EFFECT OF TRACE ADDITIONS OF MAGNESIUM

ON CREEP CRACK GROWTH OF A SUPERALLOY

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Abstract

The present work has shown that the addition of Mg in superalloy can significantly influence its creep crack growth. The creep crack growth could be divided into four stages. An optimum addition of Mg to superalloys can prolong the initial stage of creep crack growth, decrease the crack growth rate and prolong the creep rupture lives. The optimum amount of Mg addition can also increase the transient point of crack growth C* in lodga/dt-log C* curve.

Introduction

Many investigations ^[1,2,3] over the last ten years have shown that the mechanical properties, including hot workability, tensile ductility and creep resistance, can be markedly improved by the proper addition of trace amounts of Mg to nickel-base superalloys. Studies have shown that the segragation of Mg to grain boundaries is the main cause for the improvement of superalloy properties. The segregation of Mg to grain boundaries can decrease the grain boundary energy, enhance the cohesion of the grain boundary, promote spherodizing of the carbides and change the distribution and morphology of secondary phases at grain boundaries. The nucleation and growth of creep cracks are important aspects in creep studies, however until now, there have been few studies on the effect of Mg on the behavior of creep crack growth. Therefore, this subject was studied in this work.

Materials and Procedures

A nickel-base superalloy GH33 with a composition of Ni-20Cr-2.5Ti-0.7Al, strengthed by the Ni₃(Al,Ti) phase, was chosen as test material. The alloy was melted in vacuum induction furnace as primary alloy, then remelted into ingots with various additions of Mg. The ingots were hot-rolled into \$\phi\$ 25 mm rods. The specimens were heat treated with the heat treatment procedures, 1080°C-8h, AC; 700°C-16h, AC. The tested alloys contain 0, 0.001, 0.008 and 0.013 wt-% Mg. Single edge notch specimens were used in the test of creep crack growth, the notches were cut with a line cutting machine. Tests were conducted on the creep testing machine and crack length was measured by the direct current potential method. Test data were recorded and stored by computer.

Results

Results of creep crack growth

The specimen with 2 mm deep edge, was tested at 700°C and 343 MPa, nominal stress. The curves of creep crack length as a function of the time for the specimen with differents amounts of Mg are shown in Fig. 1. The curves could be divided into four stages: (1) In the initial stage of crack growth, new creep cracks nucleate and propagate at an extremely slow rate at the tip of fatigue pre-crack. It can be seen from Fig. 1 that the crack growth behavior in this stage is a function of Mg content. (2) In the steady-state region of creep crack growth microcracks formed at the tip of main cracks start to grow. The crack growth developed steadily with a very small acceleration, it is linear in the a-t curves. (3) Accelerated propagation of creep cracks occured in this stage. The growth rate of cracks is accelerated markedly, the a-t curves becomes bent. (4) Fast propagation of creep occurs in the last stage. The cracks propagate with very high rate until rupture, the a-t curves are perpendicular to the coordinate axis.

The influence of Mg on the creep crack growth are described as follows: (1) Mg has an obvious effect on the time of the initial stage as show in Table I. The specimen with the optimum addition of Mg has the longest initial stage, but the cracks in the specimen without or with excessive Mg started to propagate following shorter initial stage. (2) Mg also markedly influenced the growth rate of creep cracking in the steady-state region. The highest rate of crack growth was found in the specimen without Mg and the lowest growth rate in the specimen with the optimum amount of Mg, and higher rate of crack growth was found with excessive additions of Mg.

