The Influence of B$_4$C on the Fluidity of Ti-6Al-4V-xB$_4$C Composites

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The fluidity of Ti-6Al-4V-xB$_4$C composites is investigated by using a vacuum fluidity test. It is found that the solidification paths of Ti-6Al-4V are changed by B$_4$C additions. Differences in solidification processes dramatically affect the fluidity of Ti-6Al-4V-xB$_4$C composites. With the increase of B$_4$C additions, the fluidity of Ti-6Al-4V-xB$_4$C composites is not monotonically decreasing, it drops to a valley initially and then increases. [doi:10.2320/matertrans.M2014142]

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1. Introduction

Due to the considerable potential for improvements in properties and service temperature, titanium matrix composites (TMCs) reinforced with ceramic particles have drawn a great attention.$^{1-4}$ In recent years, there are many in situ techniques to synthesize TMCs, such as mechanical alloying,$^5$ powder metallurgy$^6$ and solidification process.$^7$ Traditional ingot metallurgy plus self-propagation high-temperature synthesis reaction between titanium and B$_4$C has become a popular method to fabricate TiB and TiC reinforced TMCs due to its low manufacturing cost and high efficiency.$^8,9$ However, the factor of significant difference in hardness between the ceramic reinforcements and titanium matrix leads to poor machining properties of the TMCs, the cutting tool is easy to be weared during the machining of these materials.$^{10}$ Moreover, it is difficult to machine a TMCs work-piece with complex configurations and dimensions. These disadvantages limit the application and development of TMCs. Superplastic deformation have been used by Wang and Lu to solve these problem.$^{11}$ However, it needs equipments to serve at high temperature (over 800°C), and thus increases the manufacturing cost. So, the low-cost investment casting, using the near-net-shape casting technique, is a potential method of forming TMCs components.$^{12}$

The fluidity refers to the ability of molten metal to flow before being stopped by solidification,$^{13}$ which is affected by metallurgical and casting factors, such as composition, the mode of solidification, superheat, latent heat, surface tension, viscosity, degree of super heat, mold material and surface characteristics.$^{14}$ The composition and solidification mechanism are usually considered as the most important factors.$^{15}$ In the casting process, the fluidity of a cast alloy plays a key role as it affects the quality and soundness of the cast products. However, there are little relevant work reported either theoretically or experimentally in TMCs casting. The present study aims at testing the fluidity of TMCs, and develop the study by altering the addition of B$_4$C to understand the fluidity mechanism to make TMCs industrial castings.

2. Experiments Procedures

In this study, three different compositions of Ti-6Al-4V-xB$_4$C ($x = 0, 0.48, 0.97$ mass%) were manufactured and examined. Ti-6Al-4V-xB$_4$C composites were synthesized by common titanium casting technologies according to the reaction: 5Ti + B$_4$C = 4TiB + TiC. The cast ingots were prepared from sponge titanium, Al, Al–V (47.5 mass% V) and B$_4$C powder in consumable vacuum arc-melting furnace. The weight percentages of reactants are listed in Table 1. To achieve the chemical homogeneity of the composites, the ingots were melted three times before casting.

Spiral fluidity test was carried out in vacuum consumable kish furnace. The casting mold for spiral tests is made from high purity graphite, consisted of a pouring basin, and a triple Archimedian spiral cavity with trapezoidal cross-section. The three different composition ingots were remelted in vacuum consumable kish furnace with a vacuum between $10^{-2}$ and $10^{-1}$ Pa, respectively. The same melting parameter, such as melting current, melting voltage and the same preheating temperature 200°C of the mould were used in the test. The molten metal was poured from the furnace to the pouring basin with the same weight in order to have the same initial metallostatic pressure head on the flowing metal. To identify the microstructure difference along the spirals, the specimens for SEM were wire-cut from different positions of the spiral cast samples. The microstructures were characterized by a FEI-QUANTA-250 scanning electron microscope.

