LOW CYCLE FATIGUE IN TITANIUM ALUMINIUM FORMED BY CENTRIFUGAL SPRAY DEPOSITION①

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ABSTRACT The push-pull low cycle fatigue (LCF) behaviors of Ti-48Al-2Mn-2Nb (mole fraction, %), which was formed by centrifugal spray deposition (CSD) under a low pressure vacuum condition, were investigated under the control of total cyclic strain amplitude at ambient temperature. The results show that the available cyclic strain amplitude regions of TiAl alloy are very narrow, $\Delta\varepsilon_t/2$ equals 0.1% ~ 0.25%, and no cyclic hardening or softening are observed during low cycle fatigue processes. The fatigue lives of CSD samples can be improved by hot isostatic pressing (HIP). The characteristics of dislocation configurations of samples experienced different strain amplitudes have been analyzed by means of transmission electron microscopy (TEM).

Key words centrifugal spray deposition (CSD) Ti-48Al-2Mn-2Nb low cycle fatigue

1 INTRODUCTION

As a result of low density, high strength, good oxide resistance and excellent creep resistance, titanium aluminum alloys based on γ-TiAl are currently considered as one of the most prospective structural materials for elevated temperature applications in the future[1-3]. It is well known that fatigue of structural materials is an important field, which should be highlighted and studied deeply. However, as its low plasticity of TiAl alloy at ambient temperature, the research works about low cycle fatigue tests have less been studied and reported[4, 5]. Moreover, it is very difficult to conduct LCF under cyclic strain control. One of the authors[6] investigated some mechanical properties of Ti-48Al-2Mn-2Nb alloy produced by centrifugal spray deposition (CSD) under vacuum condition. His results show that the elongation of CSD TiAl alloy is about 3% in tensile test at ambient temperature, while 38% compressed ratio is obtained in compression test at ambient temperature. So it indicates that this new forming process can improve the plasticity of intermetallics and presents a possibility of carrying out cyclic strain fatigue. The present work tries to study deeply the effect of CSD processing on the low cycle fatigue (LCF) of the TiAl alloy. Obviously, this work has the significance and applicant value to understand the behavior of TiAl intermetallics.

2 EXPERIMENTAL

2.1 Preparation of TiAl alloy

The nominal composition of γ-TiAl alloy

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was Ti-48Al-2Mn-2Nb (mole fraction, %). The alloy was produced by centrifugal spray deposition (CSD) at Interdisciplinary Research Centre (IRC) in Materials for High Performance Applications, University of Birmingham, UK. The alloy was first melted by a plasma torch, and then remelted and sprayed under a low vacuum pressure condition[7]. The spray forming facilities were housed in a subsidiary chamber that was mounted underneath the induction crucible. The normal procedure, prior to spraying, is to evacuate the forming chamber and then back-fill with argon and then re-evacuated to a low vacuum pressure of 3 Pa. During spray forming, the melt was bottom poured through a graphite nozzle under a positive pressure of 170 kPa, and fell freely onto a water-cooled copper disc which was positioned 250 mm below the graphite nozzle and rotated at 3 000 r/min. Centrifugal forces broke up the stream into droplets, which were sprayed approximately horizontally onto the inside surface of a preset steel substrate. As a result, a ring preform was obtained with 400 mm diameter, about 150 mm axial height and 10 mm thickness.

The as-sprayed alloy showed a typical lamellar structure with some small pores, and the porosity levels were related to the spraying distance[8]. In order to close the porosity of CSD blank, a hot isostatic pressing (HIP) process, 1 250 ℃, 150 MPa, 4 h in argon atmosphere, has been used.

2.2 Low cycle fatigue tests

For convenience, the samples which undergoes centrifugal spray deposition or hot isostatic pressing are called CSD or HIP respectively. The samples for low cycle fatigue were machined from the CSD and HIP blanks respectively into gauge dimensions of 5 mm × 6 mm × 15 mm using spark-erosion machine. The surfaces of LCF samples were ground and well polished for the purpose of surface appearance observation.

