SAND2007-7488C

THE INFLUENCE OF Gd AND B ON THE SOLIDIFICATION AND WELDABILITY OF A Ni-Cr-Mo ALLOY

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With financial support from the National Spent Nuclear Fuel Program

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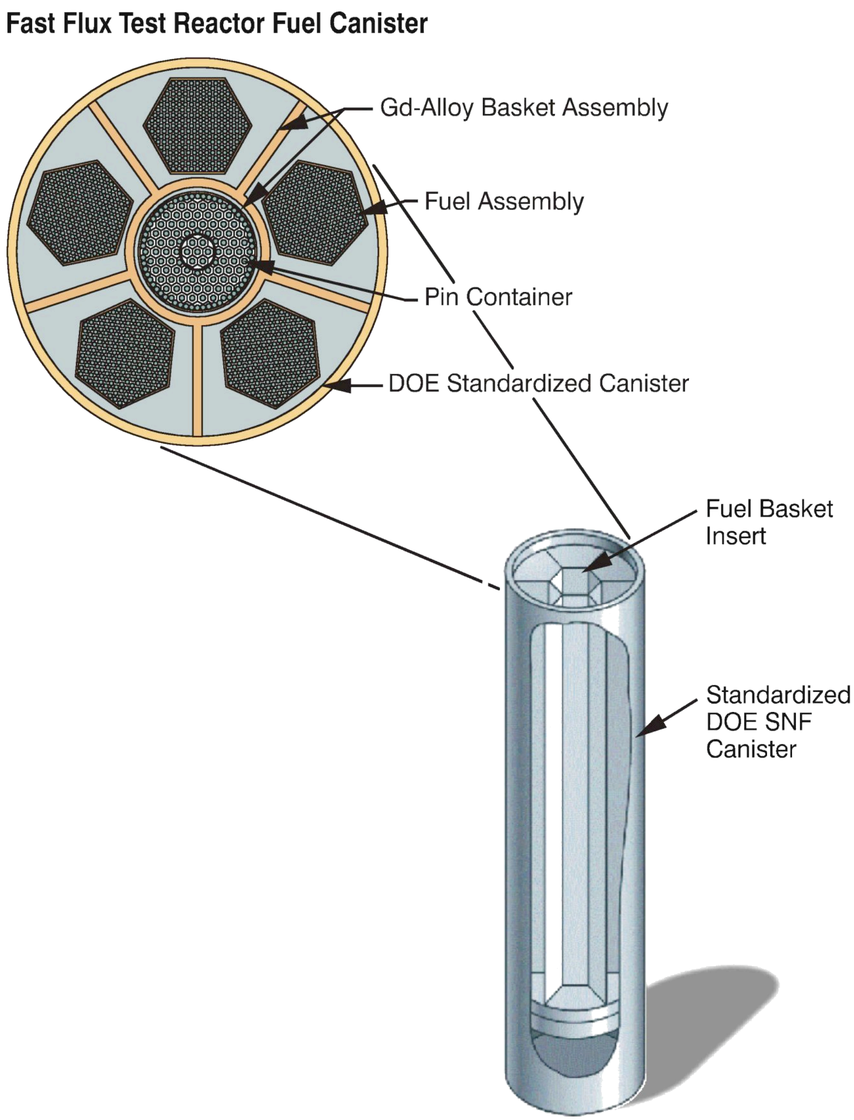
Background and Motivation



- Ni-16Cr-16Mo-2Gd Alloy developed for disposal of spent nuclear fuel
- Exhibits good hot working, weldability, and very high neutron cross section
- Current plan: Weld with a Gd-free filler metal, which can produce variations in fusion zone Gd concentration, ΔT, and f_e
- B additions spheroidize Ni_5Gd intermetallic. May improve mechanical properties, but need to consider potential adverse effect on weldability

Objectives: **Determine the influence of Gd and B on the solidification behavior and resultant weldability of Ni-16Cr-16Mo alloys**

