Article ID: 1003－6326(2004)03－0459－05

Effects of rapid heating cyclic heat treatment on microstructures and compression mechanical properties of TiAl-based alloy ①

PENG Chao-qun(彭超群)[1], HE Yue-hui(贺跃辉)[1], HUANG Bai-yun(黄伯云)[1], P. K. Liaw[2]
(1. State Key Laboratory for Powder Metallurgy, Central South University, Changsha 410083, China;
2. Materials Science and Engineering Department, University of Tennessee,
Knoxville, TN 37996-2200, USA)

Abstract: By means of rapid heating cyclic heat treatment, the microstructure of a TiAl-based alloy was refined. The colony size and lamellar spacing were measured to be 50 μm and 0.12 μm, respectively. The compression mechanical properties were determined at room temperature and the best comprehensive mechanical properties can reach $\sigma_{0.2}$ of 745.1 MPa, σ_p of 1 672.2 MPa and δ of 19.40%. The improvement of mechanical properties is caused by the microstructural refinement and the phase interface nucleation contributes a lot to the refinement of microstructure.

Key words: TiAl; compression mechanical properties; microstructural refinement; phase interface nucleation
CLC number: TG 146 **Document code:** A

1 INTRODUCTION

Due to their advantages in density, specific rigidity, high-temperature strength and burning resistance and so on, the TiAl-based alloys are considered a new generation of structural materials of the greatest application potential[1-3]. Like most other intermetallics, the room-temperature brittleness is the largest barrier which limits their practical applications as high-temperature structural materials, and how to improve their room-temperature ductility is a challenging task. In the coming years, the emphases will be put on how to further determine the relationships among the processing, microstructure and mechanical properties[4].

Because of their convenience in near net shaping and low cost, the foundry methods will be the first way for the TiAl-based alloys to obtain industrial applications[2]. But the as-cast TiAl-based alloys are generally composed of coarse lamellar colonies, and their room-temperature ductility is almost zero. Only through refining the microstructures by alloying, thermomechanical treatment, or special heat treatment, can the room temperature ductility of the cast alloys be improved, and then can they be applied practically. By means of the above methods, several kinds of microstructures were developed[5-17]. It is proved that it is more probable for the fine fully-lamellar(FFL) microstructure to succeed in applications.

ZHANG et al[13-15], WANG[16] and XIE et al[17] separately studied the effects of cyclic heat treatments on microstructures and mechanical properties. The common points of the technologies adopted by them lie in: relatively low heating rates, long holding times, and high cooling rates, and intermediate phase transformations by which the fully lamellar (FL) microstructures form.

In order to reduce the risk of the rapid cooling and long holding time at high temperatures to harm the shape and size of foundry of a TiAl-based alloy during heat treatment for refining the microstructure, the authors proposed a new cyclic heat treatment technology characterized by high heating rates, short holding times and relatively slow cooling rates for the TiAl-based alloys. In this work, the authors examined the effects of various heat treatment parameters, such as heating rate, holding temperature, holding time, cooling rate and cycle number on the microstructures and hardness of a TiAl-based alloy by means of a Gleeble-1500 thermal simulator. Based on the above study, the authors prepared specimens for compression mechanical properties tests using a GP-30A type induction heating machine. Finally, the formation mechanisms of the FFL α_2/γ microstructures in this technology were discussed.

2 EXPERIMENTAL

The test material used is as-cast Ti-33Al-3Cr (mass fraction, %) with a colony size of about 800 μm (Fig. 1). The schematic representation of the cyclic heat treatment technology is shown in Fig. 2. The simulation tests were performed on a Gleeble-1500 thermal simulator; the induction heat treatments were finished on a GP-30A type induction heating machine.

