[Article ID] 1003- 6326(2002)04- 0592- 04

Recent advances of wrought TiAl alloys①

ZHANG Ji(张 继), LI Shi-qiong(李世琼), ZOU Dun-xu(邹敦叙), ZHONG Zeng-yong(仲增墉)
(High Temperature Material Research Division, Central Iron and Steel Research Institute, Beijing 100081, China)

[Abstract] The research achievement on wrought TiAl alloys gained recently in Central Iron and Steel Research Institute, China, was contributed. The progresses mainly include the improved hot deformability and homogenized microstructure after hot deformation due to the significant effects of micro-alloying process. Isothermal compressive test indicated that the TiAl containing minor Ni exhibits better plastic flow behavior and enlarged process window. The effect of Ni on modifying hot deformability of TiAl can be enhanced by incorporated addition of Mg. TEM observations suggested that Ni addition activates dislocations as well as twins at beginning stage of hot deformation and thereafter the higher-density dislocations promote the dynamic recrystallization inside γ-TiAl lamellae. It is also identified that breakdown of α_2-Ti_3Al lamellae produces new dislocation-free γ-TiAl grains. On the other hand, the homogeneity of deformed microstructure can be increased by transforming the microstructure of the Ni-containing TiAl from original lamellar structure to equiaxed grains before hot deformation.

[Key words] wrought TiAl; micro-alloying; hot deformability; microstructure
[CLC number] TG 146.2 **[Document code]** A

1 INTRODUCTION

Two-phase gamma TiAl alloys have good strength retention ability at high temperatures which, in combination with low density, makes them very promising to be high temperature structural materials[1]. During the last decade, cast TiAl has approached to the applications in particular in automobile engines because of the available casting technique used for commercial Ti alloys and success in modifying the microstructure and properties by heat treatment and XD^{TM} method[2, 3]. However, thermal mechanical processing/treatment is still more effective in refining the microstructure of TiAl alloys comparatively[4, 5]. The main roadblock to the advance of wrought TiAl alloys is their high technology cost induced by limited hot workability. Besides, the deformed microstructures of TiAl are not yet homogeneous enough to produce much more reliable mechanical properties[6]. Therefore, the competence of wrought TiAl alloys relies on the noticeable improvement of their hot deformability and microstructure uniformity after hot deformation.

The efforts for modifying the hot deformation behavior of gamma TiAl alloys to date mainly include alloy design and multi-step processing[7]. It has been identified that two-phase Ti-(44～49)Al alloys, which are favored by the room temperature ductility and other properties, exhibit similar plastic flow behavior and dynamic recrystallization process. Commonly used alloying elements such as Cr, Nb and V are not yet found to be effective in increasing the hot deformability of gamma TiAl alloys[8]. Minor additions of B have shown benefits to the hot deformation and dynamic recrystallization. But the improvement of hot deformability was mostly suggested to be the extrinsic contribution of the precipitated borides[9]. Intermediate hot working is an effective method to develop proper microstructure for subsequent shaping processing. But, it raises the technology cost further and bring about additional limits to the applications of TiAl alloys due to the pronounced size reduction of the pancakes. Recently, micro-alloying process is considered based on the evidence that minor additions of Ni can promote the lamellar degradation at the temperatures suitable for the hot deformation of TiAl alloys[10～12].

In this paper the effects of Ni and (Ni+ Mg) micro-alloying processes are reviewed by the isothermal compressive tests. The mechanisms of minor Ni additions in TiAl are also discussed based on TEM and SEM observations of the microstructures after different amounts of deformation.

