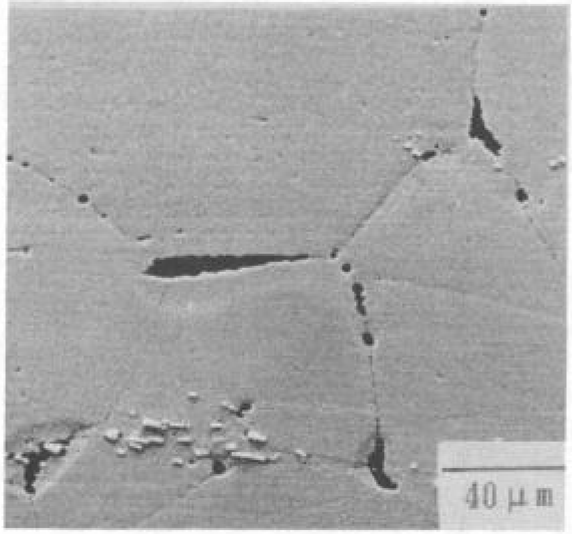


a) without Mg-addition b) with Mg-addition

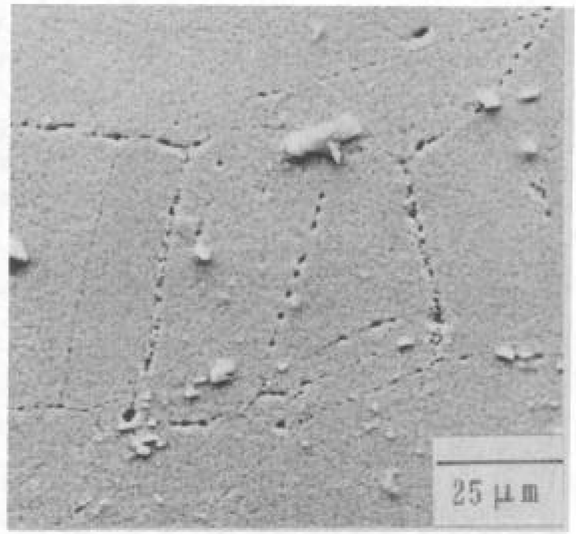
Fig.6 SEM-Fractographs of Stress-Rupture Specimens

Two types of cracks have been found in the longitudinal section of the specimens. One is wedge-like cracks which form owing to the grain boundary sliding, as shown in fig.7a. In fig.7b, the other type cracks are shown which arises from the coalescence of micro-voids in grain boundaries, verticle to the direction of the applied stress. As magnesium increases, the percentage of wedge cracks decreases from 70% in the case of without Mg to 40% in the case of with Mg. Excessive magnesium raises the percentage of wedge cracks again, as indicated in fig.8.

Significant changes in carbide morphology take place owing to the magnesium addition. The carbides are considerably spheroidized. It is shown in fig. 9, for alloy B, that the percentage of rod-like carbides decreases with



a) Wedge-crack



b) Cavitation-crack

Fig. 7 SEM - Micrographs of Creep Specimens

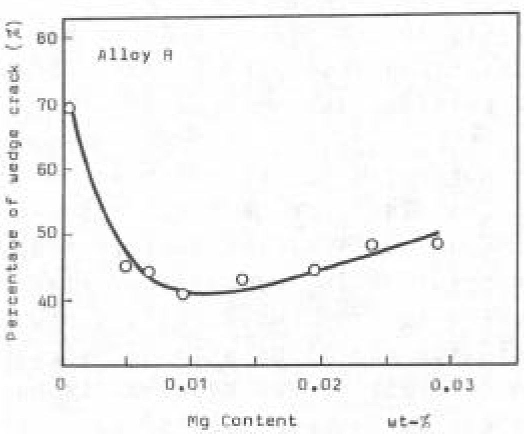


Fig.8 Relation between the Percentage of Wedge-Cracks and Mg-Content

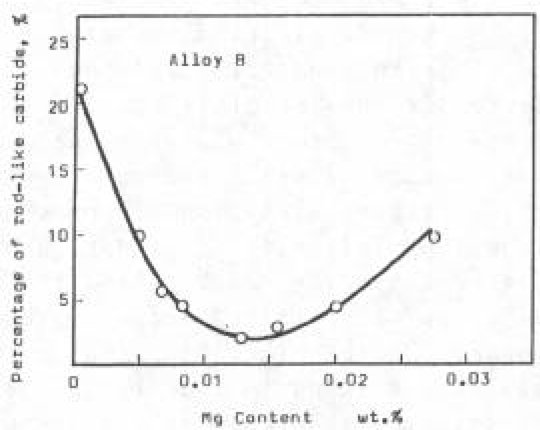


Fig.9 Relation between the Percentage of Rod-like Carbides and Mg-Content

the addition of magnesium.

