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Morphological evolution of primary TiC carbide in laser clad TiC reinforced FeAl intermetallic composite coating①

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Abstract: The novel rapidly solidified TiC/FeAl composite coatings were fabricated by laser cladding on the substrate of 1Cr18Ni9Ti stainless steel, particular emphasis has been placed on the growth morphologies of TiC carbide and its growth mechanism under a constant solidification conditions. Results show that the growth morphology of TiC carbide strongly depends upon the nucleation process and mass transportation process of TiC forming elements in laser melt pool. With increasing amount of titanium and carbon in melt pool, the growth morphology of TiC carbide changes from block-like to star-like and well-developed dendrite. As the amount of titanium and carbon increases further, TiC carbide particles are found to be irregular polyhedral block. Although the growth morphologies of TiC are various, their advancing fronts are all faceted, illustrating that TiC carbide grows by the mechanism of lateral ledge growth.

Key words: TiC carbide, growth morphology; TiC/FeAl composite coating; laser cladding
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1 INTRODUCTION

Iron aluminum based on FeAl intermetallic alloy was expected to be an important and potential high temperature material, because its good resistance to oxidation and corrosion, low density and high temperature melting point[1-2]. However, the intrinsic properties of FeAl intermetallic alloy, such as low ductility and low fracture strength, limited its industrial applications. How to improve mechanical properties of FeAl intermetallic alloy and expand its industrial application realm was an important research aspect for material workers. Transition metal carbide (MC type) was often used as an effective strengthening phase in metal matrix composites (MMCs), nickel-base superalloys and high alloy steels due to their high hardness, low density and excellent high-temperature stability, and therefore TiC particles reinforced FeAl intermetallic matrix composites were expected to possess excellent mechanical properties. In recent years, a few studies have been carried out to utilize titanium carbide reinforced FeAl intermetallic matrix composites by the melt infiltration processing and powder metallurgy[3-6]. It is necessary to study the growth morphologies of TiC carbide because the growth morphology, size and distribution of TiC carbide have strong effect on the comprehensive mechanical properties, but little attempt has so far been made on study for TiC carbide growth morphology in FeAl intermetallic matrix composites. Previous investigations[7-10] have revealed that solidification parameters such as solidification cooling rate, thermal gradient, growth velocity were important factors governing TiC carbide growth morphology in nickel-base superalloy. Unfortunately, only few study for effect of molten alloy composition on carbide growth morphology has been published in open literature. In this paper, TiC particles reinforced FeAl intermetallic matrix composite coating was fabricated using laser cladding, and the morphological evolution and growth mechanism of TiC particles were studied.

2 EXPERIMENTAL

The stainless steel of 1Cr18Ni9Ti, 15 mm × 10 mm × 8 mm in size, was selected as the substrate material for laser cladding treatment, and the surface of substrate was cleaned and coated with black paint in order to increase the laser absorption coefficient of the material. The experiments of laser cladding were carried out on a 5 kW CO_2 laser materials processing system equipped with a 4-axis computer numerical controlled (CNC) work table. The laser clad processing was conducted under argon protective atmosphere. The nominal chemical composition (molar fraction, %) of powder blends were Fe-28Al-1Ti-1C, Fe-28Al-4Ti-4C, Fe-28Al-10Ti-10C, Fe-28Al-15Ti-15C and Fe-28Al-20Ti-20C respectively, and the preplaced powder bed were approximately 1.5 mm in thickness. The laser processing parameters were:

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laser power 3.0 kW, beam diameter 3.0 mm, laser scanning speed 5 mm/s.

The transverse and longitudinal sections of laser clad coating were mechanically polished and etched by $HCl + H_2O$ (1:1) solution at room temperature. Microstructure and the growth morphologies of primary TiC carbide in laser clad TiC/FeAl coating were examined by Nephot-II optical microscope (OM) and Kyky-2800 scanning electron microscope (SEM) with EDS attachment. The constitution phases of laser clad coating were identified by X-ray diffraction method using Rigaku D/max 2200 type with Cu K_α radiation operated at a voltage of 40 kV, a current of 40 mA and scanning rate of 5°/s.

