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The morphological evolution of the axial structure and the curved columnar grain in the weld

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ABSTRACT

The competitive growth of microstructures in the entire weld pool for both the Al–Cu alloy and the pure aluminum was simulated by the cellular automata method to comparatively investigate the micro-mechanisms for the morphological evolution of the axial structure and the curved columnar grain in the weld. The competitive mechanism of grains during the epitaxial growth and the morphological evolution of the grain structure in the weld with various welding speeds were studied. The results indicate that both the thermal conditions and the solidification characteristic of the weld metal exert an important influence on the grain competition and the resulting structure in the weld. For the Al–Cu alloy, the dendritic structure with a large S/L interface curvature appears during the epitaxial growth. The preferential orientation affects the competition result obviously. Owing to the anisotropic growth kinetics, the straight axial structure forms at low welding speeds. With the increase of the welding speed, the width of the axial region decreases and eventually disappears. For the pure aluminum, the S/L interface during the epitaxial growth is planar, and the grain competition is controlled by the thermal conditions completely. The columnar grains curve gradually to follow the highest temperature gradient direction at low welding speeds and become straight at high welding speeds.

1. Introduction

The solidification behavior of the molten pool controls the grain structure and then affects the ultimate mechanical properties of the weld [1]. The morphological evolution of the grain structure in the weld is mainly determined by the competitive growth of grains with different preferential orientations in the entire molten pool. The welding parameters exert an important influence on the grain structure evolution through changing the transient thermal conditions during the competitive growth of grains [2–6]. Besides the transient thermal conditions, the solidification characteristic of the weld metal also affects the competitive growth of grains and the resulting structures in the weld. Quite different grain structures may be obtained even under the same welding condition. Fig. 1 summarizes the morphological evolution of the typical grain structures with different welding speeds. As shown in Fig. 1(a) and (c), the straight axial structure [7–9] and the curved columnar grain [10] form in the welds of the aluminum alloy and the high-purity aluminum, respectively, at low welding speeds. With the increase of the welding speed, both the axial structure and the curved columnar grain become to the centerline structure, as shown in Fig. 1(b) and (d), respectively. To clearly reveal the micro-mechanisms for the morphological evolution of the axial structure and the curved columnar grain, it is necessary to investigate the effects of both the transient thermal conditions within the entire pool and the solidification characteristic of the weld metal on the competitive growth of grains. However, welding is a multi-field coupling, time dependent and highly non-linear process. It is difficult to observe the highly dynamic solidification behavior in the welding process through the conventional experimental methods.

With the development of the computational power and the numerical model, the morphological evolution of the solidification structure could be simulated directly by the Phase field (PF) [11–16] and the cellular automata (CA) [17–24] methods. Some investigations have been performed to simulate the morphologies of the solidification structures in the molten pool. Pavlyk [25] and Zhan [26,27] simulated the dendrite morphology in the molten pool of the gas tungsten arc welding (GTAW) by the CA method. A two-dimensional model combining the FEM and the CA technique was developed to simulate the dendrite growth in the laser-

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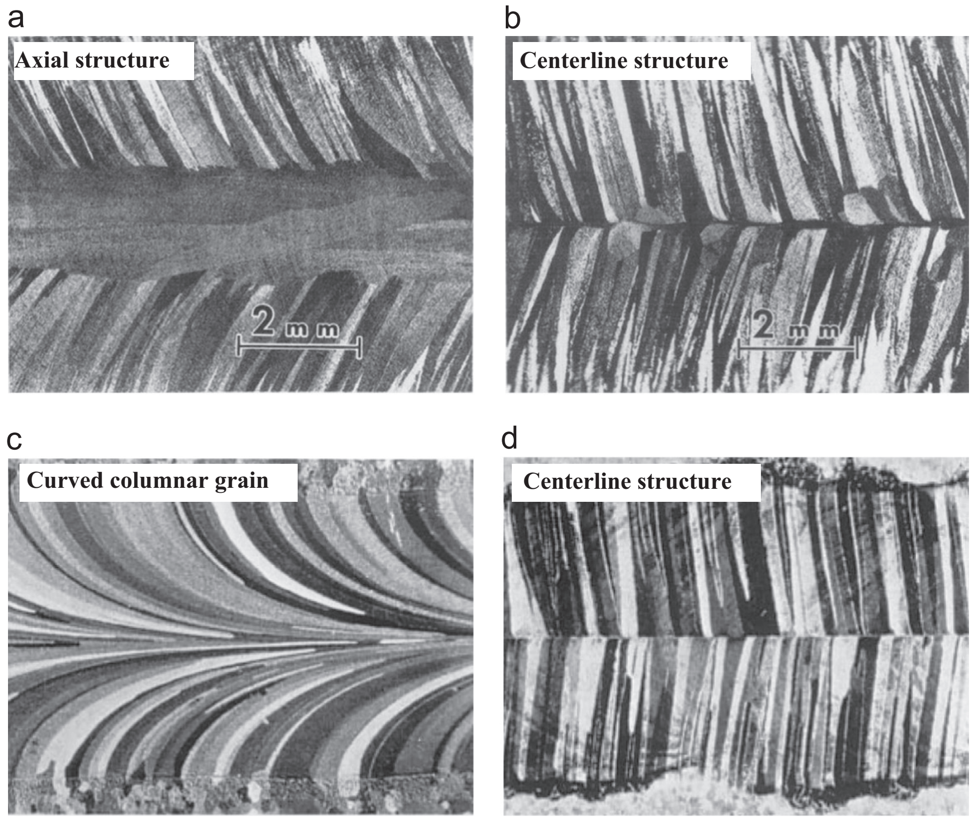