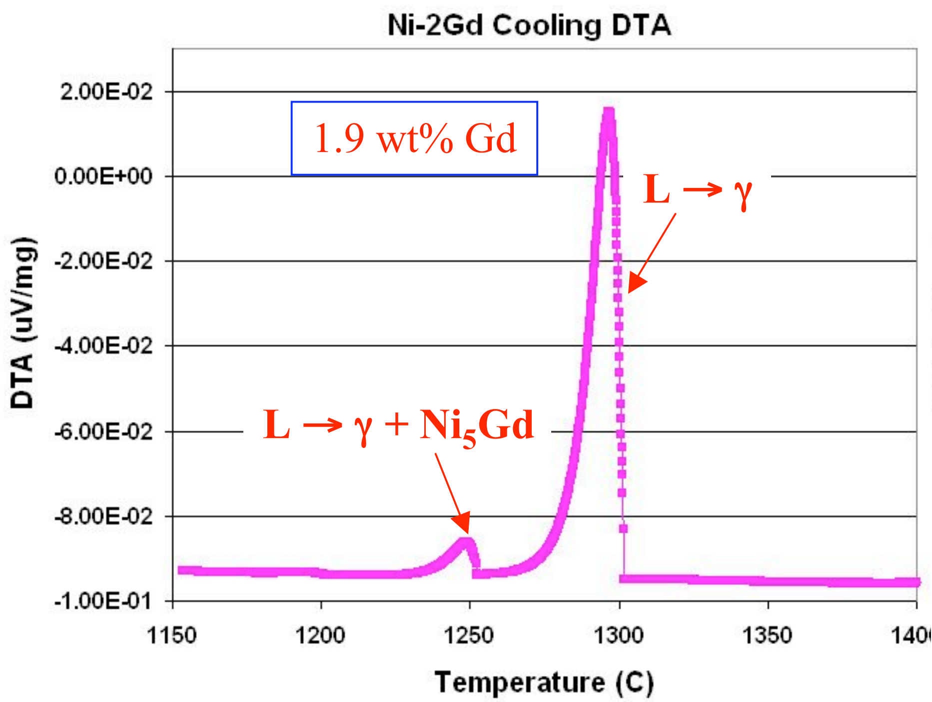
Approach

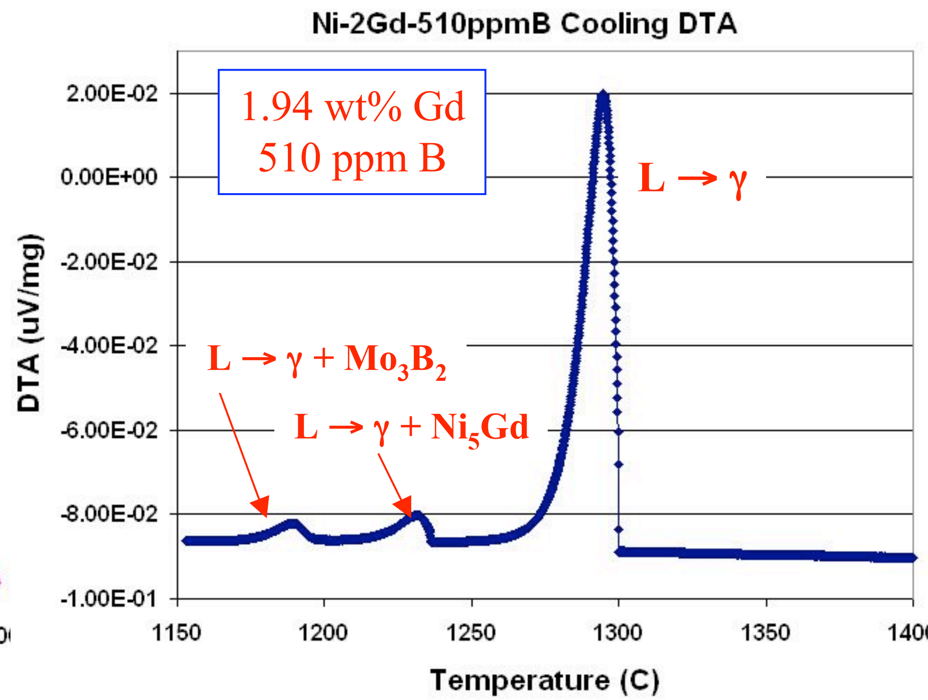
Experimental Alloys

Ni	Mo	Cr	Fe	Gd	P	S	Si	O	N	C	B (ppm)
Bal.	15.9	16.1	0.088	0.00	<0.001	<0.001	0.088	0.0024	0.0040	0.0065	---
Bal.	15.67	16.00	0.016	0.46	<0.001	<0.001	0.070	0.0044	0.0045	0.0052	---
Bal.	15.53	16.08	0.017	1.01	<0.001	<0.001	0.081	<0.001	0.0044	<0.005	---
Bal.	15.56	15.91	0.015	1.49	<0.001	<0.001	0.070	<0.001	0.0039	0.0064	---
Bal.	15.16	15.95	0.016	1.90	<0.001	<0.001	0.070	0.0021	0.0041	0.0065	---
Bal.	15.12	15.56	0.016	2.45	<0.001	<0.001	0.071	0.0056	0.0043	0.0066	---
Bal.	14.34	16.44	0.040	2.08	<0.005	NT	<0.01	0.0040	0.0010	0.0060	40
Bal.	14.8	16.2	0.037	1.94	<0.001	<0.001	0.009	0.0021	0.0045	0.0086	230
Bal.	14.6	15.8	0.03	2.02	<0.005	<0.005	0.030	<0.005	0.0020	0.0135	510

- **Differential Thermal Analysis (DTA): Liquidus and eutectic-like reaction temperatures**
- **Varestraint Testing: Susceptibility to solidification cracking**
- **Microstructural Characterization:**
  - **Imaging and Quantitative Metallography via LOM and SEM**
  - **Phase ID conducted via electron backscattered diffraction**

Typical DTA Results





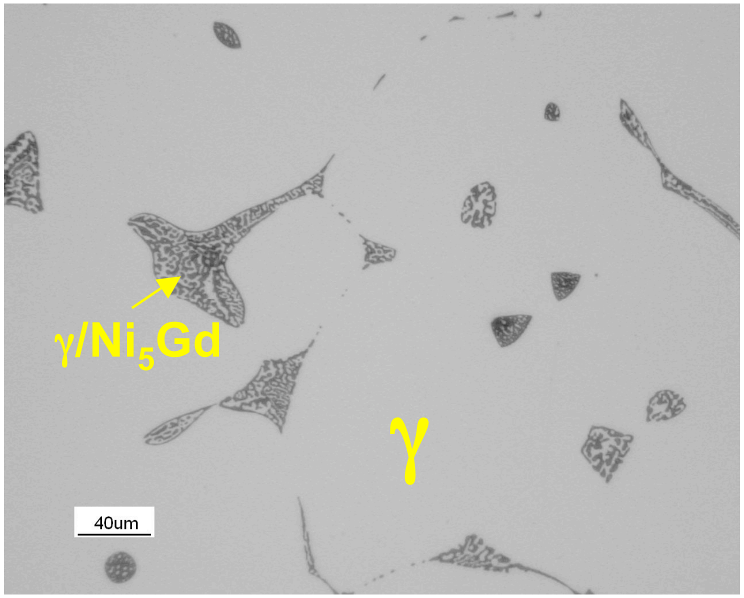
B-free alloys:

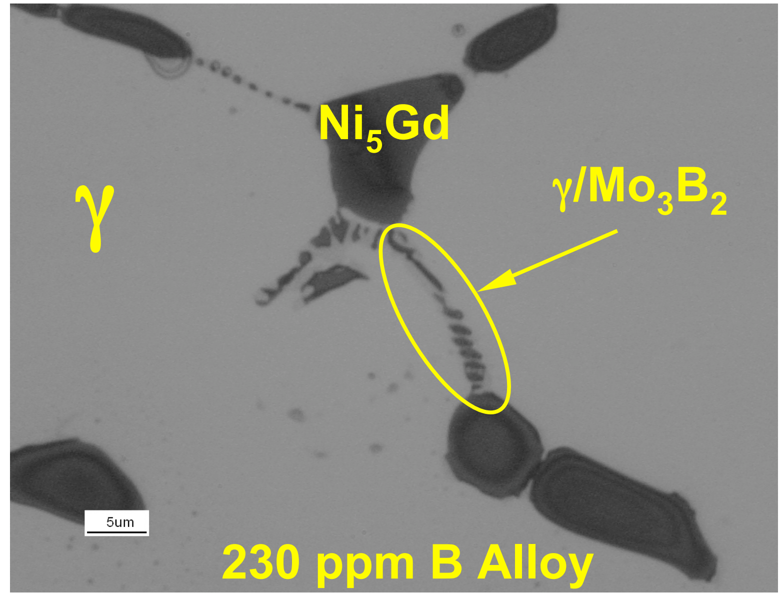
- Solidify via: (1) L → γ; followed by (2) L → γ + Ni_5Gd

