CREEP DEFORMATION AND FRACTURE OF DZ40M DIRECTIONALLY SOLIDIFIED COBALT-BASE SUPERALLOY AT HIGH TEMPERATURE①

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ABSTRACT The creep deformation and fracture of DZ40M directionally solidified cobalt-base superalloy have been investigated at 900 ℃ under stress in the range of 105 ~ 125 MPa. The microstructures, fractures and substructures of crept specimens have been examined by SEM and TEM. The results showed that DZ40M alloy exhibits a high creep ductility and its stress dependence of steady state creep rate is of a typical feature of precipitation hardened alloys, its creep behaviour is closely related to microstructural change. During creep, the primary carbides M_7C_3 and MC dissolved and the secondary $M_{23}C_6$ carbide profusely precipitated, which strengthens the matrix effectively. Creep cracks initiate at the primary carbides and propagate transgranularly. The surface of specimens was oxidized severely and the preferential oxidation of the primary carbides deteriorated creep rupture strength.

Key words directional solidification cobalt-base superalloy creep fracture

1 INTRODUCTION

DZ40M alloy is a newly developed directionally solidified cobalt-base superalloy based on conventional X40 alloy. Compared with X40 alloy, it has a higher strength and ductility and its service temperature can be raised by 45 ℃[1,2]. Studies on high temperature creep of superalloys are of significance and much attention has been paid to them. However, research work has mainly concentrated on nickel-base and iron-nickel-base superalloys[3,4]. Cobalt-base superalloys have been less documented. The present work investigates the creep behaviour of DZ40M alloy at 900 ℃ and observes its microstructures, substructures and fracture surfaces.

2 EXPERIMENTAL

The master alloy was prepared in a 25 kg vacuum induction furnace, whose nominal composition is as follows (mass fraction, %): Cr 25, Ni 11, W 7.5, C 0.45, Ta 0.25, Ti 0.15, Zr 0.15, Mo 0.2, Al 0.8, B 0.05, Co balance. The directional solidification of the alloy was performed in a conventional vacuum unidirectional solidification furnace, type ZGG-0.002, with a mould withdrawal device. Cylindrical rods of the alloy, 16 mm in diameter and 140 mm long, were produced at a withdrawal rate of 7 mm/min and with a thermal gradient of about 50 ~ 60 K/cm at the solid/liquid interface. Cylindrical specimens with a gage length of 50 mm and a diameter of 8 mm were machined longitudinally from the as-cast bars. Creep tests were conducted under a constant load at 900 ℃. The stresses were chosen as 105, 115, and 125 MPa. The columnar grain orientation of the alloy developed by directional solidification was determined by means of X-ray diffractometer with Cu target. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM)

① Received Jul. 21, 1998; accepted Oct. 5, 1998

were used to observe microstructures, fracture surfaces and substructures.

3 RESULTS AND DISCUSSION

3.1 Microstructures of as-cast DZ40M alloy

Fig.1 shows the microstructures in the longitudinal and transverse sections. The alloy matrix is a well-developed columnar grained austenite and X-ray diffraction demonstrated that their ⟨001⟩ direction was parallel to the growth axis (Fig.2). There are two kinds of primary carbides, M_7C_3 and MC located at grain boundaries and interdendritic regions[5].

3.2 Creep curves

Fig.3 shows the creep curves of the alloy at 900 ℃ and various stresses. At 125 and 115 MPa, the alloy exhibited pronounced primary, secondary and tertiary creep stages, while at 105 MPa, the lowest stress, the tertiary creep stage did not appear within 780 h. Also, it can be seen