2 EXPERIMENTAL

Nominal compositions of studied alloys are Ti-46.3Al-2.0V-1.0Cr-0.5Ni (denoted as TAC2-M), Ti-46.3Al-2.0V-1.0Cr-0.5Ni-0.01Mg (denoted as TAC2-Mg) and Ti-46.5Al-2.5V-1.0Cr (denoted as TAC2) (mole fraction, %). They were prepared using cold crucible induction levitation melting technique and were cast into a permanent graphite mould. Heat treatment for transforming nearly fully lamellar

① [Foundation item] Project (59881004) supported by the National Natural Science Foundation of China
[Received date] 2001- 10- 08

(NL) to equiaxed near gamma (NG) was performed at 1 150 ℃ for 144 h in a vacuum atmosphere. Cylindrical specimens with size of d8.0 mm × 12 mm were taken from the cast and annealed ingots. They were coated with glass as lubricant and equilibrated at the test temperatures for 10 min before the testing commenced. The test conditions are listed in Table 1. The specimens were compressed to the engineering strains designed for evaluating the microstructure evolution and steady-state flow behavior and then quenched into water. Those compressed to a final engineering strain of 0.7 (approximately 150% true compressive strain) were inspected by non-destructive X-ray radiography for establishing process windows.

Table 1 Thermal compressive test conditions

Condition No.	Temperature/ ℃	Strain rate/ s^{-1}	Engineering strain/ %
1	950	0.01	70
2	950	0.1	70
3	1 000	0.01	70
4	1 000	0.1	5~ 70
5	1 000	1.0	70
6	1 050	0.1	70

The microstructures in slightly deformed specimens (engineering strain ≤10%) were observed mainly by TEM; while those with higher engineering strains were characterized using back-scattered electron image in SEM. The surfaces of metallographic specimens were taken in accordance with the compressive plane.

3 IMPROVEMENTS INDUCED BY MICRO-ALLOYING

Achieved advances in the wrought TiAl containing minor Ni and Mg include two aspects: improved steady-state flow behavior and enlarged process window. It is thereafter indicated that more homogenized microstructure can only be developed in the Ni-containing alloy when starting from equiaxed near gamma microstructure. The effect of Ni addition is to promote the lamellar breakdown and spheroidization during the heat treatment before hot deformation.

3.1 Plastic flow behavior

True stress—true strain curves were drawn as the firsthand evidence to demonstrate the plastic flow behavior. Those obtained at 1 000 ℃ and 0.1 s^{-1} strain rate are shown in Fig. 1. Flow softening degree, i.e. peak stress minus steady-state stress (taken as the true stress at 100% compressive true strain) has also been calculated to illustrate the materials' ability to approach to the steady-state flow during hot deformation (as shown in Fig. 2). It is clear that much lower flow-softening degree caused mainly by reduced peak stress makes the significantly improved steady-state flow behavior of Ni-containing TAC2-M alloy. The microstructure transformation before hot deformation did not modify the plastic flow behavior of TAC2-M. It indicates that Ni addition rather than microstructure factor improves the plastic flow behavior even though the microstructure evolution during hot deformation should also contribute to its flow softening.