3 RESULTS AND DISCUSSION

XRD result of laser clad composite coating, as shown in Fig. 1, indicates that laser clad composite coating consists of two phases, TiC and FeAl intermetallic alloy, illustrating that a novel rapidly TiC carbide reinforced FeAl intermetallic matrix composite coating is fabricated on substrate of 1Cr18Ni9Ti using laser cladding.

As shown in Fig. 2, the growth morphologies of TiC particles on different laser clad composite coating, indicates that the composition of powder mixture has strong effect on the carbide growth morphology. TiC carbide morphology on the laser clad coating with powder mixture of Fe-28Al-1Ti-1C (molar fraction) is found to be regularly blocky-like, which is very similar to its equilibrium growth morphology (Fig. 2 (a)). When the composition of powder mixture is Fe-28Al-4Ti-4C, the amount of titanium and carbon in melt pool increases, TiC carbide morphology changes to star-like, some saw tooth-like dunes are formed on the primary dendrite arms, and the advancing fronts of the primary dendritic arms are all faceted, as clearly shown in Fig. 2 (b). As the amount of titanium and carbon in melt pool increases, the growth morphology of TiC carbide on laser clad composite coating with composition of Fe-28Al-10Ti-10C is in well-developed dendrite, as shown in Fig. 2 (c). It is worth noting that the micro-characteristic of this dendrite is totally different from those of the conventional metallic dendrite, the advancing fronts of dendritic TiC are extremely faceted, as if some bricks stack on the primary dendrite arms. The volume fraction of TiC particles in laser clad coating with powder mixture of Fe-28Al-15Ti-15C increases and the size of TiC particles decreases to 2 - 3 μm, TiC carbide growth morphology is irregular polyhedral block, as shown in Fig. 2(d). As the amount of titanium and carbon increases further, although the carbide morphology is still irregular polyhedral block, the volume fraction of titanium carbide increases violently and its size decreases further to be about 1 μm. It is interesting that the polyhedral blocky carbide particles are agglomerated to cluster, as shown in Fig. 2(e). Moreover, the carbide growth surfaces are also made up of faceted planes by careful observation.

During the laser surface melting, the pre-placed powder mixture on the surface of 1Cr18Ni9Ti dissolves into the laser-generated melt pool, leading to in-situ reaction between titanium and carbon. Thus, it can be concluded that the growth and morphological selection of titanium carbide strongly depend upon two factors. One is carbide nucleation, the other is mass transportation of carbide forming elements in melt pool.

In this study, the solidification condition is concluded to be constant due to fixed laser processing parameters, and therefore c_i (Fig. 3), the concentration of carbide forming elements at the growing interface, is also approximately constant. The distribution coefficients for TiC carbide forming elements are smaller than unity, thus FeAl dendrite rejects these elements during its growth, and carbide forming elements enrich gradually in the melt pool. When the amount of