3. Results and Discussions

3.1 Fluidity of Ti-6Al-4V-xB$_4$C

Figure 1 shows the difference of fluidity of Ti-6Al-4V-xB$_4$C with different B$_4$C additions. Comparing with Ti-6Al-4V, the fluidity of TMCs exhibits an obvious decrease with the B$_4$C additions, which indicates that the fluidity is extremely sensitive to the addition of B$_4$C. With addition of 0.48 mass% B$_4$C, the fluidity length is significantly reduced to 168 mm, which is only 1/5 of that of Ti-6Al-4V. However, the change of fluidity versus addition of B$_4$C is not monotonically decreasing. When the B$_4$C additions is

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increased to 0.97 mass%, the fluidity length is increased from 168 to 223 mm.

The relationships between fluidity and B₄C additions in TMCs differs from those in Al-B₄C composites which decreases with the increase of reinforcements in aluminum matrix composites. However, the fluidity of Ti-6Al-4V-B₄C is not monotonically decreasing with the increase of B₄C additions. This is mainly because the effects of B₄C to the solidification of different metal matrix composites are different. Because of the low melting point of aluminum, the B₄C additions cannot melt in the liquid and remains in solid state during casting, so in Al-B₄C composites, the B₄C additions will not influence the solidification path of aluminum. Since B₄C remains solid in aluminum melt during casting, the solid B₄C particles block the metal flow and hence reduce the fluidity, which, on a macro level, exhibits a decrease in fluidity versus an increase in volume fraction of B₄C additions. However, in titanium alloy, the melting temperature is above 1700°C, and the B₄C additions will react with titanium and be dissolved in the titanium. Therefore, the solidification of TMCs will be changed by B₄C additions and the fluidity of TMCs is also affected by it, which will be discussed in detail later in this article.

### 3.2 Microstructures of Ti-6Al-4V-xB₄C spiral cast samples

To identify the microstructure difference along the spirals, the specimens for SEM were wire-cut from different positions of the spiral cast samples. The positions of specimens (a) and (b) in spiral samples of Ti-6Al-4V, specimens (c) and (d) in spiral samples of TMC1, specimens (e) and (f) in spiral samples of TMC2, are shown in Fig. 1(a). The microstructures of root position of Ti-6Al-4V spiral samples are shown in Fig. 2(a). Columnar structures can be observed clearly. All the columnar grains range in the direction of heat dissipation which is perpendicular to the mold wall. At the top of spiral samples, there are spheroidal structures instead of columnar structure, as shown in Fig. 2(b). A typical Widmanstätten structure forms in the original β spheroidal grains.

The microstructure of root positions of TMCs spiral samples are shown in Figs. 2(c) and 2(e). The dendritic structures are revealed by the distribution of white TiB whiskers on the grain boundaries. The spheroidal structures are also observed among the dendritic structures in the central portion. No dendritic structures are found at the top position of TMCs spiral samples (Figs. 2(d), 2(f)). There are only spheroidal structures in the top position of TMCs spiral samples. The clustered TiB whiskers can be seen in the top of TMCs spiral samples. There are also vortex-dispersed TiB whiskers in the central portion of TMCs spiral samples (Fig. 2(f)) which are also observed by SHANG, J. in TiB/Ti composites.

### 3.3 Discussions

The change of microstructures and fluidity is due to the change of solidification in Ti-6Al-4V-xB₄C which can be explained by Ti–Al–V ternary phase diagram and Ti–B–C ternary phase diagram as shown in Figs. 3(a), 3(b). In casting process, both liquid and solid phases co-exist throughout the entire casting process. There are a fully liquid zone in the region of the casting, a fully solid zone in the region at lower temperature, and a liquid-solid ("mushy") zone. According to Ti–Al–V ternary phase diagram, the
solidification path of Ti-6Al-4V is illustrated in Fig. 3(c). In Ti-6Al-4V alloy, the $\beta$-Ti phase is the only phase solidified from the liquid. The dendrites of $\beta$-Ti nucleate from the mold wall and grow with the advance of leading liquid-solid interface like alloys which freeze over a relatively narrow range. So, the dendrites will grow up with a columnar structures as schematically illustrated in Fig. 4(a) ($t_1$). The liquid zone exist throughout the almost entire casting, the “mushy” zone does not appear until the approaching to the end of solidification. The metal flow maintains a relatively high speed until the channel is finally choked by the columnar structures, as shown in Fig. 4(a) ($t_2$). After the solidification, the columnar structures (Fig. 2(a)) are formed at such choked place, the spheroidal structures are formed at the top of the fluid metal, as illustrated in Fig. 4(a) ($t_f$). Near the end of solidification, a liquid-solid (“mushy”) zone exists and the “mushy” will follow the flow to the top of the Ti-6Al-4V spiral samples and grow up with spheroidal structures, as presented in Fig. 2(b).

