Joining of nickel-base superalloy single crystals

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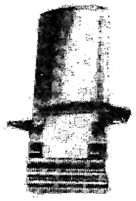
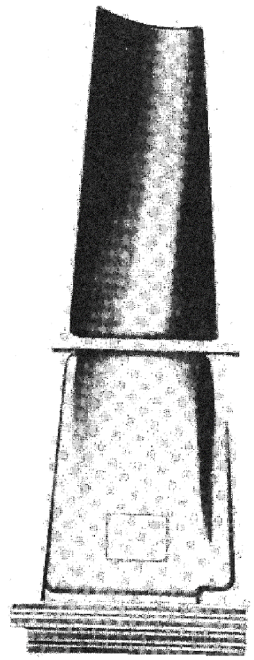
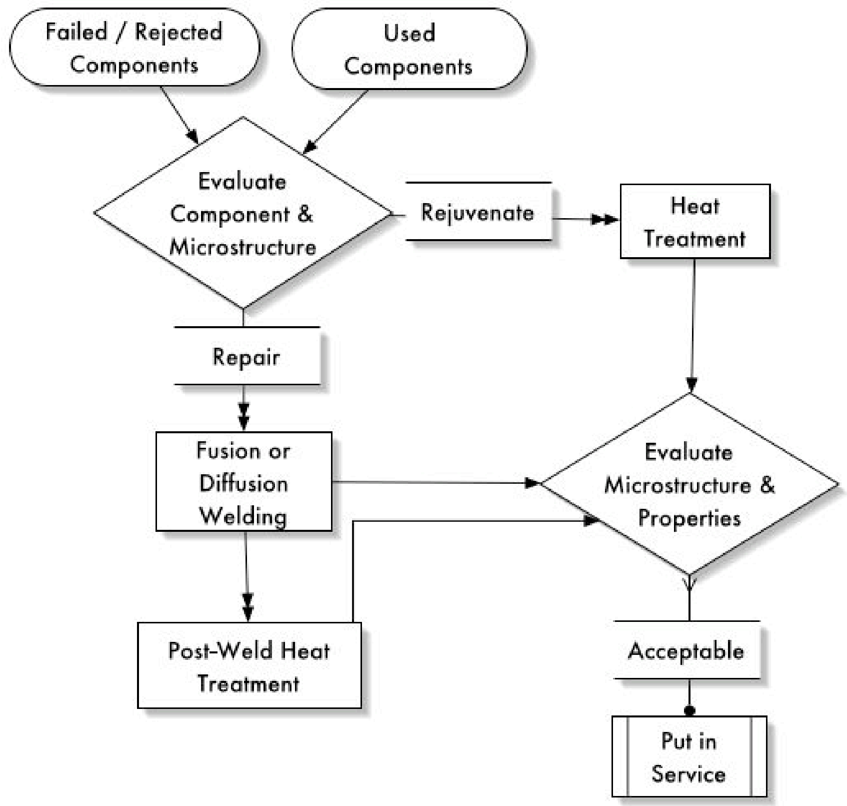
Economical reuse and reclamation of used and failed directionally solidified and single-crystal blades are necessary.



aircraft engine blade



land based turbine engine blades

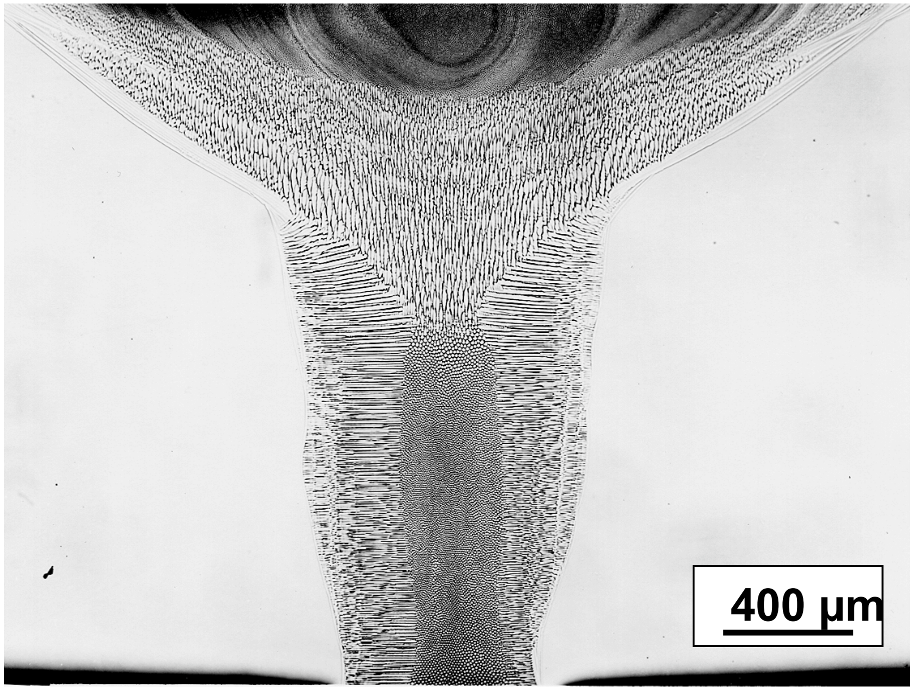


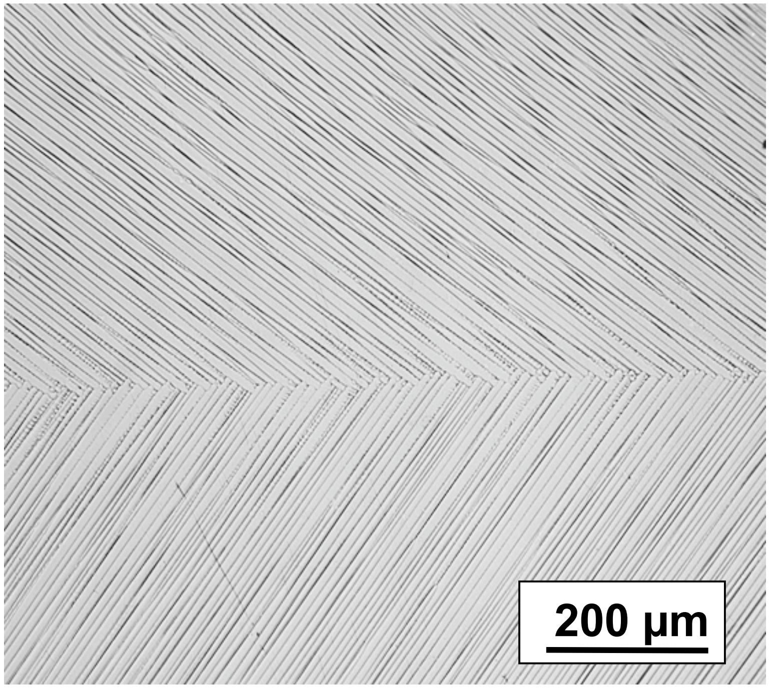
- ***Poor weldability of nickel based superalloy welds has remained a critical issue.***
- ***Welding of single crystals: necessary to develop process and process parameters.***

Outline

- ***Background***
  - ***Overview of single crystal joining research at ORNL***
- ***Important Aspects of Joining Single Crystal Ni-base Superalloys***
  - ***Crystallographic Aspects of Weld Solidification***
  - ***Solid State Decomposition***
  - ***Computational Analysis of Weldability***
- ***Ongoing Research***
- ***Summary and Conclusions***

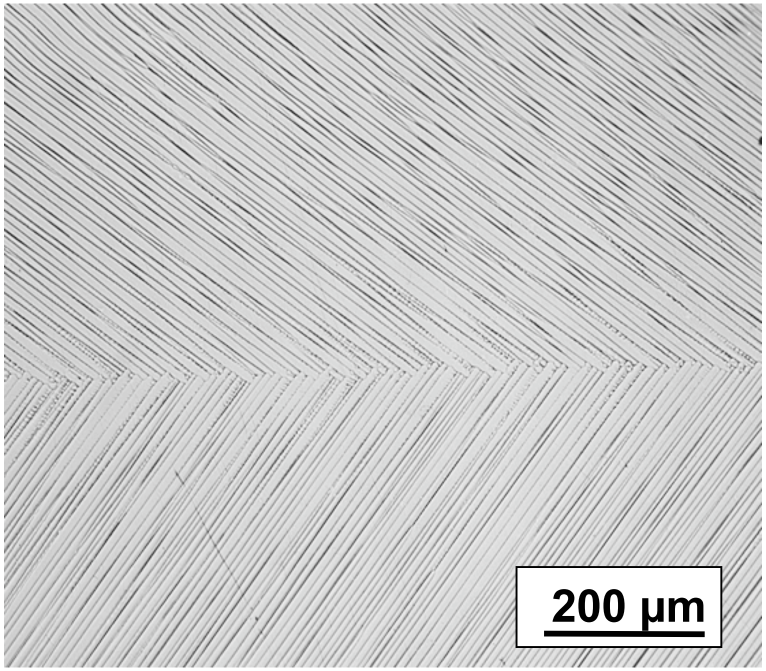
ORNL has investigated extensively welding of single crystals ranging from Fe-Cr-Ni to Nickel base superalloys.



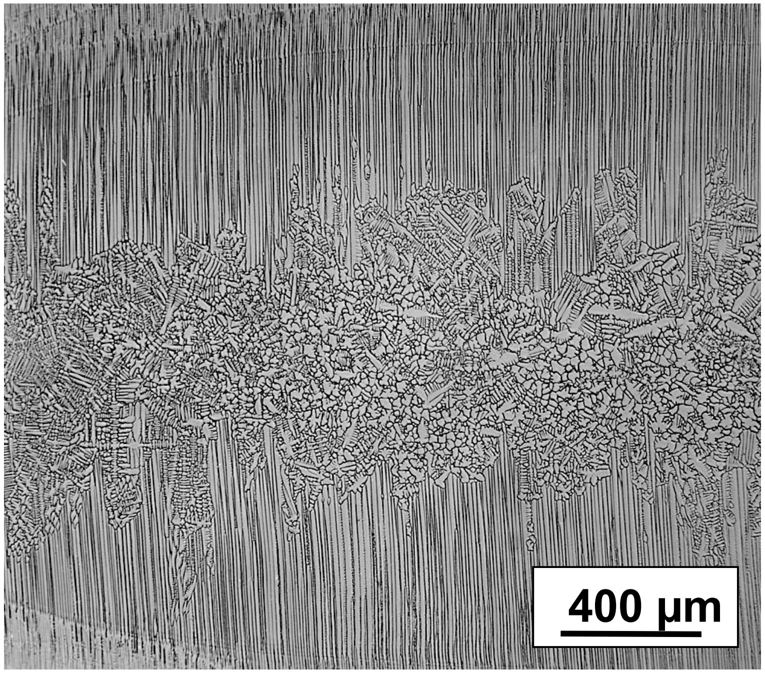


- *Electron beam and laser welding processes were used.*
- *Single crystal nature was maintained in Fe-Cr-Ni single phase alloys.*
- *A geometry model was developed to predict the dendrite growth variants.*

In related work, stray grain formation was observed upon doping Fe-Cr-Ni with small amounts of sulfur.



