Pergamon

Scripta Materialia, Vol. 38, No. 2, pp. 329–335, 1998
Elsevier Science Ltd

1359-6462/98 $19.00 + .00

PII S1359-6462(97)00444-2

THE INFLUENCE OF MAGNESIUM ON CARBIDE CHARACTERISTICS AND CREEP BEHAVIOR OF THE MAR-M247 SUPERALLOY

H.Y. Bor, C.G. Chao and C.Y. Ma*
Institute of Materials Science & Engineering, National Chiao-Tung University,
Taiwan 30050, R.O.C
*Materials R & D Center, Chung-Shan Institute of Science and Technology,
Taiwan 32536, R.O.C.

(Received April 3, 1997)
(Accepted October 7, 1997)

Introduction

Mar-M247, a typical cast Ni-base superalloy containing more than 60 vol.% γ', has been widely employed in fabricating advanced turbine blades and rotating parts in aerospace industry during the past two decades. The merits of this alloy comprise excellent creep and good oxidation resistance at elevated temperatures as the result of optimal alloy design [1–2]. However, Mar-M247, according to Engine Materials Specification(EMS)-55447 and some previous studies [3–4], remains brittle at elevated temperatures during creep and tensile tests even though considerable efforts were made in late 1970 by adding Hf to optimize microstructure, in particular γ-γ' eutectic and grain boundary (**GB**) carbide. In all, the reasons leading to high temperature brittleness in Mar-M247 can be attributed to GB intrinsic behavior, coarse or large script carbides, harmful phases(such as Laves, σ and μ), abnormal grain size and defects existed during casting.

In recent investigations, it has been shown that the microaddition of Mg in wrought superalloys significantly enhances stress rupture life, ductility and fatigue endurance at elevated temperatures [5–18]. These improvements are mainly associated with carbide refinement arising from segregation of Mg to GB and carbide/matrix interface [10,12,14,15,17]. Although, some studies related to Mg segregation phenomenon have been carried out [10,12,19,21], the true mechanisms are not fully understood. Furthermore, little work has been reported [19–21] in introducing Mg as a microalloying element in cast superalloys which are normally poor in ductility and toughness at both room and elevated temperatures. On this basis, Mar-M247 superalloy was chosen for the first time in this work for studying the influence of Mg microaddition on high temperature properties. The objectives of present study were to determine the microstructural characteristics and to investigate the creep behavior of Mar-M247 superalloy due to the microaddition of Mg, particularly in ductility. In addition, some available mechanisms associated with the microstructure change and property enhancement were discussed in this paper.

TABLE I
Chemical Composition (wt.%) of Mar-M247 Superalloy Analyzed by XRF for Major Elements and Glow Discharge Mass Spectrometer (GDMS) for Mg and Trace Elements

Alloys	Co	Cr	Mo	W	Ta	Ti	Al	Hf	Zr	Ni	C	S	P	Mg
A	10.1	8.32	0.69	9.91	3.16	1.00	5.56	1.51	0.045	bal.	0.153	0.0003	0.0003	0.0008
B	10.1	8.20	0.71	9.86	3.17	1.04	5.69	1.37	0.040	bal.	0.149	0.0002	0.0003	0.002
C	10.1	8.14	0.72	9.74	3.00	0.97	5.47	1.29	0.040	bal.	0.156	0.0003	0.0003	0.008

Experimental

The materials used in this study were melted by vacuum induction melting (VIM) at Chung Shan Institute of Science and Technology in Taiwan, followed by remelted in a vacuum furnace and cast into test bars. The pouring and mold temperatures were 1480°C and 1000°C, respectively. Three heats of Mar-M247 superalloy both without Mg(alloy A) and with Mg(alloy B and C) were prepared. The compositions of the parent alloys used in this investigation are given in Table I. The Mg content in alloy A was measured to be 8 ppm from raw materials. After casting, all test bars were subjected to heat treatment; that was 1185°C/2 hrs for solution treatment and then 871°C/20 hrs for aging. Microstructural observations were made by optical microscopy (OM) and scanning electron microscopy (SEM). The density, area fraction and Feret average (i.e. the long axis size) of various carbide particles in as-cast and heat-treated samples were measured using a LECO 2000 image analyzer. Thirty optical microscope adjoining fields from the polished samples were taken at a magnification of 500 times for each specimen. High temperature tensile tests were carried out at 899°C using an Instron mechanical testing machine. The creep test was conducted under 760°C/735 MPa using SATEC M3 creep testers. The gauge size of test bars was 6.3 mm in diameter and 26 mm in length. The fracture surfaces were examined in a Joel-6400 SEM equipped with EDS for microanalysis.