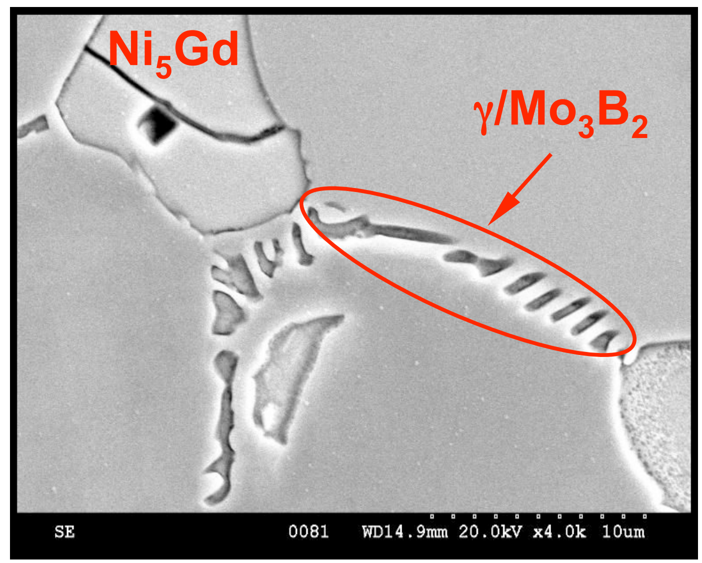
B-containing alloys:

- Solidify via: (1) L → γ; followed by (2) L → γ + Ni_5Gd; followed by (3) L → γ + Mo_3B_2
- B addition lowers the L → γ + Ni_5Gd reaction temperature

Typical Microstructures







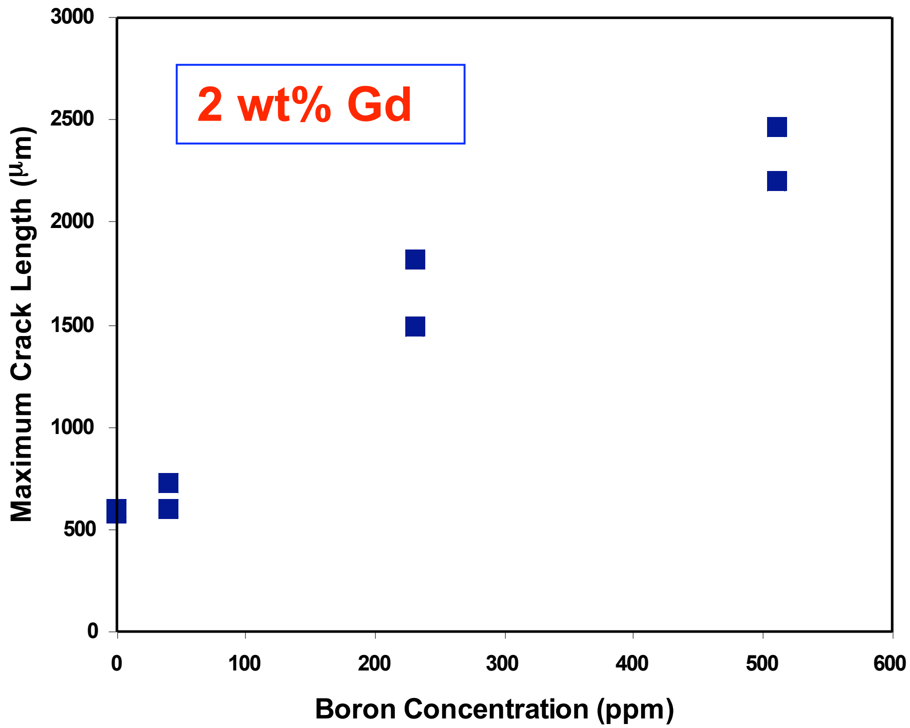
B-Free Alloys

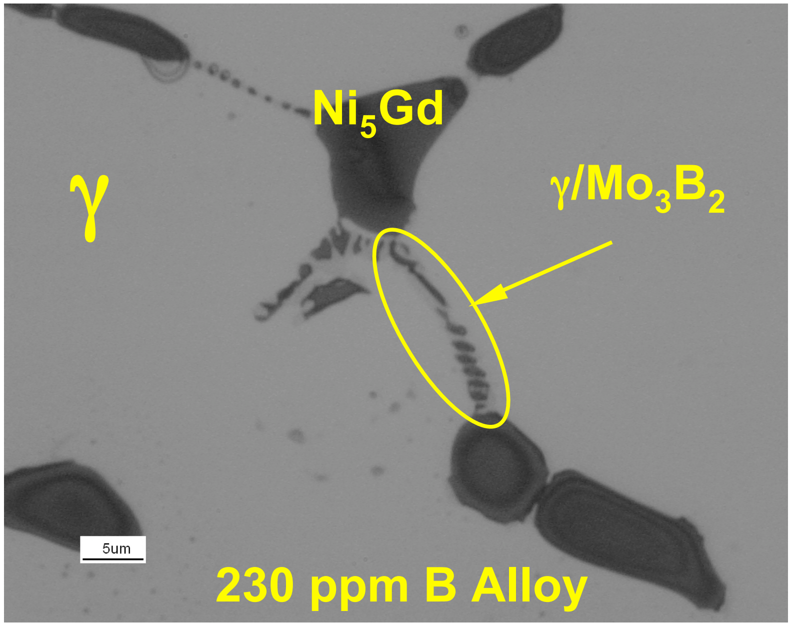
- Exhibit γ matrix and γ/Ni_5Gd

B Alloys

- γ/Ni_5Gd changes from lamellar to divorced morphology
- Ni_5Gd phase becomes spheroidized
- The γ/Mo_3B_2 forms along grain boundaries

Weldability Results: B Alloys





Adverse Effects of Boron:

- B extends ΔT by ~ 60 °C and expands crack-susceptible solid +liquid region

  B-Free: Solidification terminates with $L \rightarrow \gamma + Ni_5Gd$ at 1260 °C and ΔT ~ 140 °C

  B-Alloys: Solidification terminates with $L \rightarrow \gamma + Mo_3B_2$ at 1200 °C and ΔT ~ 200 °C

- Boron rich eutectic liquid wets grain boundaries extensively and probably restricts solid bridging