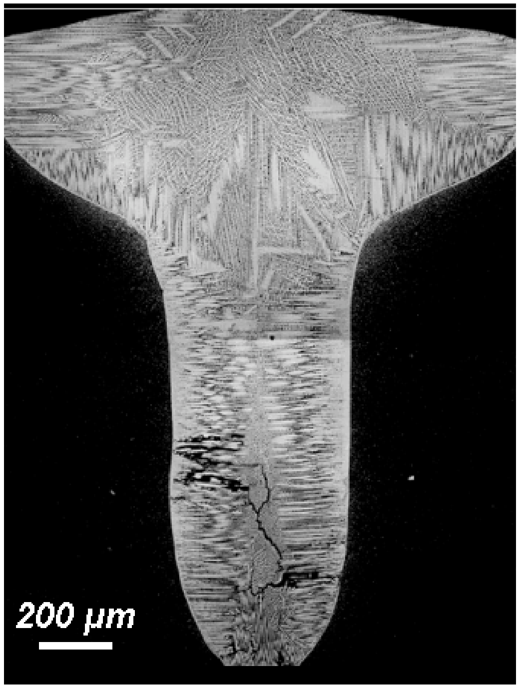
Fe-15Cr-15Ni

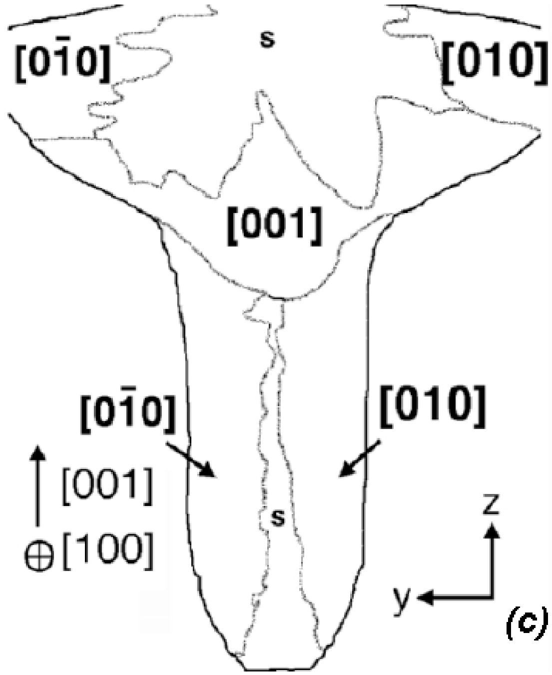


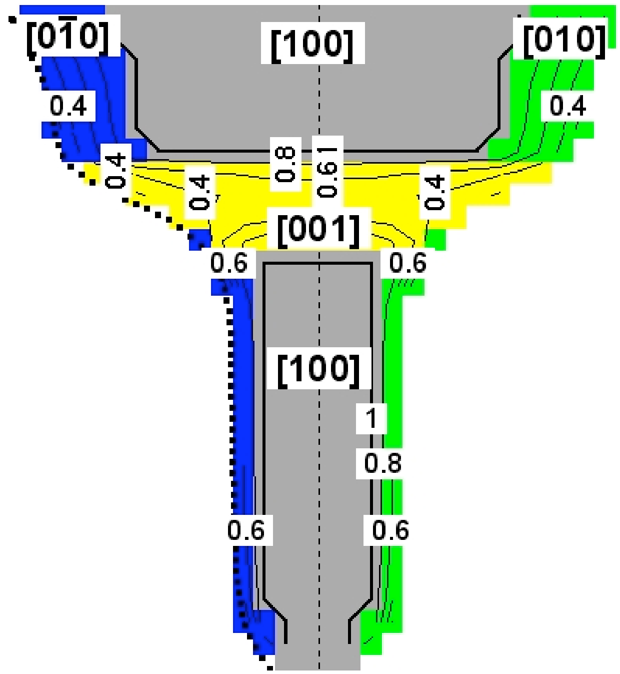
Fe-15Cr-15Ni + S

- *The result was interpreted based on constitutional undercooling theory.*

Fe-Cr-Ni research was extended to fusion welding of PWA-1480 single crystals.

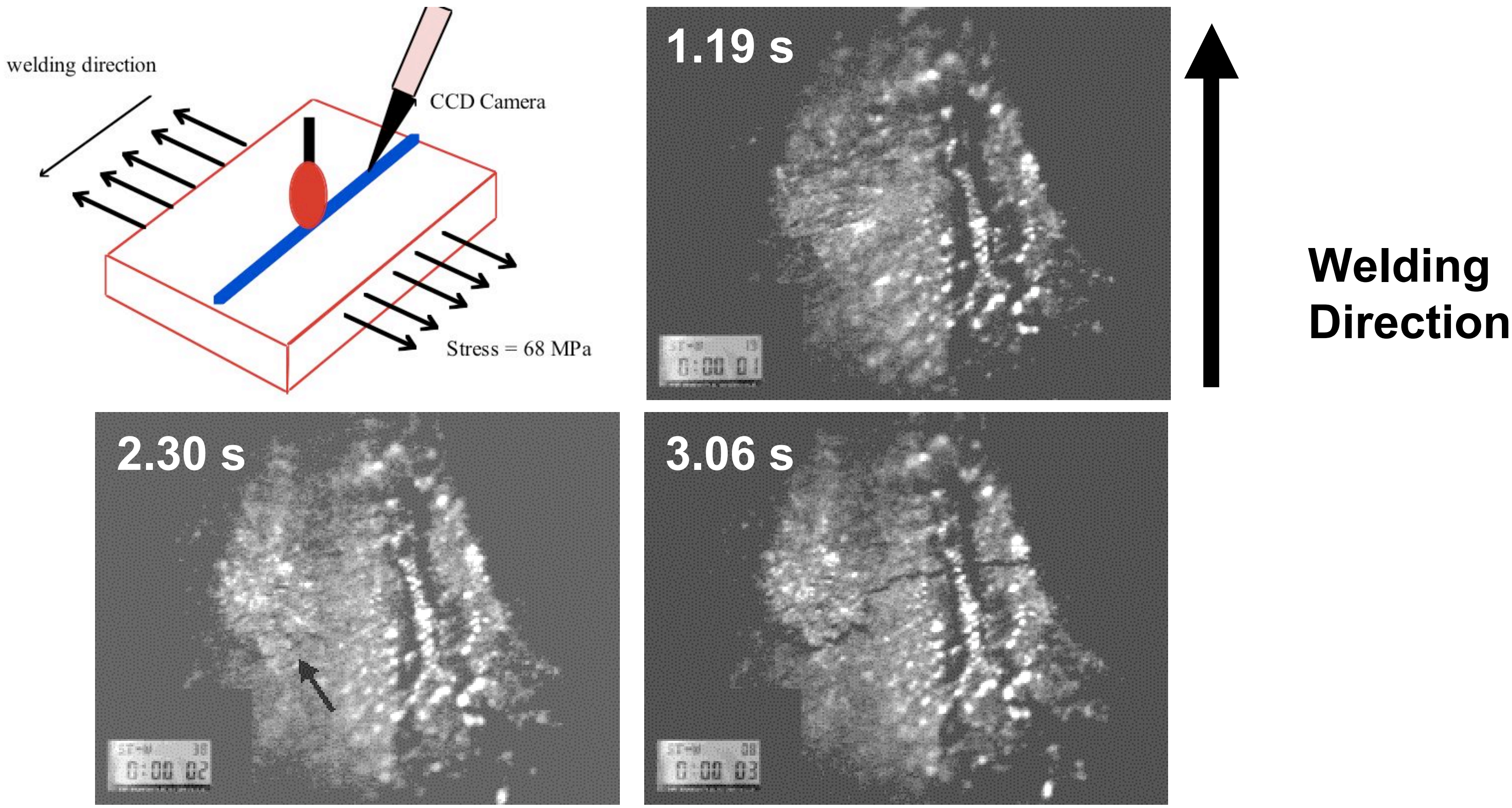






- *Crystal growth directions were in agreement with geometric model.*
- *Stray grains occur in the region of maximum dendrite growth velocity.*
- *Solidification cracks were observed in association with stray grains.*
- *By preheating the base material to 500 °C cracking can be avoided.*

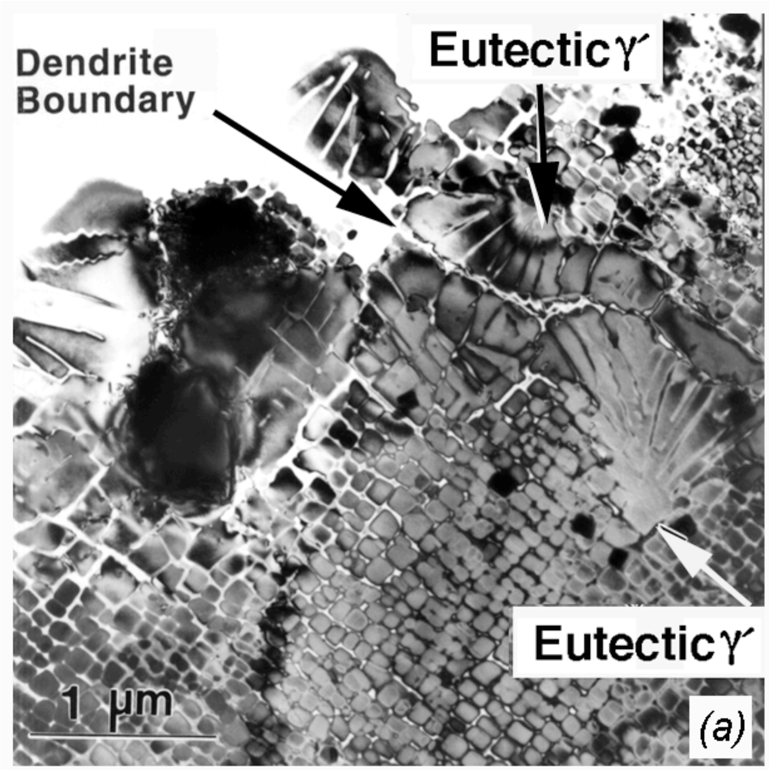
Sub-solidus cracking were also observed in some single crystal alloys.



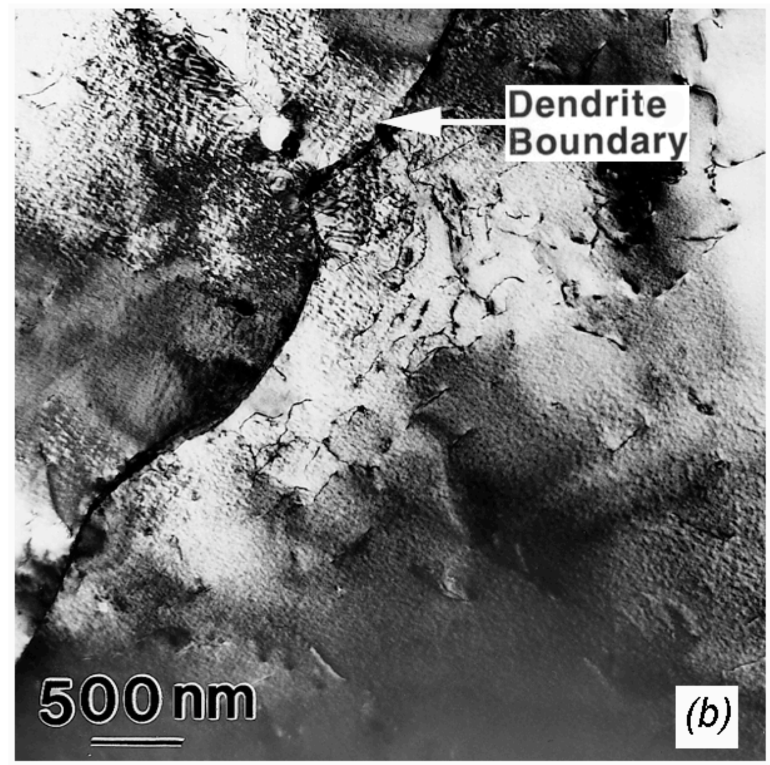
- ***Weld cracks in M738 (~IN738) was transverse in nature.***
- ***By using proper heat-treatment, weld cracking tendency was reduced.***

Solid state decomposition of γ phase leads to different γ′ precipitate characteristics.

PWA1480 EB Weld - 500°C Preheat



CMSX-4 Pulsed Laser Weld - No Preheat



- ***Microstructure evolution is related to differences in cooling rate.***

Summary of previous research:

- ***Weld solidification cracks were severe in nickel base superalloy welds.***
- ***By preheating and welding at low speed (2 - 6 mm/s) crack free welds can be obtained by using electron beam and laser beam welding processes.***
- ***The cooling rates have a large influence on the microstructure evolution.***

- ***Goals of the current work:***
  - ***Systematic experimental and theoretical research to understand the physical processes that occur in fusion welding of commercial nickel base superalloy single crystals***

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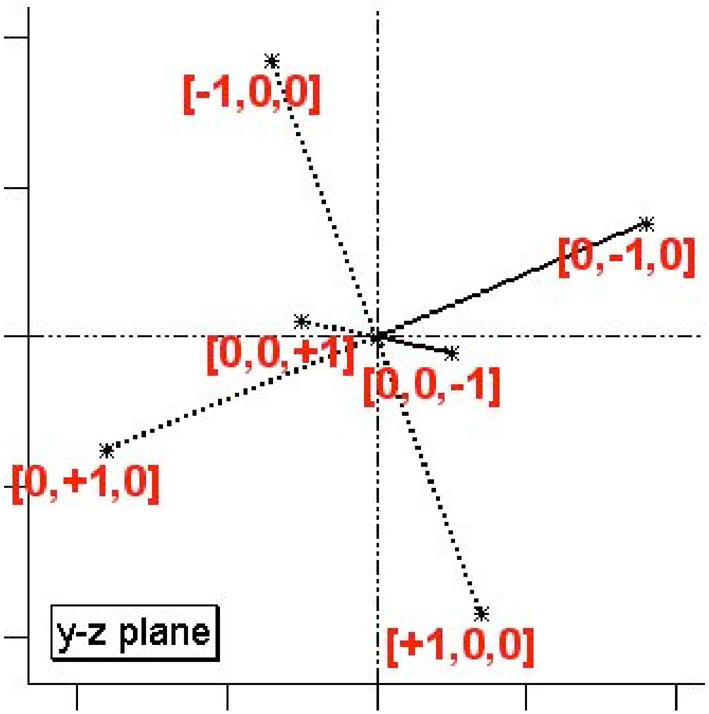
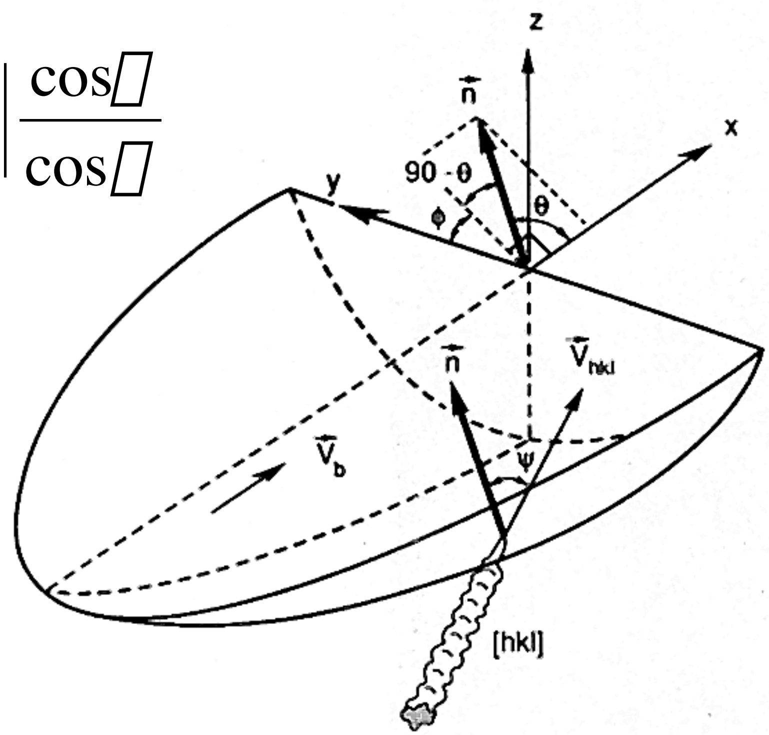
In recent work, the effect of base metal crystal misorientation with welding direction was evaluated.