Fig. 1. The gas tungsten arc (GTA) welds of the aluminum alloy [7] at the welding speeds of (a) 0.3 and (b) 0.6 m/min, and the high-purity (99.96%) aluminum [10] at the welding speeds of (c) 0.25 and (d) 1 m/min The welds shown in this figure are full penetrated in order to obtain the two-dimensional solidification structures.

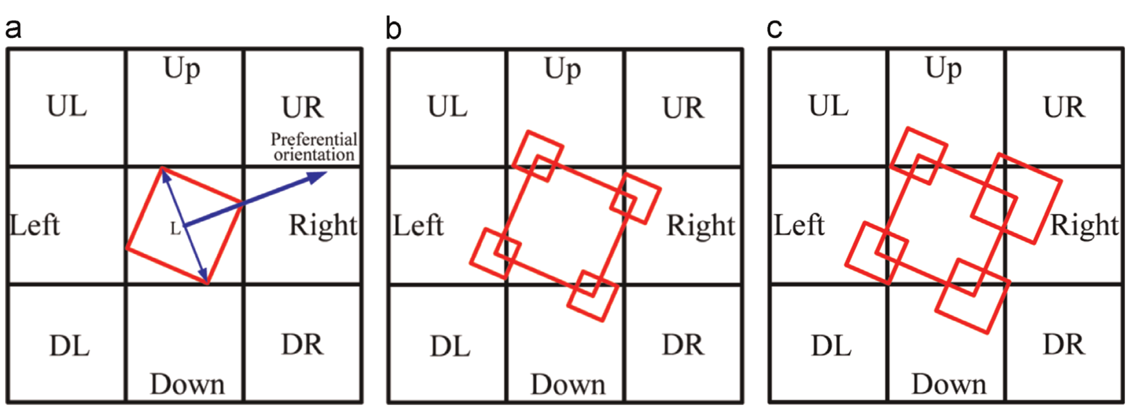

Fig. 2. The capturing algorithm of the present CA model. (a) A square-shaped nucleus grows with the defined preferential crystal orientation. (b) The central cell captures the new interface cells from its neighboring cells. (c) The new interface cells begin to grow.

engineered net shaping process by Yin [28]. Tan [29–31] developed a two-dimensional CA–PF model to simulate the dendrite growth during solidification, which adopted the PF method for the calculation of growth kinetics and a basic CA model to track the S/L interface. Moreover, a further study on the growth of grains and sub-grain dendrites during the laser keyhole welding was performed which adopted a three-dimensional CA model to predict the meso-scale grain growth and a two-dimensional CA–PF model to predict the micro-scale dendrite morphology. Chen [32] proposed a coupled CA–FE model to predict the grain structure morphology during the GTAW. Bordreuil [33] adopted a two-dimensional CA model to predict the grain structure. Farzadi [34] compared the microstructure morphologies at different locations along the fusion boundary using the PF method. The evolution of the primary dendrite arm spacing in the laser powder deposition of the Ti–Nb alloys was simulated using the PF model by Fallah [35]. Montiel [36] used the PF model to study the solidification structure in the resistance spot weld of the AZ31 alloy. The effects of the cooling rate, temperature gradient and the nature of the inoculant particles on the columnar to equiaxed transition (CET) were investigated, and the simulated results were compared with the experimental observations and the previously developed