LCF tests were carried out on an electro-servo-hydraulic Sehnck (100 kN) testing machine, in State Key Laboratory for Fatigue and Fracture of Materials, IMR, Chinese Academy of Science. A push-pull test was performed under total cyclic strain control at ambient temperature, with the stress ratio $R = -1$, the frequency $f = 0.1$ Hz and a triangular waveform. During testing, the cyclic stress-strain curves were recorded on an X-Y plotter.

2.3 Microstructure observation

Thin foils cut from the uniform strain regions of deformed LCF samples were prepared by twin-jet electropolishing. Microstructure of the samples was examined on a transmission electron microscope (TEM 2000EX) operating at 160 kV.

3 RESULTS AND DISCUSSION

3.1 Properties of LCF

The low cycle fatigue lifetime N_f and the total cyclic strain amplitude $\Delta\varepsilon_t$ of the CSD and HIP samples are listed in Table 1. Furthermore, it can be clearly seen from Fig. 1 the relationship of LCF lifetime and the total cyclic strain amplitude. The LCF life is obviously prolonged with the decreasing of cyclic amplitude. Comparing with the LCF properties of CSD and HIP samples, it can be found that HIP samples show better properties than that of CSD samples within the tested cyclic strain amplitudes. It indicates from Fig. 1, generally speaking, that the $\lg \Delta\varepsilon_t - \lg N_f$ curve of HIP is above that of CSD samples so that the lifetime of the HIP samples could be longer than that of CSD samples under the same cyclic strain amplitude. Obviously, their microstructure and plasticity affect the LCF properties of the CSD and HIP. The reason is that the as-sprayed samples exist unavoidably pores, where 2.2% porosity of CSD is detected by means of an image analysis system[9], so that the micro-voids could become a source of fatigue crack initiation during the push-pull cyclic processes. However, the LCF lifetime of HIP samples increases because hot isostatic pressing process closes efficiently the porosity produced by CSD, in which the porosity is only 0.03%. Therefore, the fatigue crack initiation sources decrease and the local stress concentration is relieved. On the other hand, microstructures of CSD and HIP are quite different. The microstructure of CSD revealed lamellar colonies, whose size was about 100 μm in diameter. But a duplex microstructure, which was consisted of lamellar structures and gamma equi-axed grains, was obtained in HIP sample, as shown in Fig. 2. The results of tensile and compressive test[10] show that the plasticity of HIP with a duplex microstructure is better than that of CSD with a lamellar microstructure. This indicates that gamma equiaxed grain is of benefical to plastic deformation. The ability of homogeneous plastic deformation of samples increases because gamma equiaxed grain in duplex structure is beneficial to improve the uneven deformation in the lamellar structure[2, 11], and then to increase the LCF properties of TiAl alloy.

During the push-pull fatigue test under cyclic strain control, the cyclic stress-strain process has been successfully conducted, but the cyclic strain is limited at narrow strain ranges, that is $\Delta\varepsilon_t/2 = 0.1\% \sim 0.25\%$. When the half-cyclic strain amplitude $\Delta\varepsilon_t/2$ is larger than 0.3%, the sample fractures rapidly so that its cycle life is less one cycle, which means it could not form a whole cyclic hysteresis loop. It can be seen from Table 1 that the cycle life is very sensitive to cyclic strain amplitude, that is, when $\Delta\varepsilon_t/2 = 0.2\%$ ($\Delta\varepsilon_p/2 = 0.0167\%$), cycle life is no more than 50 cycles. But when $\Delta\varepsilon_t/2 = 0.1\%$ ($\Delta\varepsilon_p/2 = 0.0012\%$), cycle life is more over 10^4 cycles. This characteristic sensitivity to the cyclic strain amplitude is obviously related to

Table 1 Data of LCF of CSD and HIP samples

Procedure	$\frac{\Delta\varepsilon_t}{2}$/ %	$\frac{\Delta\varepsilon_p}{2}$/ %	Δp / kN	N_f/ cycles
CSD	0.10	0.0012	9.6	10474
	0.15	0.0049	14.9	501
	0.175	0.0106	15.8	325
	0.20	0.0167	19.8	50
	0.225	0.0287	20.8	44
	0.25	0.0390	22.0	30
HIP	0.15	0.0060	13.1	2350
	0.175	0.0142	17.4	457
	0.20	0.0200	18.3	155
	0.225	0.0281	20.8	43
	0.25	0.0367	20.8	28

