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Author(s)	Mei, Bingchu; Miyamoto, Yoshinari
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Fabrication of Dense TiAl/Ti₂AlC Composites by Pulsed-Electric Current Sintering and Their Mechanical Properties[†]

Bingchu MEI* and Yoshinari MIYAMOTO**

Abstract

Dense TiAl/Ti₂AlC composites were produced from mixed powders of Ti, Al, and TiC by pulsed-electric current sintering. The sintered products mainly consisted of TiAl and Ti₂AlC phases and showed different microstructures depending on the composition. When 7vol%TiC was mixed in the starting powders, the Ti₂AlC particles were uniformly dispersed in the Ti-Al matrix with the duplex structure containing γ and lamellar phases. When 15vol%TiC was used, the product was composed of an interpenetrating network of the Ti₂AlC and TiAl phases. After the heat treatment, however, both microstructures changed to that of Ti₂AlC particles dispersed uniformly in the matrix of a single γ phase. The fracture toughness, flexural strength and hardness of these composites were evaluated.

KEY WORDS: (Pulsed-Electric Current Sintering) (TiAl/Ti₂AlC composites) (Microstructures) (Mechanical Properties)

1. Introduction

Titanium aluminides are candidate materials for replacement of heavier superalloys¹⁻²⁾. These ordered intermetallic compounds can offer improved high-temperature properties, high specific strength and oxidation resistance. However, the ductility is still limited.

Fabrication of titanium aluminide composites with ceramic particles is one way to improve their properties²⁻⁴⁾. For example, the incorporation of ceramic particles can stabilize a fine matrix grain size, that leads to higher toughness and strength. The Ti₂AlC was found to have both properties of a metal and ceramic-like ductility and refractoriness⁵⁻⁹⁾. Therefore, introduction of a small amount of Ti₂AlC particles into the TiAl matrix may offset some of its shortcomings without a large deterioration of its metallic properties.

A pulsed-electric current sintering (PECS) technique¹⁰⁻¹¹⁾ was used to prepare the Ti-Al/Ti₂AlC composites in this work. The process can achieve the material synthesis and densification simultaneously and rapidly. The main purpose of this work was to examine the possibility of fabrication of dense TiAl/Ti₂AlC composites by PECS and investigate their microstructures

and mechanical properties.

2. Experimental Procedure

TiC, Ti and Al powders were used as raw materials. Their particle sizes were about 45 μ m, 50 μ m and 1.5 μ m, respectively. A chemical analysis showed that the principal impurities of Ti powders were O ~ 2800ppm, H ~ 120ppm, N ~ 120ppm, Cl < 100ppm, Fe ~ 49ppm, and Mg < 30ppm, those of Al powders were Mg ~ 21ppm, Si ~ 14ppm, Fe ~ 11ppm, and Cu ~ 11ppm, and TiC has a purity of 99.9%. The powders were well mixed in various ratios of (Ti - 48at% Al) with 0, 7, 15 and 30vol% TiC expecting the reaction Ti + Al + TiC \rightarrow TiAl + Ti₂AlC. The mixtures were then subjected to PECS at 873, 1173 and 1423K in vacuum at 2Pa for 6 minutes. The PECS apparatus (Model SPS-1050, Sumitomo Coal Mining Co. Ltd.) is shown schematically in Fig.1. The sintering pressure was 30 MPa. Some of products were heat treated at various temperatures in vacuum. X-ray diffraction (XRD) and electron probe micro-analysis (EPMA) were used to characterize the product phases and microstructures.

