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# Improving hot deformability of TiAl alloys by minor additions of Ni and Mg①

SU Xi(苏 曦), ZHANG Ji(张 继), LI Shi-qiong(李世琼), ZHONG Zeng-yong(仲增墉)
(Central Iron & Steel Research Institute, Beijing 100081, China)

**[Abstract]** In order to develop feasible hot processing technologies, hot workability of TiAl alloys need to be improved. The hot deformability of tested alloys, Ti-46.5Al-2.5V-1.0Cr and Ti-46.3Al-2.5V-1.0Cr-(0.3~0.5)Ni-(0.01)Mg (mole fraction, %), was evaluated by hot compression tests over the temperature range from 950 to 1 050 ℃ and strain rate range from 0.01 to 1.0 $s^{-1}$. It was found that the hot deformability of TiAl alloys was obviously improved by minor additions of Ni and Mg.

**[Key words]** TiAl alloys; hot deformability; microalloying; nickel; magnesium
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## 1 INTRODUCTION

TiAl alloys are potential aerospace engine materials because of their low density and high performance at elevated temperature[1]. Several cast TiAl alloy components have been evaluated by the aviation industry[2]. Wrought TiAl alloys, however, are not yet widely accepted since poor hot workability is still a key factor to be considered for the engineering application[3]. TiAl alloys need to be deformed at high temperature and slow strain rate. The restricted deformation conditions cause the technological cost to still too high. In order to develop feasible hot processing technologies, microalloying was considered to be a good way to improve the hot deformability of TiAl alloys without obvious influence of microstructure and mechanical property[4].

It was found that Ni can enlarge the γ phase zone in Ti-Al phase diagram and have an effect to stabilize γ phase. The minor addition of Ni can be beneficial to the lamellar degradation and promote the transformation from $\alpha_2$ phase to γ phase[5]. Mg can improve the hot deformability of TiAl alloys[6]. In this study, Ni and Ni plus Mg microalloying were applied to improve hot workability of TiAl alloys.

## 2 EXPERIMENTAL

The nominal compositions of TiAl alloys used in this study are shown in Table 1. The alloys were prepared by cold crucible vacuum induction levitation melting technique (CCVILM) and dropped into a graphite mould to produce ingots of 40mm in diameter. All ingots were hot isostatic processed (HIP) at 1 260 ℃, 130 MPa for 2 h to remove cast defects. Cylindrical specimens with a height to diameter ratio of 1.5 (8 mm in diameter and 12 mm in height) were prepared from ingots by electro-discharge machining (EDM) and surface grinding.

**Table 1** Nominal compositions of tested alloys

| Alloys | Ti | Al | V | Cr | Ni | Mg |
|---|---|---|---|---|---|---|
| TAC-2 | Bal. | 46.5 | 2.5 | 1.0 | – | – |
| TAC-2M | Bal. | 46.3 | 2.5 | 1.0 | 0.5 | – |
| TAC-2M1 | Bal. | 46.3 | 2.5 | 1.0 | 0.3 | 0.01 |
| TAC-2M2 | Bal. | 46.3 | 2.5 | 1.0 | 0.5 | 0.01 |

The hot deformability was evaluated through isothermal compression tests at constant strain rate using a computer controlled MTS machine. The temperatures range from 950 ℃ to 1 050 ℃, and strain rates range from 0.01 $s^{-1}$ to 1 $s^{-1}$. The isothermal compression tests were conducted in air to 70% reduction in height (approximately a true strain of 1.50). A high temperature lubricant consisted of glass powder and special resin was chosen not only to minimize bulging, but also to protect specimens from oxidation.

The compressed specimens were cooled in water to keep the high temperature microstructures and then subjected to macro- and micro-scopic examination. The material was not considered to be hot workable at a particular combination of temperature and strain rate if cracks were observed in the deformed specimens. The microstructures were examined with optical microscope (OP) and image analyzer (IA). All specimens for microstructure examinations were mechanically polished and etched in a special solution of 5 mL HF+ 10 mL $HNO_3$+ 85 mL $H_2O$ because of the Ni-bearing alloy is difficult to etch in normal etch[7].

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## 3 RESULTS AND DISCUSSION

### 3.1 Starting microstructure

It is found that all as-cast tested alloys consist of nearly fully lamellar (NL) microstructure, which is common in two-phase TiAl alloys. Porosity was removed successfully after HIP, but the as-cast microstructure was not obviously changed, as shown in Fig. 1. It consisted primarily of ($\alpha_2$+ $\gamma$) lamellar colonies with non-linear grain boundary. The directions of lamellar are disordered from one colony to another. Small amounts of equiaxed grains appeared in regions around the lamellar colony boundaries and inside the lamellar colonies.