① **Received date:** 2003－09－15; **Accepted date:** 2004－01－20
Correspondence: PENG Chao-qun, PhD; Tel: +86-731-8877197; E-mail: pengcq@hotmail.com or f-ysxb@mail.csu.edu.cn

Fig. 1 Optical microstructure of as-cast TiAl-based alloy

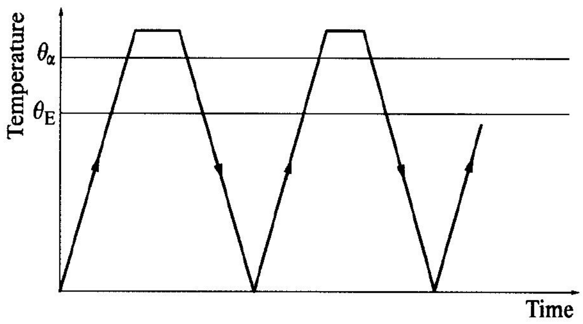

Fig. 2 Schematic representation of cyclic heat treatment technology

3 RESULTS AND DISCUSSION

3.1 Direct heating treatment

In order to simultaneously examine the effects of various heat treatment parameters, such as heating rate, holding temperature, holding time, cooling rate, and cycle number on the microstructures and hardness of the tested material and reduce the test number, the $L_{16}(4_5)$ orthogonal test table (Table 1) was adopted. Because it is sensitive to crystal structure, microstructure and morphology, the change of hardness can indirectly reflect their changes. The range analysis results of HV_5(loading 49 N) hardness is also shown in Table 1, in which I_j, II_j, III_j and IV_j represent the sum of HV_5 values of level I, II, III and IV in jth column; R_j represents the difference between the maximum and the minimum among I_j, II_j, III_j and V_j.

Because the range (difference between the maximum and minimum observations) quantity reflects the degree of the effect of a factor on the index (some property) value, it is easy to know the sequence of the effects of the factors on the indices from the sequence of the ranges. It is clear from Table 1 that the sequence of the effects of the 5 factors on the hardness is υ_h, t, υ_c, θ, n. Therefore, the effect of the heating rate on the hardness is the most obvious and it must be strictly controlled and emphatically studied.

Table 1 Range analysis results of HV_5 values

Sample No.	Level υ_h	θ	t	υ_c	n	Mean value of HV_5
1	1	1	1	1	1	352
2	1	2	2	2	2	316
3	1	3	3	3	3	319
4	1	4	4	4	4	289
5	2	1	2	3	4	288
6	2	2	1	4	3	340
7	2	3	4	1	2	358
8	2	4	3	2	1	322
9	3	1	3	4	2	325
10	3	2	4	3	1	297
11	3	3	1	2	4	317
12	3	4	2	1	3	277
13	4	1	4	2	3	339
14	4	2	3	1	4	383
15	4	3	2	4	1	359
16	4	4	1	3	2	354
I_j	1 276	1 304	1 363	1 370	1 329	ΣHV_5= 5 234
II_j	1 308	1 335	1 240	1 294	1 353	
III_j	1 215	1 353	1 349	1 258	1 275	
IV_j	1 435	1 242	1 282	1 313	1 277	
R_j	220	111	123	112	78	

υ_h —Heating rate: 25, 50, 75 and 100 ℃/s;
θ —Holding temperature: 1 310, 1 320, 1 330 and 1 340 ℃;
t —Holding time: 2, 3, 4 and 5 min;
υ_c —Cooling rate: 20, 40, 80 and 160 ℃/s;
n —Cycle number: 1, 3, 5 and 7

Various kinds of microstructures can be obtained in the TiAl-based alloys according to different heat treatment conditions, such as a duplex microstructure, equiaxed near-gamma microstructure, near-lamellar microstructure and fully-transformed microstructure. Several typical kinds of microstructures obtained in the orthogonal tests are shown in Fig. 3, in which (a) is a typical lamellar structure, (b) is a duplex microstructure, (c) is a mixed microstructure, and (d) is a massive microstructure.