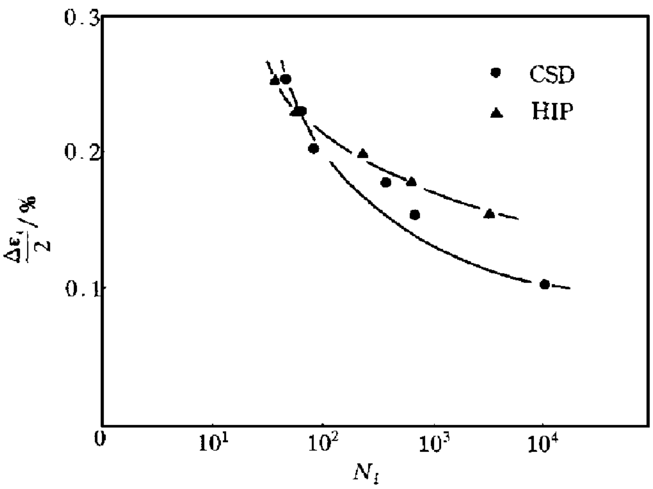

Fig. 1 $\Delta\varepsilon_t$ vs N_f relationship of CSD TiAl and HIP samples

Fig. 2 Microstructures of CSD and HIP samples
(a) —Lamellar microstructure of CSD samples;
(b) —Duplex microstructure of HIP samples

the low plasticity and high elastic module of TiAl alloys.

Another behavior should be here noted that no matter under which state —CSD or HIP, the cyclic hardening or softening behavior has not been displayed obviously. The testing observation shows that from the first cycle to fracture cyclic hystersis loops trend towards steady, and cyclic strain amplitude is almost not changed too. The results indicate that, on one hand, this alloy is a cyclically stable material under the LCF condition, on the other hand, it is because that during the LCF process the sample only undertakes lower cyclic strain amplitude as the low plasticity and high elastic module of TiAl alloys. From Table 1, it is found that HIP can prolong the LCF life, and affect the stress as well as cyclic strain amplitude, but it does not obviously affect the cyclic hardening and softening behavior and the stability of cyclic hysteresis loops.

3.2 Coffin-Manson relationship

During LCF process, the cyclic strain amplitude is an important factor. The results of the LCF lifetime N_f and cyclic strain amplitude $\Delta\varepsilon_p$ were calculated and it is found that they are corresponding to the following relationships

CSD: $\Delta\varepsilon_p(N_f)^{0.66} = 3.6 \times 10^{-3}$

HIP: $\Delta\varepsilon_p(N_f)^{0.32} = 1.1 \times 10^{-3}$

Fig. 3 plots the two curves, and it can be seen that the cyclic strain amplitude of HIP samples is higher than that of CSD samples under given cycles. The result means that HIP samples could endure longer LCF lives than CSD samples could do at the same cyclic strain amplitudes, or it means that they could undertake larger cyclic strain amplitude than CSD samples could do at the same lifetime. It shows the same change rules as mentioned above.