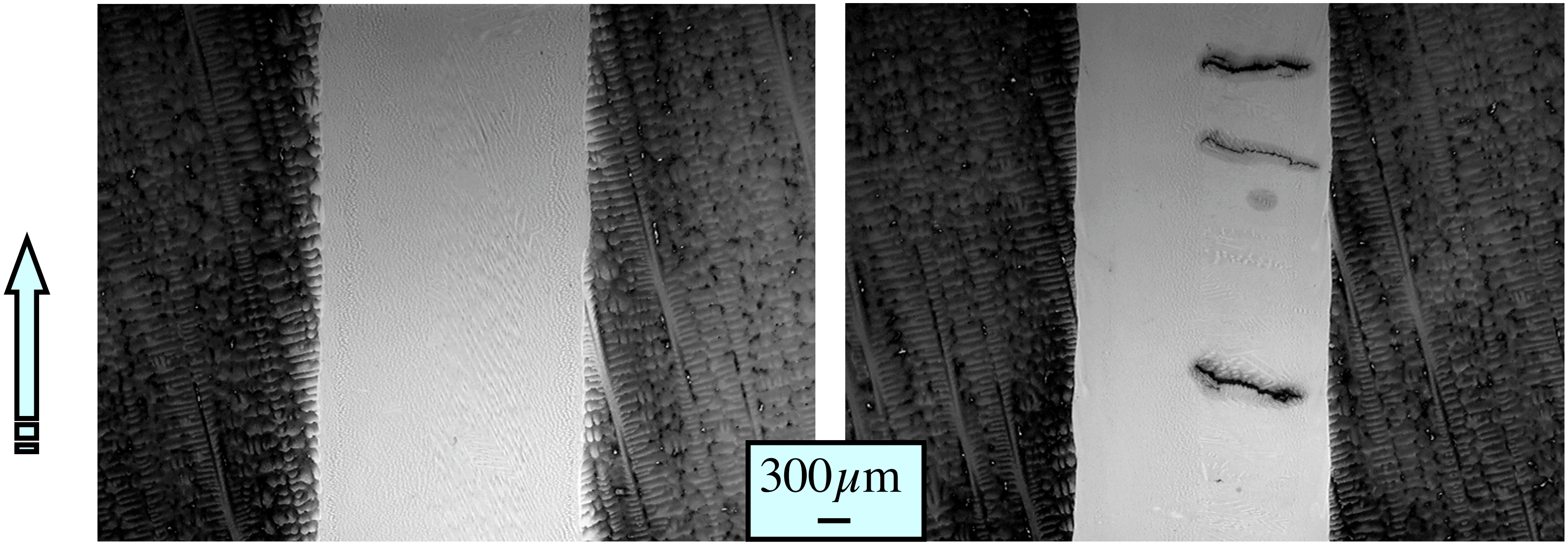
$$\left|\vec{V}_{hkl}\right| = \left|\vec{V}_{weld}\right| \frac{\cos\square}{\cos\square}$$



- Laser welds were made on thin sheets of N5 (Ni-6.2 Al-7.5Co-7Cr-1.5Mo-5W-3.00Re-6.5Ta-0.15Hf-0.004 - 0.05C wt.%) single-crystal nickel-base superalloy.
- Crystal orientations were characterized with Laue diffraction.

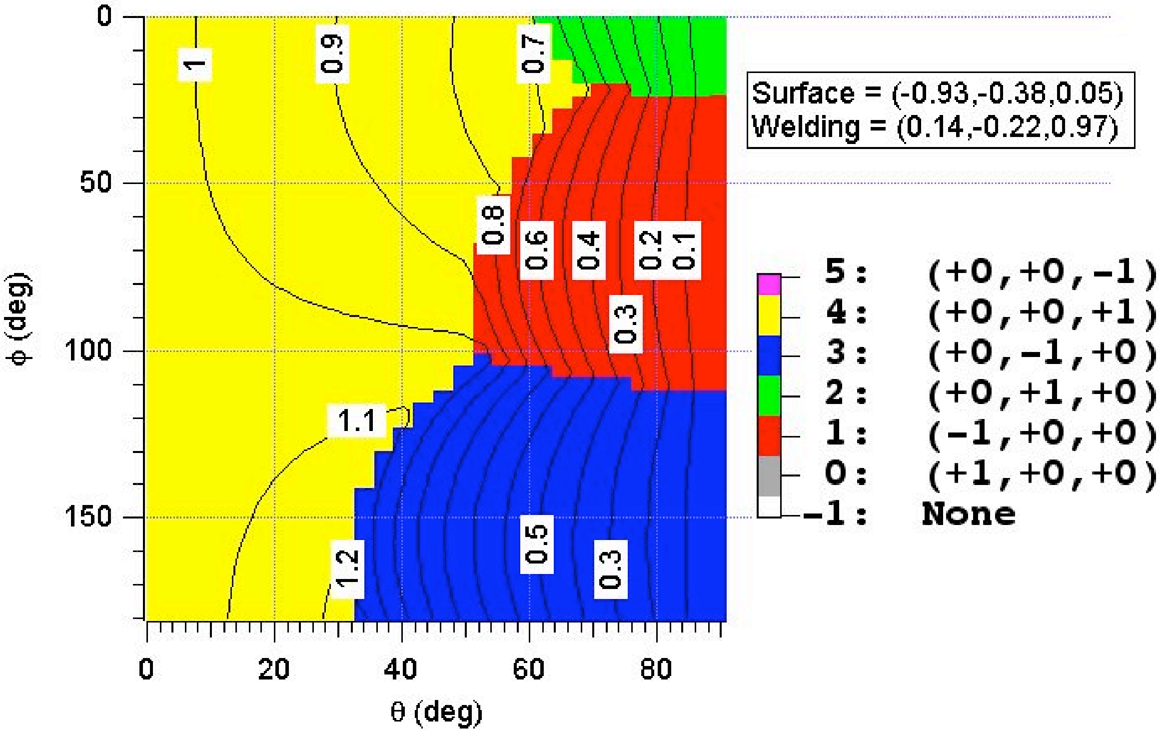
At high welding speeds, weld cracking was promoted. Interestingly, the cracks were observed in only one side!

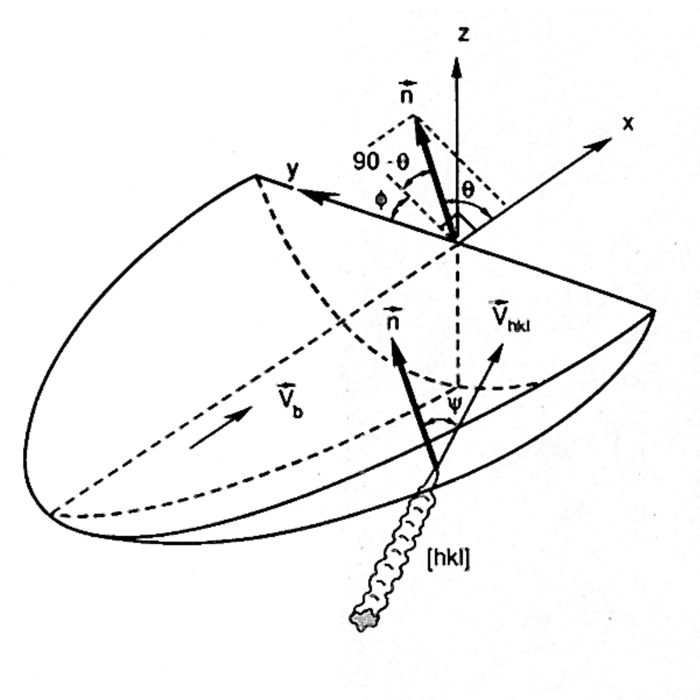
4.2 mm/s **12.7 mm/s**



- ***Cracking phenomena were investigated with orientation imaging microscopy, geometric model and computational heat-transfer and stress analyses models.***

Geometry model predicts the growth of dendrites with [001], [0,-1,0], [0,1,0] and [-1,0,0] variants.

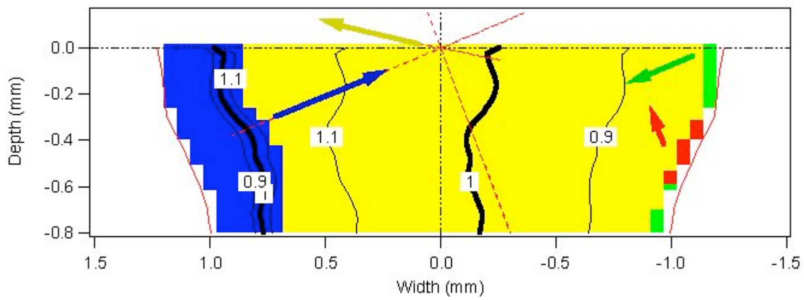


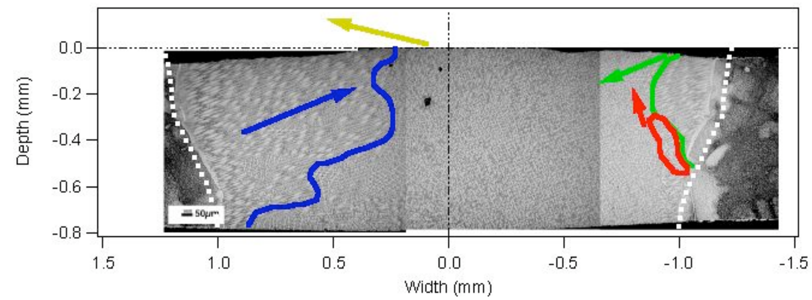


- ***Asymmetry in crystal growth and associated changes in dendrite growth velocities were predicted.***

Geometry model predicts asymmetric growth for both welding speeds.

