

ERIF Final Report

The Impact of Carbides on the Permeability of Dendrites: Characterization and Modeling

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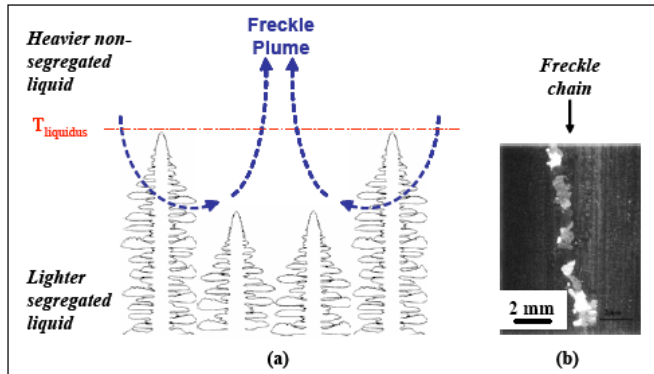


Figure 1: (a) fluid flow in the mushy zone, and (b) micrograph of a freckle chain [2].

Introduction:

The formation of macroscopic grain defects during the directional solidification of single crystal Ni-base superalloys can have a significant impact on resulting fatigue and creep properties of critical structural components used in a variety of aerospace applications and gas turbines for power generation. Common casting defects in Ni-base superalloys include freckles, Figure 1, which consist of channels comprised of small equiaxed grains or dendrite fragments that are aligned parallel to the solidification direction. Each of the individual grains in

a freckle chain is misoriented with respect to the $\langle 001 \rangle$ direction. Additionally, the composition of the equiaxed grains present in the freckle chains is enriched with elements rejected to the interdendritic regions (Ta and Al) and significantly different from the bulk crystal(s). Because of the adverse effects of high angle grain boundaries on mechanical properties, the presence of either of these unacceptable casting defects in single crystal components results in rejection of the component and significantly decreases overall manufacturing yields.

The formation of freckle defects in unidirectionally solidified Ni-based superalloys is attributed to localized fluid flow resulting from thermosolutal convection. Multicomponent Ni-based superalloys often contain significant levels of refractory alloying elements, such as W, Re, Ta and Mo, to provide high temperature creep resistance. During dendritic solidification, these constituent refractory elements also tend to segregate strongly to either the solid or the liquid phase. Within the solid + liquid “mushy zone”, large compositional gradients can often develop due to microsegregation of the alloying additions. In high-refractory content alloys, the density of the solute contained within the mushy zone can often be less than the density of the bulk liquid. Since single crystal castings are generally withdrawn from the hot zone and unidirectionally solidified in an orientation anti-parallel to gravity, a liquid density-inversion can evolve between the solute and bulk liquid. When the buoyancy forces associated with the lower density solute reaches some critical value, the system becomes unstable and localized plumes of flowing solute erupt from within the mushy zone. The plumes then cause erosion and/or fragmentation of the secondary dendrite arms and form freckle chains upon solidification, Figure 1.

Modeling and Characterizing the Permeability of Dendritic Structures

The formation of freckles depends on numerous parameters, one of the most important being the permeability of the mushy-zone. Experimental measurements of permeability are very difficult to achieve essentially because of the changing morphology of the microstructure over time due to coarsening and back-diffusion effects in the solid. Difficulties may also arise from significant temperature variations throughout the sample during the test. Recently, advanced serial sectioning techniques have been developed to quantitatively measure the mushy zone permeability of the dendritic microstructure of a single crystal Ni-base superalloy in 3-D during solidification. A series of two-dimensional images were acquired and reconstructed using image processing techniques to generate a 3-D image. Comparison of the experimentally measured microstructural features in the dendritic mushy zone, Figure 2, to simulated 3-D meso-scale solidification microstructures, Figure 3, were found to exhibit good agreement.

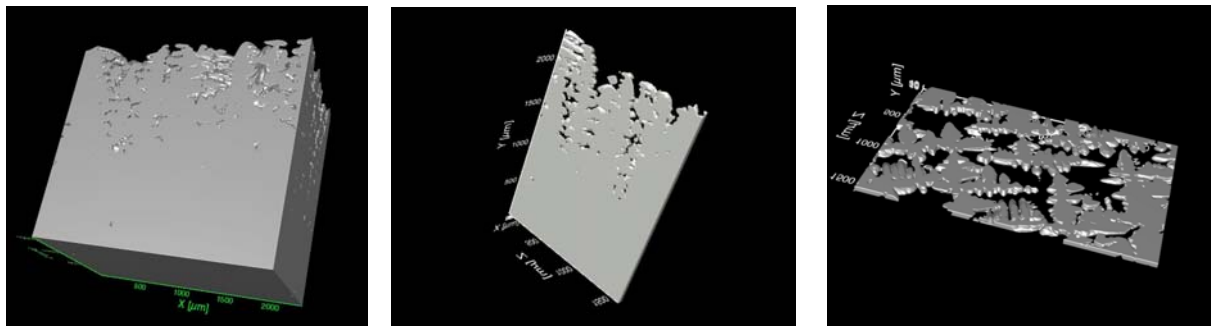


Figure 2: Reconstructed 3-D image of the mushy zone of a directionally solidified Ni-base superalloy.