The minor addition of Ni and Mg did not produce any new phase. But with the increase of Ni addition form 0 to 0.5% (mole fraction), the average colony size was about 450(m in TAC-2, 800 μm in TAC-2M, 610(m in TAC-2M1, and 820 μm in TAC-2M2 respectively.

### 3.2 Processing window

Processing maps of the tested alloys for isothermal compression were constructed with the test temperatures and strain rates, as shown in Fig. 2. The process windows in this study are referenced as the shadow regions in the processing maps, under which the specimens were compressed to 70% engineering strain without splitting[8].

The effects of the Ni and Mg additions on the hot deformability of TiAl alloys can be revealed by comparing their process windows with that of TAC-2. It is clear that the additions of 0.3% Ni and 0.01% Mg (mole fraction) can lower the temperature of the process window down to 950 ℃ at the 0.01 $s^{-1}$ strain rate. The alloy with 0.5% Ni (mole fraction) additions has remarkably enlarged processing windows. The lowest temperature in the processing window of TAC-2M is 950 ℃ corresponding to the 0.01 $s^{-1}$ strain rate, and the critical strain rate of the processing windows is up to 0.1 $s^{-1}$ strain rate at 1 000 ℃. The incorporate addition of 0.01% Mg enhances the benefit of the 0.5% Ni additions by raising the critical strain rate up to 0.1 $s^{-1}$ at 950 ℃. Thus, the 0.5% Ni additions seem to be the superior factor to improve the hot deformability of the studied TiAl alloys.

The average colony size of TiAl alloys containing Ni and Mg are larger than that of TAC-2. Ordinarily, the larger colony size of TiAl alloys could not be beneficial to hot deformability[9]. The modification of the hot deformability in this study is therefore suggested to be the contribution of the Ni and Mg microalloying process.