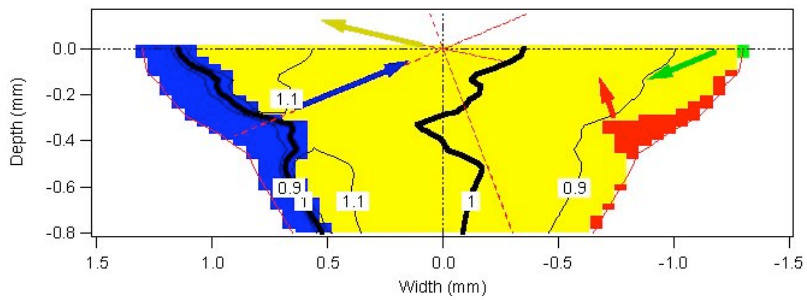
4.2 mm/s

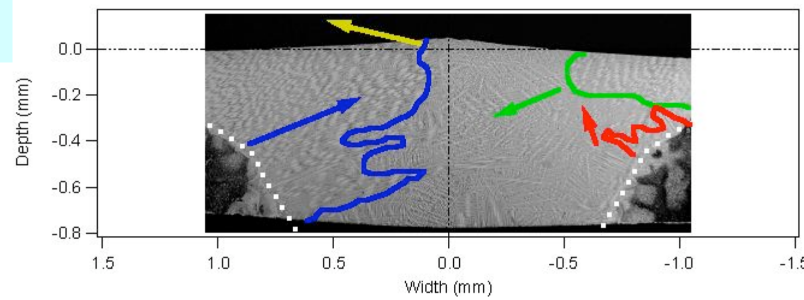




[0,-1,0] **[0,1,0]** **[0,0,1]** **[-1,0,0]**

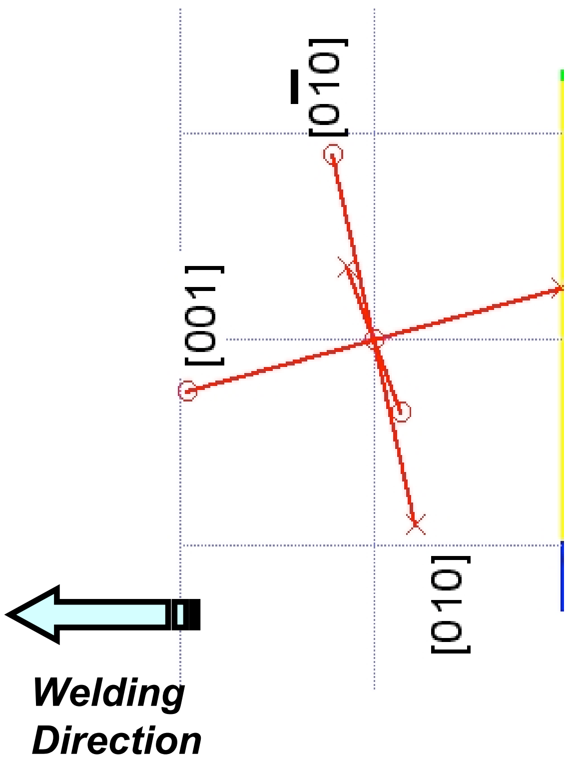
12.7 mm/s



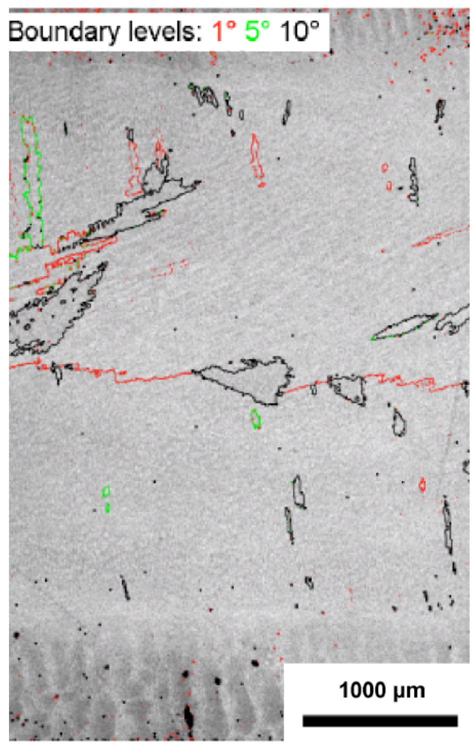


- ***Increase in welding speeds leads to large area fraction of [0,0,1] growth with velocity ratio reaching >1.***
- ***Stray grains and cracking were observed only at high speed welds.***

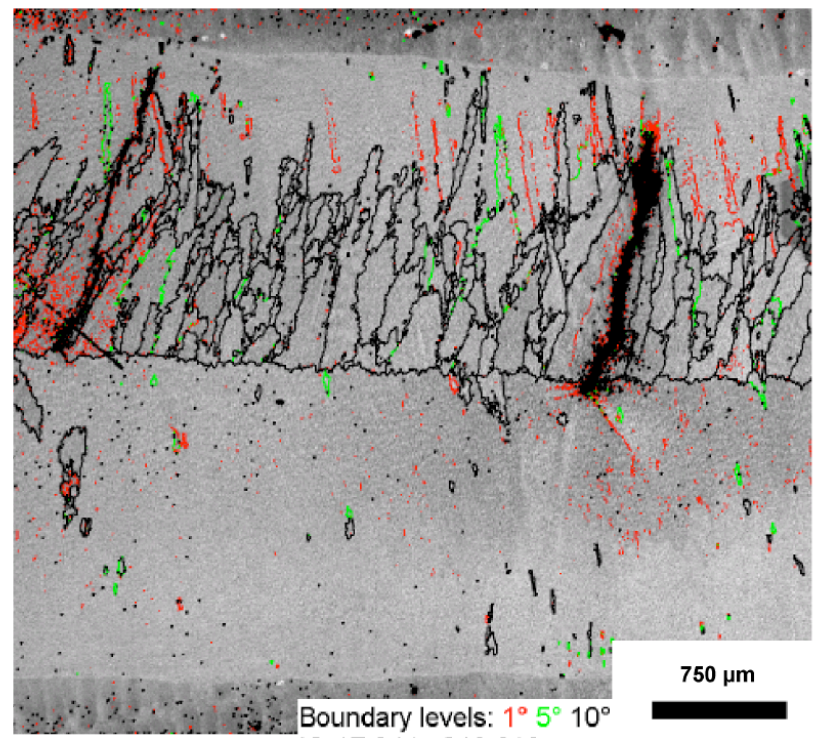
As welding speed increased to 12.7 mm/s, numerous stray grains with large misorientations formed and were associated with cracks.



4.2 mm/s

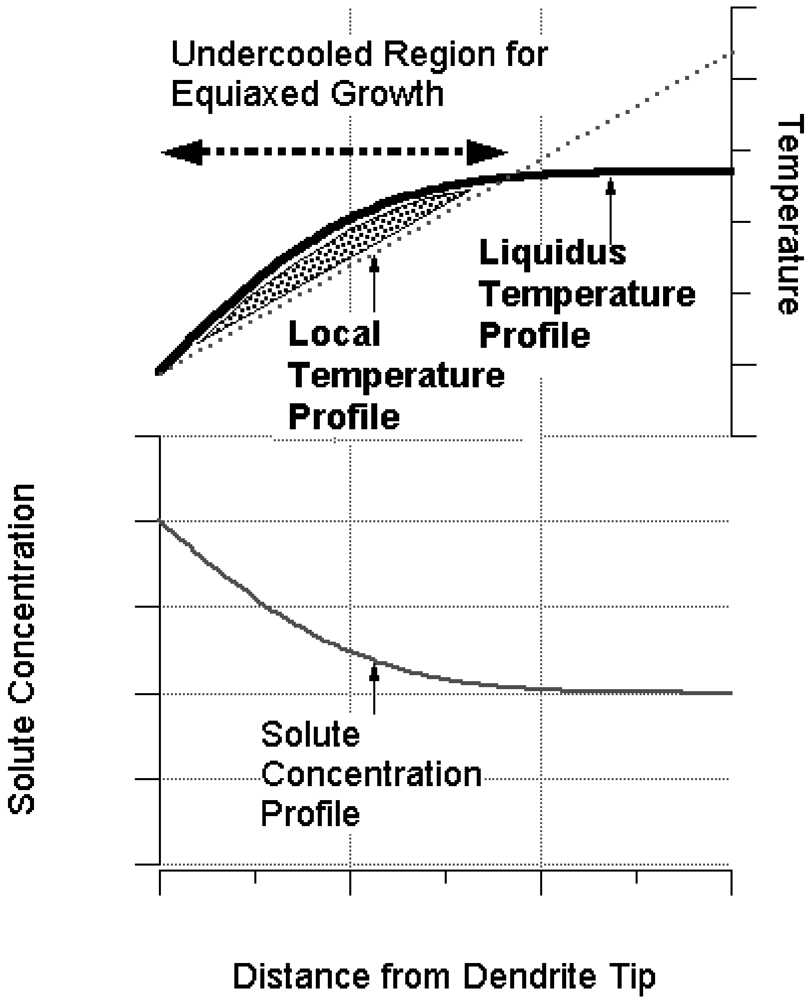


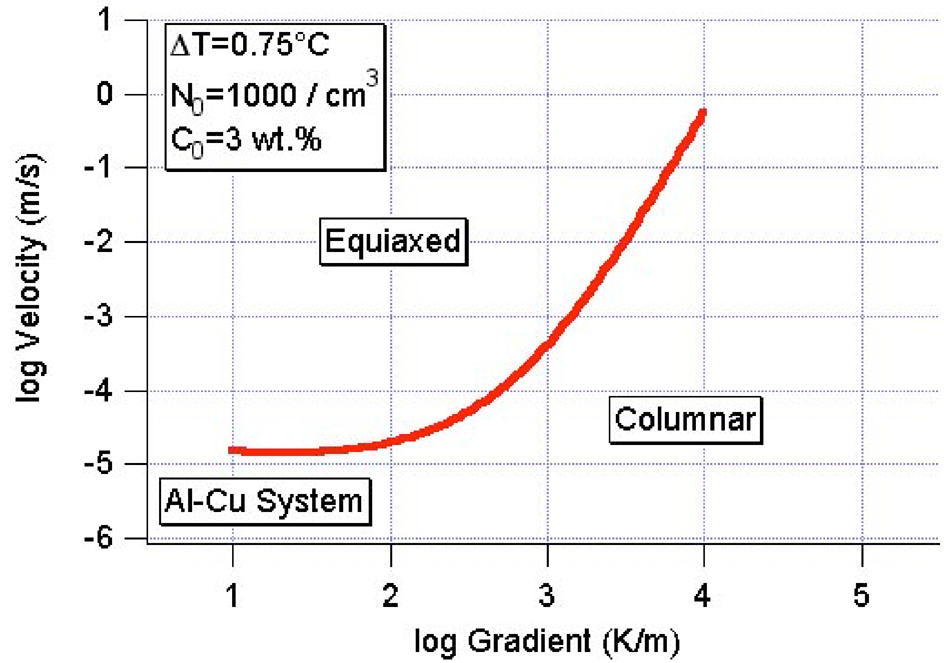
12.7 mm/s



- ***Most stray crystals were observed in [0,0,1] zone.***

Formation of stray grains can be explained by the constitutional undercooling model.

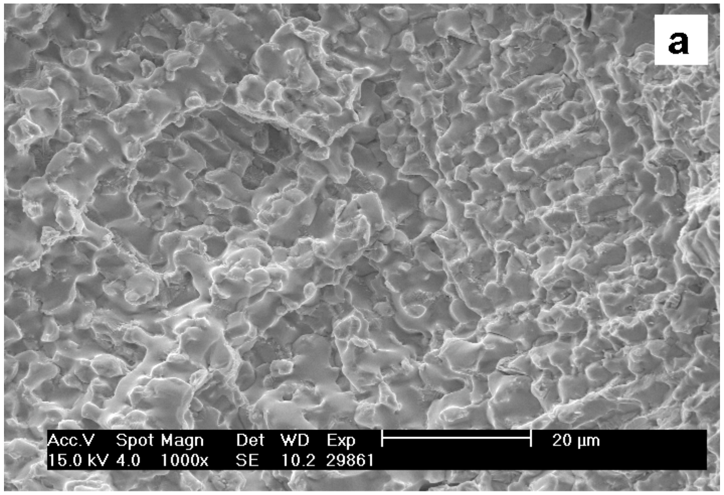


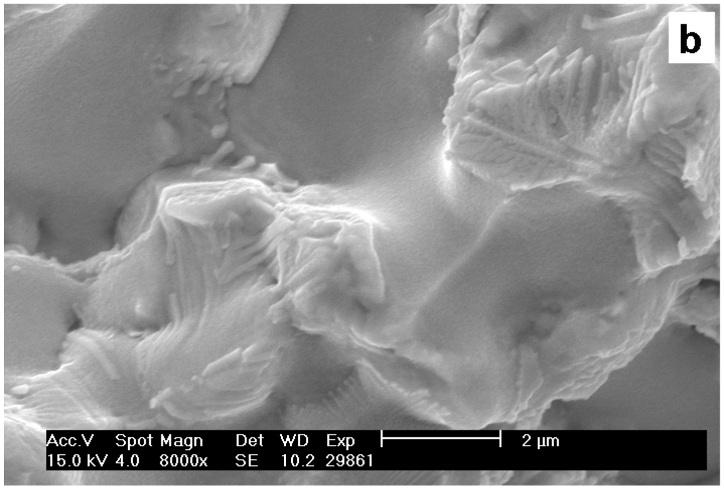


M. Gaumann, Trivedi and Kurz, Materials Science and Engineering, A226-228, 1997, p. 763-769.

- ***Probability of "stray" or equiaxed grain formation increases with an increase in constitutional undercooling. For a given temperature gradient, the probability of stray grains increases with an increase in welding speed.***

