Transport phenomena during the solidification processing of wrought alloys

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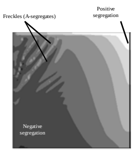
The main thrust of this research is the study of transport phenomena at the micro- and macroscale in materials processing, particularly solidification processes. The use of predictive models that describe the macroscopic phenomena dominating the development of microstructure is necessary to understand the fundamental science and practice of materials processing. The results of these predictions are compared to results from bench top experiments and tests performed in industrial settings. The goal is to aid understanding of the complicated physics of solidification, the diagnosis of defects in processing, and suggesting solutions.

Transport phenomena

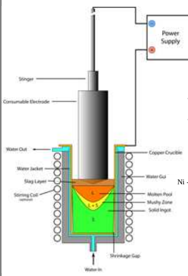
- Macroscopic *heat and mass transfer* and *fluid flow* cause a macroscopic *distribution of microstructure* in real materials processing
- The study of these transport phenomena in real solidification processes is done by a combination of numerical analysis and industry-scale experiments

- **Macrosegregation:** ingot-scale inhomogeneity in composition due to fluid motion
- Causes nonuniformity in mechanical properties and microstructure distribution
- Cannot be removed by homogenization heat treatments



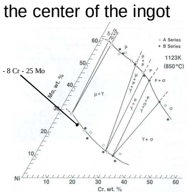
- The origin of this defect is in the solute partitioning during alloy freezing. Differences in freezing rates for different elements results in local liquid composition changes which, with the temperature gradients, cause density gradients in the liquid. These density differences drive the flow which transports and redistributes the solute throughout the ingot.

Electroslag Remelting

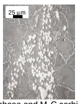


Macrosegregation in Ni-8Cr-25Mo

If ingot diameter is too large, μ phase formation during aging is mostly near the center of the ingot



Ni-rich isothermal section of Ni-Cr-Mo phase diagram at 850 °C, showing the two-phase $\mu + \gamma$ region (Raghavan, et al., 1984)



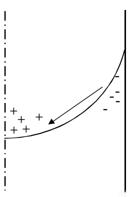
μ phase and M_6C carbides in γ matrix (provided by Haynes Intl.)

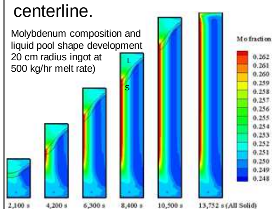
Centerline μ phase precipitation due to Mo enrichment of interdendritic liquid (not much segregation of Cr)*

* T. Morillon, M. Dayananda, and M. J. M. Krane, in symposium on "Modeling Heat Treating Processes," ASM Heat Treating Society Conference and Exposition, Pittsburgh, PA (9/05).

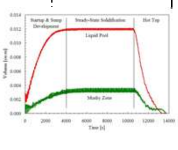
Liquid near liquidus interface is more dense than bulk fluid because it is colder and molybdenum is more dense than nickel and chromium.

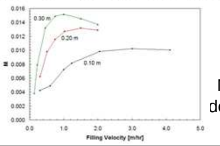
Flow throughout process is down liquidus interface, from crucible towards centerline.





Molybdenum composition and liquid pool shape development 20 cm radius ingot at 500 kg/hr melt rate)



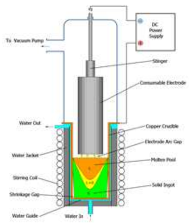


Average macrosegregation in ingot

$$M = \left[\frac{1}{V}\int_V \left(\frac{C^{Mo} - C_0^{Mo}}{C_0^{Mo}}\right)^2 dV\right]^{\frac{1}{2}}$$

Model predicts increasing, then decreasing, macrosegregation as filling velocity increases

Vacuum Arc Remelting



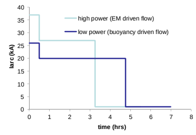
Prediction of macrosegregation and tendency for beta fleck development in Ti-10V-2Fe-3Al

Fe segregates into liquid ($k^{Fe} = 0.28$), Al into solid ($k^{Al} = 1.23$), and V segregation is negligible ($k^V \approx 1.0$)

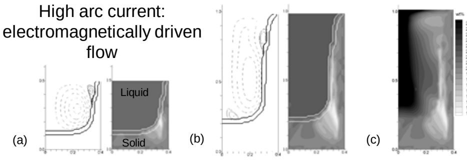
Positive segregation of β-stabilizers (Fe, V) and negative segregation α-stabilizer (Al) correlated to formation of beta flecks

How do macrosegregation patterns develop as function of arc current?

Flow and iron composition patterns during process for high and low arc current levels:

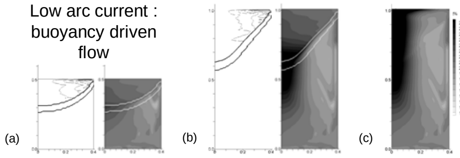


High arc current: electromagnetically driven flow



(a) Strong counterclockwise flow driven by electromagnetic forces stirs liquid region and removes Fe-rich, Al-depleted liquid from mushy zone during filling. (b) Once full, the current is turned off and flow is controlled by buoyancy. The liquid pool becomes stratified, leading to much higher segregation near centerline of final ingot (c).

