INFLUENCE OF TLP BONDING ON CREEP DEFORMATION OF A NICKEL-BASE SINGLE CRYSTAL SUPERALLOY AT HIGH TEMPERATURE

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Abstract

The creep substructures of TLP joint of a nickel-base single crystal superalloy at different creep stages are investigated at 982℃/248MPa. The results show that the creep process of TLP joint consists of primary stage, steady stage and tertiary stage obviously. The creep curve shape of TLP joint is similar to that of matrix sample without bonding. The deformation substructures of different parts of TLP joint are almost same and this indicates the deformation of TLP joint is homogeneous. During creep deformation, there are more dislocations appeared in matrix sample and dislocation interactions are much pronounced than these observed in TLP joint.

Introduction

Nickel-base single crystal superalloys with high volume fraction of γ′ precipitates have been widely used owing to their excellent high temperature properties. However, high content of γ′ former elements in single-crystal superalloy, such as aluminum and titanium, makes it difficult to produce crack-free joints by conventional fusion weld techniques. Transient liquid-phase bonding (TLP bonding) has been considered as a promising method to join single crystal superalloys and some research results and practical applications have been reported [1, 2]. TLP process consists of melting of interlayer, substrate dissolution, isothermal solidification and homogenization. After TLP process, an interface free joint is obtained and no remnant of brittle phase in the bonding region. The element distribution and microstructure of TLP joint are almost uniform. Efforts are put to investigate TLP process or apply this technique in various materials since the advent of TLP process. Analytical model of TLP process [3, 4], application of TLP technique in distinct materials [5-9] and improvement of TLP process [10] can be seen in many literatures. It is a pity that most of those research concerned on the microstructure evolutions during bonding, mechanical properties compared with matrix sample or the mathematical model of TLP process. There is little information available when it comes to the deformation mechanism of TLP joint.

As we know, high temperature creep deformation is very important for applications of superalloys, and creep deformations of single crystal superalloys were investigated extensively [11-14]. Therefore, the creep deformation of TLP bonded single crystal superalloys is also of significant importance. In our previous work, the creep rupture properties, creep ductilities of TLP joint at high temperature were investigated [15, 16], but the creep deformation of TLP joint is still not clear.

In this paper, the creep deformation substructures of TLP joint at different creep stages are investigated in detail in order to clarify the substructure characteristics of TLP joint completely.

Experimental Procedures

In our experiments, an as-cast Ni-Cr-Co-W-Mo-Ti-Al-Ta system nickel-base single crystal suerpalloy with (001) orientation was chosen as base metal. During bonding, the (001) orientation was aligned perpendicular to the joint interface. A schematic of the creep specimens is shown in Fig.1. The Ni-15Cr-3.5B(wt.%) amorphous interlayer was prepared by melt spinning process. The thickness and width of interlayer were 45-60μm and 4-8mm. The faying surfaces used for TLP bonding were mechanically polished using 800 grade emery paper to make the surface smooth. Prior to bonding operation, specimens and interlayer were ultrasonically cleaned in acetone for 15min and dried in cool air. For the purpose of comparison, matrix sample that did not be bonded and subjected to same heat treatments were crept at the same time.
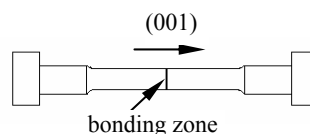

Fig.1 Schematic of the tensile creep specimens

During TLP bonding, interlayers were inserted between two pieces of base metal, taking care to ensure the orientation of the base metal samples was congruent with each other. The piled specimens were bonded in a vacuum chamber of 3×10^{-3} Pa with an applied pressure of about 3MPa. The bonding condition was 1230℃ for 8 h. After bonding, specimens were cooled to room temperature in vacuum chamber. All test specimens were subjected to a heat treatment procedure consisting of a three-step solution treatment(1295℃/8h AC+1305℃/8h AC+1310℃/8h AC) and a two-step aging treatment (1080℃/4h AC+870℃/24h AC) before the mechanical testing. The heat-treated specimens were machined into constant load creep specimens with gauge length of 25mm and a gauge diameter of 5mm.

The creep test condition was 982℃/248MPa. Some creep tests were carried out to failure to obtain the creep properties. In order to observe evolution of substructures during creep deformation, some tests were interrupted at different creep stages. Creep tests were performed in air. Deformation substructure was observed using transmission electron microscope (TEM). A TLP joint consisted of bonding zone and substrate zone. Therefore, TEM

disks of TLP joints were cut from bonding zone and substrate zone, respectively. The TEM foils were prepared by twin-jet thinning electrolytically in a solution of 7% perchloric acid and 93% alcohol at -30℃.