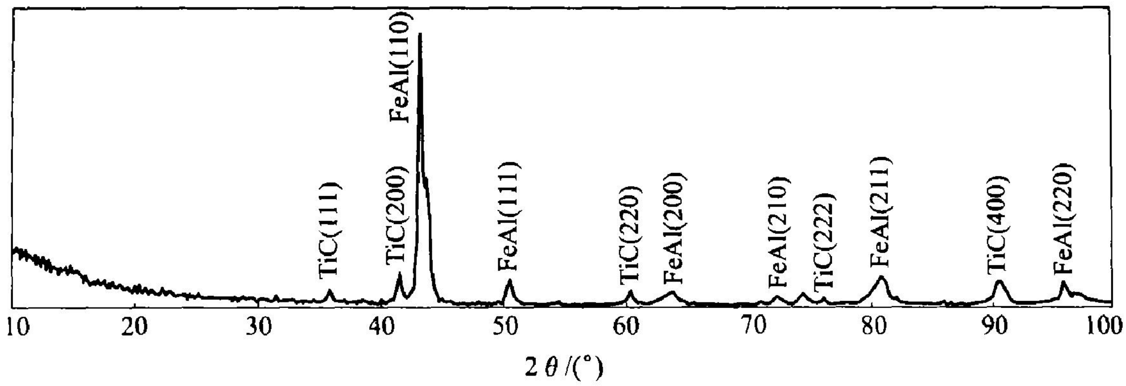

Fig. 1 XRD result of laser clad coating with powder mixture of Fe-28Al-4Ti-4C

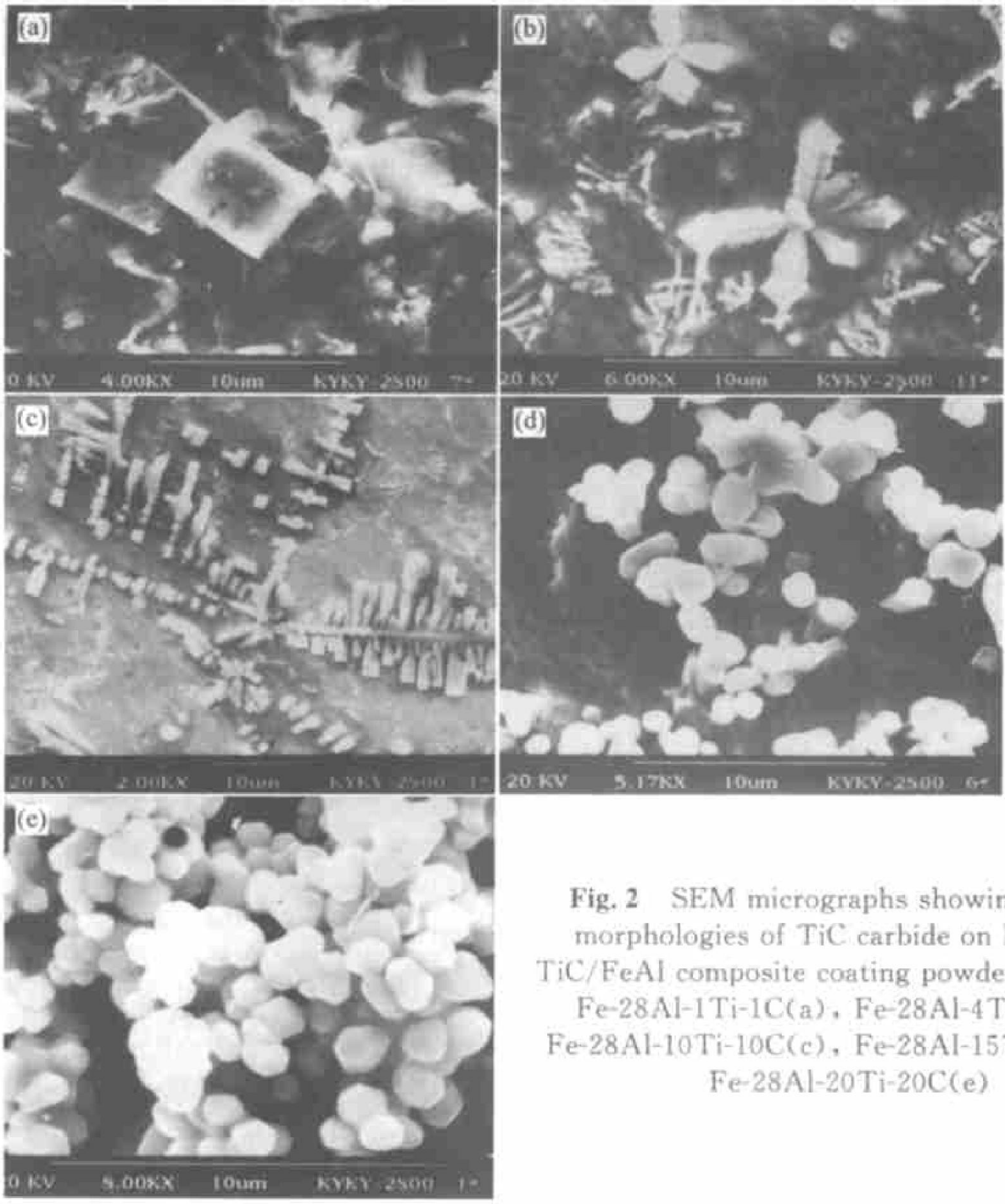

Fig. 2 SEM micrographs showing growth morphologies of TiC carbide on laser clad TiC/FeAl composite coating powder mixture of Fe-28Al-1Ti-1C(a), Fe-28Al-4Ti-4C(b), Fe-28Al-10Ti-10C(c), Fe-28Al-15Ti-15C(d), Fe-28Al-20Ti-20C(e)