Discussion

In publications, it is an opinion of some workers that the role of magnesium is owing to its desoxydation and desulphidation. In fact, however, magnesium is also a microalloying element. This problem will be discussed subsequently.

1. The Mg-distribution is an essential factor for the study on the mechanism of its effects. The results of the studies by the authors of this papar [1, 2, 3, 4] have indicated that magnesium is a surface-active element inclined to segregate to grain boundaries and carbide/matrix interfaces. Magnesium causes the change in the energy of grain boundaries and interfaces and thereby results in the spheroidization of carbides. On the

other hand, the results of phase analyses reveal that magnesium can dissolve in γ matrix in small amount, and enter into γ' phase and carbides. For alloy B with 0.005% Mg, the magnesium concentration in γ, γ' and carbide phases is 0.0024 %, 0.0076% and 0.0238% respectively. The magnesium dissolved in γ' phase and carbides, leads to the compositional changes, i.e. increases the contents of W, Mo and Ti in the phases and therefore changes their lattice constants (fig. 10). The presence of Mg in grain boundaries and matrix improves the properties of the alloys. Besides, very small amount of inclusion formed by magnesium acting with P, S and Si can usually be found in the alloys.

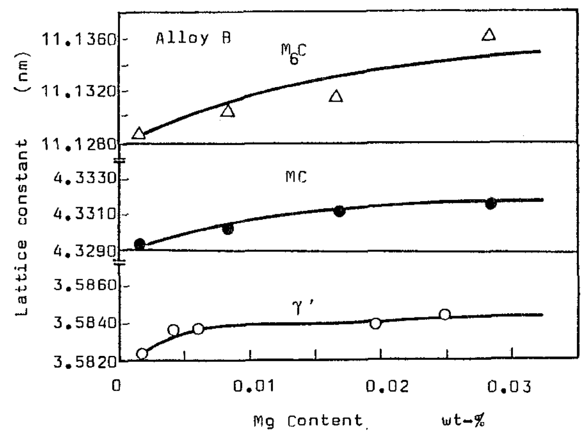
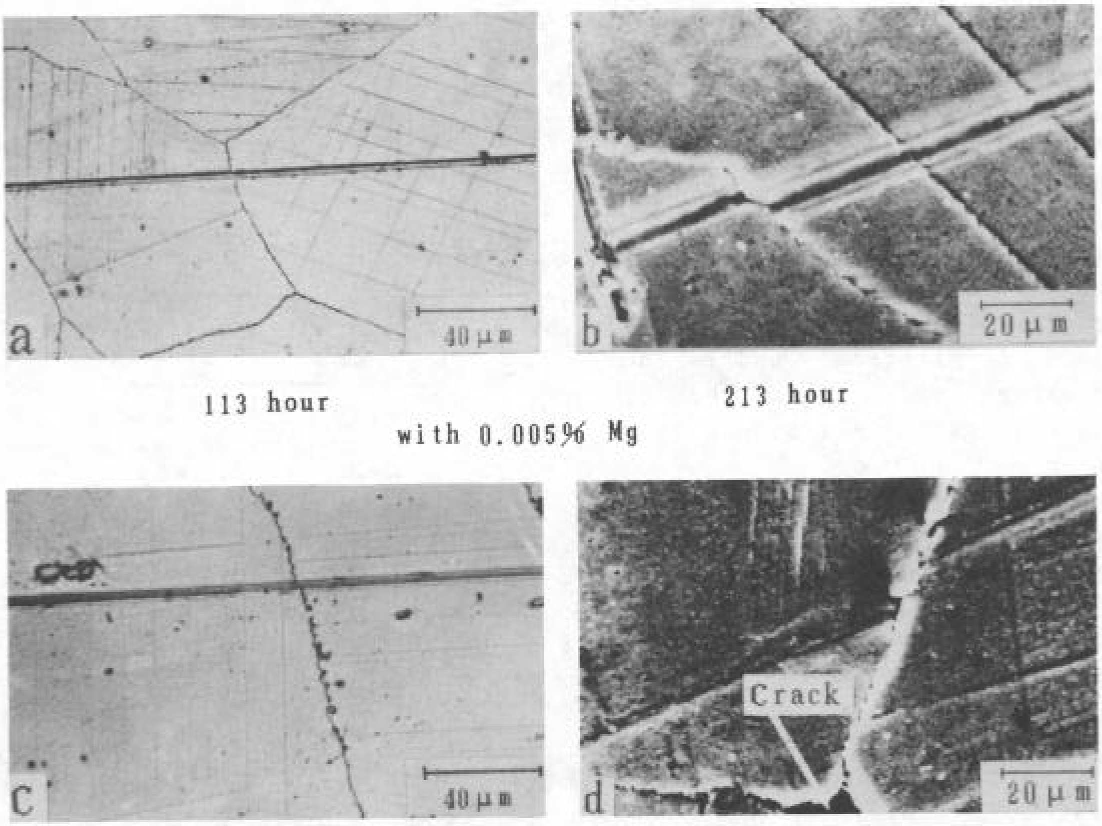