The previous studies indicate that the cooling rate plays a main role in the transformation of α phase. Wang et al[18, 19] reported that, at small cooling rates, the lamellar microstructure is predominant; at intermediate cooling rates, Widmanstatten microstructures and feather-like microstructure will form; while at very high cooling

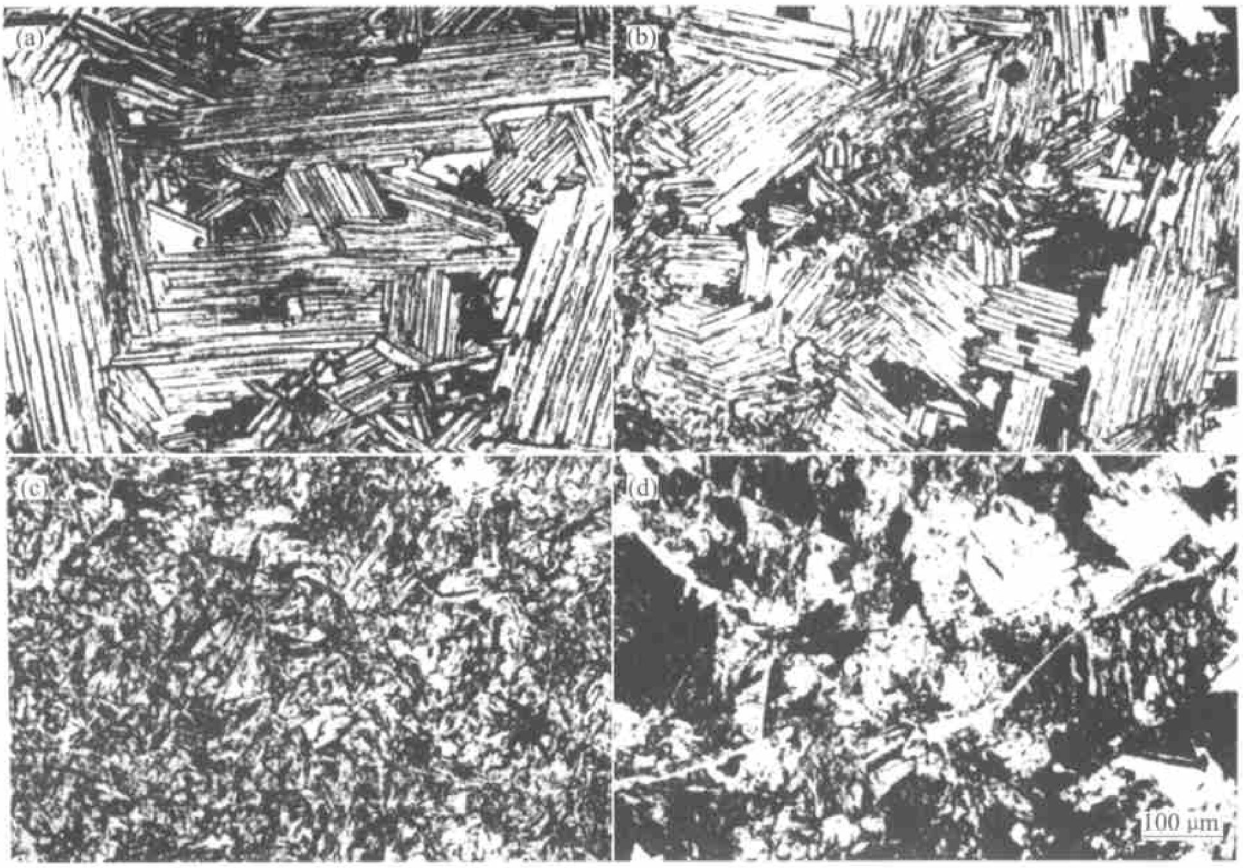

Fig. 3 Four kinds of typical microstructures obtained by orthogonal cyclic heat treatments
(a) —Typical lamellar microstructure; (b) —Duplex microstructure;
(c) —Mixed microstructure; (d) —Massive microstructure

rates, massive transformation will occur. McQuay et al[20] reached similar conclusions and observed the various microstructures mentioned above. Therefore, in order to obtain FFL α_2/γ microstructures, relatively small cooling rates were adopted in the following study.

3.2 Induction heat treatment tests

The induction heat treatment is one of the most commonly used and most effective ways to achieve rapid heating. A GP-30A type portable induction heating machine was applied to prepare rapid heating cyclic heat treatment specimens (heating rate ≈ 220 ℃/s), and the Gleeble-1500 thermal simulator was employed to measure the compressive mechanical properties before and after aging.