The sintered samples were cut into bar specimens of

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^{*} Visiting Research Scholar,
(Professor,Wuhan University of Technology)

^{**} Professor of Osaka University

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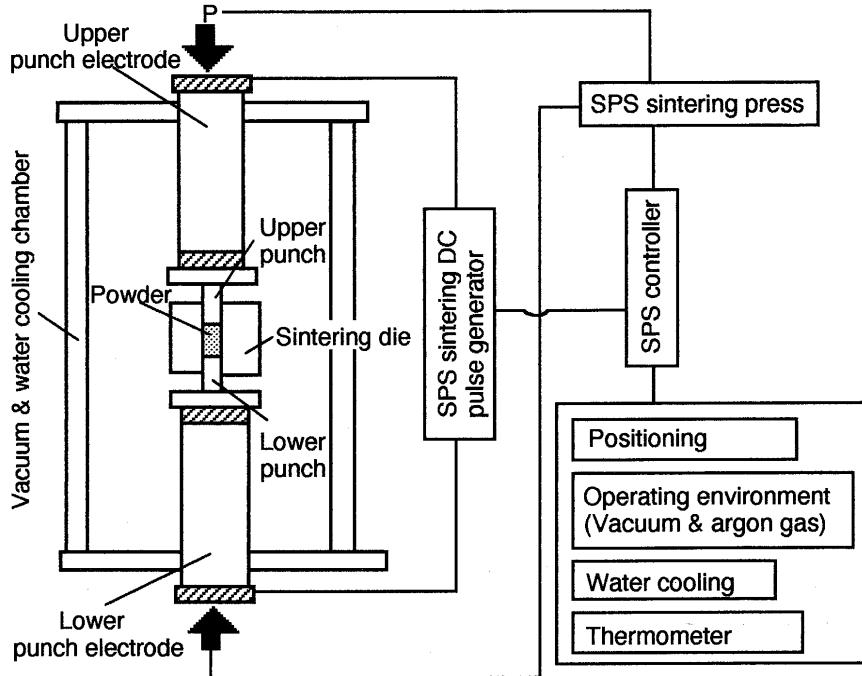


Fig. 1 A schematic diagram of the pulsed-electric current sintering system.

3 x 5 x 20 mm. The specimens were polished to a diamond surface finish of 3 μ m before the test. Some of the polished specimens were used for measurements of three-point bending strength with a span of 18mm and a cross head speed of 0.5 mm/min at room temperature and for fracture toughness by a single-edge notched beam method¹². The hardness of the samples was determined by using a Vickers hardness testing machine with an indentation load of 196N. The bending strength and fracture toughness were calculated as the average of three specimens, while the hardness is the average value of ten measurements for each sample.

3. Results and Discussion

Figure 2 shows XRD profiles of the products obtained from the starting composition of (Ti - 48at% Al) - 7vol% TiC which was sintered at different temperatures. When the sintering temperature was 873K (lower than the melting point of aluminum), the product contained TiAl₃, TiAl, Ti₃Al, Ti and TiC phases. At 1173K, the diffraction peaks of Ti₂AlC appeared, but the TiC phase still existed in the sample. When the sintering temperature was 1423K, there TiAl, Ti₃Al and Ti₂AlC appeared in the sample, suggesting that TiC was used up

to form the Ti₂AlC. When the product sintered at 1173K was subjected to a heat treatment at 1423K (Fig.2c), it consisted of the same phases as the product sintered at 1423K (Fig.2d). This result also showed that TiC can be completely transformed to Ti₂AlC at 1423K or lower. From Fig.2e, it can be seen that the peaks of Ti₃Al disappeared after the sample sintered at 1423K was treated at 1473K. These results suggest that the matrix phase approaches the initial composition following the heat treatment at about 1423K.