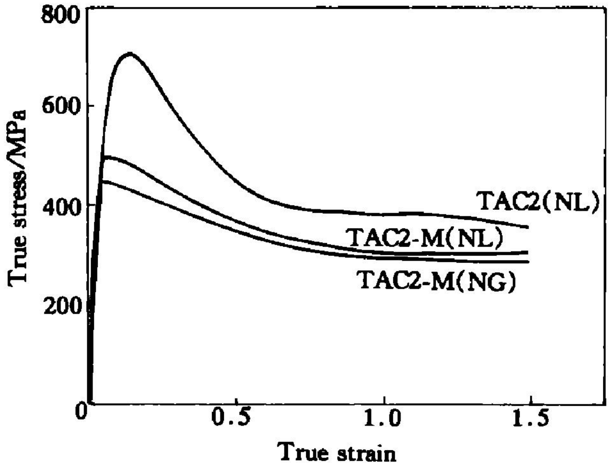

Fig. 1 True stress—true strain curves at 1 000 ℃ and 0.1 s^{-1} strain rate

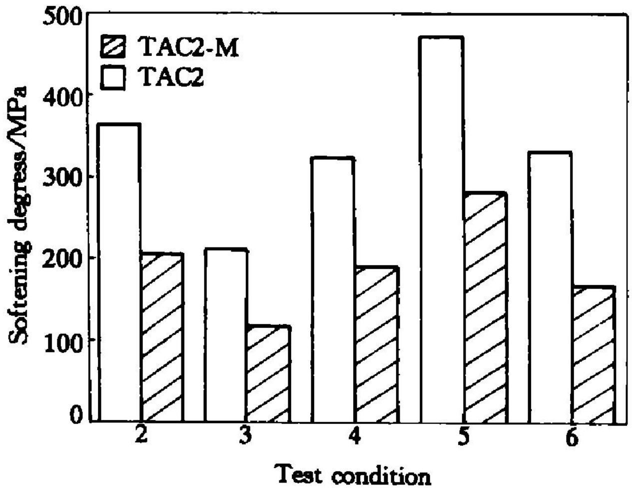

Fig. 2 Flow softening degree of studied alloys

3.2 Process windows

Deformation maps of the tested alloys were constructed with the test temperatures and strain rates as coordinate axis (as shown in Fig. 3). The process windows refer to the shadowed regions in the deformation maps, under which the specimens were compressed to 70% engineering strain without splitting.

It is clear that the alloys with 0.5% Ni additions have remarkably enlarged the process windows no matter starting from the cast or annealed states. The incorporate addition of 0.01% Mg enhances the benefit of Ni additions by raising the critical strain rate up to 0.1 s^{-1} at 950 ℃.

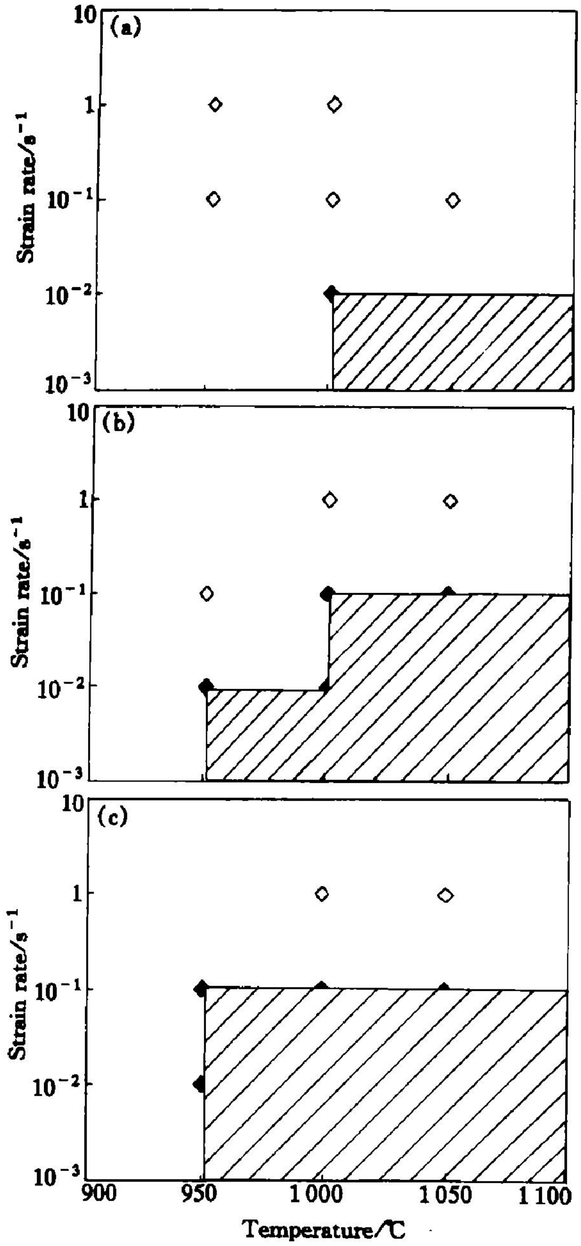

Fig. 3 Deformation maps of TAC2 starting from cast microstructures (a), TAC2-M starting from either cast or annealed microstructures (b); and TAC2-Mg starting from cast state (c)

3.3 Homogeneity of deformed microstructure

It is found that microstructure in TAC2-M alloy is quite homogeneous after the deformation starting from equiaxed NG microstructure (as shown in Fig. 4 (a)). But, neither TAC2-M nor TAC2 has uniform microstructure after compressed to 70% height reduction if starting from lamellar microstructure. It has been suggested that Ni additions promote the lamellar breakdown and segment coarsening during annealing at 1 150 ℃, which generated the lamellar spheroidization and microstructure refinement[10]. While, the lamellae oriented in hard deformation mode in TAC2-M alloy were bent but not recrystallized by heavy deformation (as shown in Fig. 4(b)).