Results and Discussion

Creep Curves of TLP Joint and Matrix Sample

The entire creep curves for TLP joint and matrix sample are illustrated in Fig.1 (a)(b).

(a) TLP joint

(b) matrix

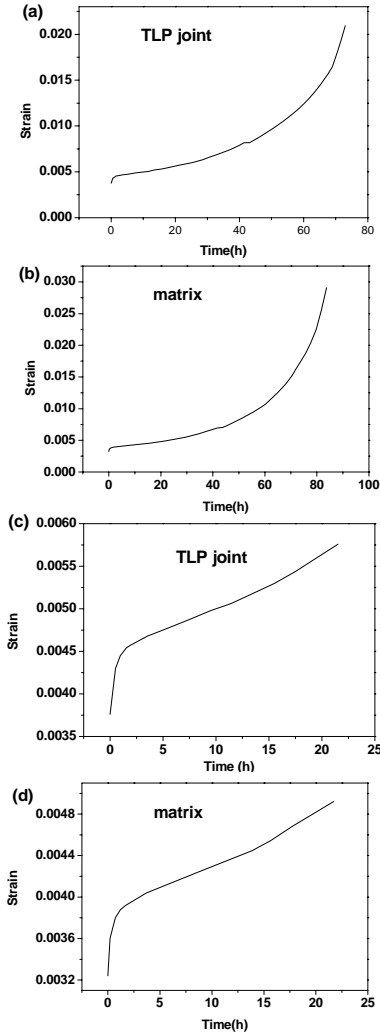**(c)** TLP joint

(d) matrix

Fig.1 Creep curves for TLP joint and matrix sample
(a) creep curve for TLP joint (b) creep curve for matrix sample (c) early portion of creep curve for TLP joint (d) early portion of creep curve for matrix sample

It can be seen that the creep curves of TLP joint is similar in shape to that of matrix sample, and both the creep curves are composed of primary stage, steady stage and tertiary stage obviously. Both TLP joint and matrix sample show no incubation period before the creep strain develops. Fig.1 (c)(d) show the early portions of the creep curves for TLP joint and matrix sample on an expanded time axis respectively. With careful observation, it can be seen that there is a little difference between them. The transition of

primary to steady stage of TLP joint occurs when creep strain is up to approximately 0.45%. However, for matrix sample, the creep strain value is about 0.39% that is less than that of TLP joint. This indicates that more plastic deformation takes place in TLP joint during primary stage, and the primary stage of TLP joint takes longer time than matrix sample.

Creep Properties of TLP Bonded Specimens and Matrix Sample

It is described that a microstructure and chemical homogeneous TLP joint can be obtained after TLP bonding and subsequent heat treatments [15, 16]. The creep properties of TLP bonded specimens and matrix sample are shown in Table 1. The property data shown here are average values of two samples. It is clear that the average creep life of bonded specimens is comparable to that of matrix sample, while the elongation of TLP bonded specimens is significantly lower. This is consistent with our previous result.

Table Ⅰ Creep properties of TLP bonded specimens and matrix sample

	Creep life (h)	Elongation (%)
TLP bonded specimens	81.4	21.2
Matrix sample	85.7	50.5

Creep Deformation Substructure
Creep Deformation Substructure of TLP Joint During Test

The deformation substructures of bonding zone and substrate zone for TLP joint crept to the end of primary stage (2h) are shown in Fig.2. The morphologies of γ′ precipitates remain cubic, and creep deformation is confined to γ channels. Almost all of dislocations from {111}<110> slip system appear in γ phase, and some of these dislocations with different Burgers vector interact each other and this makes the creep strain rate decrease (Fig.2(a)(c)). Parallel and paired dislocations loops also give rise to the dislocation density in the γ channels. Cross slip can also be observed as shown as black arrows in Fig.2 (b)(d). It is noted that no obvious difference in deformation substructures observed between bonding zone and substrate zone. This indicates that the creep deformation of TLP joint at this time is homogeneous.
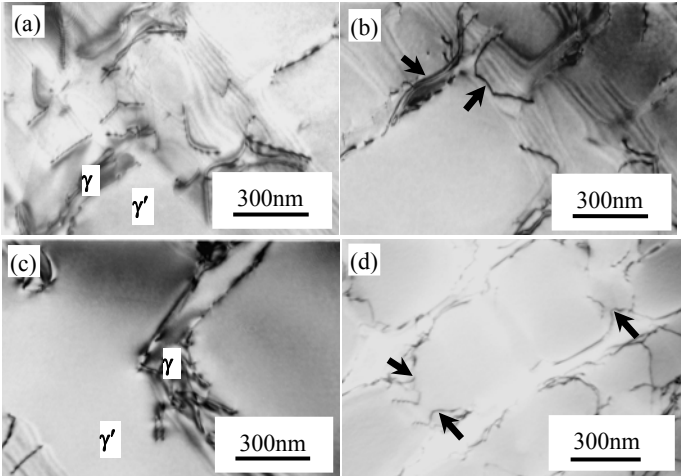