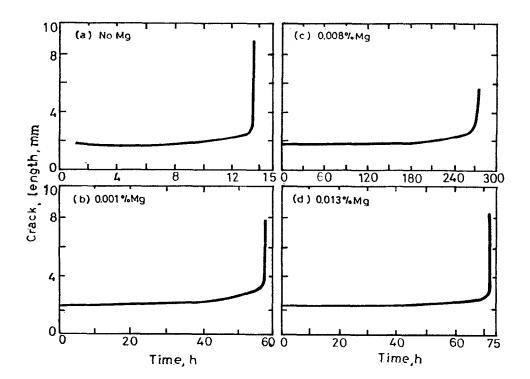


Figure 1 - Creep crack growth curves of GH33 with different amounts of Mg

Table I - Beginning time of creep cracking in specimens with different additions of Mg

Mg (Wt%)	t _b (hour)	
0	7	
0.001	22	
0.008	120	
0.013	22	

(3) It was found in case of specimens without Mg or with excessive additions of Mg, that the stage of accelerated growth of cracks was relatively short. As soon as the steady crack growth stage ended, cracks propagated rapidly. However, the specimen with the optimum amount of Mg showed a longer

Table II Crack growth rate with different amounts of Mg inthe steady-state region

Mg (Wt-%)	à _{Is}	å _{Ie}
0	3.7 x 10 ⁻²	2.0 x 1 ⁻¹
0.001	6.9 x 10 ⁻³	7.7×10^{-2}
0.008	2.0×10^{-3}	1.2 x 10 ⁻²
0.013	5.4×10^{-3}	4.1×10^{-2}

^{*} \dot{a}_{ls} - crack growth rate at the starting point of steady stage.

 $[\]mathbf{\dot{a}_{Ie}}$ - crack growth rate at the ending point of steady stage.

accelarated growth stage. In this case a clear arc part of a-t curve was found. (4) An optimum amount of Mg enhanced the creep rupture time significantly, while the alloys without or with excessive additions of Mg showed a lower creep rupture life (see Table III).

Table III Creep rupture lives of alloys with different amounts of Mg

Mg (Wt%)	t _f (hour)	
0	13.5	
0.001	55.5	
0.008	270	
0.013	72	

Growth rate of the creep crack

The creep crack growth rate is closely related to the stress-strain field at the crack tip. Due to the stress relaxation caused by creep, the stress-strain field at the crack tip changes all the time, so the modified J integral, C*, must be adopted to describe the stress-strain field around the creep crack tip [4]. The definition of C* is:

$$C^* = \int_{\Sigma} W^* \ dy - Ti \ \frac{\partial ui}{\partial x} \ ds \tag{1}$$

It can be calculated by the formula:

$$C^* = a \left(\frac{1}{\beta_1}\right)^{n+1} h_1 \left(\frac{a}{b}, n\right) \dot{\varepsilon} \sigma / \left[\eta^{n+1} \left(1 - \frac{a}{b}\right)^n\right]$$
 (2)

where, a, i, o and b are crack length, steady-state creep rate, nominal stress and specimen width,

respectively; $h_1\left(\frac{a}{b},n\right)$ is a function of a/b and n, and can be determined from the data; β_1 =

1.072; n is the creep index and

$$\eta = \left[\left(\frac{2a}{c} \right)^2 + 2 \left(\frac{2a}{c} \right) + 2 \right]^{\frac{1}{2}} - \left(\frac{2a}{c} + 1 \right)$$

$$c = b - a$$

The relationship of lodga/dt-logC*, is shown in Fig. 2. Each of the four curves may be divided into three stages. The first stage has a steep slope. In this stage, the crack growth rate is sensitive to C*, i.e. the minor change of C* may bring about a great change of $\Delta a/\Delta t$. This sensitivity shows the transition from creep crack nucleation to growth. The second stage, corresponding to the steady-state crack growth, has low slope. Although the change of C* was great, the change of da/dt was not apparent. The slope of the

third stage increased again, which means the crack growth is in the accelerated stage and up to fast growth. The valve of C^* , corresponding to the transient point from first stage to second stage, is called C_t^* . C_t^* shows the variation of stress-strain field at the crack tip when the cracks begin to grow clearly. From Fig. 2, the effect of Mg on the creep crack growth can be also seen. With the increase of Mg content, the curves move down to the right, i.e. the crack growth rate decreases. On the other hand, addition of Mg increases the tranient point C_t^* of the crack growth. When the addition of Mg is excessive, the curve moves up to the left, the benificial effect of Mg disappeared.