### 3.3 True strain—true stress curve

The plastic flow behavior of the tested alloys is

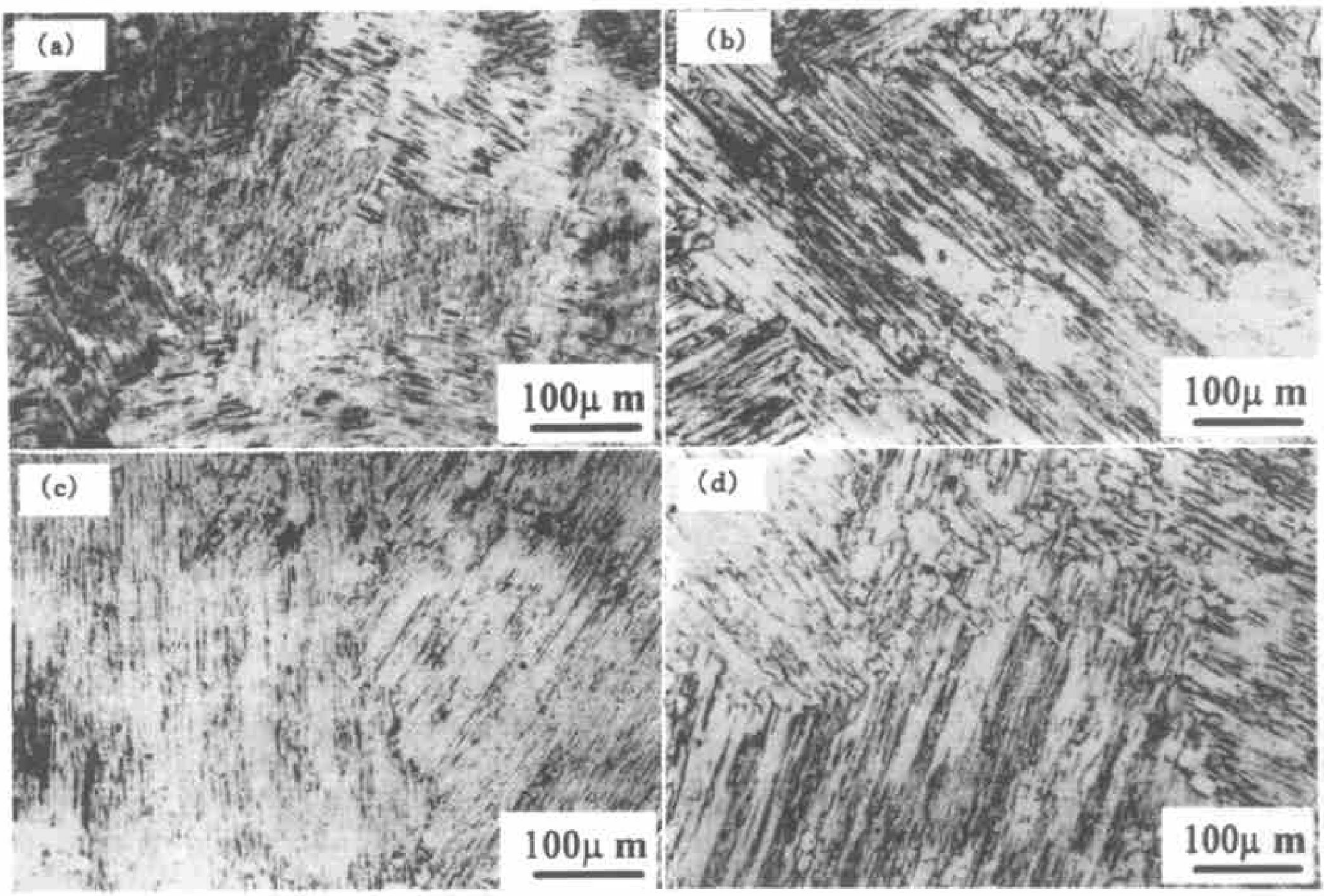


**Fig. 1** Starting microstructures of TiAl alloys
(a) —TAC-2; (b) —TAC-2M; (c) —TAC-2M1; (d) —TAC-2M2

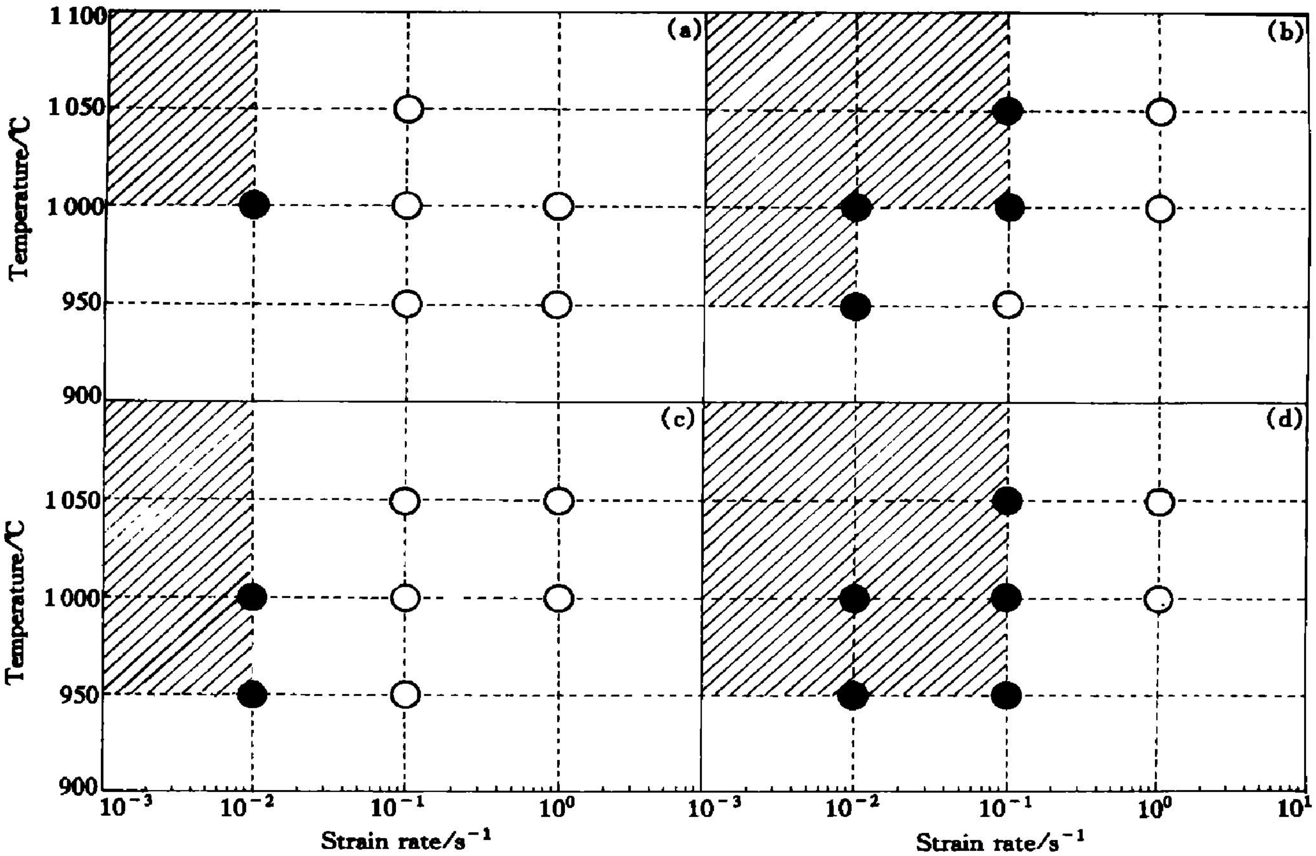


**Fig. 2** Processing maps of TiAl alloys at 70% reduction in height
(a) —TAC-2; (b) —TAC-2M; (c) —TAC-2M1; (d) —TAC-2M2

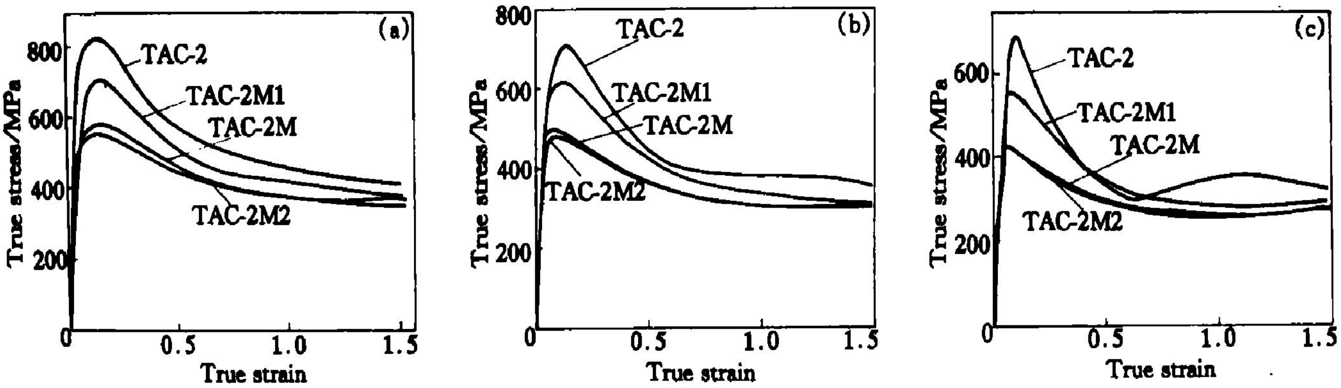


**Fig. 3** Flow curves of tested alloys at different conditions
(a) —950 ℃, 0.1 $s^{-1}$; (b) —1 000 ℃, 0.1 $s^{-1}$; (c) —1 050 ℃, 0.1 $s^{-1}$

illustrated with true stress —strain curves in different test conditions, as shown in Fig. 3. For comparison, true stress —true strain curves of tested alloys at 950 ℃, 0.1 $s^{-1}$; 1 000 ℃, 0.1 $s^{-1}$; and 1 050 ℃, 0.1 $s^{-1}$ are drawn in Fig. 3 (a), (b) and (c) respectively. Almost all true stress —true strain curves exhibit work hardening, flow softening and steady state flow. The flow softening in this kind of true stress —true strain curves is not caused by dynamic recovery, but caused by dynamic recrystallization[10].

It was found that the peak stress and the flow softening degree (the deference between peak stress and steady stress) of the tested alloys decreased with increasing Ni content. The incorporated additions of Mg slightly lowered the peak stress and the flow softening degree further. So, the better steady-state flow behavior coincides well with the larger process windows in this study.