SEM micrographs of the products sintered at 1423K are shown in Fig.3 and Fig.4, which correspond to the samples with the starting compositions (Ti - 48at% Al) - 7vol% and 15vol% TiC, respectively. These photos show entirely different microstructures. Before the heat treatment (Fig.3a and 3b), the Ti₂AlC particles with a fine size (2-5 μ m) of spherical and/or columnar forms are uniformly dispersed in the Ti-Al matrix. The matrix possesses a partial lamellar structure, that is, a duplex structure consisting of the lamellar phases containing Ti₃Al (α_2) + TiAl (γ) and a single γ phase. Upon the heat treatment (Fig.3c and 3d), the lamellar structure of the matrix disappears, while the morphology of Ti₂AlC is still very similar to that in Fig.3a and 3b. This result is consistent with that of the XRD analysis (Fig.2d and 2e). In the latter sample with 15vol% TiC, it was observed

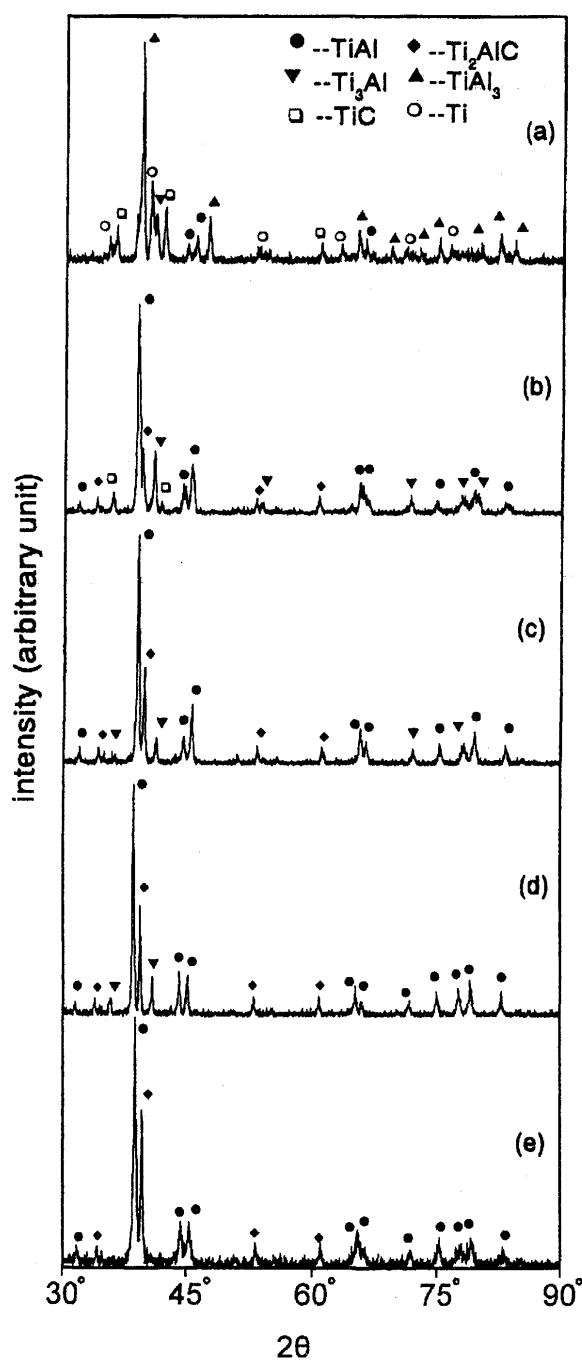


Fig.2 X-ray diffraction patterns of samples with the starting composition (Ti-48at%Al)-7vol%TiC.
 (a)sintered at 873K, (b)sintered at 1173K, (c)treated at 1423K for 2hrs after sintered at 1173K,
 (d)sintered at 1423K, (e)treated at 1473K for 2hrs after sintered at 1423K.

that the Ti_2AlC phase and γ phase link together and an interpenetrating network structure was formed before the heat treatment, as seen in Fig.4a and 4b. After the sample was subjected to the heat treatment, the Ti_2AlC phase changed to separated particles and dispersed in the matrix consisting of the single γ phase, as shown in Fig.4c. The

microstructure of the sintered sample with the starting composition (Ti - 48at% Al) - 30vol% TiC was similar to that of the (Ti - 48at% Al) - 15vol% TiC as seen in Fig.4. These microstructural evolutions depending on the starting compositions and process conditions need to be studied in more detail.

