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Letter

Microsegregation in directionally solidified dendritic-cellular structure of superalloy CMSX-4

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Abstract

A directionally solidified sample of superalloy CMSX-4 was investigated to show the effect of crystal orientation on the segregation distribution. The solute distribution of alloying elements across a dendritic cell was measured. Due to the preferred crystal growth in $<100>$ orientation the segregation profiles in this direction is much flatter than that in $<110>$ orientation.

Keywords: Microsegregation; Directional solidification; Dendritic cell; Superalloy

Dendritic cell (or cellular dendrite) is an important structure morphology between regular cell with circular geometry and typical dendrite with secondary branches [1,2]. Chalmers has introduced the term 'cellular dendrite' for the plate-like dendrite with primary and secondary arms forming orthogonal plates, to differentiate them from the branched dendrites observed during free growth into undercooled melts [3]. According to the observation of Morris and Winegrad [1], the cellular dendrites grow as straight columns of cruciform cross-section and without periodic secondary branching. The arms of the cruciform are continuous flanges parallel to (100) type planes. While the structure formation of the cellular dendrite was clearly characterised, few studies have been concerned with solute redistribution of alloying elements in this structure.

In the present work the segregation distribution of alloying elements across a directionally solidified dendritic cell was measured, to indicate the difference of the segregation distribution along different crystal orientations. The experiment was performed on the nickel-based superalloy CMSX-4, with composition listed in Table 1. Cylindrical samples of the alloy were directionally solidified in a Bridgman type LMC-furnace (Liquid Metal Cooling). At a constant temperature gradient $G = 11.1$ K mm^{-1} the critical velocity for the morphological transition cell dendrite was determined to be 0.125 mm min^{-1}. A sample was quenched during directional solidification at this velocity. Within the mushy zone transverse sections were cut at different distances from the dendrite tip, corresponding to different fractions of solid. Fig. 1 presents some characteristic cross-sections showing an array of adjacent dendritic cells. During the thickening process the distance from the cell centre to the solid–liquid interface is dependent not only on the local fraction solid, but also on crystal orientation, due to the effect of the crystallographic anisotropy. Since $<100>$ is the preferred direction for the crystal growth in cubic metals, the cross-section of the dendritic cells are cruciform with orthogonal arms pointing in $<100>$ directions, as observed in castings of many other alloy systems [1,2].

Within a cross-section of this sample, EDX line scans were taken across a single cell. As indicated by the lines

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Table 1
Measured composition of the used superalloy CMSX-4 (wt.%)

Al	Co	Cr	Re	Ta	Ti	W	Hf	Mo	Ni
5.0	10.02	6.32	2.78	6.04	1.0	5.83	0.51	0.36	Bal

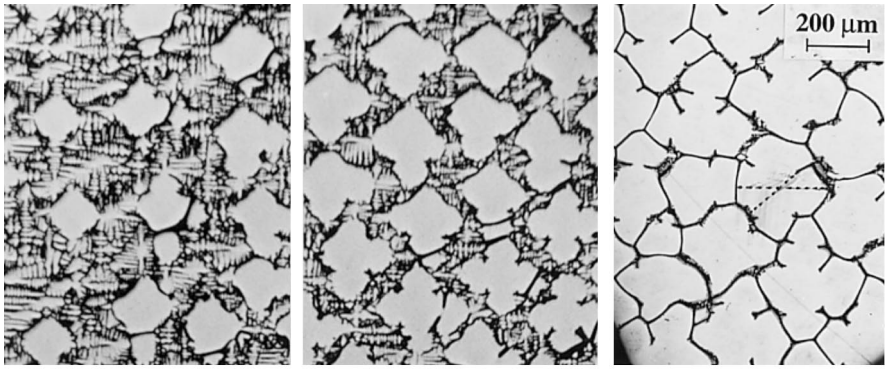

Fig. 1. Micrographs of transverse sections in the mushy zone of the quenched sample. The corresponding fraction solid is about 0.19, 0.58, and 0.91, respectively. (c) The measuring paths of the EDX line scans across a cell are shown.

in Fig. 1(c), the concentration of the alloying elements was measured along both $<100>$ and $<110>$ direction of the cell section.

In Figs. 2 and 3 the measured solute profiles are plotted versus the distance from the cell centre, along $<100>$ and $<110>$ direction, respectively. The elements Ta, Al and Ti enrich the intercellular region, showing a trend expected for partition coefficients k less than unity. On the other hand the elements Co, W and Re segregate inversely to the cell core. The element Cr shows a homogenous distribution across the cell, indicating a partition coefficient nearly equal to unity. From Figs. 2 and 3 it appears that the segregation trends along both directions are similar. But the measuring path along $<110>$ direction is much shorter. That means the solute inhomogeneity along this direction is more pronounced than that along $<100>$ direction.