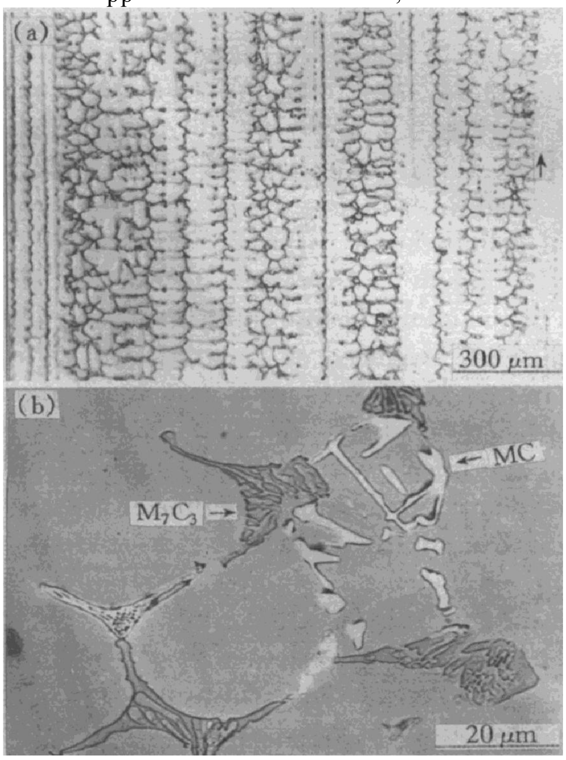

Fig.1 Microstructures of as-cast DZ40M alloy in (a) longitudinal and (b) transverse sections

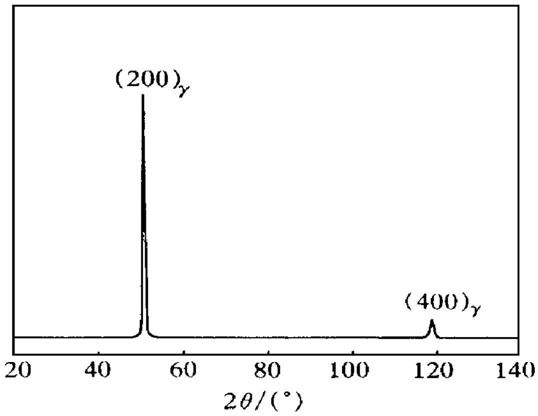

Fig.2 X-ray diffraction pattern of as-cast DZ40M alloy in transverse section

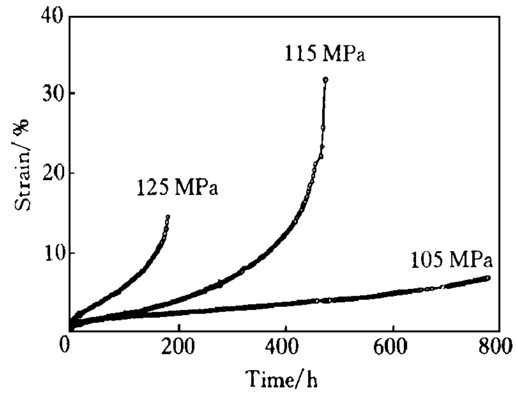

Fig.3 Creep curves of DZ40M alloy at 900 ℃

that the higher the stress, the larger the creep deformation and the steady creep rate. DZ40M alloy demonstrated an excellent creep ductility. It should be attributed to the columnar grained structure with ⟨001⟩ preferential orientation. Because the load was applied at the growth axis of the alloy, i.e. ⟨001⟩ direction, slip systems {111}⟨110⟩ of the fcc matrix were at the direction of maximal shear stress, that is, the easiest slip direction. Consequently, the potential ductility was developed fully.

In Fig.4, it can be seen that there exists no linear relationship, but a "break". This is a typical feature of precipitation hardened alloys[6-8].