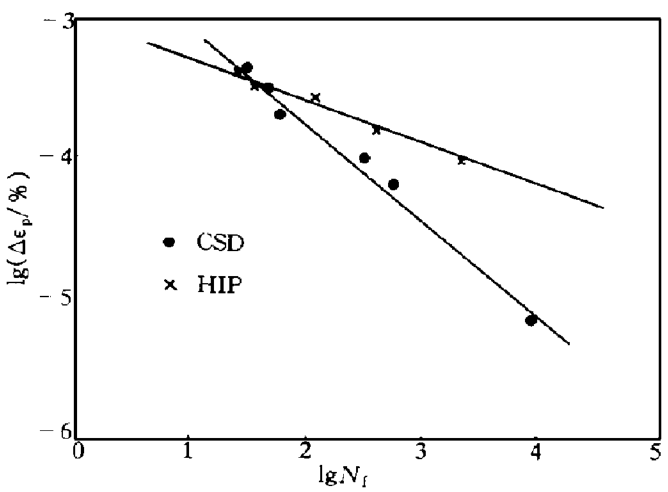

Fig. 3 lg $\Delta\varepsilon_p$ —lgN_f curves of CSD TiAl and HIP samples

3.3 Dislocation configuration of deformation after LCF

As well known, the main reason of low plasticity of TiAl alloy is lack of enough slip systems. Therefore, dislocations are difficult to set in motion during deformation. However, dislocation may be easier to move under the cycling load than in uniaxial tensile or under compression loads. The dislocation configuration observation of samples after LCF deformation shows that there is a great effect of the cyclic strain amplitudes and cycle numbers on the dislocation configuration. Fig. 4(a) shows that the dislocation configuration is composed of stacking faults or twinning under high stress and low cycles. This kind of configuration is related to decreasing of stacking fault energy after adding alloying elements. With the decreasing of cyclic strain amplitude and the increasing of cycle numbers, the super-dislocation is made to set in motion, which can be decomposed locally into dislocation loops or ridge dislocations as shown in Fig. 4(b). While in the process of low stress and high cycle numbers, the dislocation configuration shows a fine, linear, straight dislocation and then forms a tangle dislocation, as shown in Fig. 4(c). This kind of structure is similar to the dislocation structure formed in those typical face central cubic alloys during the early fatigue deformation. The formation of tangle dislocations indicates that the cross-slip occurs in the fatigue process. The dislocation configurations are obviously related to the cyclic strain amplitude and cycle numbers. However, it is a complex problem so far, especially in the aspects of the dislocation evolution and the directional arrangement of dislocation during LCF process, which needs detailed and deep study in future.