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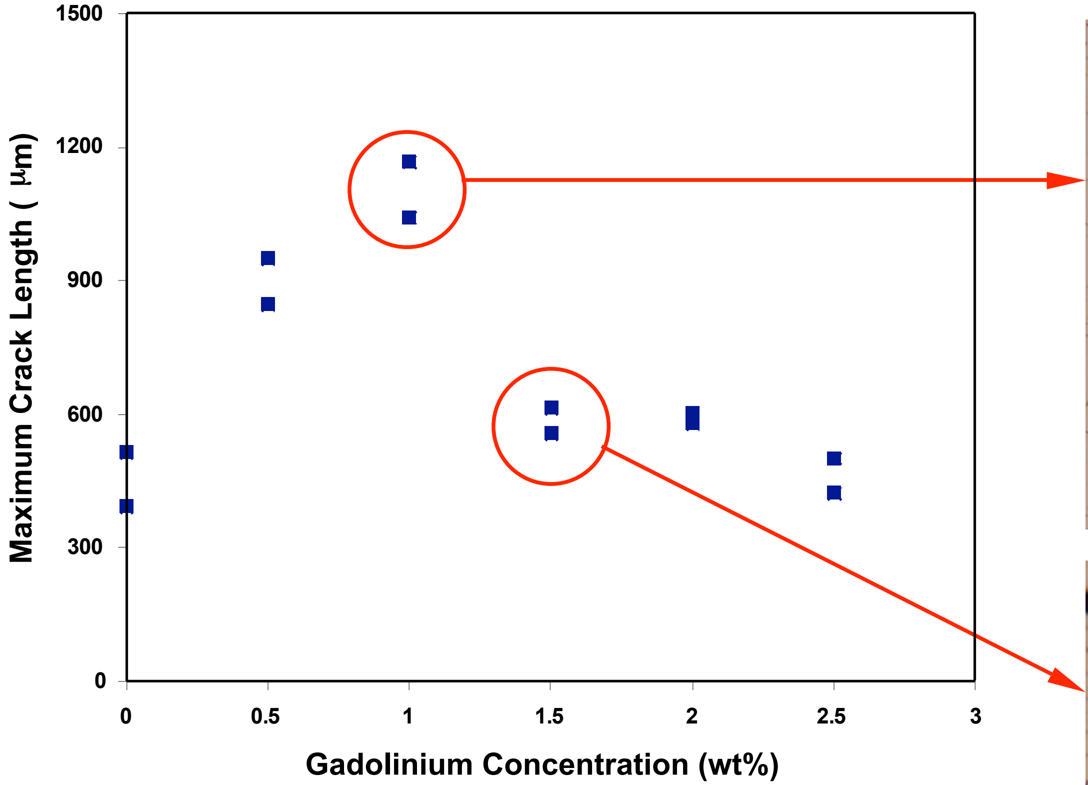
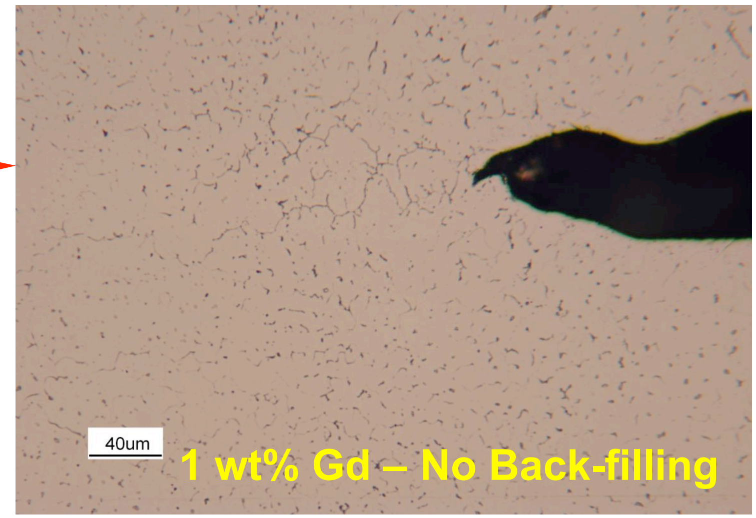
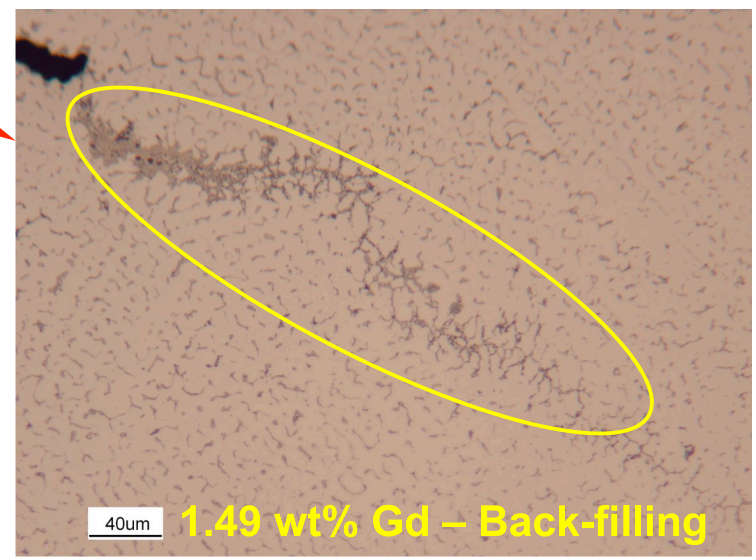
Weldability Results: B-Free Alloys