Fig.10 The Relation between Mg-Content and Lattice Parameters of Carbides and γ'-Phase

2. Mg located at the grain boundaries and carbide/matrix interfaces lowers the grain boundary energy and the interfacial energy, increases the interface cohesion and reduces the rates of crack initiation and propogation [5] Furthermore, the spheroidized carbides improve the stress distribution state at grain boundaries and thus decreases the possibility for wedge crack formation. Hence the coalescence of grain boundary microvoids nucleated by carbides becomes the prominent mechanism of carck initiation. This can be also deduced from the similarity of figures 8 and 9. As a result of the factors mentioned above, the crack initiation and propogation in the tertiary stage of creep are retarded and thus the rupture life is substantially prolonged. On the other hand, magnesium addition can allow a large grain boundary sliding to coordinate the grain deformation, and even in strongly deformed specimen, no cracks would be easily formed. Therefore the stress rupture and creep elongation are improved noticeably. The experiments conducted by the authors [5] indicated that magnesium could purify grain boundaries through binding with S and P, etc. This also contributes to the improvement of stress rupture property.

Magnesium addition is proved to be favorable to the grain boundary sliding by vacuum creep test. In the test, line markes were set on the polished surfaces of specimens so that the grain boundary sliding could be measured. For the specimen containing magnesium, small sliding occured at the time of 113 hour during the test. Great sliding happened at 293 hour, but no cracks appeared at that time. For the specimen without Mg-addition, the grain boundary sliding was smaller compared with that containing magnesium. No visible sliding occured at 130 hour on the test, but noticeable grain boundary sliding happened abruptly at 170 hour and wedge cracks were found at the triple grain boundary (fig.11).

3. The fact that Mg reduces steady creep rate within the range of low strain rate is related to the presence of magnesium in matrix. It is well known that creep mechanism is very complicated and varies under different conditions. Lagneborg et al [6] studied the creep behavior of



113 hour 213 hour

with 0.005% Mg

130 hour 190 hour

without Mg

Fig.11 Grain Boundary Slip in Creep Test

precipitation-strengthened alloys under various stresses at intermediate temperatures and pointed out that under low stress condition, i.e. at low strain rate, dislocation movement could not be realized by Orowan mechanism or cutting γ' particles, but otherwise by dislocation climbing over γ'particles. Only when the stress increased to a certain value , the Orowan mechanism or that of cutting γ'particles would play a dominent role.

Within the range of low strain rate, the climbing of dislocation over γ'particles depends upon the vacancy concentration in matrix. The experimental result indicates that magnesium has an influence on the vacancy activation energy of the alloys. Fig.12 demonstrates that activation energy of vacancy increases as concentration of magnesium increases in the alloys. Compared with that containing no magnesium , the alloy with magnesium has a faster increase in the activation energy. The vacancy activation energy, Q_v, is calculated from the increment of electrical-resistivity based on the following equation, where $\triangle\rho$ is the in-

$$\triangle \rho = D \cdot \exp(-Q_v / KT)$$

crement of electrical-resistivity due to vacancy and D is a constant.

The increase in vacancy activation energy of Mg-contained alloy causes the decrease in vacancy concentration , therefore the climbing velocity of dislocation over γ'particles reduces and a low steady creep rate proceeds. When the stress is raised to a certain value and the Orowan mechanism and / or the mechanism of cutting γ′-particles become to be prominent in creep strain, the influence of the vacancy concentration arising from magnesium will disappeare. The dislocation configurations are demonstrated in fig.13 for alloy A under both low stress and high stress creep conditions. It can be seen that only single dislocations exist at the matrix / γ′ interfaces under low stress, whereas dislocation rings or pairs are present under high stress condition.

It has been found that magnesium influences the steady creep rate in the range of $\dot{\varepsilon} < 10^{-3} mm \cdot mm^{-1} \cdot hr^{-1}$, this result agrees with that proposed by Lagneborg et al introducing the mechanism of dislocation climbing over γ′ particles.