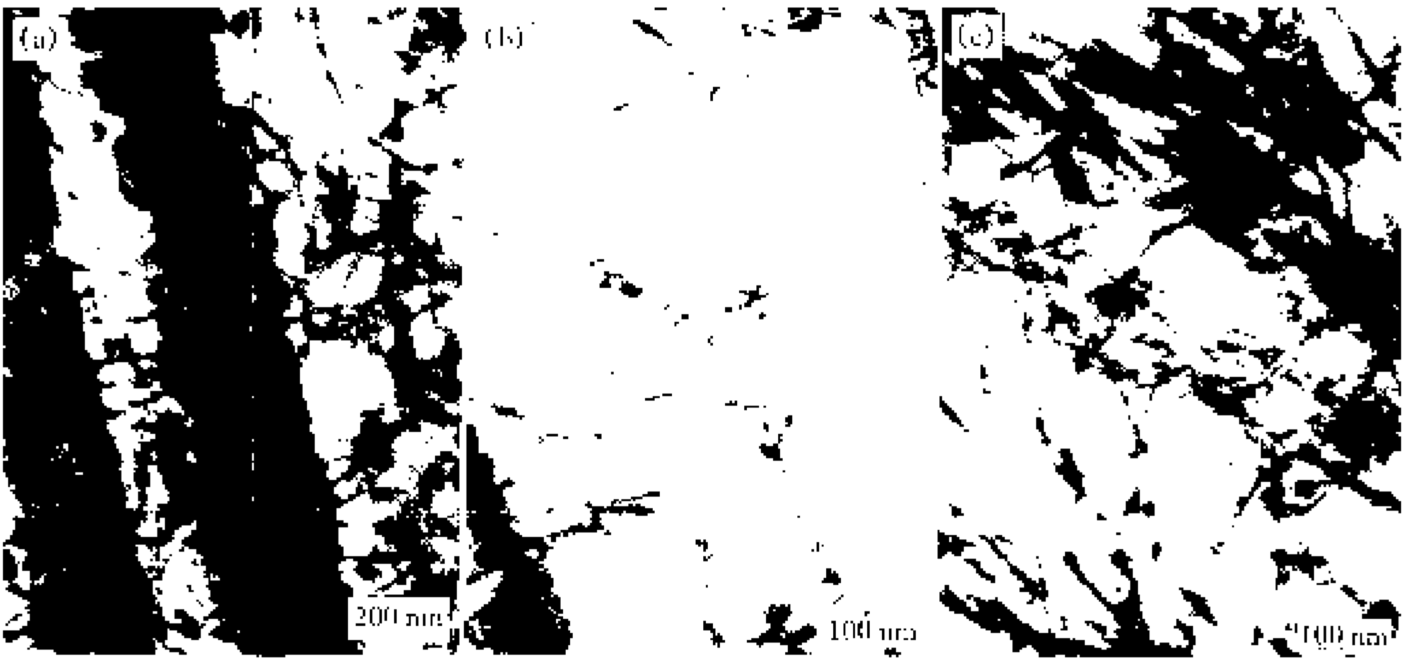

Fig. 4 Dislocation configuration of CSD samples under different cyclic strain amplitudes
(a) $-\Delta\varepsilon_t/2 = 0.2\%$, $N_f = 50$ cycles; (b) $-\Delta\varepsilon_t/2 = 0.175\%$, $N_f = 230$ cycles;
(c) $-\Delta\varepsilon_t/2 = 0.1\%$, $N_f = 501$ cycles;

4 CONCLUSIONS

The low cycle fatigue of Ti-48Al-2Mn-2Nb (mole fraction, %), formed by CSD and treated by HIP, has been well conducted under the control of total cyclic strain amplitude at ambient temperature. The following main results are obtained:

(1) Compared with the CSD states, HIP can improve the low cycle fatigue life. It is because HIP closes the porosity formed by CSD process, and forms a duplex structure that improves the plasticity of TiAl alloy.

(2) The cyclic stress-strain of LCF is limited at narrow strain amplitudes regions of $\Delta\varepsilon_t/2 = 0.1\% \sim 0.25\%$, and no cyclic hardening or softening are observed during LCF process no matter CSD or HIP is.

(3) The relationship of LCF lifetime N_f and cyclic strain amplitude $\Delta\varepsilon_p$ tends to follow the well-known Coffin-Manson relationship. It can be written as follows:

CSD: $\Delta\varepsilon_p(N_f)^{0.66} = 3.6 \times 10^{-3}$

HIP: $\Delta\varepsilon_p(N_f)^{0.32} = 1.1 \times 10^{-3}$

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REFERENCES

1 Lipsitt H A. In: Koch C C, Stoloff N S and Liu C T eds. High-temperature Ordered Intermetallic Alloys, IMRS Symp Proc, Pittsburgh, USA, 1985, 39: 351 - 363.
2 Kim Y-W. JOM, 1989, 41(7): 24- 30.
3 Kim Y-W. JOM, 1994, 46(7): 30- 39.
4 Shibata H, Tokaji K, Ogawa T *et al*. Int J Fatigue, 1996, 18(2): 119- 126.
5 Malakondaiah G and Nicholas T. Metall Mater Trans, 1996, 27A: 2239- 2251.
6 Chen Wenzhe. PhD Dissertation, (in Chinese), Xi′an: Xi′an Jiaotong University, 1997.
7 Dowson A, Jacobs M H, Young J M *et al*. In: Kim Y-W. Wagner R and Yamaguchi M eds. Gamma Titanium Aluminides, TMS, Warrendale, PA, 1995: 483- 490.
8 Chen Wenzhe, Jacobs M H and Loretto M H. The Chinese Journal of Nonferrous Metals, (in Chinese), 1996, 6(3): 86- 89.
9 Chen Wenzhe, Qian Kuangwu and Gu Haicheng. Physical Testing and Chemical Analysis A, (in Chinese), 1997, 33: 18- 21.
10 Chen Wenzhe, Xie Hua, Qian Kuangwu *et al*. Mater Sci Eng, 1997, A234- 236: 245- 248.
11 Kim Y-W and Dimiduk D M. JOM, 1991, 43(8): 40- 47.

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