4 MECHANISMS OF Ni ADDITION

TEM observations showed that dislocations and deformation twins in TAC2-M alloy are obviously denser than those in TAC2 alloy after compressed to 5% engineering strain that corresponds to the stress still lower than the peak value for both alloys. It indicates that dislocations in Ni-containing TiAl are more activated. Lamellar breakdown induced by Ni addition was also observed (as shown in Fig. 5). A larger number of equiaxed γ grains were found in TAC2-M alloy when engineering strain increased to 10%, i.e. the level around the peak stress. It was identified that

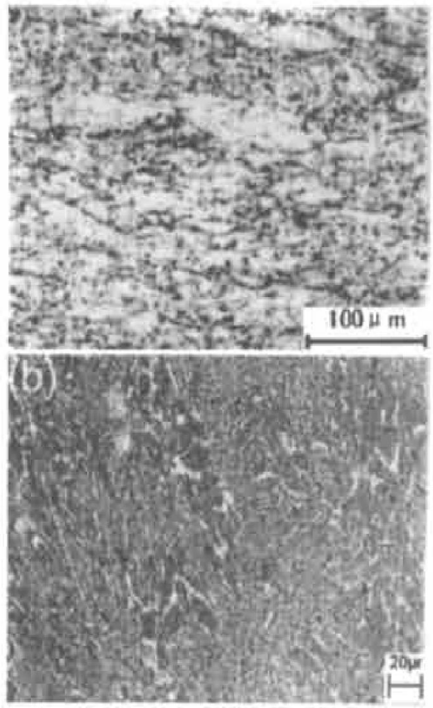

Fig. 4 Microstructures of TAC2-M when starting from equiaxed near gamma (a) and nearly fully lamellar microstructure (b) after compressed to 70% height reduction

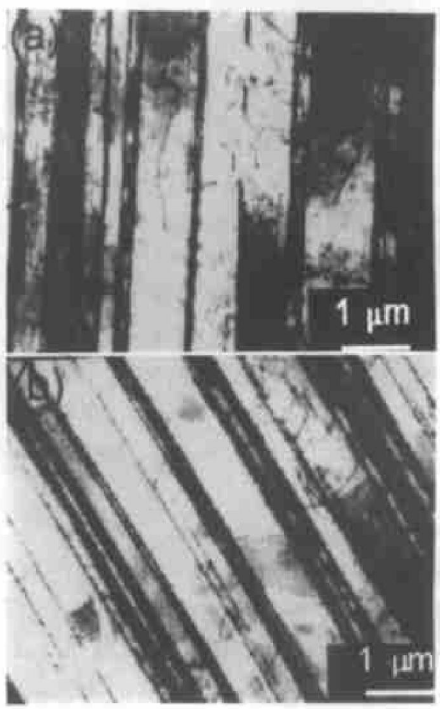

Fig. 5 TEM morphologies showing dislocations, twins as well as lamellar in TAC2-M (a) and TAC2 (b) after compressed to 5% engineering strain

those dislocation-free γ grains either nucleate inside original γ lamellae or transform from α_2 lamellae's degradation (as shown in Fig. 6). So, the flow softening in Ni-containing TiAl should be induced not only by dynamic recrystallization but also by the lamellar degradation.

