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Vacuum induction melting and solidification of TiAl-based alloy in graphite crucibles

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ABSTRACT

The effect of vacuum induction melting and solidification in graphite crucibles on chemical composition, microstructure and mechanical properties of Ti-46.6Al-5Nb-0.2B-0.2C (at.%) alloy was studied. The induction melting and solidification under a vacuum pressure of 1×10^4 Pa (low vacuum) has no significant effect on the content of the alloying elements such as Ti, Al, Nb and B but leads to an increase of carbon content to 0.49 at.%. A vacuum pressure of 6.8 Pa (medium vacuum) leads to an increase of C content to 0.68 at.% and decrease of Al content to 45.5 at.% due to its evaporation loss on the expense of increasing Ti and Nb. The medium vacuum results in lower cooling rates, coarser columnar grain structure and finer interlamellar spacing compared to those of the samples prepared under the low vacuum. The Vickers microhardness and hardness of the samples prepared under the medium vacuum is higher than that of the samples prepared under the low vacuum. The melting and solidification under the medium vacuum leads to an increase of compression yield and peak flow stresses at temperatures of 850 and 900 °C compared to those of the as-solidified samples prepared under the low vacuum.

1. Introduction

Reduction of fuel consumption, greenhouse gas emissions and weight play an important role in the design of aircraft and automotive engines [1–3]. TiAl-based alloys can fulfil some requirements of designers for such specific applications because of their low density, high specific strength, good microstructure stability, high oxidation resistance and good creep properties [4–8]. Precision casting has been identified as the most cost-effective route for production of TiAl-based components such as turbocharger wheels and turbine blades [9–12]. Most of the precision casting techniques use induction melting in cold or ceramic crucibles. Vacuum induction melting in the cold crucibles reduces contamination of TiAl-based components but increases casting cost and rejection rate [13–15]. Several crucible and mould materials such as ZrO_2, Y_2O_3, CaO and graphite have been evaluated for melting and casting of TiAl-based alloys but none of them has been found to be absolutely inert against their melts [12,16–23]. The oxide ceramics showing the highest thermochemical stability and low contamination such as ZrO_2 and Y_2O_3 are expensive and CaO is sensitive to the humidity [24]. On the other hand, the graphite is a cheap material with a good formability for processing melting crucibles and moulds. Barbosa and Ribeiro [16] have reported that melting of TiAl-based alloys in graphite crucibles leads to high contamination by carbon ranging from 3 to 7 at.%. Such high content of carbon results in formation of coarse primary carbide particles during solidification [25,26]. Čegan et al. [27] have applied vacuum induction melting in a graphite crucible and reported increase of carbon content only by 0.3 at.% in Ti-47Al-8Nb (at.%) alloy. As reported by several authors [22,28–30], alloying by carbon improves high-temperature strength and creep resistance of TiAl-based alloys. Hence, vacuum induction melting and solidification in graphite crucibles is of large interests for processing of carbon-containing TiAl-based components with improved high-temperature mechanical properties in a cost-effective way.

The aim of this work is to study vacuum induction melting and solidification of TiAl-based alloy in graphite crucibles. The effect of two different vacuum pressures (low and medium vacuum) on chemical composition, microstructure and mechanical properties of as-solidified samples is reported and discussed.

2. Experimental procedure

Samples of the studied TiAl-based alloy with a chemical composition given in Table 1 and weight of 130 g were induction melted in graphite crucibles with an inner diameter of 45 mm and length of 75 mm. Before melting, vacuum chamber of induction melting furnace was evacuated to a vacuum pressure of 4.5 Pa and flushed with argon three times. The alloy was induction heated to a melt temperature of 1640 °C and hold at this temperature for 30 s under a vacuum pressure

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Table 1
Measured chemical composition (at.%).

Sample	Ti	Al	Nb	B	C	O	N
Initial alloy	47.8 ± 0.2	46.6 ± 0.3	5.0 ± 0.1	0.22 ± 0.02	0.19 ± 0.02	0.16 ± 0.02	0.030 ± 0.003
MV	48.2 ± 0.2	45.5 ± 0.3	5.2 ± 0.1	0.22 ± 0.02	0.68 ± 0.02	0.17 ± 0.02	0.030 ± 0.003
MG	47.4 ± 0.2	46.6 ± 0.3	5.0 ± 0.1	0.21 ± 0.02	0.49 ± 0.02	0.25 ± 0.03	0.050 ± 0.004