Using EDX for the measurement of the composition of the refractory elements Re, W and Ta one must be aware of the fact that the peaks of their X-ray intensities lie very close together. This could lead to a shift of one concentration at the cost of the concentration of another element. In case of elements with inverse segregation behaviour like Ta and W or Re this could flatten the concentration profiles of these elements.

Fig. 4 shows a direct comparison of the measured results for four characteristic elements along the two different orientations. For all elements the segregation profiles along $<100>$ direction are flatter than in the $<110>$ direction. The reason is the preferred crystal growth in $<100>$ orientation, leading to the cruciform cross-section and corresponding isoconcentrations, as shown in Fig. 1. Therefore the segregation distribution in irregular cellular structure is not only a function of the distance from the cell centre, but a function of crystal orientation.

While microsegregation in commercial alloys is of considerable interest, extensive work has been done to predict the microsegregation in cellular and dendritic microstructures (for dendrites the primary stalks and the secondary arms are normally simplified as cells). In the current models [4–8], modified on the base of the original Scheil expression [9], cellular segregation is taken as the result of the unidimensional cell thickening process in the radial direction. Segregation profiles are then described as a function of the distance from the cell centre. It is clear that these models are only suitable for the regular cells with circular geometry. For dendritic cells with flanged structure, the segregation distribution on a cell section is no more the same along different directions, as shown in Figs. 2–4. Even for typical dendritic structure, the cross-section of the primary stalks and the secondary arms are also more or less cruciform, due to the effect of the crystallographic anisotropy. It is apparent that the similar solute redistribution behavior as given

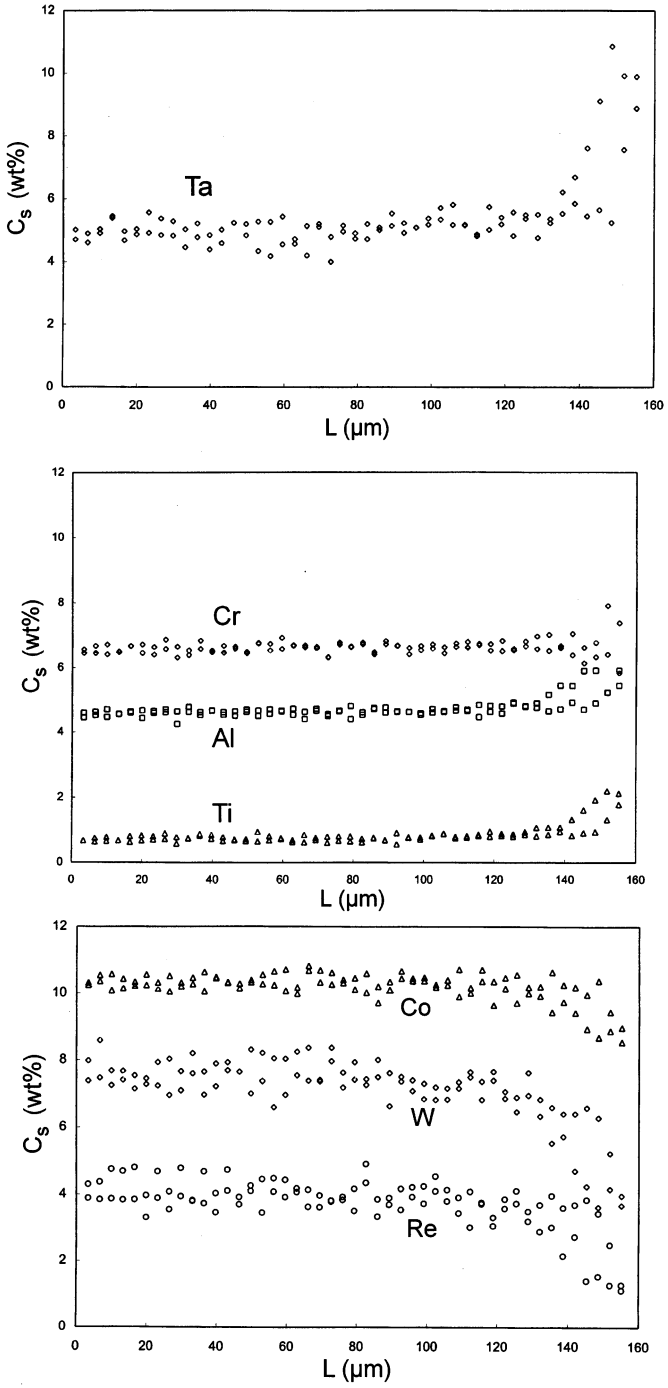

Fig. 2. Measured solute distribution plotted vs. distance from the cell centre, along $<100>$ direction.