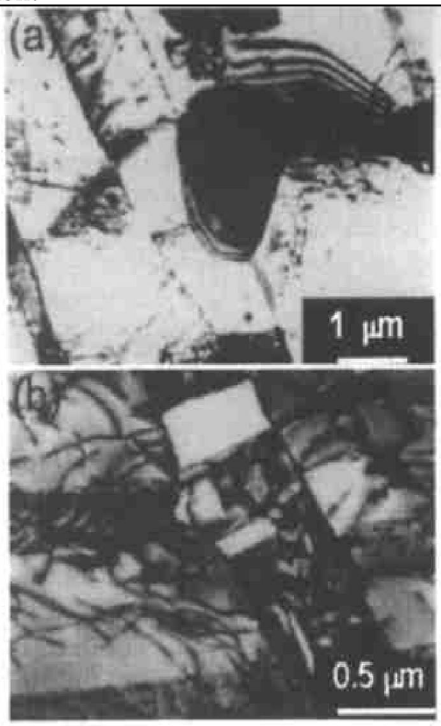

Fig. 6 TEM morphologies showing equiaxed grains nucleate inside original γ lamellae (a) and transform from α_2 lamellae's degradation (b) in TAC2-M after 10% compression

5 SUMMARY

This study demonstrates that micro-alloying process significantly improves both plastic flow behavior and hot workability of TiAl alloys. TEM observations suggest that Ni additions activate dislocations as well as deformation twins at the beginning stage of hot deformation. Therefore, comparatively denser dislocations promote the dynamic recrystallization inside γ-TiAl lamellae in the Ni-containing TiAl alloy. Besides, breakdown of α_2-Ti_3Al lamellae also produces dislocation-free γ-TiAl grains. Moreover, it has been found that transforming the as-cast lamellar microstructure to equiaxed grains before hot deformation can increase the homogeneity of deformed microstructure of TiAl.

ACKNOWLEDGEMENTS

This work is involved in the Sino-Swedish Cooperation on Science and Technology sponsored by Swedish NUTEK and the Ministry of Science and Technology of China.

[REFERENCES]

[1] Yamaguchi M, Inui H, Ito K. High temperature structural intermetallics [J]. Acta Mater Title, 2000, 48: 307-322.

[2] Dimiduk D M. Systems engineering of gamma titanium aluminides: impact of fundamentals on development strategy [J]. Intermetallics, 1998, 6: 613-621.

[3] Austin C M, Kelly T J, McAllister K G, et al. Aircraft engine applications for gamma titanium aluminide [A]. Nathal M V, Darolin R, Liu C T, ed. Structural Intermetallics, TMS [C]. Warrendale PA, 1997. 413-425.

[4] Kim Y-W. Ordered intermetallic alloys(III) —gamma titanium aluminides [J]. JOM, 1994, 46(7): 30-39.

[5] ZHONG Z Y, ZHANG J, LI S Q, et al. Microstructure modifications of wrought and cast TiAl alloys [J]. Trans Nonferrous Met Soc China, 1999, 9(S1): 188-193.

[6] Seetharaman V, Semiatin S L. Plastic-flow and microstructure evolution during hot deformation of a gamma titanium aluminide alloy [J]. Metall Mater Trans A, 1997, 28A: 2309-2321.

[7] Fuchs G E. The effect of processing on the hot workability of Ti-48Al-2Nb-2Cr alloys [J]. Metall Mater Trans A, 1997, 28A: 2543-2553.

[8] Imayev R M, Salishchev G A, Imayev V M, et al. Hot-deformation of gamma TiAl alloys: fundamentals and application [A]. Kim Y-W, Dimiduk D M, Loretto M H, ed. Gamma Titanium Aluminides 1999 [C]. TMS, 1999. 565-674.

[9] Angela Szaruga, Rothenflue L, Srinivasan R, et al. The workability of XD titanium aluminides with low volume of TiB_2[J]. Script Metall Mater, 1992, 26: 1565-1570.

[10] ZHANG J, ZHANG Z H, SU X, et al. Microstructure preparation and hot-deformation of Ti-46.2Al-2.0V-1.0Cr-0.5Ni alloy [J]. Intermetallics, 2000, 8: 321-326.

[11] ZHANG J, SU X, Strom E, et al. Effects of minor addition of Ni on hot-deformation behavior of gamma TiAl alloy [J]. Mater Sci Eng A, 2002.

[12] ZHANG J, SU X, Strom E, et al. Process windows of gamma TiAl alloys containing minor Ni and Mg [J]. J of Materials Processing Technology, 2002.

(Edited by YANG Bing)