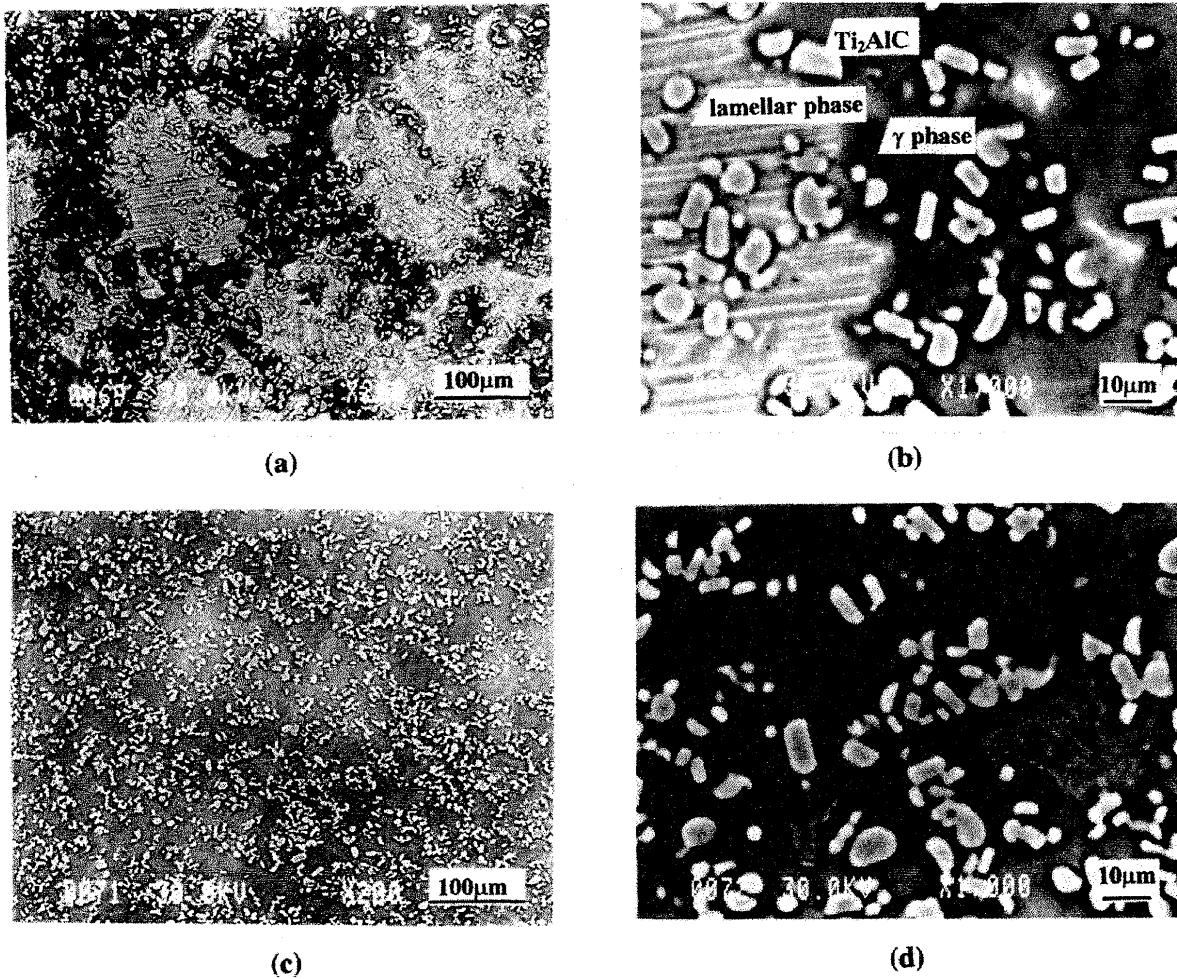


Fig.3 Microstructures of samples with the starting composition (Ti-48at%Al)-7vol%TiC.
(a, b) sintered at 1423K, (c, d) treated at 1473K for 2hrs after sintered at 1423K.