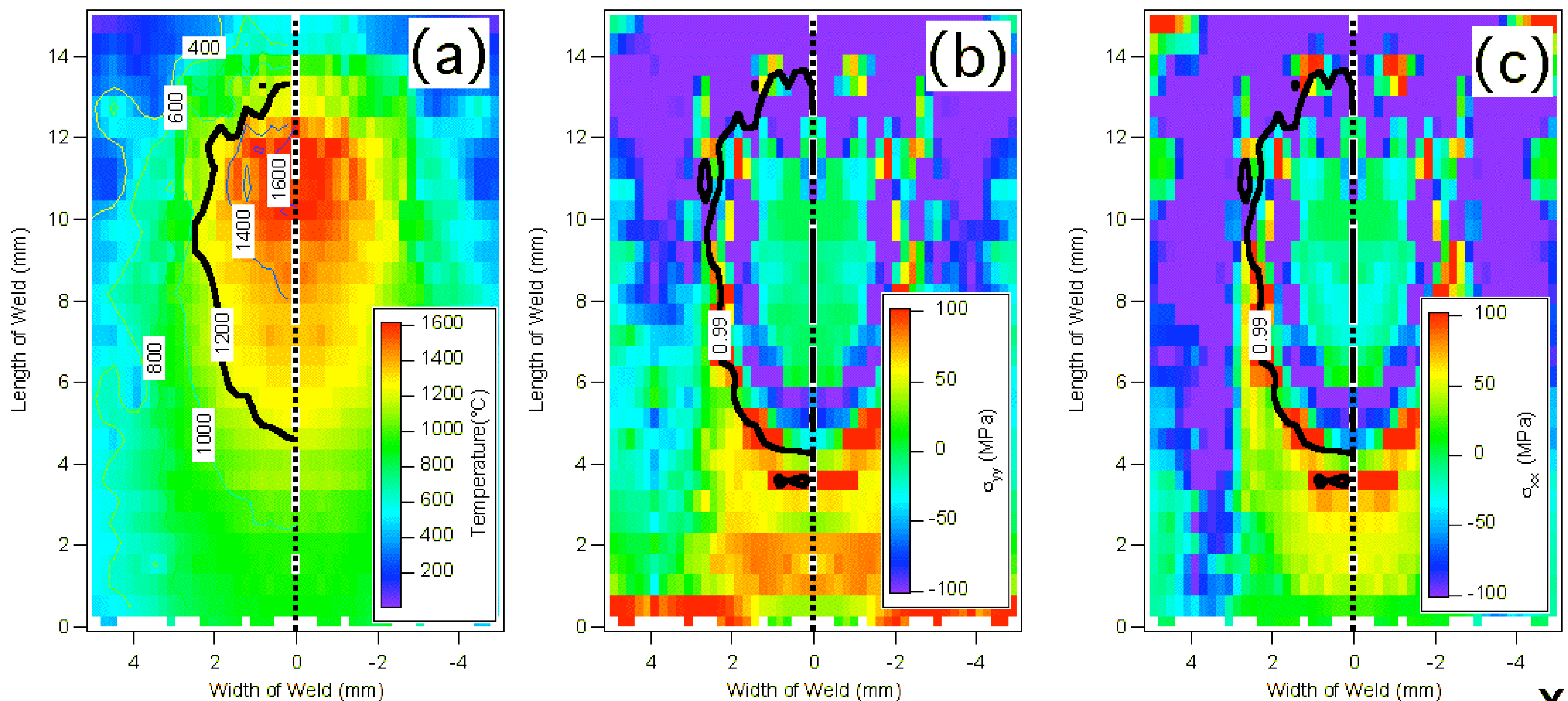
Scanning electron microscopy shows dendritic regions on the cracked surface and supports the hypothesis that cracking occurred during solidification.

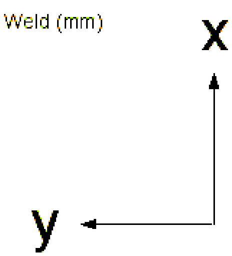




- *In addition to the presence of liquid film along dendritic boundaries, there must be a tensile stress to initiate cracks.*
- *Supporting work was performed with computational heat transfer and stress evolution models using SYSWELD® a commercial finite element package.*
- *Temperature and stress distribution for welds made at 4.2 and 12.7 mm/s welding speed were analyzed.*

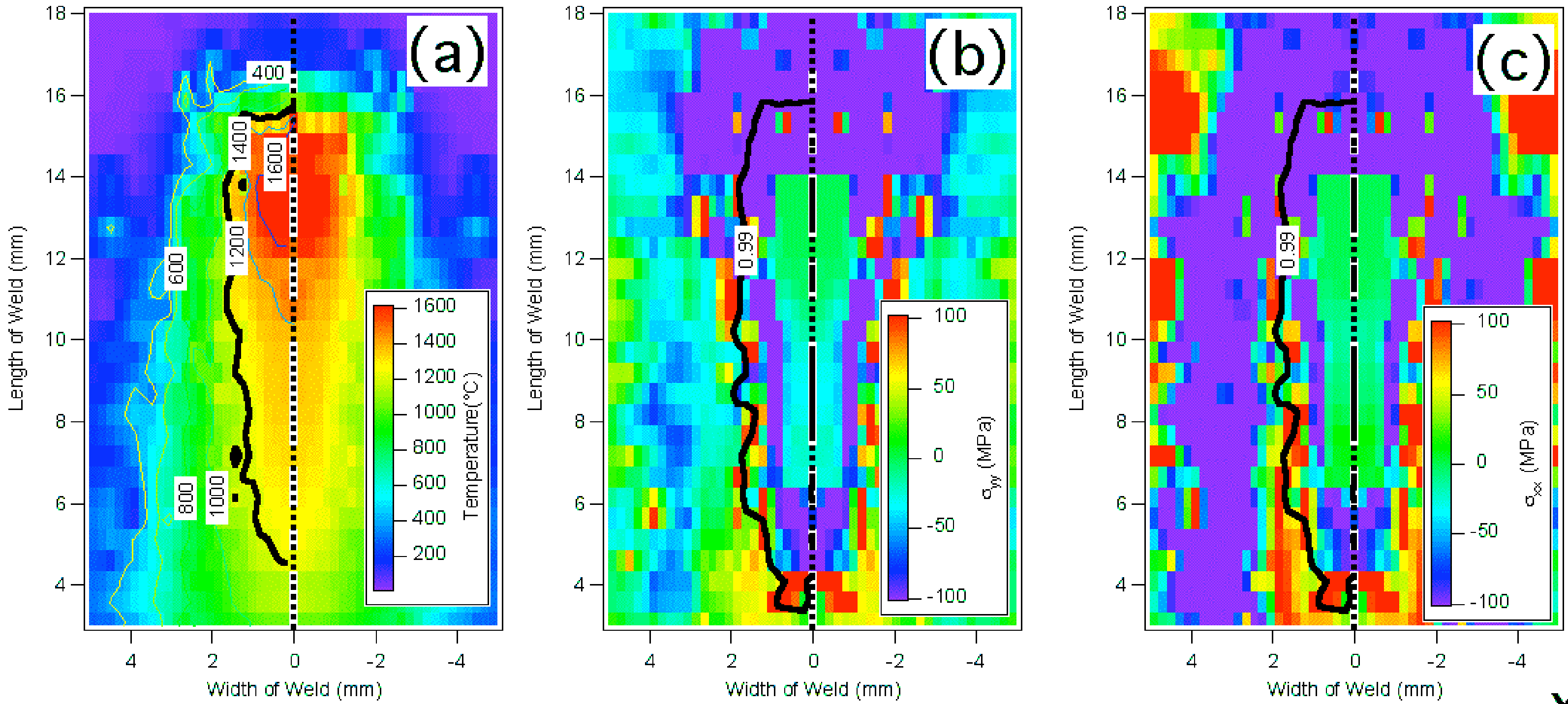
Tensile thermal stresses develop as the solid fraction reaches 0.99 in the weld region: (Speed=4.2 mm/s)



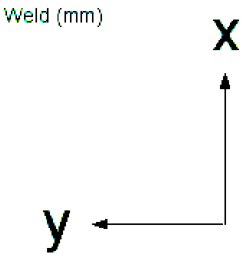


- ***Both σ_{xx} and σ_{yy} are tensile.***

At higher welding speeds (12.7 mm/s) the weld regions at solidus temperature experience stresses twice that of yield strength at that temperature.



- ***This work shows that cracking is due to complex interactions between crystallography, solidification grain structure and thermomechanical conditions.***



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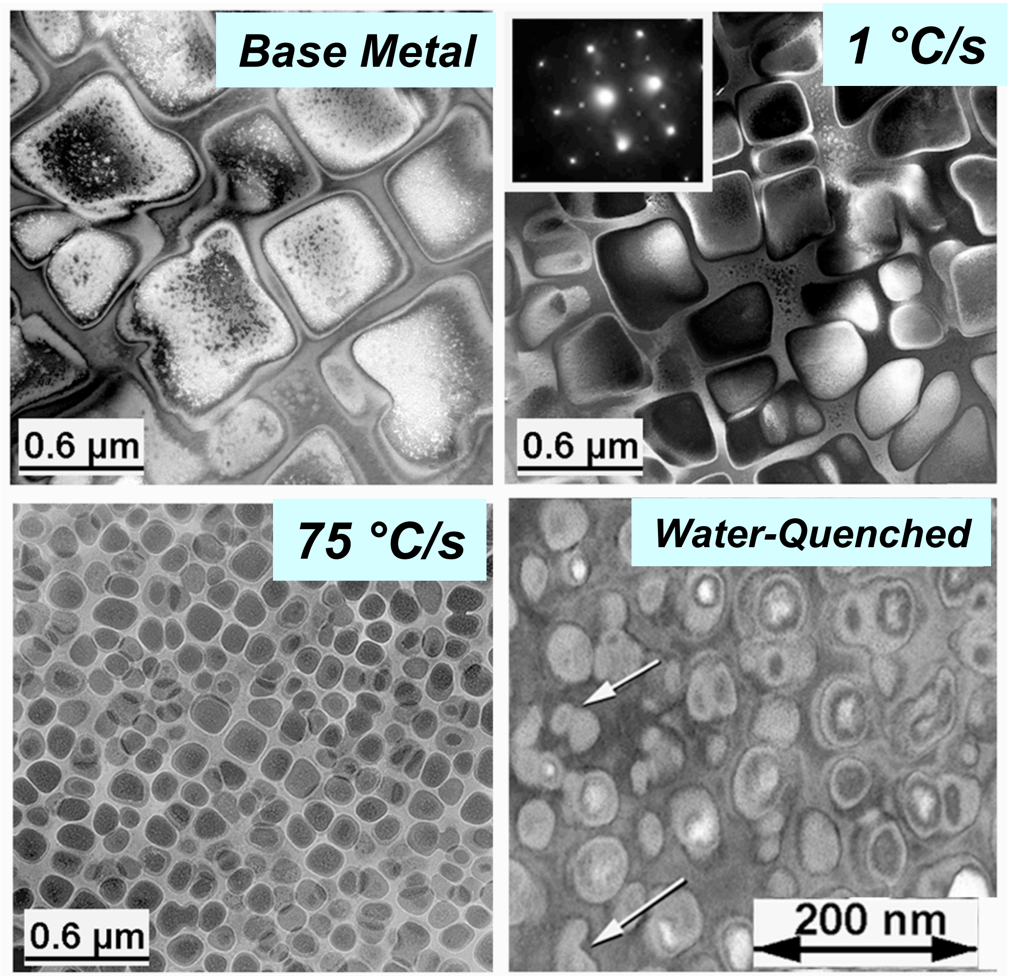
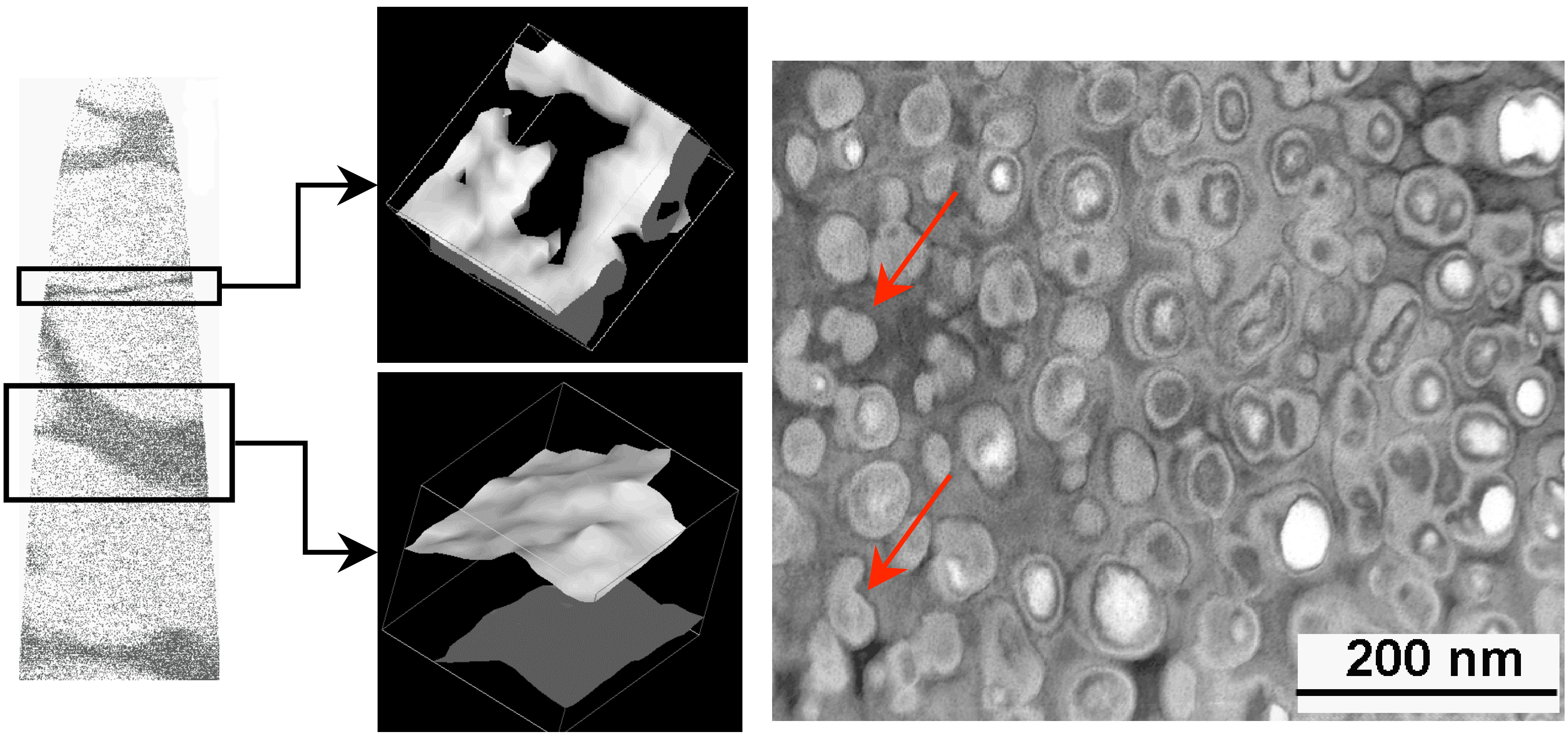
Microstructural evolution in CM247DS [Ni - 5.5% Al - 8.0% Cr - 0.8% Ti - 9.0% Co - 3.2% Ta - 9.5% W (wt.%)] alloy was characterized after continuous cooling from 1300 °C.