Fig. 4 shows the optical microstructure and transmission electron microscopy (TEM) morphology of G-5 sample prepared by the induction heating cyclic heat treatment, from which the colony size and lamellar spacing were measured to be about 50 μm and 0.12 μm, respectively.

Based on the compression load deformation curves measured at room temperature, the largest flow stress σ_p, the yield stress $\sigma_{0.2}$ and the compression ratio δ of the G-5 series specimens were calculated using the data processing software equipped with

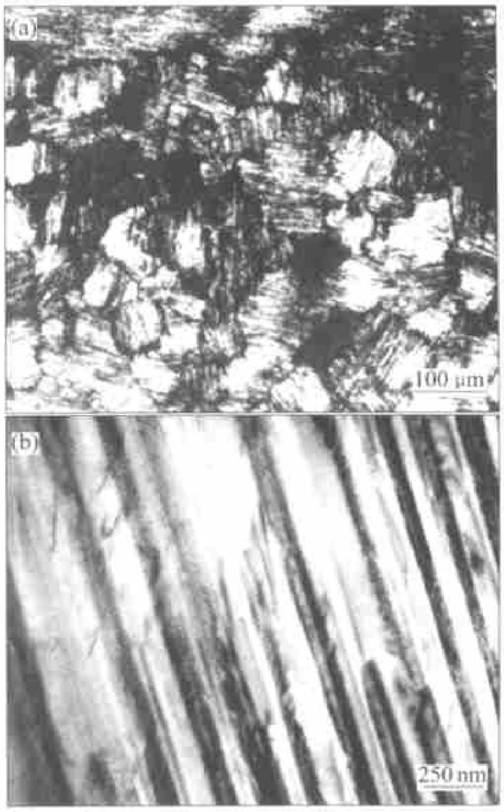

Fig. 4 Optical microstructure and TEM morphology of G-5 sample prepared by induction heating cyclic heat treatment

the Gleeble-1500 thermal simulator, as listed in Table 2.

Table 2 Largest flow stress σ_p, yield stress $\sigma_{0.2}$ and compression ratio δ in compressive tests at room temperature for G-5 series samples and as HIPped TiAl sample

Sample No.	$\sigma_{0.2}$/MPa	σ_p/MPa	δ/%
G-5	728.3	1 385.00	10.9
G-5+ 1 000 ℃, 12 h	666.7	1 389.1	13.8
G-5+ 1 000 ℃, 24 h	745.1	1 672.2	19.4
G-5+ 1 000 ℃, 36 h	806.6	1 742.0	14.1
G-5+ 1 000 ℃, 48 h	646.7	1 356.2	13.1
As-cast	596.0	1 174.9	11.6

The improvement of the mechanical properties of the alloy can be mainly ascribed to the near-FFL microstructure obtained by the rapid heating cyclic heat treatment.

4 MODEL FOR NUCLEATION AND GROWTH OF FFL MICROSTRUCTURE

Different from the conventional heat treatments and the cyclic heat treatments at relatively slow heating rates, the rapid heating cyclic heat treatment can rapidly and directly refine the coarse cast lamellar microstructure, and the refining effect is very obvious. Generally, it is not easy for the neocrystallization(The change of crystal structure occurring in the metals or alloys with allotropic change on cooling or heating through the transformation temperature.)[21] nucleation to occur at the phase interfaces, because there exists strict coherent relationship between the α and γ phases of the TiAl-based alloys, and the interfacial energy is low. But in the rapid heating cyclic heat treatment process, the practical holding temperature is higher due to strong superheating, and belongs to the range in which the α phase is very stable. The decomposition of the α phase occurs when held in the α phase field, thus making the α interface protrude into the α phase and forming small convex regions of the α phase, as shown in Fig. 5. They will be transformed into fine α_2/γ lamellae on the following cooling. Fig. 6 shows the process of the formation of phase nuclei at the α/γ interfaces and the transformation of the α phase nuclei into α_2/γ lamellae on cooling. The newly formed α_2/γ lamellae represents an angle of 60° or 120° with the primary lamellae, referring to Fig. 5. This is caused by that the new phases form favorably in the form of lamellae on specific habit planes along specific habit directions of the matrix so as to reduce the transformation resistance.