Results

The microstructure of Mar-M247 superalloy (alloy A) after normal heat treatment contains cuboidal γ' phase, γ-γ' eutectic, Chinese script MC and grain boundary $M_{23}C_6$ carbides, as shown in Fig. 1. Among them the area fraction of carbide was around 2.4%. The results of microstructure analysis show that Mg additions have no influence on grain size (Fig. 2). It remains 2–3 mm under the casting condition

Figure 1. Microstructure of Mar-M247 superalloy (alloy A) subjected to 1185°C/2 hrs for solution treatment followed by 871°C/20 hrs for precipitation.

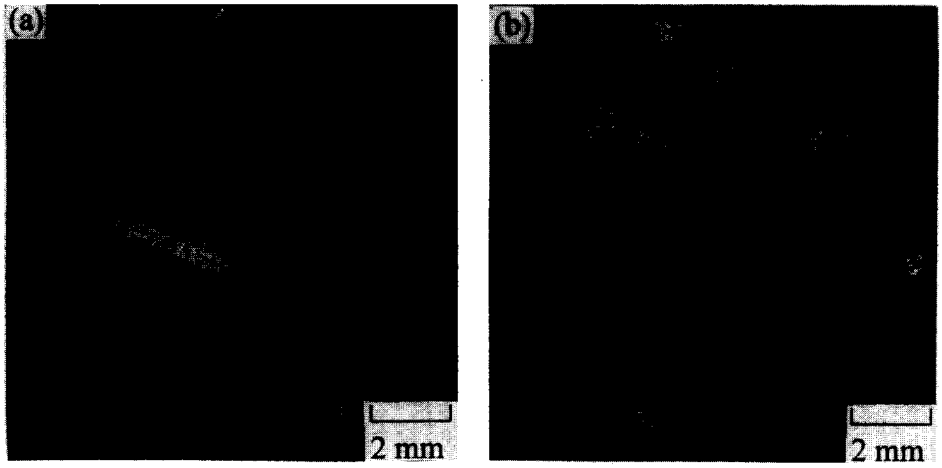

Figure 2. Grain sizes of Mar-M247 superalloy (a)without and (b)with 80 ppm Mg microaddition.

mentioned above. However, it is obvious in Fig. 3 that 80 ppm Mg addition in Mar-M247 decreases not only interdendritic precipitates of carbide amount, but also changes its morphology from script (plate-like) to globular and discrete form. In other words, the percentage of script-like carbides can be reduced due to optimal addition of Mg. The results of image analysis indicate that the area fraction of carbide particles is unaffected by microaddition of Mg (Fig. 4(a)). However, the carbide particle density clearly increases with increasing Mg contents(Fig. 4(b)). These results depict that optimal addition of Mg makes carbides finer and spheroidal, including both MC in matrix and $M_{23}C_6$ at GB. Feret average measurement illustrates the same outcome of carbide refinement, since the values are declined from 5.2 μm (without Mg) down to 3.6 μm (80 ppm Mg), as shown in Fig.4(c).

The tensile properties of Mar-M247 with various Mg contents tested at 899°C are listed in Table II. Obviously, a drastic improvement in ductility brings about as the result of microaddition of 80 ppm Mg. The ultimate tensile strength remains unaffected as Mg goes from 0 to 80 ppm, although there is around 10 reduction in yield strength. According to creep test results, Mg can remarkably enhance the 760°C/735 MPa creep life and ductility as well, as indicated in Fig. 5. The alloy with 80 ppm Mg exhibits three different stages during creep, while the alloys without Mg or only with little Mg addition (20 ppm) have no tertiary stage of creep. Obviously, the creep lives increase with increasing Mg

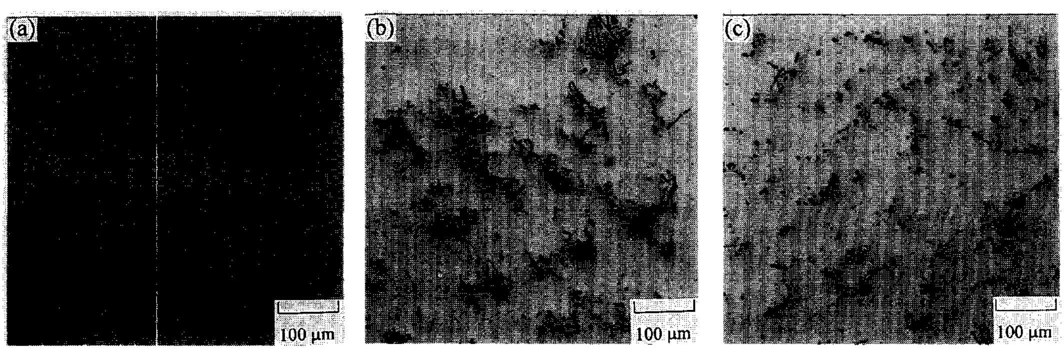

Figure 3. Carbide morphology and distribution of Mar-M247 superalloy (a) without, (b) with 20 ppm and (c) with 80 ppm Mg addition.