Fig.2 Dislocations of TLP joint developed at primary stage

(a)(b) dislocations in bonding zone   (c)(d) dislocations in substrate zone

The deformed substructures of bonding zone and substrate zone of TLP joint formed at steady stage (50h) are shown in Fig.3. The directional coarsening of γ′ particles taken place in both bonding zone and substrate zone, and N-type rafts form in the direction perpendicular to the external stress (Fig.3 (a)(b)). Hexagonal dislocation networks form at γ-γ′ interfaces (Fig.3 (c)). It is worth noting that in some area square-shaped dislocation networks can be found (Fig.3 (d)). With reference to previous work [17], square-shaped dislocation networks may result from interaction of two sets of dislocations, and under the function of dislocation line tension, square-shape dislocation networks will transit into hexagonal dislocation networks.
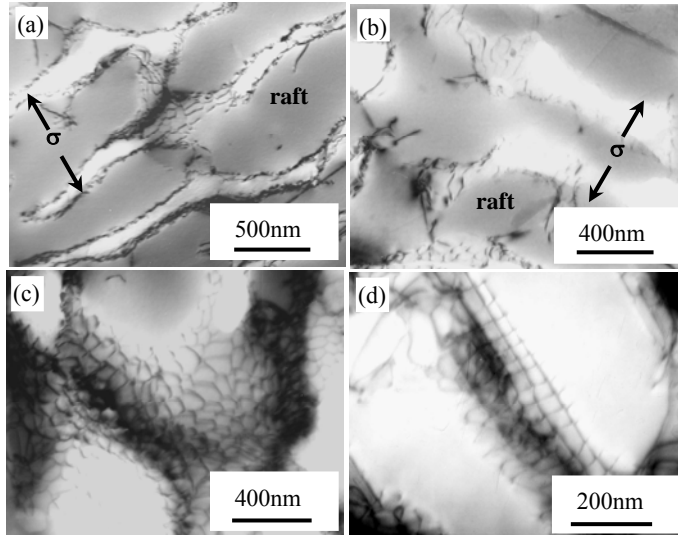

Fig.3 Dislocations of TLP joint after crept for 50h
(a) rafts of γ′ phase in bonding zone (b) rafts in substrate zone (c)(d) dislocation network in bonding zone

Creep Deformation Substructure of Matrix Sample During Creep Test

With respect to matrix sample that did not be bonded, the substructures developed at primary stage are shown in Fig.4. The γ′ precipitates are cubic in shape. Dislocation movement is mainly restricted in γ channels, and nearly all γ channels are filled with high-density dislocations, and amounts of cross-slipping dislocations are observed (Fig.4 (a)). With higher magnification view, there are many long straight dislocations which lie at about 45° to the cube face of γ′ particles just as those in area A in Fig.4 (b). Those dislocations are mixed in nature and referred to as 60° dislocations [11, 14]. Furthermore, these long straight dislocations are contained in the vertical γ channel which covers a few γ′ particles. When a long dislocation encounters a narrow horizontal γ channel, bowing out in the horizontal γ channel will take place, and there are zigzag formed in long dislocations as shown as arrows in Fig.4 (b). Another marked deformation feature appeared is the primary dislocation network due to dislocation cross slipping (Fig.4 (c)). It can be seen that two sets of dislocations intersect and this contributes to the probability of formation of interfacial dislocation networks.

Compared with substructures in TLP joint of this stage, it is clear that more dislocations appear in matrix sample. The intersection among these dislocations may result in obvious hardening in primary stage. This can accelerate the transition from primary to steady creep stage. This is also proved by the comparison of early stages of the creep curves for TLP joint and matrix sample (Fig.1 (c)(d)).
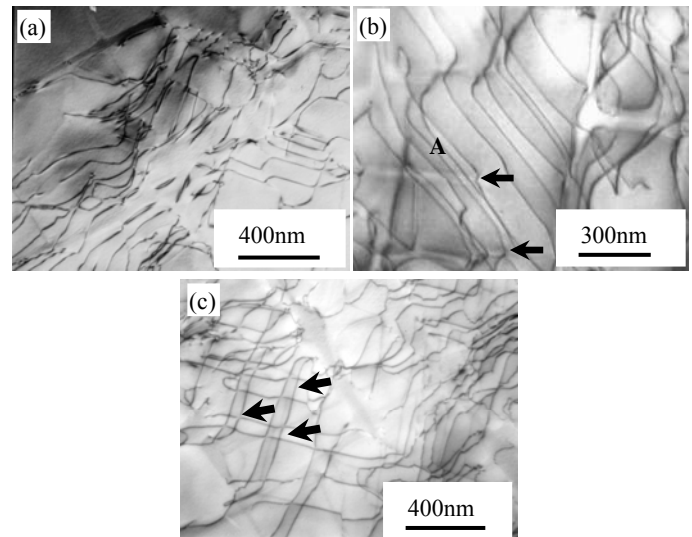