With B$_4$C additions, the solidification paths of Ti-6Al-4V-xB$_4$C composites are changed a lot (as shown in Fig. 3(d)). During the cooling procedure, the $\beta$-Ti phase is the first phase...
precipitated from the metal liquid. The $\beta$-Ti dendrites, which is first precipitate on the channel wall (as shown in Fig. 4(b) (t1)), arise from heterogeneous nucleation mechanism. The composition of molten metal is changed by the precipitation of $\beta$-Ti primary phases, and goes to the eutectic composition. With the temperature goes down, the $(\beta$-Ti + TiB)_m binary eutectics are precipitated from the molten metal. And the growth of dendrites will be interrupted by the precipitated TiB whiskers. The interrupted $\beta$-Ti dendrites or $\beta$-Ti phases of binary eutectic may also be re-melted by the heat of new casting molten alloys with high temperature. This process may be enhanced by the flowing liquid metal, which brings thermal pulses to the dendrite tip, strains the dendrite tip somewhat, carries the melted off arms and TiB reinforcements following the flow to the top of the TMCs spiral samples. The solidified small spheroids, which are caused by the melted off arms or binary eutectics, suspend in the liquid with TiB whiskers. The suspensions lead to an increase of viscosity of the metal liquid. The fluidity of TMCs goes down by the increased viscosity. Furthermore, the hindrance caused by dendrite arms with irregular growth surfaces is much greater than that of comparatively smooth crystallization interface front of pure metals or eutectic alloys. Thus, the fluidity of TMCs is worse than Ti-6Al-4V alloys.

As shown in Fig. 3(d), the TMCs metal fluid solidifies like alloys which freeze over a relatively wide range, in which the
fully liquid zone disappears quite early in the solidification, and the “ mushy” zone exists throughout the entire casting. When the dendrites, which grow up from the channel wall, reach half of the casting thickness, the liquid metal flow in channel will stop (Fig. 4(b) (t2)). When the flow stops, the dendritic structures can be kept by the precipitation of TiB whiskers (Figs. 2(c), 2(e)), and the re-melted dendrite arms will grow to new spheroidal grains (Fig. 4(b) (t1)). With the temperature drops, the ternary eutectics of (β-Ti + TiB + TiC) are solidified from the liquid and the liquid change into a solid. So, there is a “non-dendritic” structure from a “dendrite multiplication” mechanism and that is obtained at the top position of TMCs spiral samples (Figs. 2(d), 2(f)), as illustrated in Fig. 4(b) (t1).

Combined with Ti–B–C ternary phase diagram, the composition of TMC2 is much closer to the ternary eutectic than TMC1. It is well established in the literature that the eutectic alloys have a longer fluidity length than off-eutectic alloys. So the fluidity value of TMC2 is greater than TMC1.

In TMCs, independent TiB whiskers will flow as slurry and cluster in the swirling flow as slurry (as schematic in Fig. 4(b) (t2)). The clustered TiB whiskers are shown in Figs. 2(d), 2(f). Due to the Magnus effect, TiB reinforcements are vortex-dispersed in the central portion of TMCs spiral samples (Fig. 2(f)).

4. Conclusions

The study has shown that the fluidity of Ti-6Al-4V-xB4C is changed dramatically by B4C additions. The results can be summarized as follows:

1) With addition of 0.48 mass% B4C, the fluidity length is significantly reduced to 168 mm which is only 1/5 of that of Ti-6Al-4V. However, the change of fluidity versus B4C additions is not monotonically decreasing. When B4C addition increases to 0.97 mass%, there is a little increase of the fluidity length from 168 to 223 mm.

2) With B4C additions, the solidification paths of TMCs are changed, the TMCs metal fluid solidifies like alloys which freeze over a relatively wide range, which causes a dramatic decrease of fluidity. Due to the suspensions composed of melted off β-Ti dendrite arms and TiB reinforcements in TMCs melt fluid, the fluidity goes down. With the increase of B4C, the composition of TMC2 is much closer to the ternary eutectic than TMC1, which causes the fluidity going up.

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