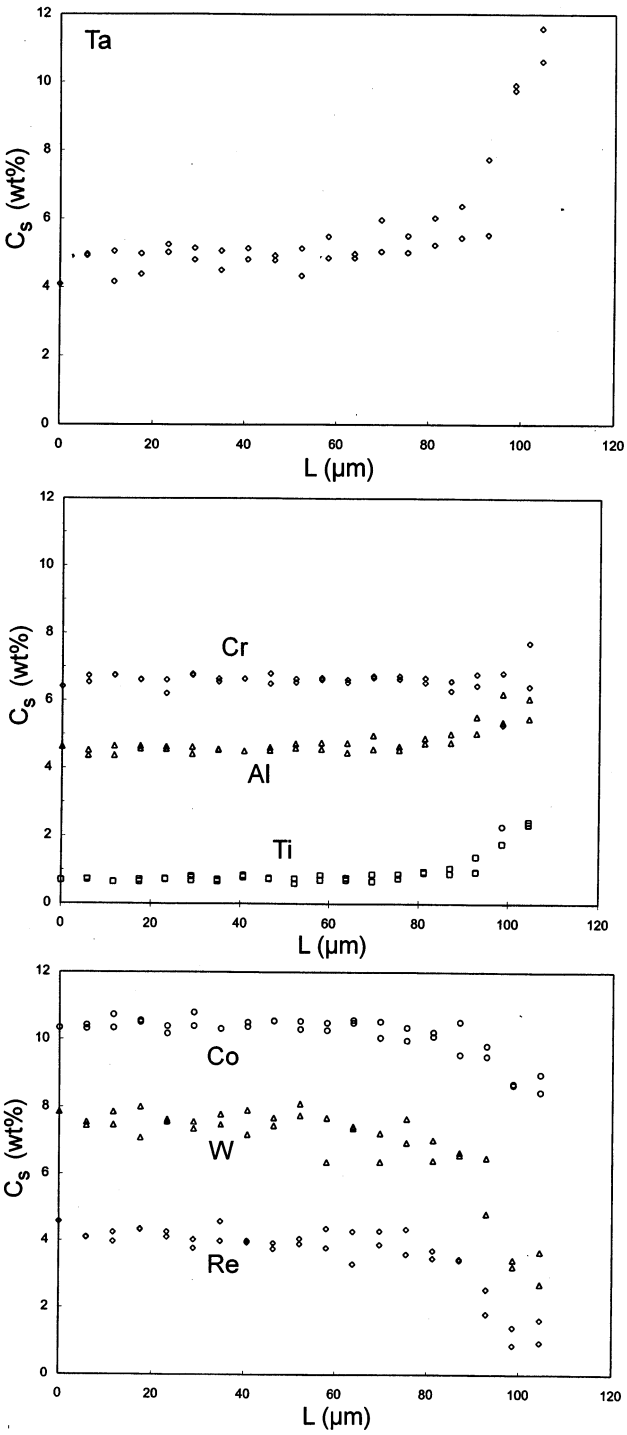

Fig. 3. Measured solute distribution plotted vs. distance from the cell centre, along $<110>$ direction.

in Figs. 2–4 will be also found in the dendrite stalks and arms. To describe such segregation behavior in cellular and dendritic structure more reasonably, the anisotropy of crystal growth should be taken into account.

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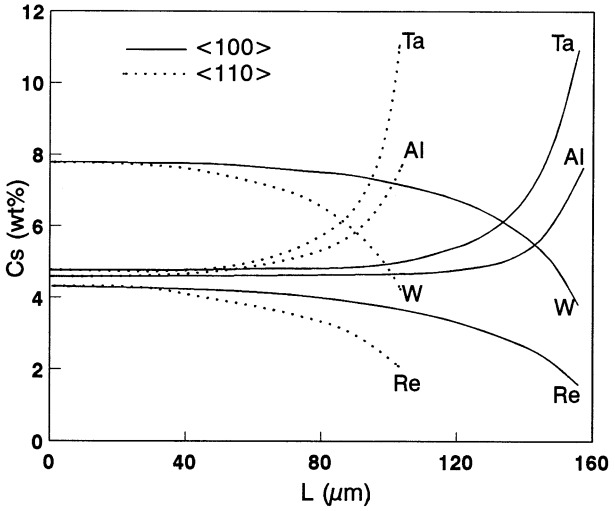

Fig. 4. Comparison of segregation distributions of some alloying elements across the cell, along $<100>$ and $<110>$ direction.

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