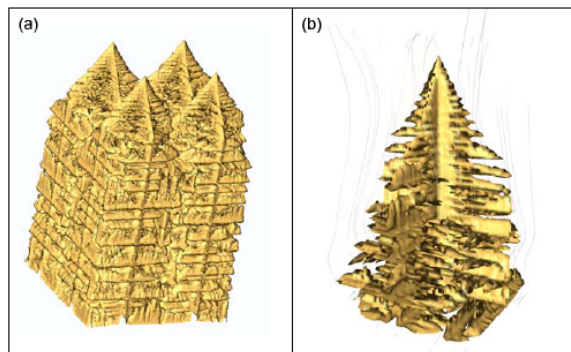


Figure 3: (a) Three-dimensional simulation of the directional solidification of a binary Ni-Ta alloy, and (b) flow lines around an isolated dendrite.

The onset of fluid flow due to thermosolutal convection occurs when the ratio of the buoyancy to the surrounding viscous forces exceeds some critical value. Hence, a correlation should exist between the Rayleigh criterion and the tendency for an alloy to develop convective instabilities. Beckermann and Worster have applied a modified version of the Rayleigh criterion to effectively describe formation of convective plumes associated with the onset of thermosolutal convection during directional solidification.

Rayleigh numbers, Ra , associated with the various experimental alloy compositions were estimated using the results from the differential thermal and segregation analyses. By relating the

mean permeability of the mushy zone, \bar{K} , to the spacings between the primary dendrite arms, λ_1 , the Rayleigh number can be modified in the following manner:

$$Ra = \frac{\Delta\rho}{\rho_o} \frac{gh\bar{K}}{\alpha\nu}$$

The solidification characteristics of a large number of experimental Ni-base superalloys were assessed as a part of this study and the addition of minor levels of carbon were shown to significantly reduce the frequency of solidification defects. The present study was aimed at elucidating the role of carbon in defining the permeability within the interdendritic regions of the mushy zone and directly influencing the formation of freckles in Ni-base superalloys. Various mechanisms associated with the physical presence of these carbides within the mushy zone were investigated. Consistent with the modeling efforts, preliminary results strongly suggest that the primary effect of carbon can be attributed to the formation of carbide networks that lower the permeability of the dendritic structure during solidification and restrict the ability for convective instabilities to form. The effects of minor carbon additions on the solidification characteristics on Ni-base superalloys were represented in a modified form of the Rayleigh criteria that better captures the effects of carbon in Ni-base superalloys, Figure 4b.

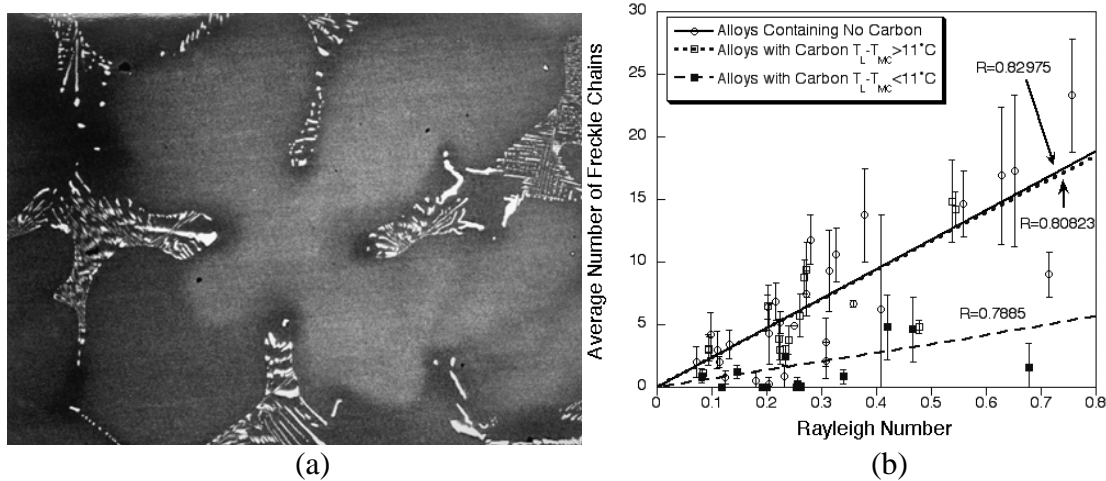


Figure 4: (a) SEM image of a dendritic microstructure showing the presence of carbides surrounding the core. (b) Incidence of freckle chains plotted as a function of the Rayleigh number. Carbon containing alloys were found to be highly resistant to freckle formation.

Summary

Results from this investigation are highly relevant to the manufacture and operation of advanced aero-engines as well as gas and steam turbines for power generation. Much of this work will form the basis of a new computational design tool can be used to assist alloy development efforts and make these materials more amenable for manufacture. Moreover, much of the preliminary information obtained as part of this study will be used to form the basis of an NSF GOALI proposal between the PI and Rolls-Royce.