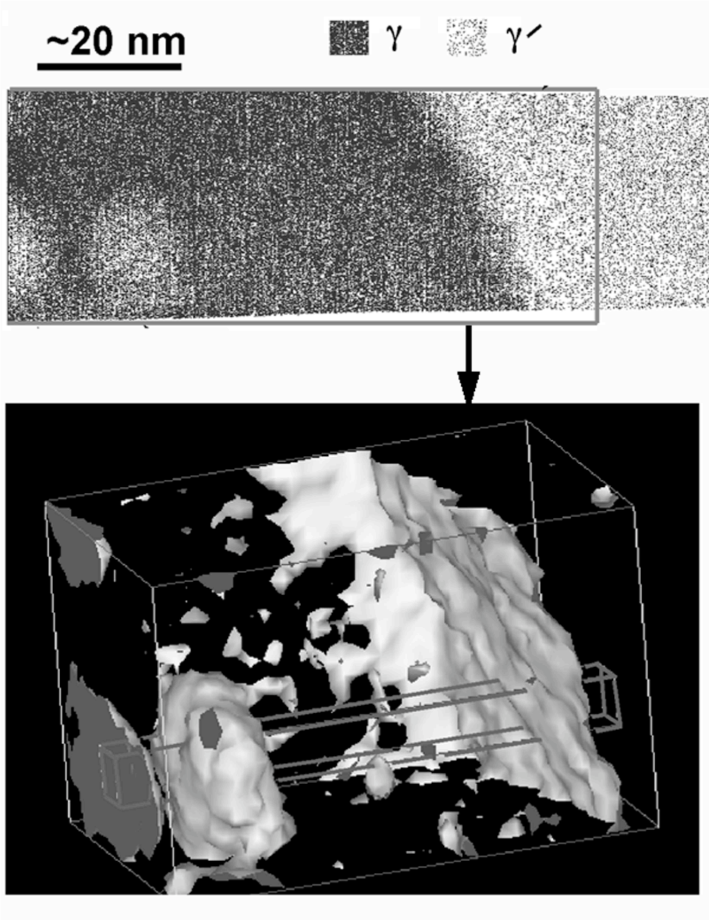
- *Change is more dramatic on water-quenching the sample.*
- *The result can be rationalized with nucleation and growth theories.*
- *Change in shape from cuboidal to irregular with increase in cooling rate was also observed.*
- *Reference: Babu et al Acta Materialia, December 2001.*

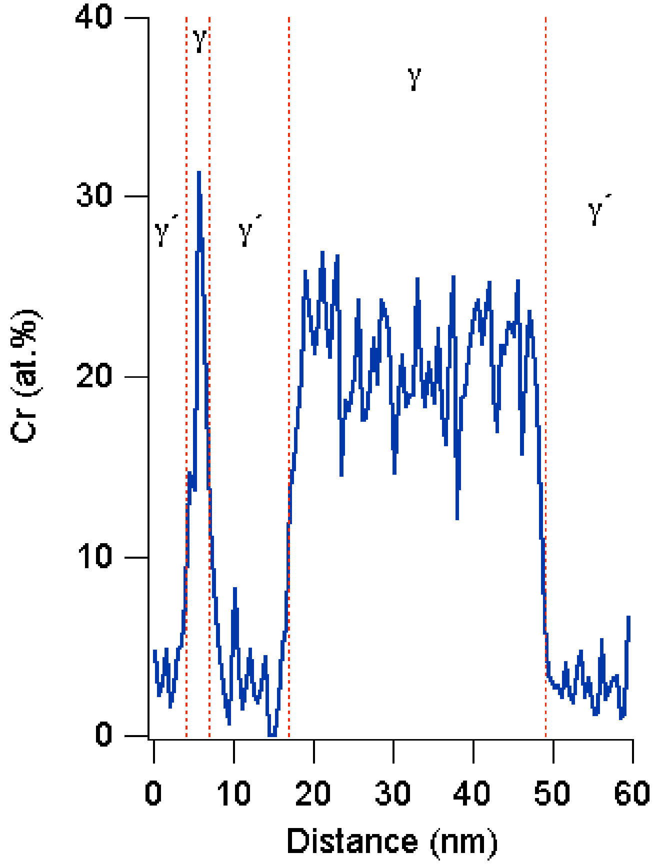
Interconnected and distinct precipitates were observed in the water-quenched sample.



- *Thin regions in between the interconnected were not enriched in chromium and the reasons for this are unclear.*

Primary and secondary precipitates were observed in the samples cooled at 1 °C/s.





- *The region in between the secondary precipitates was enriched in chromium.*

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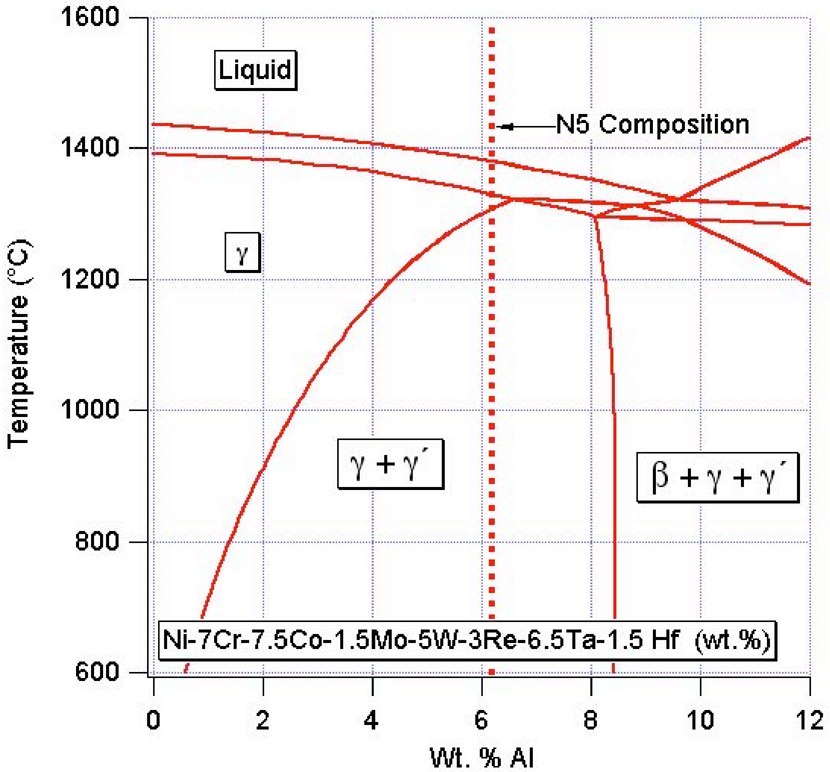
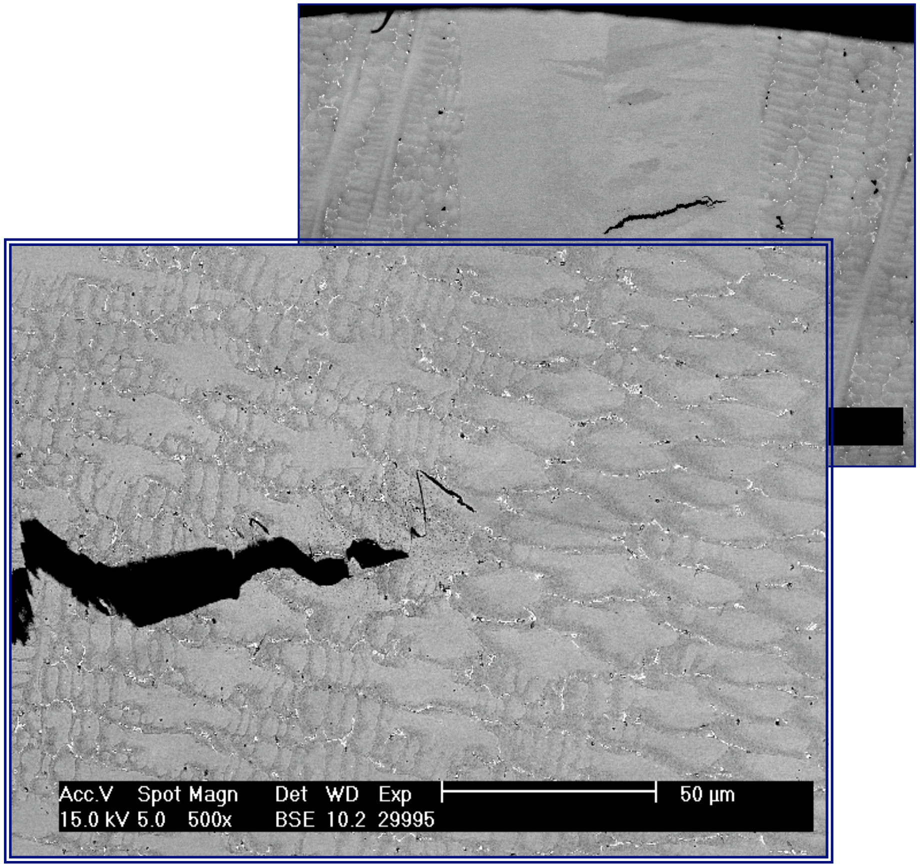
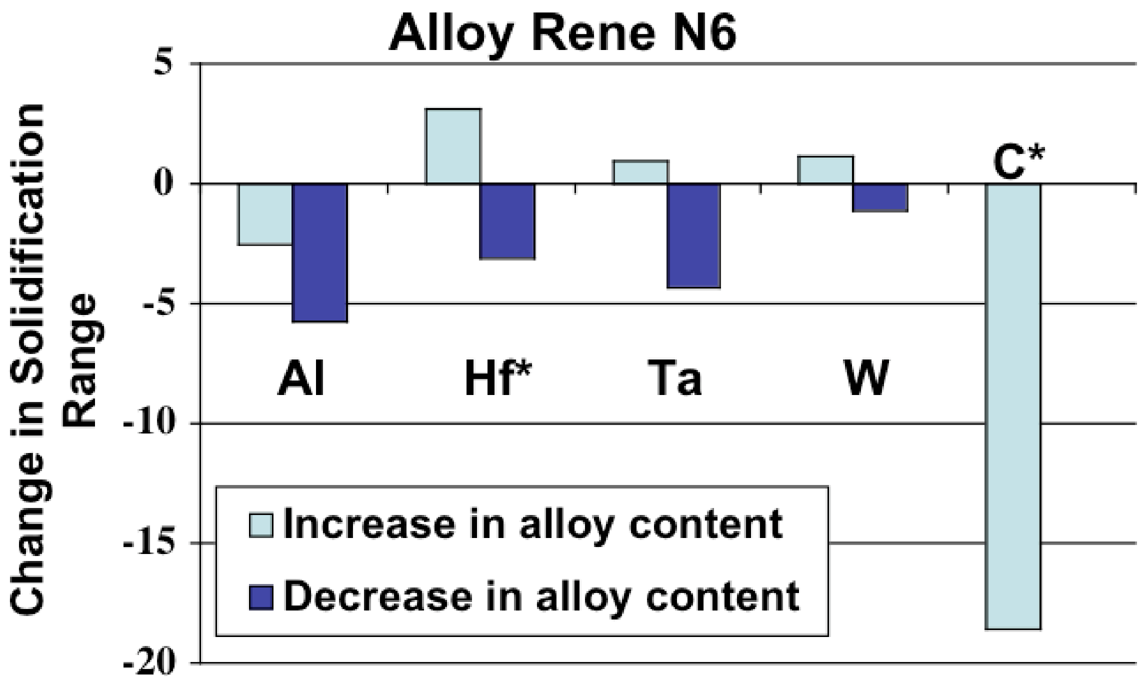
Simple phase diagram calculations can indicate the tendency to form low melting eutectics.