The fracture toughness (K_{IC}) of the composites produced is shown in **Fig.5**. For the as-sintered product with added 7vol% TiC, the toughness was $43 \text{ MPam}^{1/2}$, which was 15% higher than that of the as-sintered sample of the pure TiAl matrix. After the heat treatment, the toughness decreased to $29 \text{ MPam}^{1/2}$ which was 20% lower compared to the value of the pure TiAl product which was heat treated. However, it can be still compared with that of the as-sintered TiAl ($30 \text{ MPam}^{1/2}$). For the sample with 15vol% TiC, the fracture toughness was evidently lower than the value of the pure TiAl although it increased to $23 \text{ MPam}^{1/2}$ following the heat treatment. The sample with 30vol% TiC was very brittle, so that its toughness is not shown here. These results suggest that the introduction of small quantities of Ti₂AlC can improve the fracture toughness, probably due to the dispersion effect of hard particles, however further increase of Ti₂AlC content tends to form a network

structure of the brittle Ti₂AlC phase resulting in lowering the toughness. Both the lamellar structure of TiAl and the appropriate content of Ti₂AlC dispersion should lead to the higher toughness.

The bending strength of samples is shown in **Fig.6**. The sample with 7vol% TiC showed higher strength than the pure TiAl. When the TiC content was more than 7vol%, the strength decreased as the fracture toughness decreased. The heat treatment could not exercise a significant effect on strength, unlike on the fracture toughness. The load - deflection curve showed the plastic deformation at higher deflection range. This plastic deformation may limit the bending strength.

The hardness increased with the increase of TiC addition as shown in **Table 1**. The hardness of the sample with 30vol% TiC could not be measured since the indentation mark was very illegible.

