Growth morphology and mechanism of MC carbide under quasi-rapid solidification conditions

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Abstract

The carbide of group IVB and group VB elements, i.e., MC carbide, is an important constitution and strengthening phase for many alloy tool steels and cast nickel-base superalloys. Since the as-solidified growth morphology, size and distribution have an important influence on both the mechanical properties and hot workability, research on the solidification behavior of MC carbide is an important subject for cast superalloys and many high alloy tool steels. The growth morphology and mechanisms of MC carbide, under slow-cooling and rapid solidification conditions, has been studied intensively as functions of the solidification cooling rate. The solidification behavior of MC carbide under quasi-rapid solidification conditions has not been reported in the open literature. In this paper, the growth morphology and mechanism of an MC carbide (TiC type) under quasi-rapid solidification conditions is studied in a laser surface alloyed coating on a titanium aluminide alloy Ti–48Al–2Cr–2Nb (at.%). The growth morphology of the quasi-rapidly solidified MC carbide with a cooling rate of 4×10⁴°C is found to be dendritic with strong faceted, double zigzag brick-stacking growth characteristics on the dendrite arms. The growth mechanism of the MC carbide is found to be a brick-stacking/double zigzag micro-branching lateral growth from steps on the intersecting {111} planes. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: MC carbide; Quasi-rapid solidification; Growth morphology; Faceted crystal

1. Introduction

As an interstitial phase with high melting point, excellent high temperature stability and wear resistance, the carbide of group IVB and VB elements (hereafter called MC carbide) such as TiC, VC, etc. is used widely as one of the most important strengthening phases for alloy tool steels and nickel-base superalloys as well as many high temperature wear-resistant coating materials [1–4]. Since the as-solidification growth morphology and its distribution have a critical influence on both the mechanical properties and processing workability of the materials, the solidification behavior and processing of MC carbide are two of the important research subjects for these MC carbide-strengthened materials. Considerable research has been carried out under slow-cooling, near-equilibrium solidification conditions with a solidification cooling rate of less than 10⁴°C/s for correlating the growth morphology, growth mechanism of MC carbide with solidification processing conditions for a series of nickel-base superalloys and steels [1–4]. It is well understood that MC carbide is either in octahedral or in irregular blocky and Chinese script morphologies under slow-cooling, near-equilibrium solidification, conditions. The equilibrium solidification growth morphology of MC carbide is octahedral, but it shifts to irregular blocky and Chinese script shapes as the solidification conditions deviate from equilibrium conditions [4]. The growth mechanism is the typical faceted growth mechanism, i.e. lateral growth from existing steps or ledges on the close packed {111} planes on the growing crystal surfaces [3,4]. Under rapid solidification conditions with solidification cooling rates ranging from 9×10³ to 1.4×10⁵°C/s, the growth morphology of MC carbide (TiC type) was found to be peculiar, radially branching flower-like colonies in a laser surface melted Ni-base superalloy, while the growth mechanism was still identified as lateral growth from surface micro-steps or micro-ledges originating from twins and screw dislocations on the crystal surfaces [5–8]. Under quasi-rapid solidification conditions, no information on the growth morphology and mechanism of MC carbide is reported in the open literature. In this paper, the solidification growth morphology and mechanism of MC carbide (TiC type)
under quasi-rapid solidification conditions with a solidification cooling rate of approximately $4 \times 10^{2} \text{C/s}$ are studied in laser surface alloyed (carbonized) coatings on a $\gamma$-TiAl intermetallic alloy. The quasi-rapidly solidified MC carbide is found to have a special well-developed MC carbide morphology having strong faceted and brick-stacking growth characteristics on the dendrite arm surfaces. The growth mechanism is discussed and a growth model is proposed for the unique quasi-rapidly solidified MC carbide dendrite.

2. Experimental procedures

To eliminate the interference of melt inheritance on the growth morphology of MC carbide and to flexibly adjust the solidification cooling rate, laser surface 'in situ' alloying with carbon is utilized to realize the quasi-rapid solidification of MC carbide. A $\gamma$-titanium aluminate alloy Ti–48Al–2Cr–2Nb having a fully lamellar microstructure is selected as the substrate material for laser surface alloying treatment. The surface of the $\gamma$-titanium aluminate specimens, $6 \times 10 \times 30$ mm in size, preheated to 600$^\circ$C and coated with graphite powders of approximately 0.1 mm in thickness, is melted by a 9 kW continuous wave CO$_2$ laser. During laser surface melting, the coated graphite powders dissolve into the laser induced surface melt bath, leading to the in situ alloying of the surface with carbon. The carbon in situ alloyed melt bath solidifies after the forward movement of the laser beam and a composite coating reinforced by TiC type MC carbide is produced on the surface of the $\gamma$-TiAl specimens. The solidification cooling rate of the laser surface alloyed coating is regulated by varying the laser surface alloying processing parameters and is estimated by a simplified numerical calculation method [5]. The laser surface alloying processing parameters are: laser beam power 8.5 kW, beam diameter 3–4.5 mm, and beam scan-rate 13.2–16.7 mm/s. The MC carbide growth morphologies and the microstructure of the laser surface alloyed coatings are characterized by OM, SEM and XRD.