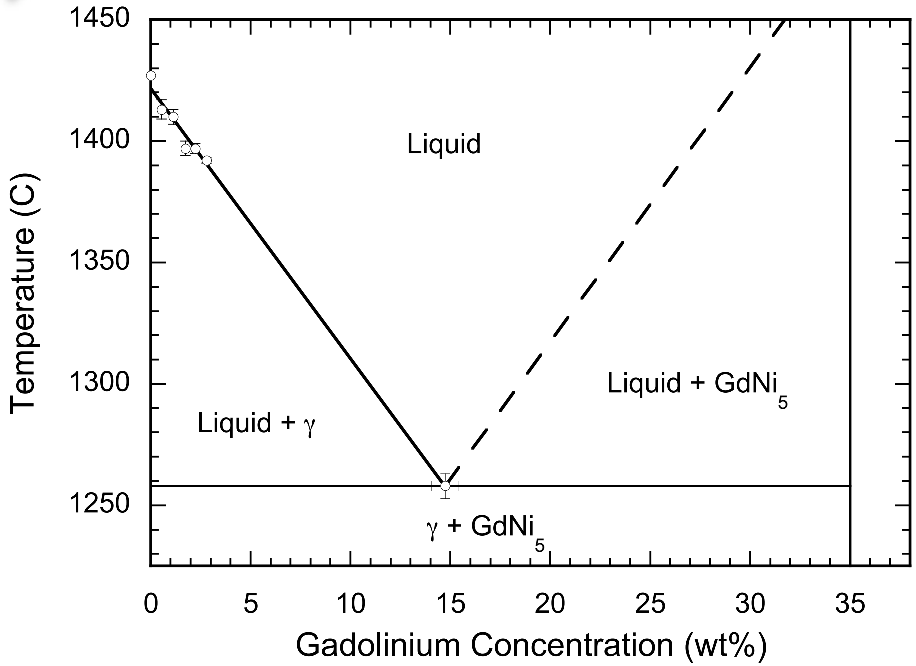


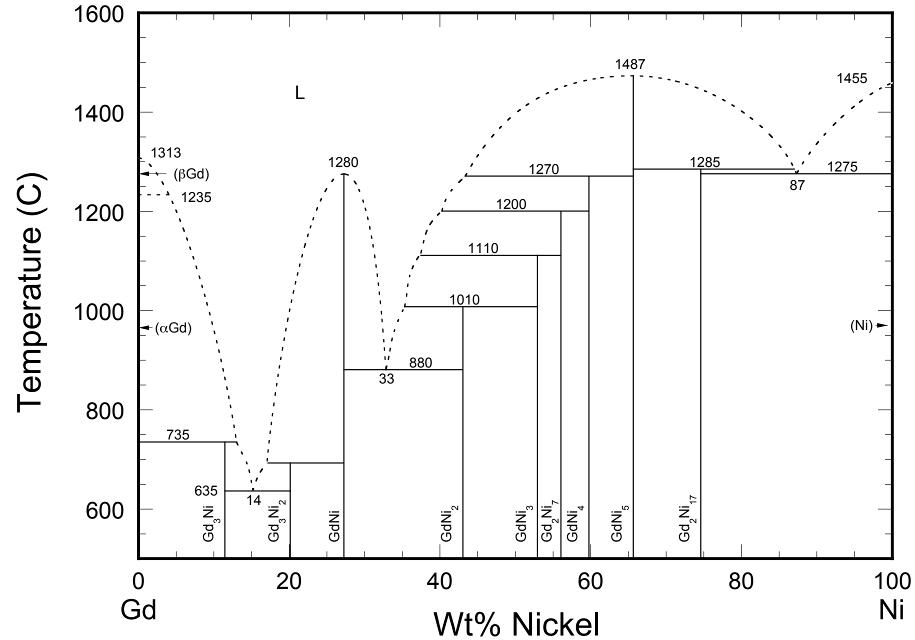


- Cracking susceptibility (at 4% augmented strain) increases up to ~ 1 wt% Gd, then decreases to a level comparable with Gd-free alloy

- Crack healing due to back-filling of eutectic liquid observed above 1.5 wt% Gd

Understanding the Weldability of Gd Alloys





- **Solidification cracking susceptibility controlled in part by ΔT and f_e**
- **ΔT - increases size of crack susceptible mushy region**
- **f_e - Adversely affects cracking susceptibility up to 7-10 vol. %, reduces cracking susceptibility beyond this value due to cracking healing**
- **Pseudo-binary diagram developed and can be used to asses each of these factors as a function of Gd concentration**

From Phase Diagram }

$$f_e = \left[\frac{C_e^{Gd}}{C_o^{Gd}}\right]^{\frac{1}{k-1}} \qquad T_L = T_o + m_L C_o^{Gd} \qquad \Delta T = T_o + m_l C_o^{Gd} - T_e$$

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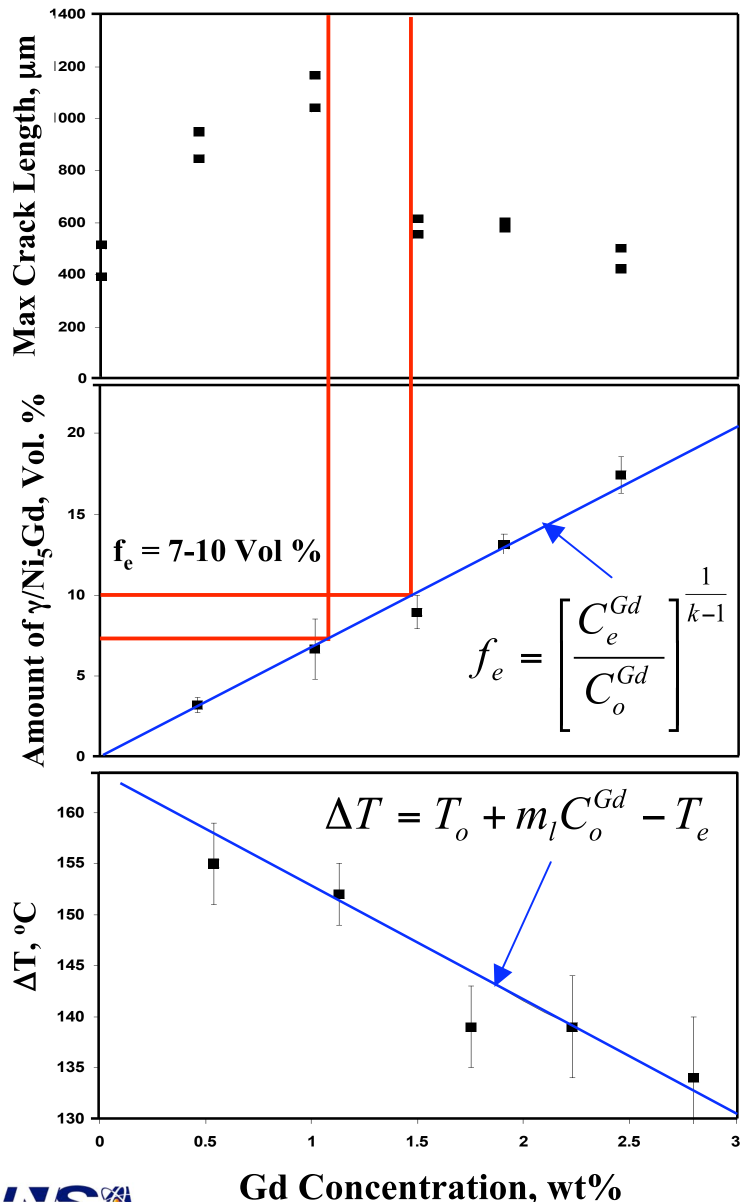
Interpreting Weldability Results



Initial increase in Gd level:

- Slight decrease in ΔT,
- Significant increase f_e
- Cracking susceptibility increases and reaches max. at ~ 1 wt% Gd.