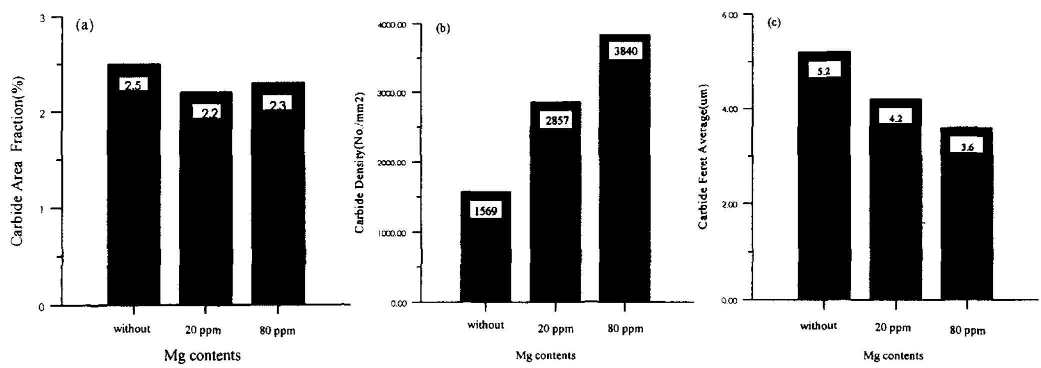

Figure 4. Image analysis results of (a) carbide area fraction (b) carbide density and (c) carbide Feret average in Mar-M247 superalloys. Feret Average is defined as the long axis size of carbide particles.

contents up to 80 ppm. The same result is also found in creep elongation. In Table III, creep elongation of some specimens without Mg addition is even lower than the EMS-55447 requirement of 2% when creep-tested under 760°C/735 MPa. For the specimens with 80 ppm Mg, however, elongation is effectively improved to 5.1%. Furthermore, the creep lives are also prolonged to at least 3 times in comparison with that of specimens without Mg addition. As to the steady state creep rate, it tends to be unaffected by Mg addition and remains approximately similar($10^{-8}s^{-1}$), however, the alloy with 80 ppm Mg still has a lower creep rate.

On the basis of fractographic observation from the specimens tested under 760°C/735 MPa, the fracture mode of all Mar-M247 specimens appears to be mixed, involving intergranular and transgranular in general. However, the phenomenon of intergranular fracture in alloy A is more remarkable than that of Mg additions alloys. Further, alloy A exhibits significantly cracked evidences of script carbide decohesion within grain interior (Fig.6(a)), showing that the occurrence of fracture can be formed at script carbide/matrix interface or GB carbides. In contrast, the phenomena of script carbide decohesion and interdentritic brittleness are drastically reduced in 80 ppm Mg alloy (Fig.6(b)). The fine dimples existed on fracture surface and the evidences of fine carbide decohesion reflect the improvement of high temperature brittleness in Mg-containing Mar-M247 superalloy.

Discussion

Conventional cast nickel-base superalloy are mainly strengthened through carbide precipitation at GB and γ' phase in matrix. Discrete GB carbides are generally considered beneficial since they inhibit GB

TABLE II
Tensile Test Results of Various Mg Contents in Mar-M247 at 899 °C

Mg Contents	Y.S. (MPa)	U.T.S. (MPa)	Elongation (%)
EMS-55447	420	700	4.0
without Mg	676	794	4.7
20 ppm Mg	653	812	5.1
80 ppm Mg	617	803	14.0