Fig.4 Dislocations of matrix sample in primary stage
(a) dislocations in γ phase (b) 60° dislocation (c) cross slipping of dislocations

When crept to steady stage (50h) for matrix sample, rafting of γ′ particles appears (Fig.5 (a)). There are dislocation networks at γ/γ′ interface (Fig.5 (b)). The interfacial dislocation networks are hexagonal in character and more regular than those observed in TLP joint (Fig.5 (c)). No square-shaped network is found in matrix sample at this time. This also suggests that interfacial networks in matrix sample formed earlier and developed further than those in TLP joint.
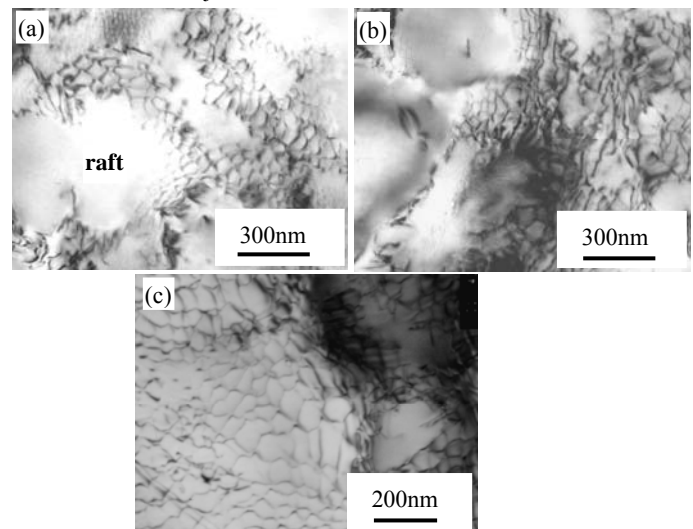

Fig.5 Dislocations of matrix sample after crept for 50h
(a) γ′ rafts (b) interfacial dislocation network (c) hexagonal dislocation network

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In our previous work [16, 18], the difference in creep elongation between TLP joint and matrix sample was discussed. The solid-solution strengthening effect of boron atoms coming from interlayer, the formation of subgrain boundaries in the bonding zone (Fig.6) and amounts of creep cavities formed during creep test result in the reduction of creep elongation of TLP joints.
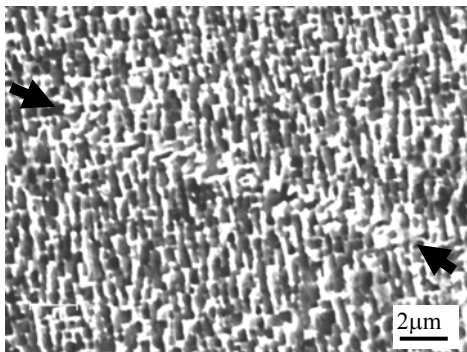

Fig.6 Subgrain boundary formed in the bonding zone of TLP joint

According to Courtney's work [19], the macroscopic shear strain of a crystal is proportional to the dislocation density. The more the macroscopic strain of alloy, the higher the dislocation density in it. This is consistent with our observation of microstructure here. From the comparison of elongations, it is apparent that plastic deformation is more pronounced in matrix sample than in TLP joint. More plastic deformation of matrix sample contributes to higher dislocation density and more significant interaction of dislocations. This feature gives rise to the probability of dislocation cross slipping in matrix sample. More frequent cross slipping of dislocations results in earlier and more regular interfacial dislocation networks. As for TLP joint, reduction of creep deformation leads to decrease of dislocation density. This results in later formation of dislocation networks, and dislocation networks are more irregular than those in matrix sample.

Conclusions

(1) The average creep life of TLP joint is comparable to that of matrix sample, but the elongation of TLP joint is much lower than that of matrix sample.

(2) The creep curve of TLP joint consists of primary stage, steady stage and tertiary stage, and the creep curve shape is similar to that of matrix sample.

(3) Based of the observation of deformation substructures in bonding zone and substrate zone from TLP joint at different creep stages, it is evident that during creep process deformation substructures of different parts are similar. This indicates that the deformation of whole TLP joint is homogeneous during creep test.

(4) Compared with substructures in matrix sample, the quantity of dislocations in TLP joint is less in primary stage. Dislocation networks form later and more irregular than those in matrix sample when crept to steady stage.

Acknowledgments

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