- *Filler metal compositions can be designed with some guidelines from multicomponent thermodynamic equilibrium calculations.*

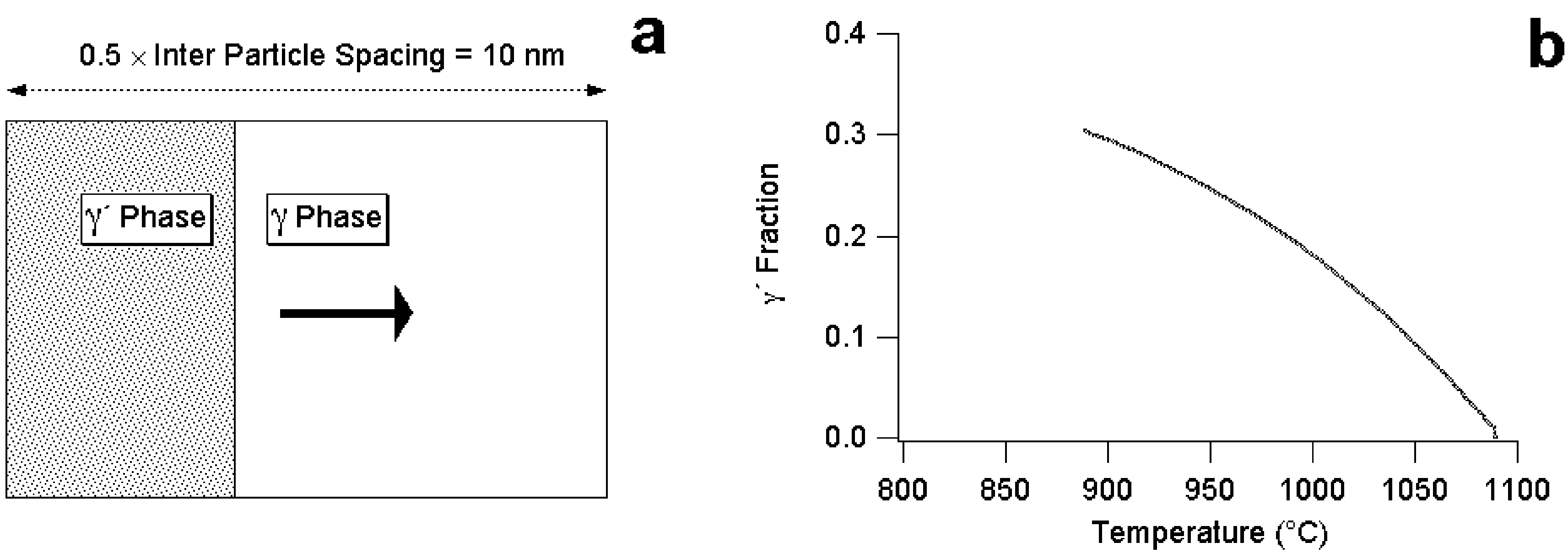
Change in solidification temperature range is related to tendency to form stray crystals.



* Hf and C are = 0.1 wt %; all others are = 1 wt %

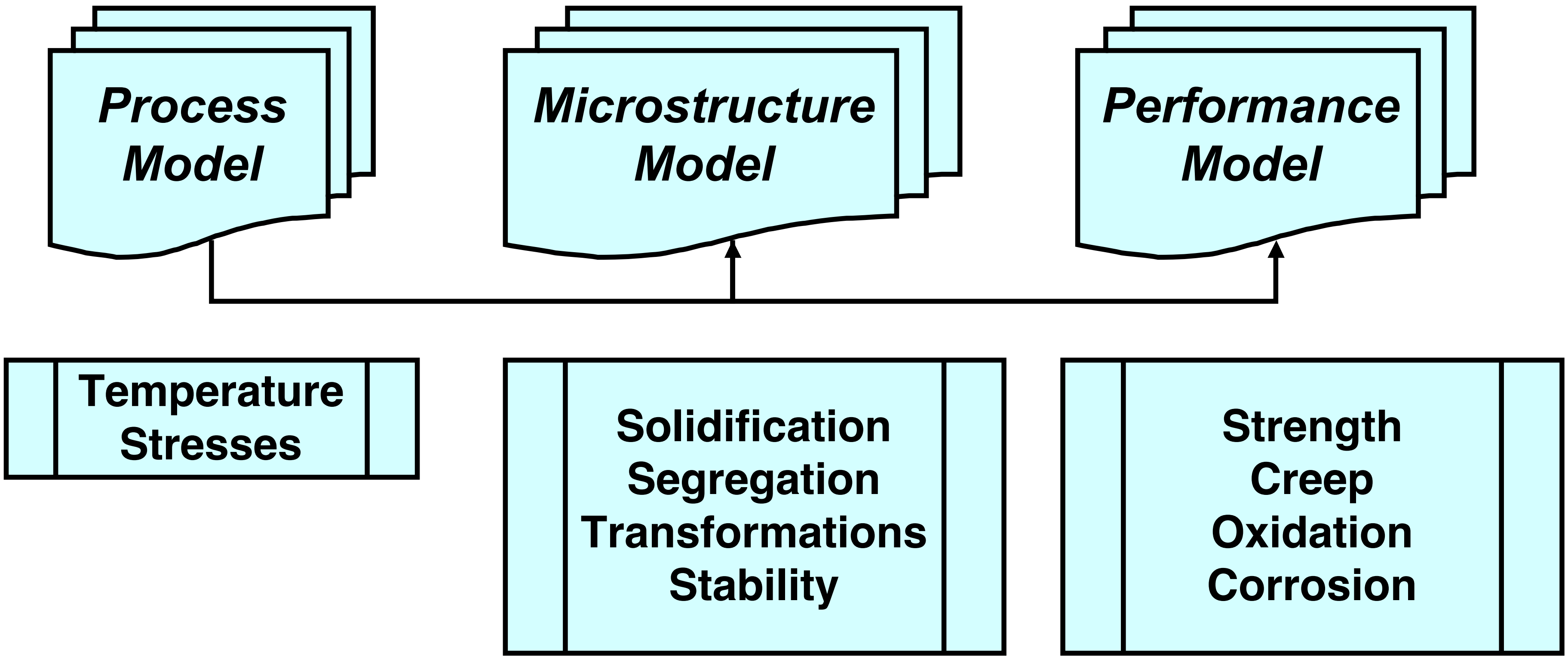
- ***Nonequilibrium solidification can be calculated and associated with solute segregation too.***

Diffusion controlled growth calculations predict the kinetics of □ formation: An example of such calculation for a sample cooling at 500°C/s from 1300°C is shown.



- *The decomposition of □occurs rapidly below 1090°C.*
- *Calculations are sensitive to inter-particle spacing and therefore need to be modified for different conditions.*

Coupling of different component models is necessary to predict the overall weldability of single crystal nickel base superalloys.



- *Current ORNL research focuses on process and microstructure model. Further work is necessary to relate them to performance of welds.*

Summary and Conclusions

- ***It is possible to join single crystal nickel base superalloys through fusion welding by using electron beam and laser welding processes with large preheat temperature (~ 500°C).***

- ***Stray grain formation and weld cracking were severe in these alloys and careful control of preheat, process parameters and restraints are needed.***

- ***Current research showed the complex interplay between crystallography, dendrite growth, phase stability and thermomechanical conditions on both solidification and solid-state cracking tendency.***

- ***Computational thermodynamics and kinetics can be used to describe both solidification and solid state decomposition.***

- ***However, nonequilibrium decomposition of □phase into mixture of □+ □′ is expected under rapid weld cooling conditions.***

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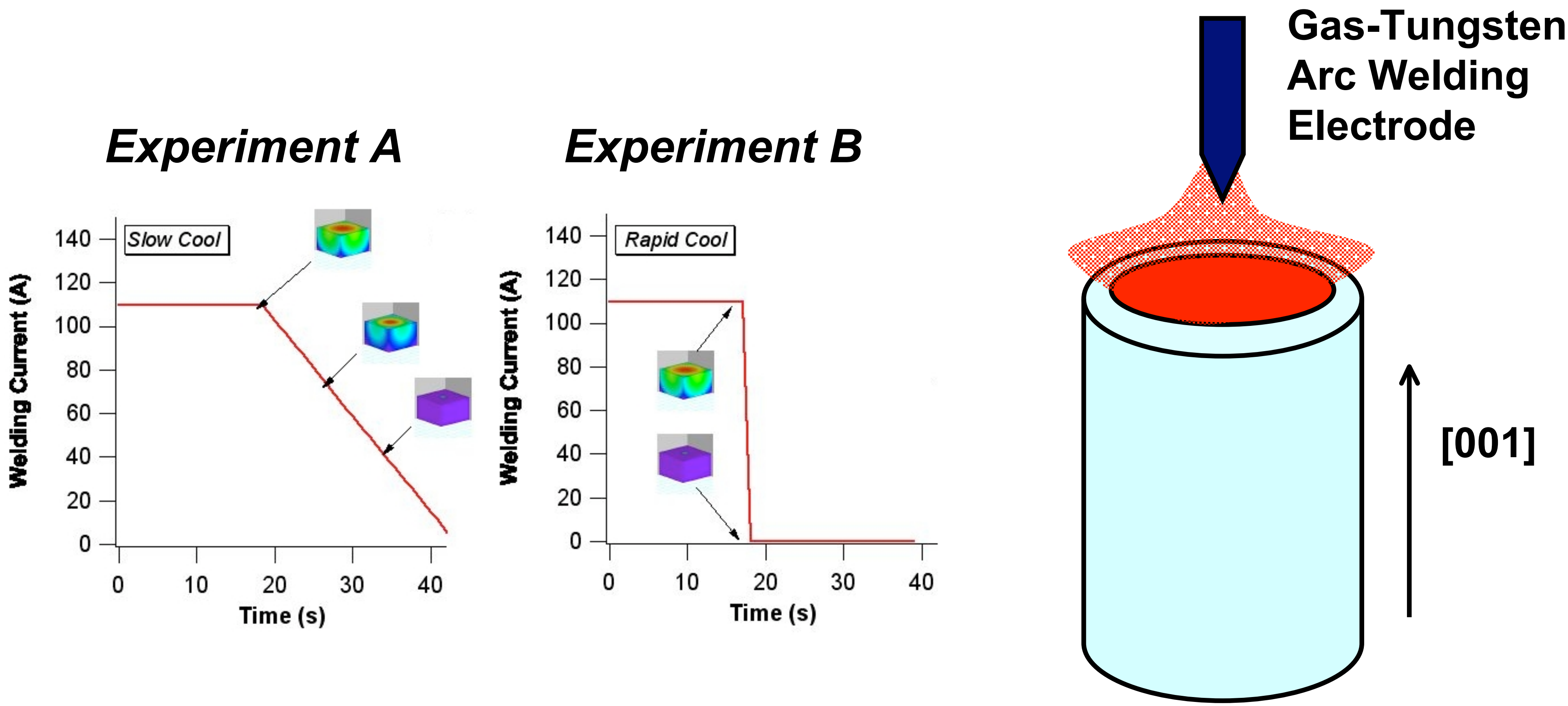
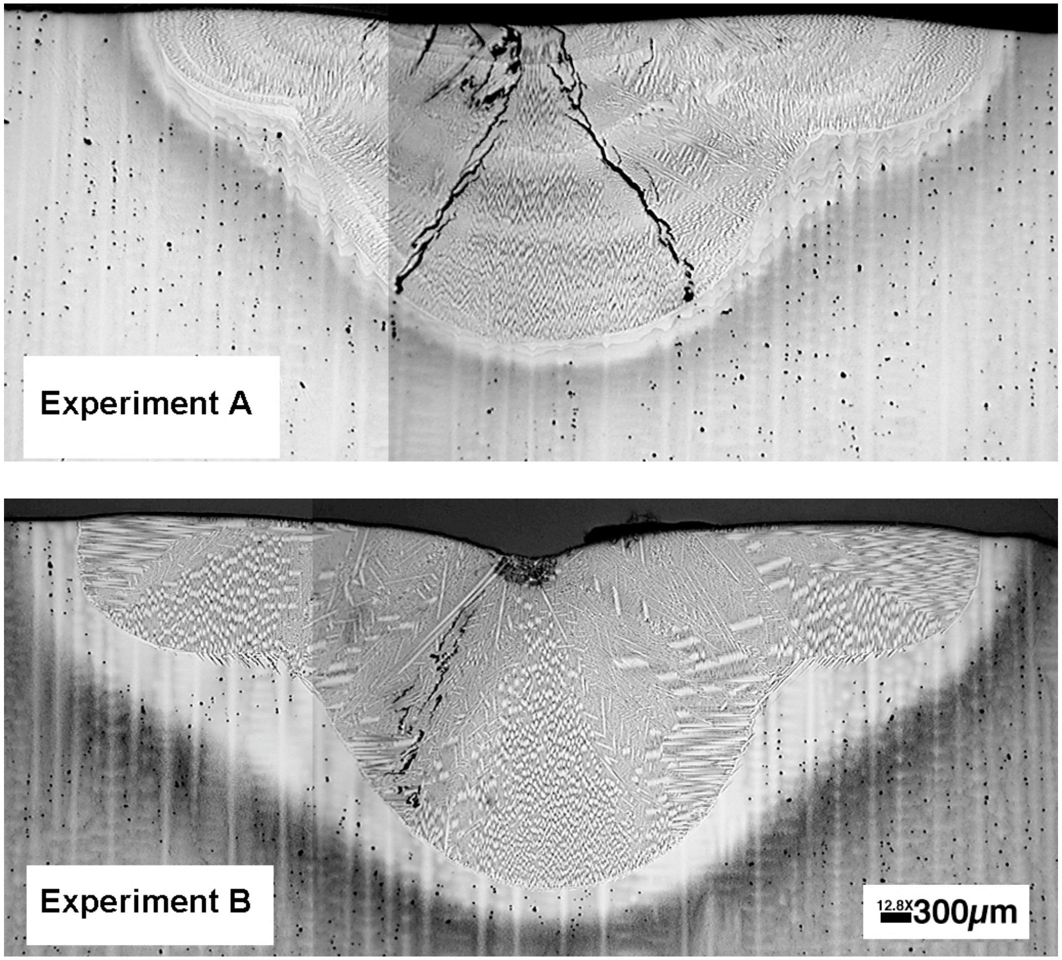
Liquid-solid interface velocity was varied by modifying the welding current slope down.