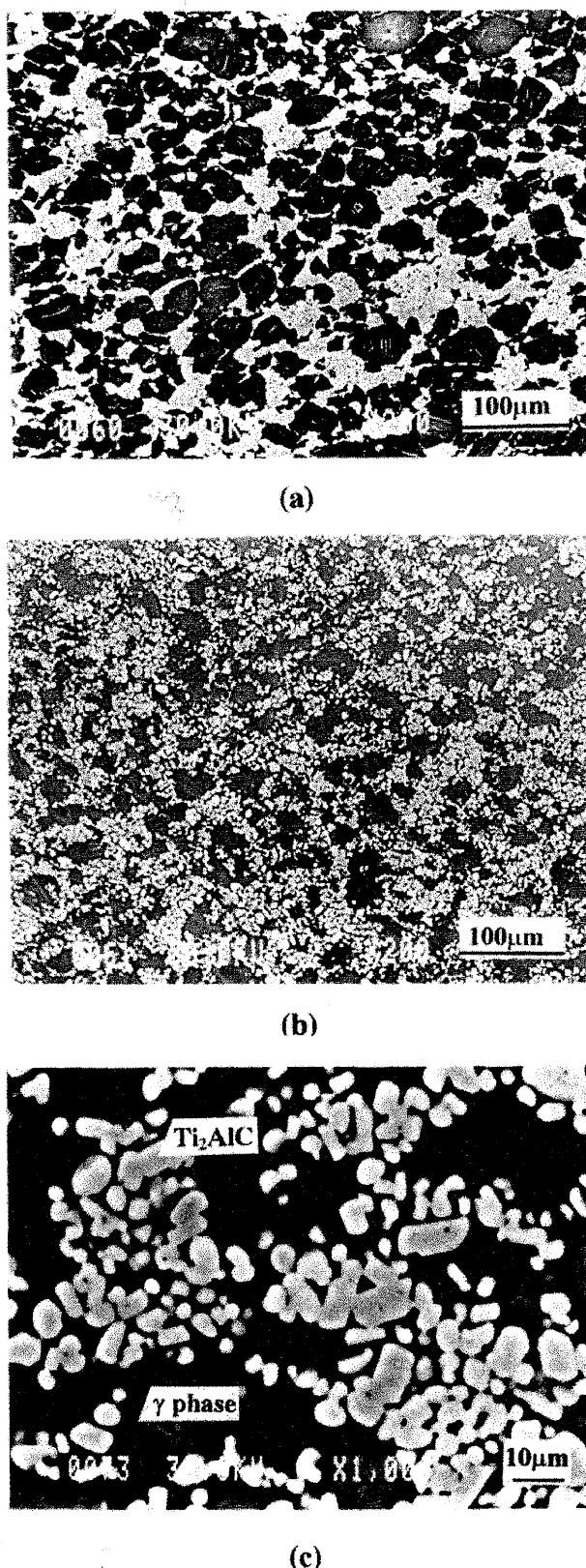


Fig.4 Microstructures of samples with the starting composition (Ti-48at%Al)-15vol%TiC.
(a) sintered at 1423K, (b, c) treated at 1473K for 2hrs after sintered at 1423K.

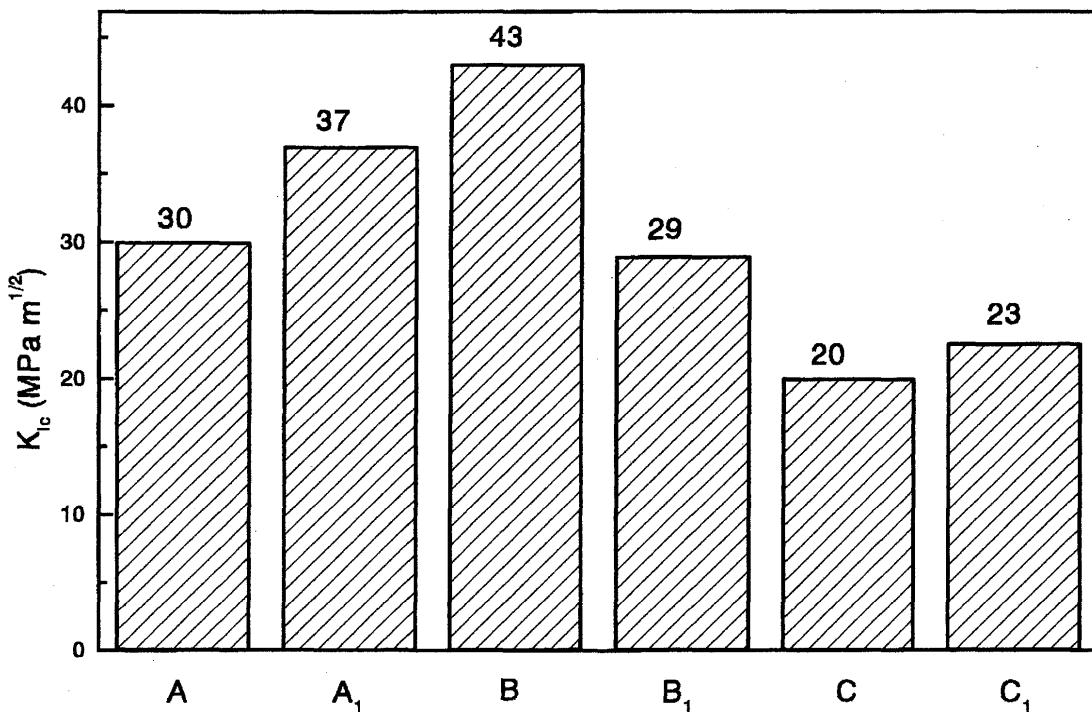


Fig.5 Fracture toughness of samples.

(A) starting composition Ti-48at%Al, sintered at 1423K, (A₁) sample A, treated at 1473K for 2hrs, (B) starting composition (Ti-48at%Al)-7vol%TiC, sintered at 1423K, (B₁) sample B, treated at 1473K for 2hrs, (C) starting composition (Ti-48at%Al)-15vol%TiC, sintered at 1423K, (C₁) sample C, treated at 1473K for 2hrs.