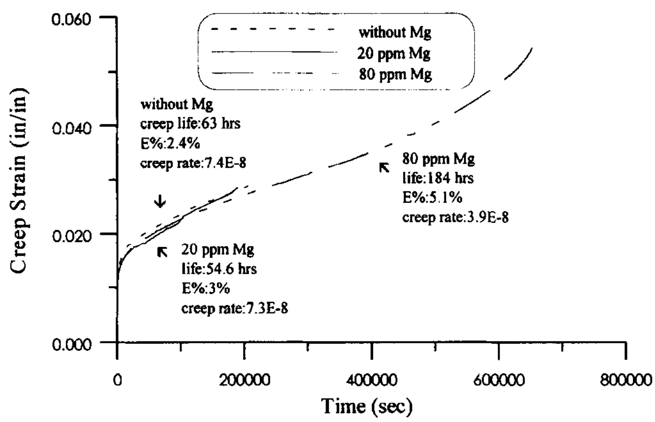

Figure 5. Creep curves of various Mg contents in Mar-M247 tested under 760°C/735 MPa.

sliding and retard the onset of creep cavitation and rupture. Hence, carbide morphology and distribution play a crucial role in determining the creep behavior of superalloys. According to the present results, microaddition of 80 ppm Mg in Mar-M247 superalloy can remarkably refine and spheroidize carbides both within grain interior and at GB. These mainly result in the increase of high temperature ductility and the improvement of creep life and ductility. The fractograghic observation also proves these relevant evidences. As has been pointed out previously, from view points of alloy design, performance and applications, Mar-M247 superalloy exhibits a high temperature brittleness under 760°C/735 MPa. This finding might give rise to more extensive usage in aerospace industries or some relevant applications.

Regarding the mechanisms of Mg microaddition in superalloy causing the ductility enhancement, Ke [23] and Chernyak [22] indicated that Mg could purify GB through binding with detrimental elements, such as S, P, O, etc. In this work, however, the contents of S, P and other trace elements determined were far below 5 ppm. It means that the improvement of high temperature ductility in Mar-M247 might not be directly related to this mechanism. In terms of energy concept, some researchers [23–27] proposed that Mg microaddition would segregate to GB and carbide/matrix interface, leading to the interfacial energy reduction between carbides and matrix. Since this effect could increase cohesion of carbide/matrix interface, retard creep crack initiation and propagation and prolong the total creep life and elongation. Some direct results [10,12,16,19,21] about Mg segregation have been reported by using AES and HRTEM, which are associated with the refinement and spheroidization of carbides. Based on the present investigation, the improvement of high temperature ductility in this system is related to the carbide refinement. Detailed studies with respect to the interfacial characteristics with the methods of

TABLE III
Creep Behavior of Various Mg Contents in Mar-M247
Tested Under 760 °C/735 MPa

Mg Contents	Creep life (hrs)	Elongation (%)	Creep Rate (s^{-1})
EMS-55447	>23	>2	—
without Mg	26~63	1.9~2.4	7.4×10^{-8}
20 ppm Mg	55~87	3.0~4.2	7.3×10^{-8}
80 ppm Mg	136~183	3.5~5.1	3.9×10^{-8}

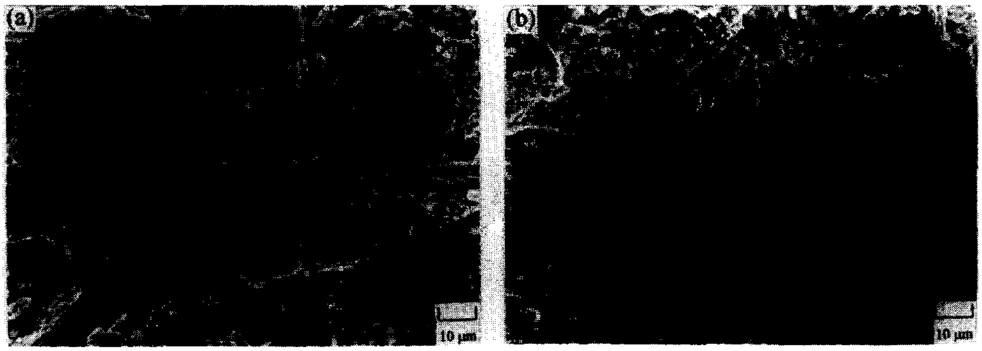

Figure 6. Fractographic observation of (a) without Mg and (b) with Mg in Mar-M247 after creep testing of 760°C/735 MPa.

structural identification and chemistry determination are worth being performed to account for these phenomena.

Finally, it should be emphasized that increase of creep life and ductility as the result of Mg microaddition in Mar-M247 might depend on the operation environments. In other words, under different creep conditions, the fractures behaviors will be controlled and determined by various deformation mechanisms. In addition, interfacial characteristics might behave in different ways and this will, of course, lead to various performance of alloys. Furthermore, the optimal amount of Mg in Mar-M247 and the effect of Mg over-addition remains unclear. More relevant work is needed to be done in the future.