3. Results and discussions

Fig. 1 shows the X-ray diffraction result of a laser surface alloyed coating on the substrate of the TiAl intermetallic alloy. It is clearly indicated that an in situ composite structure reinforced by MC carbide (TiC type) was produced in the laser surface alloyed coatings.

The typical microstructure of a laser surface alloyed in situ composite coating is shown in Fig. 2 with a solidification cooling rate of approximately $4 \times 10^{2} \text{C/s}$. The MC carbide is macroscopically in well-developed dendritic growth morphology, as shown clearly in Fig. 2.

Careful examination of the well-developed MC dendrites at high magnifications reveals that the microstructure and superficial topography of the MC dendrite arms are totally different from those of the conventional metallic dendrites. The surface of the quasi-rapidly solidified MC dendrites is strongly faceted and has a very pronounced 'brick-stacking and alternative double zigzag branching' characteristics as clearly indicated in Fig. 3(a) and (b), while the conventional metal dendrites have non-faceted surfaces. The unique dendritic growth morphology of the MC carbide implies that the growth mechanism is different from that of conventional non-faceted dendrites.

It is worth noting by a detailed examination of MC dendrite arms that the brick-branching angle between the bricking direction and the dendrite stem direction is approximately either 35 or 55°, i.e. the double zigzag branching angle is either approximately 71 or 109°, which are almost exactly the same intersecting angles between the close packed (111) planes of MC carbide. The small ‘bricks’ can be regarded as the basic growth unit and the growth of the dendrite arms is actually stacked three-dimensionally by the small bricks at the very specified

![Fig. 1. X-ray diffraction spectra of a laser surface alloyed and quasi-rapidly solidified composite coating on a $\gamma$-TiAl alloy substrate.](image)
angles to the dendrite growth direction. It is the three-dimensional alternative double zigzag stacking of the bricks along the specified stacking angles which leads to the forward growth of the dendrite arms and the macro-branching of the well-developed dendrite, as illustrated schematically in Fig. 4.

During the brick-stacking double zigzag branching and the dendrite growth process, the bricks on the dendrite arms continue to thicken. A bulky blocky or octahedral MC carbide will be formed when the brick-like plates thicken and join together if the solidification cooling rate is slow enough to allow the process to occur, as evidenced by the arrows in Fig. 3(b). It is the brick-stacking/double zigzag micro-branching growth mechanism that makes the solidification morphologies of MC carbide strongly variable with the solidification conditions, ranging from the regular octahedral under equilibrium solidification conditions, through quasi-rapidly solidified dendrite, to radially branching flower-like colonies under rapid solidification conditions.

Fig. 2. Presenting: (a) an OM; and (b) an SEM; micrograph showing the quasi-rapidly solidified MC carbide (TiC type) dendrites in the laser carbon-surface alloyed coatings.

Fig. 3. SEM photomicrographs showing the quasi-rapidly solidified well-developed TiC dendrites with: (a) faceted; and (b) brick-stacking/zigzag branching; growth characteristics on the dendrite arms.

Fig. 4. Schematic diagram of the brick-stacking and double-zigzag branching growth process and the formation of a well-developed MC dendrite having strong faceted and brick-stacking/micro-branching characteristics on its dendrite arms: (a) nucleation (an octahedral nucleus); (b) bricking or brick-branching from a nucleus; (c) dendrite growth by brick-stacking and double-zigzag branching; and (d) a well-developed MC dendrite with strong faceted and brick-stacking characteristics.
4. Conclusions

The growth morphology of MC carbide under quasi-rapid solidification conditions with a cooling rate of approximately $4 \times 10^{3}\, ^\circ\text{C/s}$ is dendritic with strong faceted, double zigzag brick-stacking characteristics on the dendrite arm surface. The growth mechanism of the quasi-rapidly solidified dendritic MC carbide is a brick-stacking/double zigzag micro-branching lateral growth process on intersecting $\{111\}$ planes.

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