The responsible mechanisms of the Ni additions are suggested as that the Ni promotes the breakdown of the lamellar structure during hot deformation as the case in the annealing process[5], and therefore has benefit to the hot deformation through dynamic recrystallization as described in Ref. [9, 11]. That the influence of Mg addition on the flow resistance observed in this study is contrary to the previous results[6] probably because it was incorporated with the Ni additions. It was found that the recrystallization promoted by Ni additions might increase the hot deformability by releasing the intense stresses in the heavily deformed region. And both ordinary and super-dislocation are more active in the alloys containing Ni. The dynamic recrystallization occurred earlier in the Ni bearing TiAl alloys than the TiAl alloys without Ni[12]. The detailed mechanisms of Ni and Mg microalloying to improve the hot deformability for the studied alloys are to date in progress.

## 4 CONCLUSIONS

1) Minor additions of Ni and Ni plus Mg obviously enlarge the process windows of TiAl alloys, which coincides well with the better steady-state flow behavior of those alloys.

2) The improving of the hot deformability and the plastic flow behavior should be the contribution of the microalloying process but not the microstructure changes induced by the additions of Ni and Mg.

3) The Ni additions appear to be the superior factor to improve the hot deformability and to decrease the peak stress and flow softening degree during the hot deformation of the TiAl alloys.

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