Further increases in Gd:

- f_e increases to point where back-filling occurs (7-10 vol. %),
- ΔT reduction becomes appreciable
- Cracking susceptibility decreases

Quantitative Assessment of Weldability Data

Size of S + L region and variation in f_L within S + L region controls cracking susceptibility and can be estimated:

Scheil equation relates fraction liquid to temperature:

$$f_L = \left[\frac{T_o - T}{T_o - T_L}\right]^{\frac{1}{k-1}}$$

Liquidus line expressed as:

$$T_L = T_o + m_L C_o^{Gd}$$

Variation in temperature within solid + liquid region estimated with Rosenthal solution:

$$T = T_p + \left(\frac{\eta P}{2\pi h r}\right) exp\left[\frac{-S(r-x)}{2\alpha}\right]$$

Combining (along centerline):

$$f_L = \frac{-m_l C_o^{Gd}}{T_o - T_p + \frac{\eta P}{2\pi h x}}$$

- **Expression permits estimation of (1) variation in fraction liquid with location and (2) size of the crack susceptible region of mushy zone as a function of alloy parameters (m_L, k,) and welding parameters (T_0, P).**

f_L = fraction liquid
T_0 = Initial temperature
h = Thermal conductivity
T = Actual temperature
η = Transfer efficiency
S = Travel speed
T_L = Liquidus temperature
P = Power
x = distance from heat source

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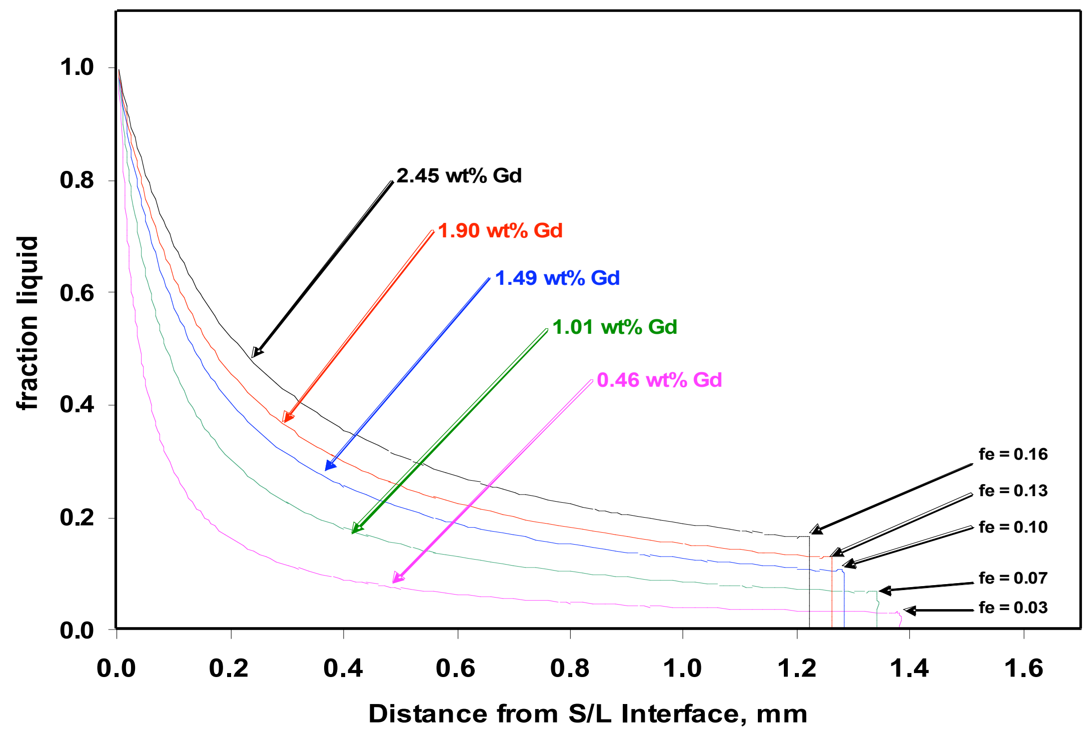
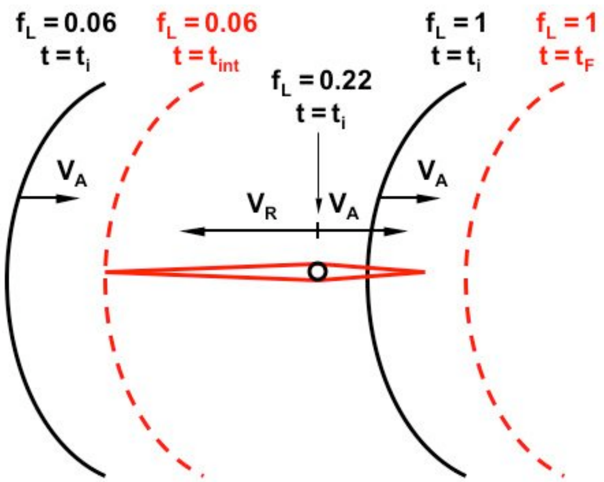
Calculated f_L - x Curves



- Gd additions have an appreciable effect on ΔT, f_e, and distribution of liquid in the mushy zone

Considerations in Longitudinal Varestraint Testing Derived from Video Observations

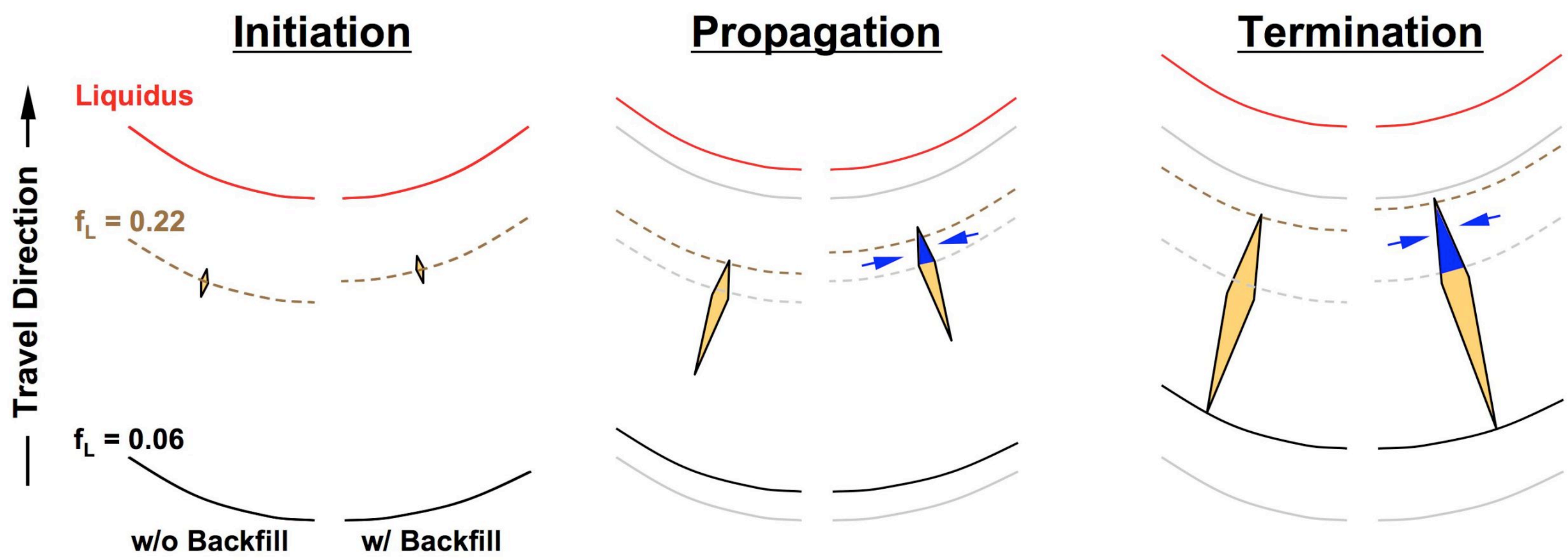


There are three primary considerations:

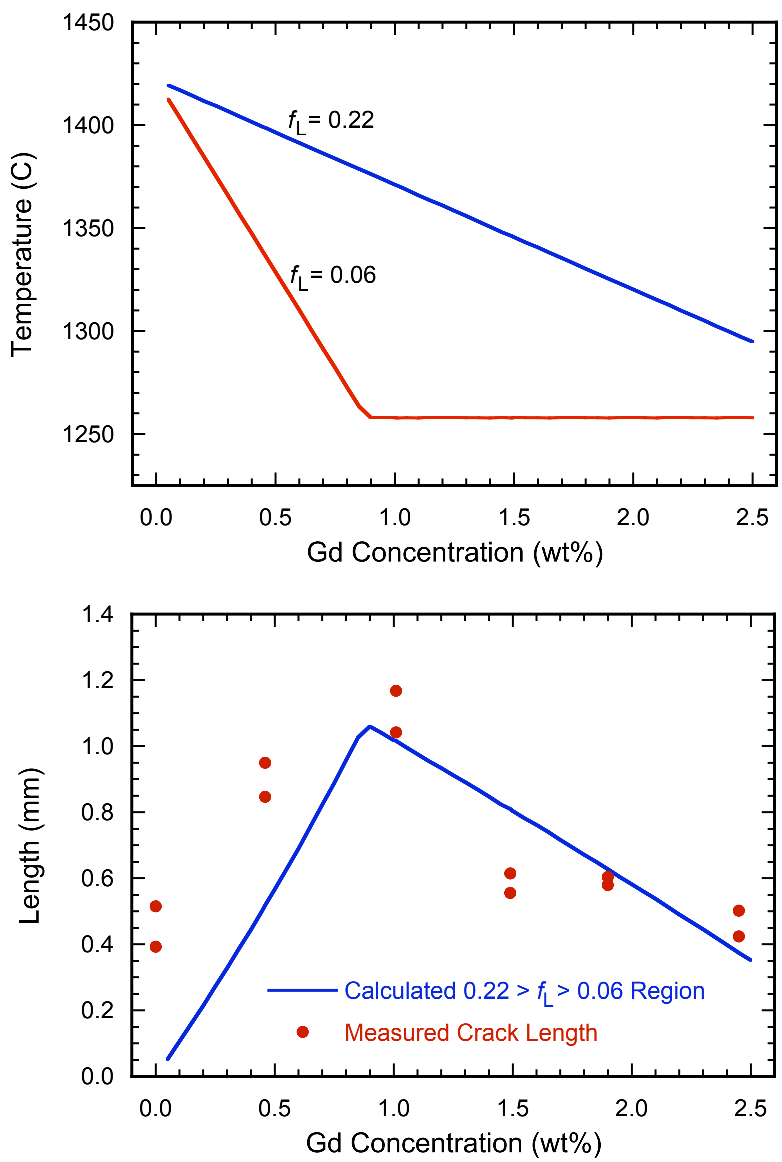
Static: Length of cracking susceptible region of mushy zone ($0.06 < f_L < 0.22$ estimated from IN 718 tests)

Dynamic: Cracking occurs within time dependent strain application and moving temperature fields

Backfilling: If eutectic liquid exists in vicinity of leading crack, infilling occurs during leading crack separation



Static Component of Cracking



- Assuming crack susceptible region of $0.06 < f_L < 0.22$ holds, the length of this region can be estimated with the combined solidification and thermal model
- Length of susceptible region is max near f_L = 0.9 wt% Gd
- However, this does not fully describe the measured crack lengths

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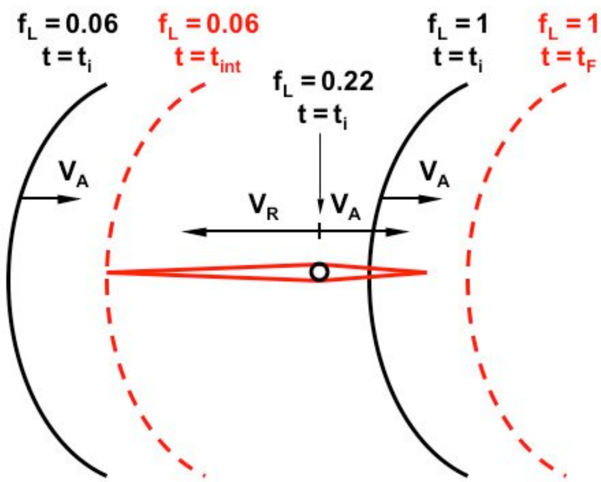
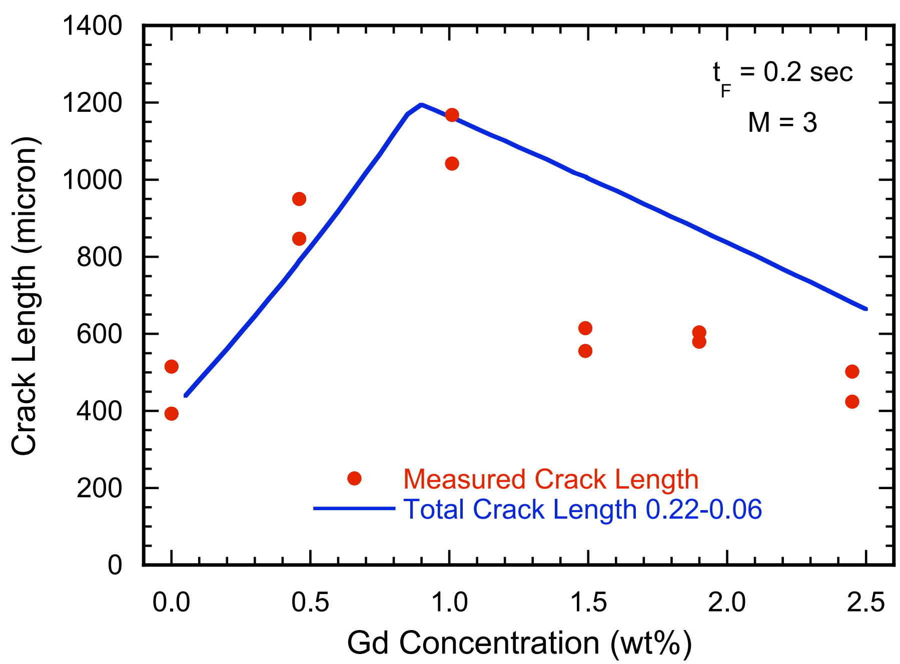
Dynamic Component of Cracking





