

Structure Control during Directional Solidification of Ni-Base Superalloys

Seong-Moon SEO

KOSEF - 10407

Senior Researcher,
Korea Institute of Materials Science, High Temperature Materials Group

Japanese Advisor : Hirofumi MIYAHARA
Associate Professor, Kyushu University

The recent interest of nickel base superalloy in large-sized industrial gas turbines for power generation has led to the decrease in the easiness of directional solidification (DS) and single crystal (SC) casting processing. The heavily alloyed chemical composition of advanced Ni-base superalloys has caused substantial increases in microsegregation during solidification, which produces undesirable non-equilibrium solidification phases, and consequently reduces their mechanical properties. In the present thesis, therefore, the development of macroscopic grain structure as well as microstructural evolution during directional solidification of Ni-base superalloys has been systematically investigated.

In chapter 1, the research background of this thesis was summarized with the historical development of Ni-base superalloys. Then, a brief description of current problems in the DS and SC casting process for Ni-base superalloys was presented followed by the research scopes of the present thesis.

In chapter 2, fundamental solidification characteristics and the influence of cooling rate on the microstructural development during the solidification of the alloy CMSX-10 and CMSX-4 were examined. The solidification of these alloys was found to be initiated with the formation of primary γ and terminated with the formation of γ/γ' eutectic. Increasing the cooling rate resulted in the increase of the solidification range of γ/γ' eutectic. The measured secondary dendrite arm spacing in CMSX-10 and CMSX-4 alloys was found to be very similar at a given cooling rate and these could be expressed as $\lambda_2=196.8 \cdot V_c^{-0.40}$. The volume fraction of γ/γ' eutectic was found to increase with increasing the cooling rate, then showed a maximum plateau of about 25.6 % for CMSX-10 and 12.4 % for CMSX-4, especially due to Re and Cr contents which significantly influence the segregation of γ' forming elements.

In chapter 3, solute redistribution behaviors during directional solidification of CMSX-10 with various solid/liquid (S/L) interface morphologies were investigated in detail. The partition coefficients of each solute element measured on the quenched planar, cellular, and dendritic S/L interfaces were found to be independent on the S/L interface morphology. Based on the results obtained from planar solidification, the variation of γ/γ' eutectic volume fraction with respect to the solidification rate in dendritic solidification regimes could be successfully

rationalized by considering the effect of back-diffusion on decreasing the extent of microsegregation. The compositional profiles of Cr clearly revealed that Cr-enriched area formed after the formation of γ/γ' eutectic. Based on the microstructural observation, the low solubility of Cr in γ' phase, and the EPMA results, it has been suggested that the final solidification of CMSX-10 alloy would be completed with the formation of supersaturated γ layer.

In chapter 4, the microstructural evolution during directional solidification of high Cr and Ti containing Ni-base superalloy IN792+Hf was clarified. The formation mechanism of undesirable non-equilibrium solidification phases was proposed by taking into account the microsegregation behaviors discussed in chapter 3. Both eta and Cr-rich boride phases were found to be the final solidification products developed from the remaining liquid after γ/γ' eutectic reaction. The limited solubility of Cr, Mo, and W in the γ' phase and the strong positive segregation tendency of B in Ni-base alloys enriched these elements in the residual liquid during γ/γ' eutectic reaction and eventually led to the formation of these phases in the final residual liquid. The (Ti+Ta+Nb+Hf)/Al ratio in the residual liquid played a significant role in the nucleation of eta phase. During the γ/γ' eutectic reaction, the formation of eta phase occurred when the (Ti+Ta+Nb+Hf)/Al ratio was greater than 2.1 as well as when the Al content was less than 8.4 at.% in the residual liquid.

In chapter 5, macroscopic solidification grain structure evolution during single crystal solidification using a grain selector was systematically investigated with an aid of 3-dimensional cellular automaton finite element (CAFE) simulation. The present CAFE model and experimental results demonstrated that the higher nucleation density at the chill surface is favorable to obtain well-aligned single crystal. The majority of the primary selection of preferential $\langle 001 \rangle$ texture was found to occur when the distance from the chill plate is greater than 18.3 mm. It was shown that reasonable agreements between the CAFE prediction and experiment can be made such as overall grain structures, texture evolutions in the grain selector as well as in the starter block, and the position where the final selection of single crystal occurs. The stray grain formation near the end of the grain selector in the experimental castings was found to be related to highly undercooled regions at a given casting condition.