3.3 Microstructures and substructures of crept alloy

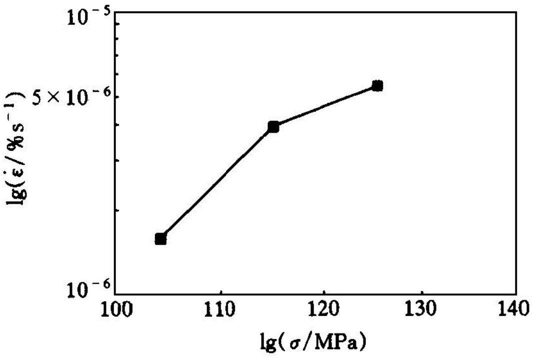

Fig.4 Steady state creep rate ($\dot{\varepsilon}$) vs stress (σ) of DZ40 M alloy at 900 ℃

Fig.5 shows a typical microstructure of the specimen after 900 ℃ creep. It can be found that the primary carbides dissolved and a profusion of secondary precipitates were produced in the matrix. The electron diffraction analysis of TEM indicated that they were $M_{23}C_6$. Like other cobalt-base superalloys, during high temperature exposure, DZ40 M alloy is thermodynamically unstable, and the dissolution of the primary carbides, M_7C_3 and MC, and the precipitation of secondary $M_{23}C_6$ carbide can occur[9,10].

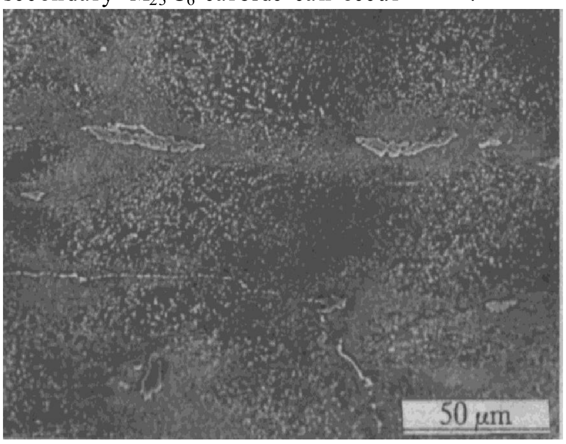

Fig.5 Microstructure of DZ40 M alloy after 192 h creep at 900 ℃ and 125 MPa in longitudinal section

The substructure after 780 h creep at 900 ℃ and 105 MPa is shown in Fig.6. It can be seen that subgrains have formed and $M_{23}C_6$ pinned up the subgrain boundaries, increased the creep deformation resistance. It is the effective strengthening role of these fine precipitates that makes DZ40 M alloy exhibit a characteristic of precipitation hardened alloys.

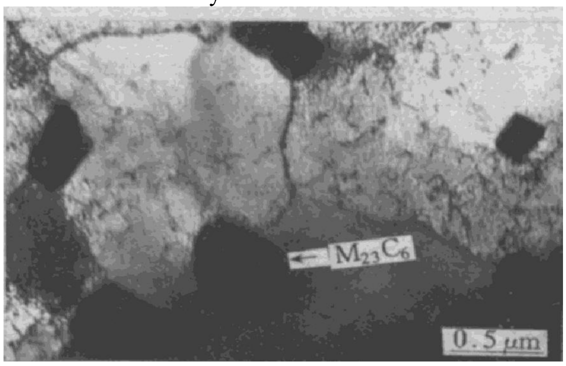

Fig.6 TEM micrograph showing substructure of DZ40 M alloy after 780 h creep at 900 ℃ and 105 MPa

3.4 Creep fracture

Fig.7 is a typical fracture surface of DZ40 M alloy after creep rupture at 900 ℃. The fracture morphology indicates that the creep fracture was ductile, which resulted from the excellent high temperature ductility and the elimination of the transverse grain boundary of DZ40 M alloy.