From the model:

- **Advancing crack length, L_A, is:**

$$L_A = t_F V_A = t_F V_{travel}$$

- **Velocity of retreating crack tip is taken as:**

$$V_R = M V_A$$

- **The length of the retreating crack is found at the intersection of the retreating crack tip with the approaching f_L = 0.06 isotherm**
- **Since video measurements were not made on the actual setup, t_F and M must be assumed (but are similar to those from the IN718 observation**
- **Provides a reasonable description of cracking when backfilling does not occur**

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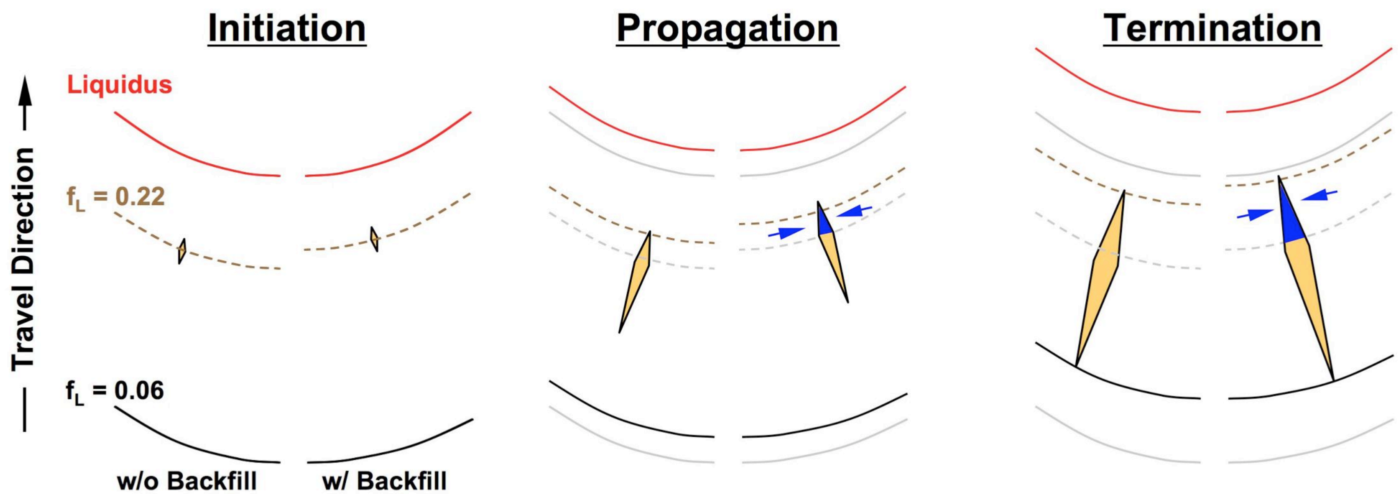
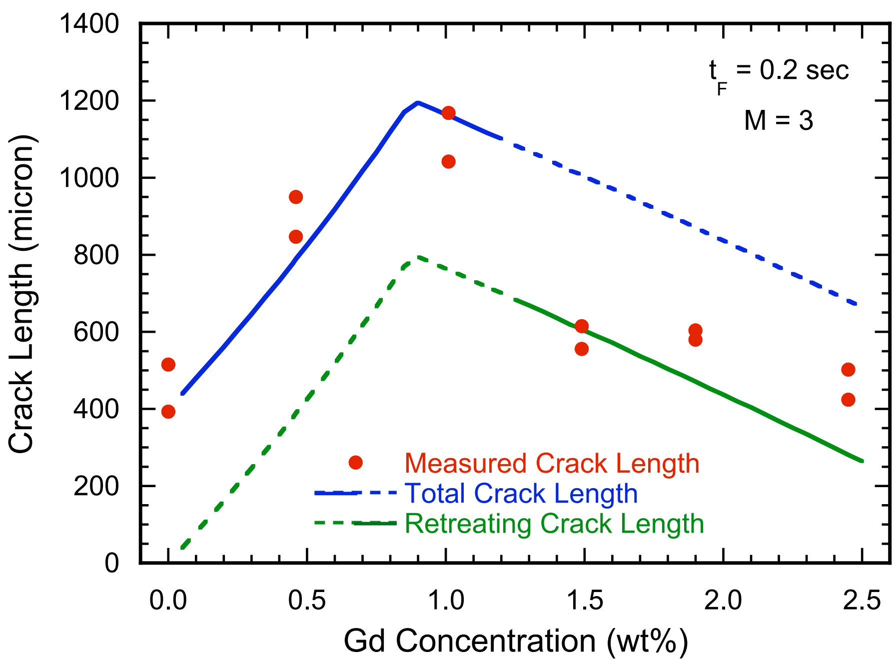
Effect of Backfilling





- To account for backfilling, we consider only the retreating crack length
- The model provides a reasonable description of the overall response
- Model sensitivities will be described at Pine Mountain

Summary

- Gd-containing alloy solidification is similar to binary eutectic systems: $L \rightarrow \gamma$; $L \rightarrow \gamma + Ni_5Gd$
- Cracking susceptibility of Gd alloys maximum at ~ 1 wt% Gd, decreases with both higher and lower Gd additions.
- B additions lead to the formation of an additional $L \rightarrow \gamma + Mo_3B_2$ reaction eutectic type reaction at ~ 1200 ^oC.
- B additions have a strong, deleterious influence on solidification cracking susceptibility.
- Potential benefit of B to spheroidize the Ni_5Gd phase is outweighed by its adverse effect on solidification cracking.
- Simple heat flow equations can be combined with solidification equations to develop f_L -x relation in S/L zone. Calculated $f_L - x$ curves provide insight into composition-weldability relations.
- Simple dynamic model provides a reasonable description of the cracking response in Varestraint tests