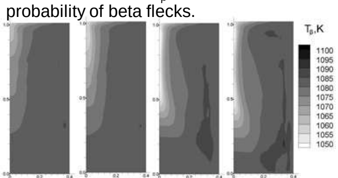
Low arc current : buoyancy driven flow



(a) Weak clockwise flow driven by thermal and solutal buoyancy forces is not strong enough to penetrate and break up stratification in liquid region. Because the flow is weaker than high power case, the overall final segregation levels (c) are much lower.

Beta transus temperature (T_β) is transition point above which only beta phase is present. Lower T_β correlates to higher probability of beta flecks.

T_β distribution as function of composition for increasing (L to R) arc current



1058 K	1054 K	1044 K	1046 K	$T_{\beta,min}$
1087 K	1087 K	1090 K	1092 K	$T_{\beta,max}$

For microstructural control during heat treat, a narrow range of T_β is desired. Low power, buoyancy driven cases (2 on left) show much lower band of T_β than high power, electromagnetically driven cases (2 on right).

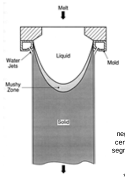
Empirical correlation for beta transus temperature:
$T_b = 1153K + 23.4C_{Al} - 8.4C_{Fe} - 12.4C_V$ * At nominal composition: $T_\beta = 1083$ K

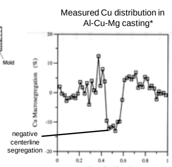
* C. F. Yolton, F. H. Froes, and R. F. Malone, *Met. Trans. A*, v.10A, pp.132-134, 1979.

Past and Current Funding sources

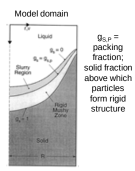
Specialty Metals Processing Consortium (VAR), Office of Naval Research Young Investigator Program (ESR), National Science Foundation (ESR), Wagstaff (VDC), Precision Castparts Corporation/Special Metals Corporation (ESR), Intel Corporation (donation of computer cluster), University of Montenegro (HDC)

Direct Chill Casting





*H. Yu and D. A. Granger, in *Aluminum Alloys-Their Physical and Mechanical Properties*, (1986).



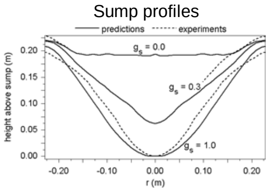
$g_{S,P}$ = packing fraction; solid fraction above which particles form rigid structure

Direct Chill Casting, used to produce most of world's wrought aluminum, frequently exhibits severe negative centerline segregation. The numerical model examined role of free-floating, equiaxed grains on segregation patterns. Predictions indicated a significant decrease in centerline composition because of accumulation of Cu-depleted solid grains at bottom of sump.

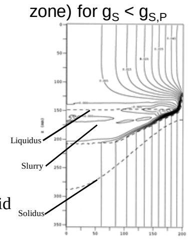
Comparisons were made with data from billets cast at Wagstaff's Spokane, Washington, research lab.**

** C. J. Vreeman, J. D. Schloz, and M. J. M. Krane, *ASME J. Heat Transfer*, v. 124, pp. 947-953, 2002.

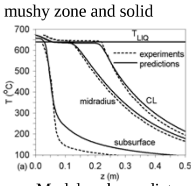
Sump profiles

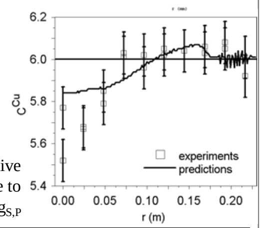


Streamlines of flow with free-floating solid (slurry zone) for $g_S < g_{S,P}$



Shallow temperature gradient in liquid and slurry regions; steep gradient in rigid mushy zone and solid

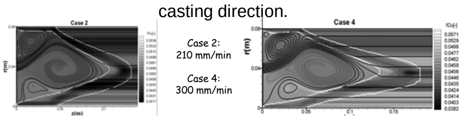




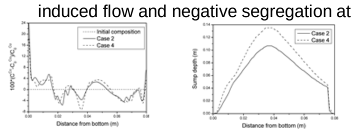
Model underpredicts negative centerline segregation due to uncertainty in $g_{S,P}$

Segregation in Horizontal DC Casting***

Horizontal casting allows longer billets and more continuous processing, but the buoyancy driven flows and segregation patterns are more complicated because gravity is normal to casting direction.



Higher speed: faster inlet jet, longer sump, more shrinkage induced flow and negative segregation at centerline



*** M. J. M. Krane and I. Vušanović, *Mat. Sci. & Tech.*, v. 24, pp. 102-107, 2009.

Current and future work

ESR: slag-metal interactions in superalloy processing; free surface effects; segregation maps in superalloys

VAR: effect of control schemes on defects; electromagnetic stirring effects

DCC: HDC with movement/settling of solid particles