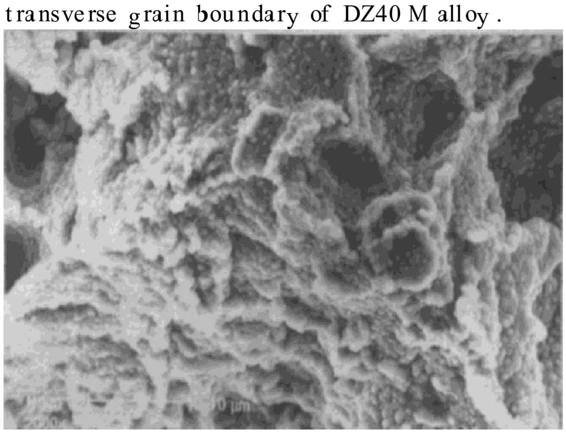

Fig.7 Fracture surface of DZ40 M alloy after creep rupture at 900 ℃ and 125 MPa

In addition, Fig.7 shows that severe oxidation has occurred on the fracture surface. The observation on the longitudinal section near the fracture exhibited that the primary carbides on the surface of specimens were oxidized preferentially, that caused fracture of the carbides themselves and cracking of the interfaces between the carbide and the matrix (Fig.8(a)). The primary carbides in the matrix are also a crack initiation site (Fig.8(b)). It can be observed that the created cracks tended to propagate perpendicular to the applied stress toward the matrix. During creep, the matrix substantially deformed and the applied stress was transferred to the primary carbides, resulting in a high stress concentration. Due to the intimate brittleness of carbides and their weak bond with the matrix, high stress caused the carbide fracture and the crack of interface between the carbide and the matrix.

Usually, the crack propagates perpendicular to the applied stress, and transverse grain boundary is a favorable path for crack propagation at elevated temperature. However, the transverse grain boundary has been eliminated in DZ40M alloy. Fig.8(b) demonstrates that the ductile matrix of the alloy blunted crack tip and reduced stress concentration, that impeded crack propagation. Evidently, the peculiar microstructure of DZ40M alloy can delay creep fracture, and increase its creep resistance.

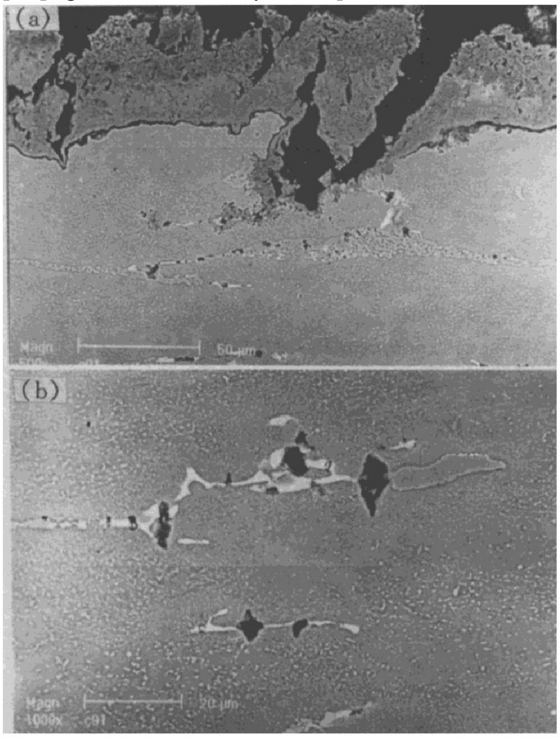

Fig.8 Longitudinal sections near fracture of DZ40M alloy after creep rupture at 900 ℃ and 125 MPa

(a) —Near the surface of specimens;
(b) —In the matrix

4 CONCLUSIONS

(1) During creeping at 900 ℃ and under stress of 105 ~ 125 MPa, the stress dependence of steady state creep rate of DZ40M alloy is of a typical feature of precipitation hardened alloys.

(2) DZ40M alloy exhibites a high creep ductility, which should be attributed to its columnar grained structure with ⟨001⟩ preferential orientation.

(3) During 900 ℃ creep, the primary carbides M_7C_3 and MC dissolve and the secondary $M_{23}C_6$ carbide profusely precipitate, which pins up subgrain boundaries and strengthens the matrix effectively.

(4) The creep rupture of DZ40M alloy is a transgranular ductile fracture and cracks originate at the primary carbides.

(5) The specimen surface oxidizes severely and the preferential oxidation of the primary carbides deteriorated creep rupture resistance.

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(Edited by Yuan Saiqian)