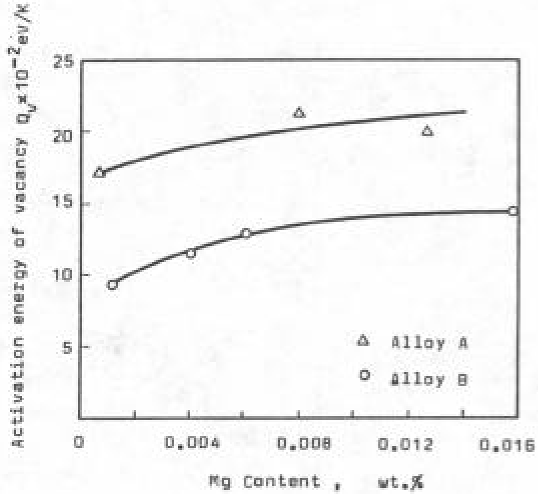


Fig.12 The Relation between Mg-Content and the Activation Energy of Vacancy

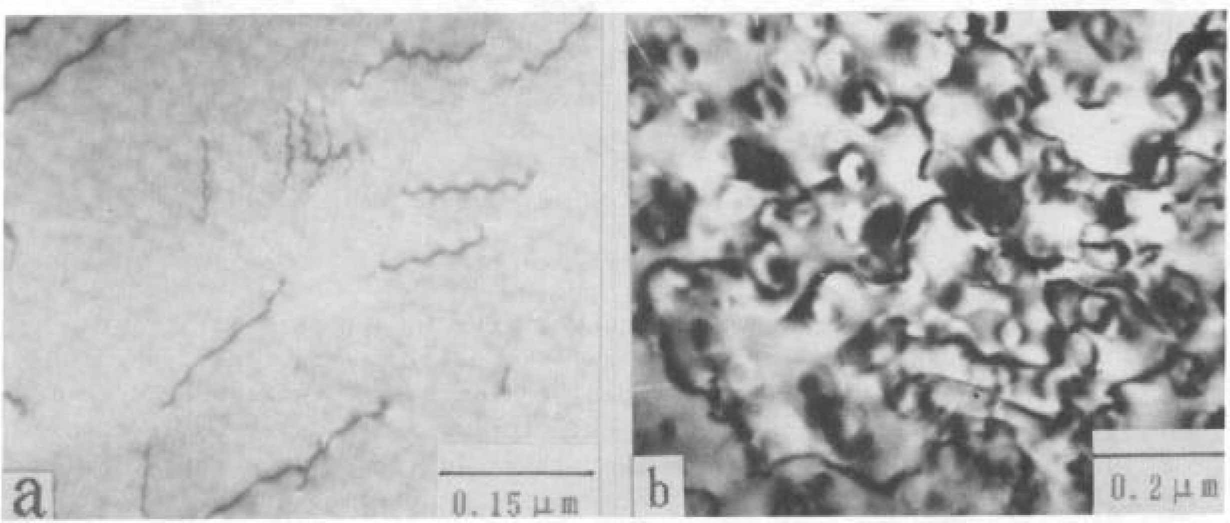


Fig.13 Dislocations in the Creep Specimens at various Strain Rate
a) low strain rate b) higher strain rate

Conclusions

By adding minor amount of magnesium to the wrought superalloys , rupture life and ductility can be significantly improved, the percentage of wedge cracks in the fractured specimens decreases and part of ductile intergranular fracture on the fracture surface increases. These are mainly related to that magnesium segregating to the grain boundaries could decrease the grain boundary enery, enhance the cohesion of the grain boundaries and the interphase interfaces, promote the spheroidization of carbides in grain boundaries and accordingly change the stress distribution around carbides, etc.

In the range of low strain rate ($\dot{\varepsilon} < 10^{-3} mm \cdot mm^{-1} \cdot hr^{-1}$), minor amount of magnesium would decrease the steady creep rate. At high strain rates, however, the effect of magnesium on creep rate would vanish. These are caused by the magnesium dissolved in the matrix. A mechanism accounting for it is proposed in this paper.

References

1. Danian Ke, Zhengyong Zhong, Acta Metall, 19(1983), No.5, A377(in Chinese).
2. Peili Ma et al, Acta Metall, 23(1987), No.3, A195 (in Chinese).
3. Peili Ma et al, Acta Metall, 23(1987), No.6, A484 (in Chinese).
4. Danian Ke, Zhengyong Zhong, Central Iron and Steel Research Institute Technical Bulletin, 3(1983) No.1, 73(in Chinese).
5. Danian Ke, Thesis for master's degree, (supervisor: Zhengyong Zhong), Central Iron and Steel Research Institute, Beijing, CHINA, 1981.
6. Lagneborg, R. and Bergmen, B., Met. Sci., (1976), No.10, Jan. 20.