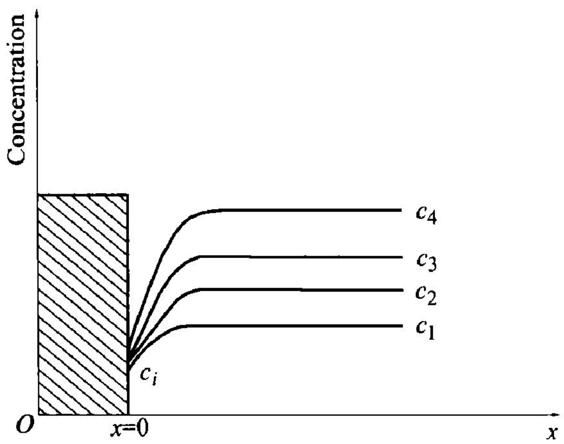

Fig. 3 Mass transportation modeling of TiC carbide forming elements in melt pool

titanium and carbon in powder mixture is lower, the distribution of TiC carbide forming elements in melt pool is indicated as c_1 in Fig. 3. Hence, the driving force for diffusion of TiC carbide forming elements from melt to carbide advancing front is small correspondingly, leading to the slow carbide growth velocity. In addition, the relatively high amount of aluminum in melt pool due to small amount of titanium and carbon in powder mixture decreases the diffusion velocity of TiC carbide forming elements and the distance between liquidus temperature and solidus temperature[11], thus constitutional undercooling in front of liquid/solid interface is difficult to occur, which avoids the dendritic titanium carbide. Therefore, the growth morphology of TiC carbide is blocky. With increasing amount of titanium and carbon in powder mixture, the distribution of TiC carbide forming elements in front of advancing front is c_2 as shown in Fig. 3, resulting in increase of driving force for carbide forming elements diffusion. Meanwhile, amount of aluminum decreases relatively, leading to decrease of prevention effort on the carbide elements diffusion. Therefore, the growth velocity of TiC carbide increases, TiC carbide forming elements diffusion required to form the equilibrium carbide shape becomes harder to satisfy[12], TiC carbide grows along octahedron apex direction ⟨001⟩[13], leading to star-like carbide. As the amount of titanium and carbon continues to increase, the growth velocity anisotropy between different planes is more distinct. TiC carbide grows rapidly along preferred growth directions and carbide morphology changes to be well-developed dendrite.

Based on above-mentioned growth theory, with increasing amount of titanium and carbon in powder mixture, carbide growth velocity might increase further, resulting in carbide coarseness. However, the size of TiC carbide decreases in laser clad coating with powder mixture of Fe-28Al-15Ti-15C, and the volume fraction of primary carbide increases. This phenomenon illustrates that the carbide nucleation is easier than carbide growth when the concentration of TiC carbide forming elements in melt pool is higher than a critical concentration. Increase in number of carbide grain no doubt limits carbide growth spacing, titanium carbide grows insufficiently, and the difference in growth velocity between different planes is weakened, thus carbide growth morphology changes correspondingly to irregular polyhedral block. As the amount of titanium and carbon increases further, although the carbide growth morphology is still in polyhedral block, carbide particles are inclined to agglomerate, as shown in Fig. 2(e). One explication for the phenomenon is the changement in interfacial energy of TiC carbide. It is well known that if $2\sigma_{L/TiC} < \sigma_{TiC/TiC}$[14], carbide particles will not agglomerate, where $\sigma_{L/TiC}$ is the interfacial energy between carbide particle and liquid melt, $\sigma_{TiC/TiC}$ is the interfacial energy between carbide particles with different orientations. In this case, the authors think that the atomic ratio of Al/Ti in melt pool is an important factor influencing carbide interfacial energy, further study of this aspect is needed to carry out afterwards.

In the present work, although TiC carbide growth morphology changes violently with the change in composition of powder mixture, these advancing fronts of TiC carbide are all faceted. It can be concluded that, therefore, the TiC carbide under rapid solidification conditions still grow by the mechanism of lateral ledge growth.

4 CONCLUSIONS

1) The composition of melt pool has a critical effect on the titanium carbide growth morphology. As the amount of titanium and carbon increases, the carbide growth morphology changes from block to well-developed dendrite and irregular polyhedral block with strong faceted growing interfaces.

2) The growth mechanism of TiC carbide under rapid solidification conditions is confirmed to remain lateral growth.

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