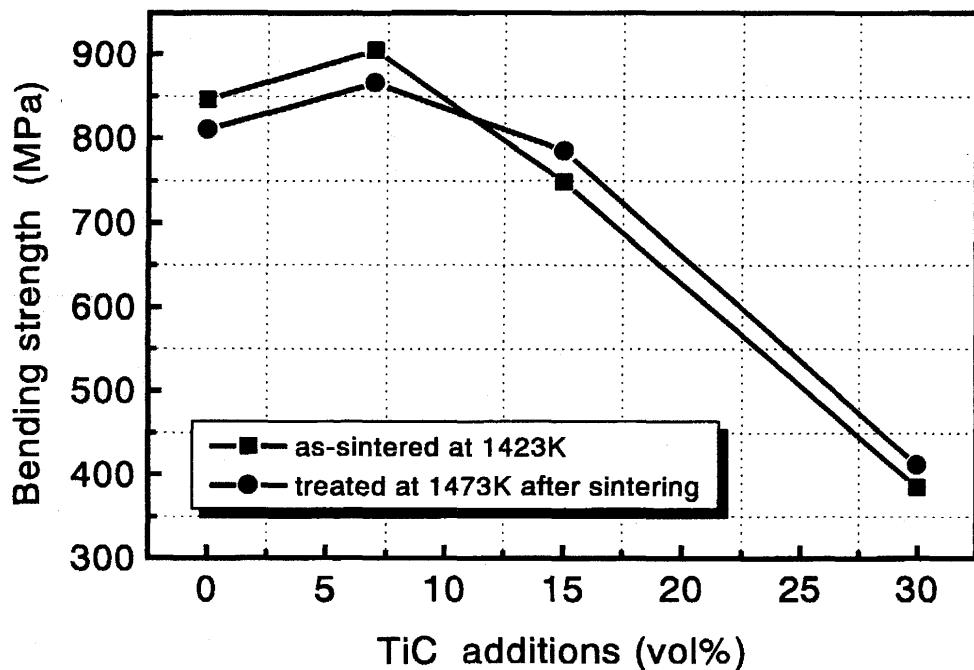


Fig.6 Flexural strengths of TiAl/Ti₂AlC composites as a function of TiC addition in the starting mixtures.

Table 1 The hardness of the samples with the different TiC additions.

TiC Content (vol%)	Hardness (GPa)	
	as-sintered at 1423K	
	Treated at 1473K	
0	2.8	2.5
7	3.5	3.7
15	3.7	4.1

note:sintering temperature:1423K, holding time: 6mins

4. Conclusions

- (1) Dense TiAl/Ti₂AlC composites could be obtained from the starting powders of TiC, elemental Ti and Al by pulsed electric current sintering. The reaction $Ti + Al + TiC \rightarrow Ti-Al + Ti_2AlC$ took place above the melting point of Al, but the temperature at which TiC was completely changed to Ti₂AlC was between 1173K and 1423K.
- (2) The microstructures changed depending on the heat treatment and the TiC contents in the starting mixture. Two different microstructures were mainly observed. In one case, the sample with 7vol% TiC, the Ti₂AlC particles produced were uniformly dispersed in the TiAl matrix with a partial lamellar structure. In another case, the sample with 15vol% TiC, the composites consisted of interpenetrating networks of the Ti₂AlC and TiAl phases. But after the heat treatment, all of them were transformed into the same microstructure consisting of dispersed Ti₂AlC particles in the matrix of TiAl.

- (3) Introduction of small quantities of Ti₂AlC phase could result in increase of both fracture toughness and strength owing to the dispersion effect of hard particles. The lamellar structure leads to higher fracture toughness. The hardness increased with introduction of Ti₂AlC.

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