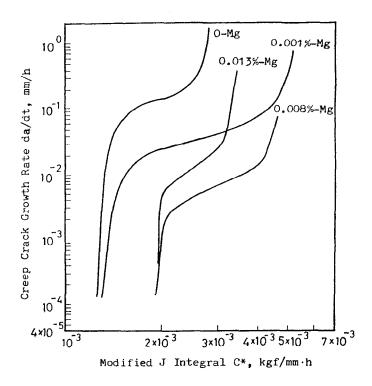


Figure 2 - Relationship between crack growth rate da/dt and modified J integral C*

Discussion

The beneficial effect of Mg on the creep crack growth is caused by its segregation to the grain boundaries. Mg can decrease the interfacal energy of the grain boundary and enhance the cohesion and the rupture energy of the boundary [5]. The previous test results of the authors has shown that with the addition of Mg, the rupture energy of grain boundaries increases (Fig. 3), which increase the critical crack nucleation energy and results in increased difficulty in nucleating cracks. Thus, the initial time of nucleation and growth of creep cracks apparently is prolonged. The increase of grain boundary cohesion adds to the resistance of crack growth, and thus decreases the steady growth rate of cracks. As a result the creep rupture lives and percentage elongation are raised. The segregation of Mg to the grain boundaries can also promote the spheroidization of grain boundary carbides (Fig. 4) and decreases the tendency to form wedge cracks, which is also another factor improving the crack growth behavior. The grain boundary carbides may resist the propagation of grain boundary cracks, and the carbides at the tip may become the nucleation center for the further growth of cracks. The stress concentration around spherodized carbides is smaller than that of plate-like carbides, therefore, the possibility of crack nucleation is decreased and

the crack growth rate lowered. Experiments have shown that Mg can also improve the creep and stress-rupture properties in alloys with very low carbon additions without grain boundary carbides. The enhancing of grain boundary cohesion by Mg is therefore the main factor for its benefical effect. The steady-state region in the da/dt-C* feature curve may be described with the following relation:

$$da/dt = B(C^*)^m (3)$$

where, B and m are constants. The relation between m and Mg amount is listed in Table IV.

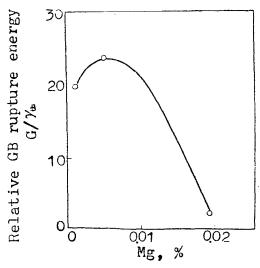


Figure 3 - Effect of Mg on the grain boundary rupture energy

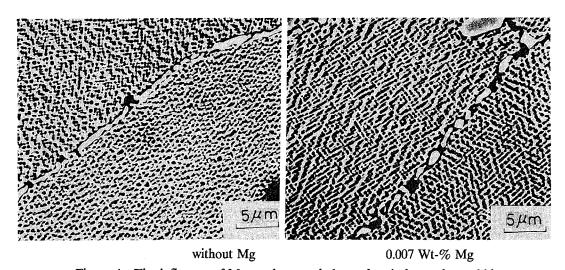


Figure 4 - The influence of Mg on the morphology of grain bounadry carbides

Table IV - The relation between exponent m and Mg content

Mg (Wt%)	m
0	1.89
0.001	1.71
0.008	2.65
0.013	4.08

The results indicate that although Mg significantly decreases the crack growth rate and prolonges the creep rupture life, it increases the sensitivity of $\Delta a/\Delta t$ C*. The research on the physical meaning of m value and physical model of the da/dt-C* relationship should be carried out in the future.

Conclusions

- (1) An optimum addition of Mg significantly prolongs the forming time of creep cracks.
- (2) The optimum amount of Mg significantly decreases the creep crack growth rate and prolongs the creep rupture lives.
- (3) In the da/dt-C* curves, which describe the characteristic of creep crack growth, the alloys with various amounts of Mg have different behavior.
- (4) An optimum addition of Mg raises the transient point C_t^* of steady crack growth.

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