Conclusions

According to the present results, it can be concluded that microaddition of Mg in Mar-M247 can change script carbide morphology and refine carbides significantly. Mg increases 899°C tensile ductility drastically when Mg contents in Mar-M247 superalloy reach 80 ppm. Also, microaddition of Mg can apparently enhance creep life and elongation of Mar-M247 superalloy under the test condition of 760°C/735 MPa. The steady state creep rate of Mar-M247, however, remains unaffected. Fractographic observation shows that the cracking evidences along script carbides are reduced in Mg-containing alloy. This improvement is strongly related to the enhancement of high temperature ductility.

Acknowledgments

The authors would like to thank Dr. C. C. Yang, Dr. J. Y. Wang, Mr. S. C. Yang and Mr. C. M. Chen for their help in mechanical property evaluation. The equipment support of processing from Dr. Y.L. Lin and Mr. J.S. Chen are thankfully acknowledged.

References

1. J. E. Doherty, B. H. Kear, and A. F. Giamei, Journal of Metals. Nov., 59 (1971).
2. D. N. Duhi and C. P. Sullivan, Journal of Metals. Jul., 38 (1971).
3. Engine Materials Specification 55447, Castings, Investment, MAR-M247, Allied-Signal Aerospace Company (1988).
4. M. Kaufman, in Proceedings of Superalloys 1984, ed. M. Cell, et al., p. 43, AIME (1984).
5. J. Schramm, US Patent No. 3512963, May 19 (1970).
6. W. H. Couts, Jr., et al., Effect of Magnesium as an Alloying Element in Inconel 718, Report AEML-TR-7s-76 (1971).

7. D. R. Muzyka. et al., Process for Making Nickel Base Precipitation Hardenable Alloys, US Patent No. 3575734, April 20 (1971).
8. J. M. Moyer, in Proceedings of Superalloys 1984, ed. M. Cell, et al., p. 443, AIME (1984).
9. D. A. Ford, Met. Technol., 11, 438 (1984).
10. G. L. Chen, D. Wang, Z. C. Xu, J. Fu, K. Q. Ni, X. S. Xie, X. Jin, E. P. Chen, and T. F. Yu, in Proceedings of Superalloys 1984, ed. M. Cell, et al., p. 611, AIME (1984).
11. K. D. Ke and Z. Y. Zhong, Acta Metall. Sin. 5, A377 (1983).
12. P. Ma and J. Zhu, Metallography, 19, 115 (1986).
13. Z. Xu, B. Qu, X. Xie, S. Zhou, and X. F. Cheng, Journal of Beijing University of Iron and Steel Technology, 9(4) (1987).
14. P. Ma, Y. Yuan, and Z. Y. Zhong, in Proceedings of Superalloys 1988, ed. S. Reichman, et al., p. 625, AIME (1988).
15. X.H. Xie, Z. H. Xu, B. Qu, and G. L. Chen, in Proceedings of Superalloys 1988, ed. S. Reichman, et al., p. 635, AIME (1988).
16. J. Zhu, Z. Y. Cheng, and H. Q. Ye, Scripta Metall. 23, 1537 (1989).
17. G. L. Chen, T. H. Zhang, and W. Y. Yang, High Temperature Technology. 6(3) (1988).
18. Y. Q. Li and Y. H. Gong, Journal of Materials Science. 27, 6641 (1992).
19. H. L. Ge, W. V. Youdelis, G. L. Chen, and Q. Zhu, Materials Science and Technology. 5, 985 (1989).
20. G. Chen, Q. Zhu, D. Wang, and X. Xie, in Superalloy 718, ed. E. A. Loria, p. 545, The Minerals, Metals Materials Society (1989).
21. Q. Zhu, D. Wang, H. Ge, and G. Chen, Acta Metallurgica Sinica. 3, A185 (1989).
22. G. S. Chyernyak, Metall. (Metalli.) SSSR. No. 1, 144 (1973).
23. D. Ke, Thesis for master's degree, Central Iron and Steel Research Institute, Beijing, China (1981).
24. D. Ke and Z. Y. Zhong, Acta Metallurgica Sinica. 19, A377 (1983).
25. P. Ma, et al., Acta Metallurgica Sinica. 19, A377 (1983).
26. P. Ma, et al., Acta Metallurgica Sinica. 23, A195 (1987).
27. D. Ke and Z. Y. Zhong, Central Iron and Steel Research Institute Technical Bulletin. 73, 3 (1983).