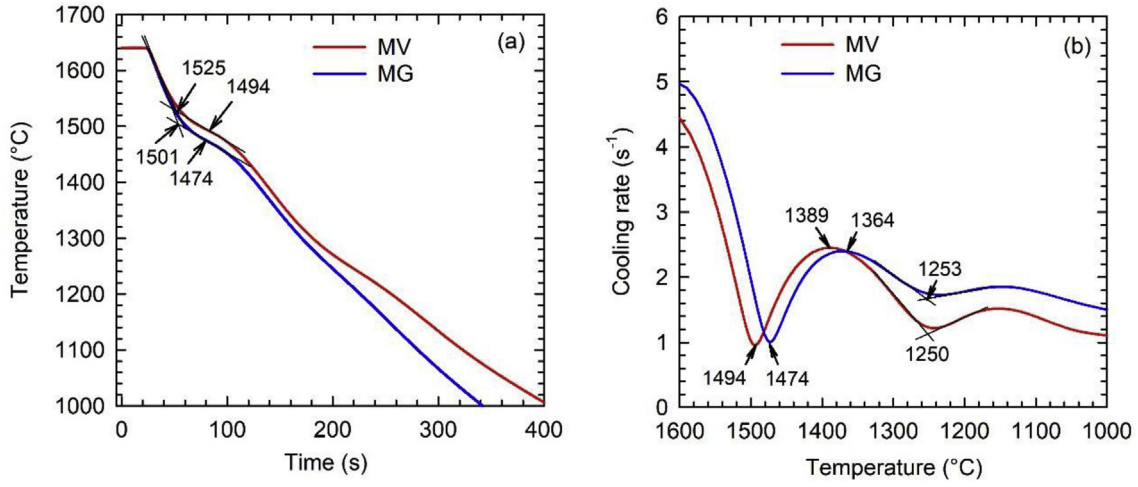

Fig. 1. Experimentally measured cooling curves for MV and MG sample: (a) Dependence of temperature on time; (b) Dependence of cooling rate on temperature. The phase transformation temperatures are indicated in the figures.

of 6.8 Pa (medium vacuum) or vacuum pressure of 1×10^4 Pa (low vacuum). The low vacuum was achieved by a partial filling of the evacuated vacuum chamber with argon (purity of 99.9995). The temperature of the melt was measured by a pyrometer. The solidification of the melt was carried out in the graphite crucibles by switching off the induction heating of the furnace. The as-solidified samples were cut longitudinally using wire spark machining.

Cooling curves were measured with PtRh30-PtRh6 thermocouple protected by a ceramic tube, which was inserted into a defined position of the graphite crucible before the melting of the charge. Acquisition of temperature-time data was performed electronically by a computer each 1 s.

Microhardness measurements were performed by a Vickers microhardness tester. All measurements were performed at an applied load of 0.5 N and dwell time of 10 s on polished and slightly etched longitudinal sections of the as-solidified samples. Instrumented hardness measurements were performed by a universal hardness testing machine. Vickers hardness tests were carried out at an applied load of 50 N, holding time at the point of load application of 2 s and rate of load application of 15 N/s on longitudinal sections of the as-solidified samples.

Cylindrical compression specimens with a longitudinal axis parallel to the longitudinal axis of the as-solidified samples were cut by a wire spark machining and finalised by turning and surface polishing to a diameter of 8 mm and length of 12 mm. Compression tests were carried out at an initial strain rate of 1×10^{-3} s^{-1} and temperatures ranging from 850 to 1000 °C under a vacuum pressure of 7 Pa using Gleeble thermo-mechanical tester 3800. The test temperature was measured by a thermocouple welded to the specimen surface. The specimens were heated to a test temperature at a rate of 6.7 °C/s and held at the test temperature for 120 s. After the compression tests to a true strain of 0.51, the tested specimens were cooled to room temperature in air.

Standard metallographic techniques such as grinding on SiC papers, polishing on diamond pastes with various grain sizes ranging from 10 to 0.25 μm and etching in a solution of 100 ml H_2O, 6 ml HNO_3 and 3 ml HF were used. Microstructural observations were carried out by optical microscopy (OM), scanning electron microscopy in back scattered electron (BSE) mode and energy dispersive spectroscopy (EDS). Carbon content and content of gases were measured by LECO CS844 and LECO ONH836 elemental analysers, respectively. Coexisting phases were identified by X-ray diffraction (XRD) analysis using diffractometer Bruker D8 and the database PDF-2 2004. Quantitative metallography was carried out on digitalised micrographs using computerised image analyser and measured data were treated by statistical methods.

3. Results

3.1. Effect on chemical composition

Table 1 shows the measured chemical composition of the studied alloy before and after vacuum induction melting and solidification in the graphite crucibles. While the induction melting and solidification under a vacuum pressure of 1×10^4 Pa (sample MG) has no significant effect on the content of the alloying elements such as Ti, Al, Nb and B, the melting at a vacuum pressure of 6.8 Pa (sample MV) leads to a decrease of Al and increase of Ti and Nb compared to those of the initial alloy. The melting and solidification in graphite crucibles leads to an increase of initial carbon content, as seen in Table 1. Although the processing parameters such as heating rate, melt temperature and holding time at a melt temperature are the same for both types of the samples, the initial carbon content of 0.19 at.% is increased by 0.49 and 0.30 at.% in the MV and MG samples, respectively. The applied vacuum pressure of 1×10^4 Pa affects also content of gases. The initial content of oxygen and nitrogen increases by 0.09 and 0.02 at.% in the MG sample, respectively.

3.2. Effect on cooling curves and cooling rates

Fig. 1 shows experimentally measured cooling curves for the MV and MG samples. It is clear that the cooling under a vacuum pressure of 1×10^4 Pa leads to a faster decrease of temperature during solidification, as seen Fig. 1a. The solidification of the MG sample starts at a