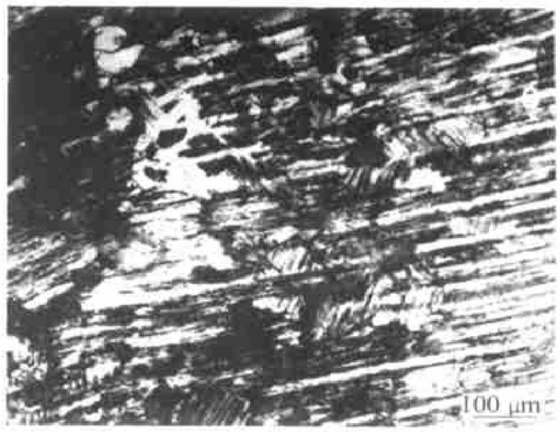

Fig. 5 Optical microstructure showing nucleation of FFL microstructures at α_2/γ interfaces

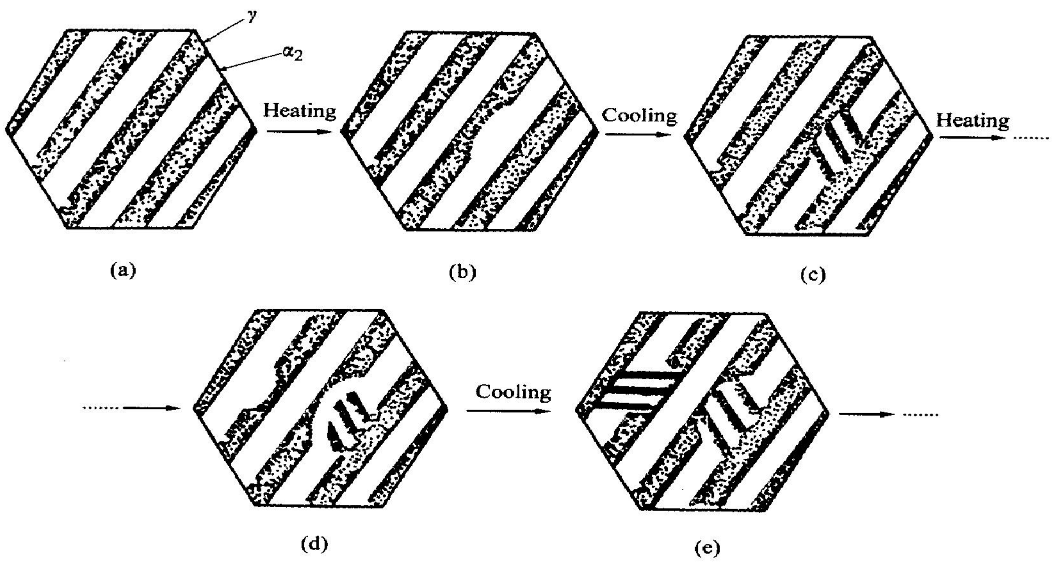

Fig. 6 Schematic diagram showing nucleation and growth at phase interfaces of FFL microstructures

5 CONCLUSIONS

1) A new cyclic heat treatment technology characterized by the rapid heating rate, short holding time and relatively slow cooling was proposed. Various kinds of microstructures are obtained by the technology under different heat treatment conditions. A FFL microstructure with a colony size of about 50 μm and a lamellar spacing of about 0.12 μm is achieved.

2) The compression mechanical properties of the studied alloy are greatly improved. The best comprehensive mechanical properties of the heat treated samples are σ_p= 1 672.2 MPa, $\sigma_{0.2}$= 745.1 MPa and δ = 19.4%, as compared to σ_p= 1 174.9 MPa, $\sigma_{0.2}$ = 596.0 MPa and δ= 11.6% of the as-cast sample.

3) A model for explaining the neocrystallization nucleation and growth of the TiAl-based alloy in the process of rapid heating cyclic heat treatment is proposed. Fast simultaneous nucleations at the grain boundaries and the $\alpha(\alpha)_2/\gamma$ interfaces account for the fast refinement of the microstructure.

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(Edited by LI Xiang-qun)