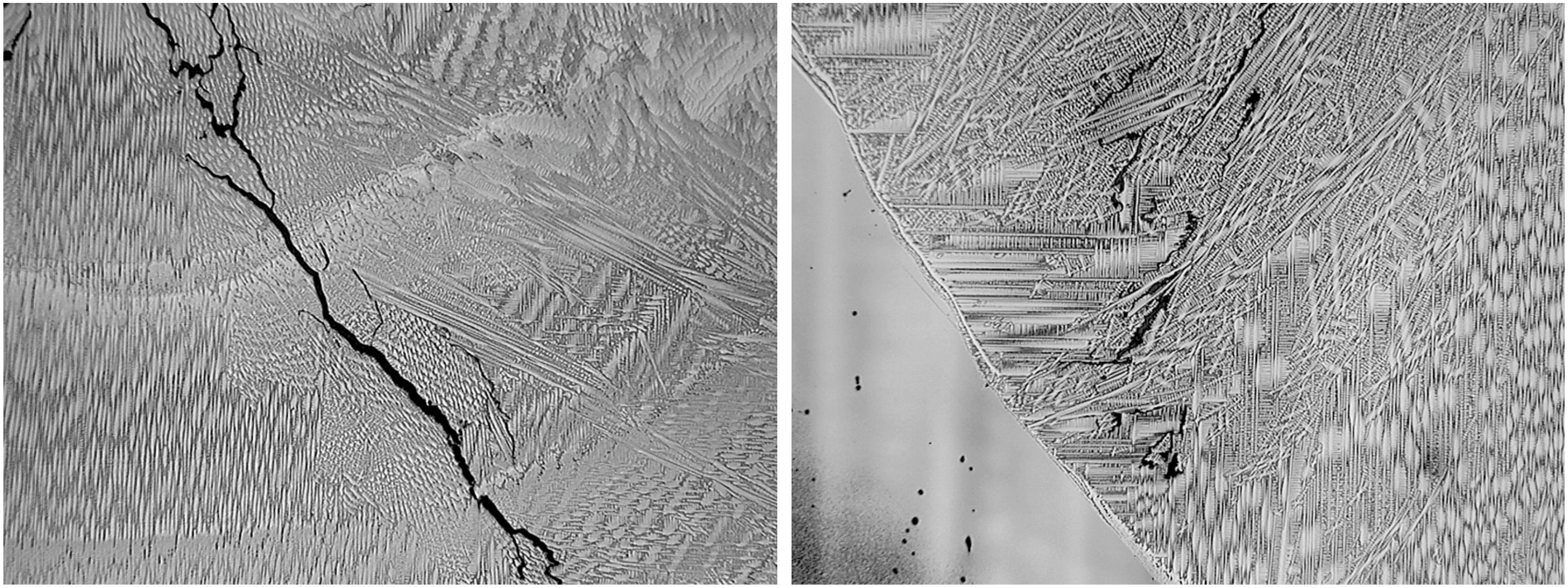
- *Experiment A induces slow cooling and Experiment B induces rapid cooling.*

Solidification grain structure was drastically altered by the change in interface velocity for a given weld pool shape.



- *Cracks were observed at locations where there is a transition from one dendritic growth direction to other direction.*
- *Further work is being performed to understand the dendrite growth and cracking due to local changes in the liquid-solid interface velocity.*

Are the dendrite-zone and stray grain boundaries inherently weak?



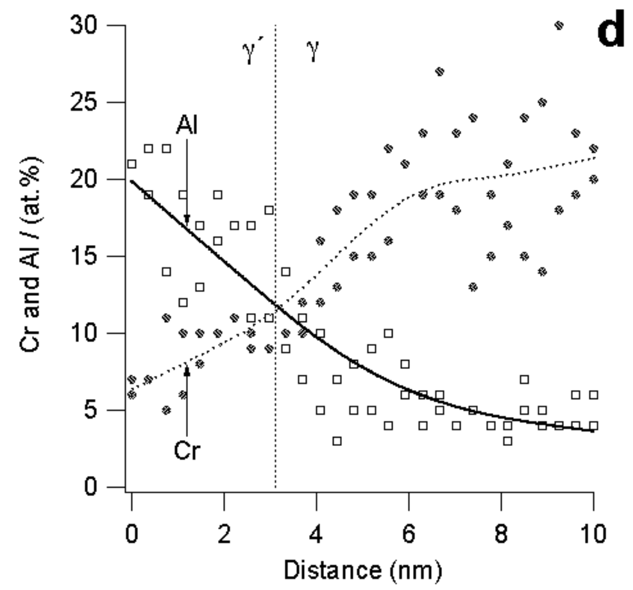
02-2055-09 TMS 75 GTA Spot Weld #10 With slope down 50X 100μm

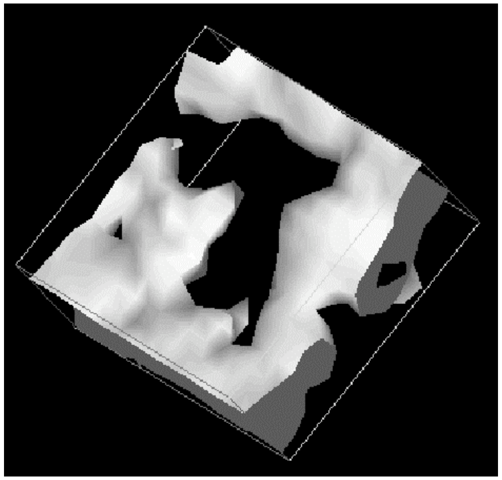
02-2054-05 TMS 75 GTA Spot Weld #9 No slope down 50X 100μm

- ***Is it related to surface energy? Wetting behavior? Why does crack not nucleate within the dendrite array?***

Challenges in predicting solid-state decomposition:

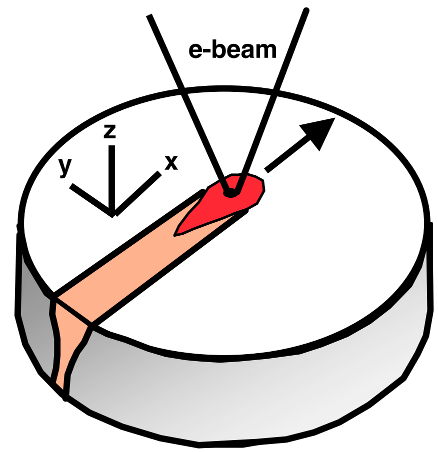
- ***The magnitude of the calculated concentration gradients are different than the measured values.***
- ***With undercooling, is it possible to decompose phase through congruent ordering and spinodal decomposition?***
- ***How can we model such changes in a multicomponent alloy?***
- ***What is the response of this microstructure to post weld heat treatment or service?***





Experimental

- ***Alloys (2- 3 mm single crystal thick sheets)***
  - ***<u>PWA-1480</u>:** Ni - 5.0Al - 10.0Cr - 1.5Ti - 5.0Co - 12.0Ta - 4.0W (wt.%)*
  - ***<u>CMSX-4</u>:** Ni - 5.5Al - 6.5Cr - 1.1Ti - 7.0Co - 7.0Ta - 6.5W (wt.%)*
    (small amounts of Mo and Re)
- ***Welding procedure***
  - ***<u>Electron Beam Welding (EB)</u>:***
    - *accelerating voltage: 100-125 kV*
    - *beam current: 7.5-10 mA, and*
    - *welding speed: 4.2 x 10^{-3} to 42 x 10^{-3} m s^{-1}*
  - ***<u>Pulsed Laser Beam(PL)</u>:***
    - *average power: 90-240 W*
    - *pulse rate: 30 - 100 s^{-1}*
    - *welding speed : 2.1 □10^{-3} (low) to 12.6 □ 10^{-3} ms^{-1} (high)*
  - ***Some of the welds were made with preheat of 500 °C***
- ***Characterization***
  - ***Optical, Transmission electron and Atom-Probe Field-Ion microscopy***
  - ***Vision-systems crack monitoring and modeling***



Summary of the weld cracking research:

- ***The stray grain formation was found to be asymmetrical due to the misorientation of base metal with welding direction.***

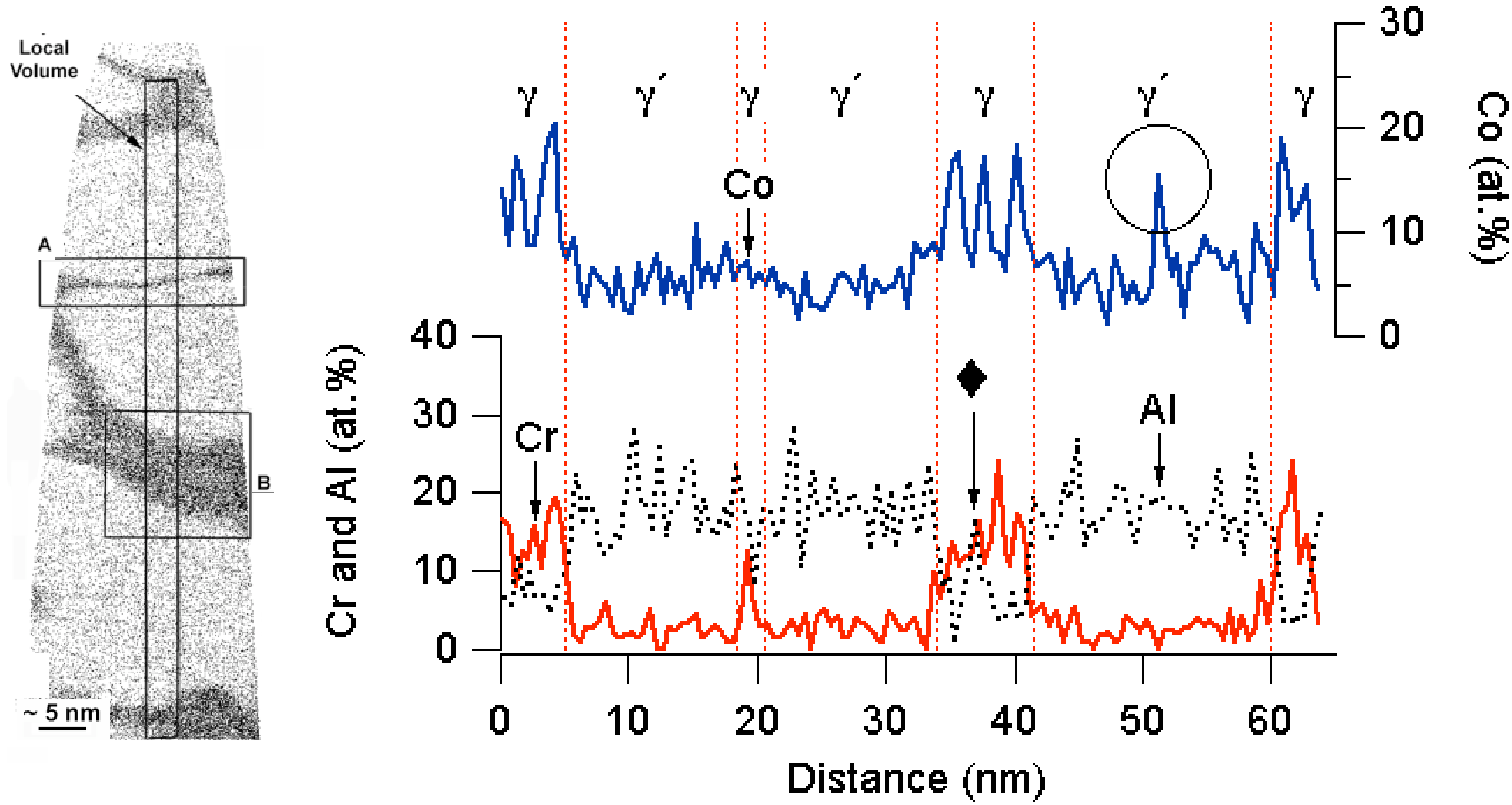
- ***The weld solidification cracks were associated with stray grains.***

- ***Geometry model can be used to predict the dendrite growth velocity which is related to stray grain formation through constitutional undercooling.***

- ***Dendritic features were observed in the fractured surface and suggested the presence of liquid film during weld cracking.***

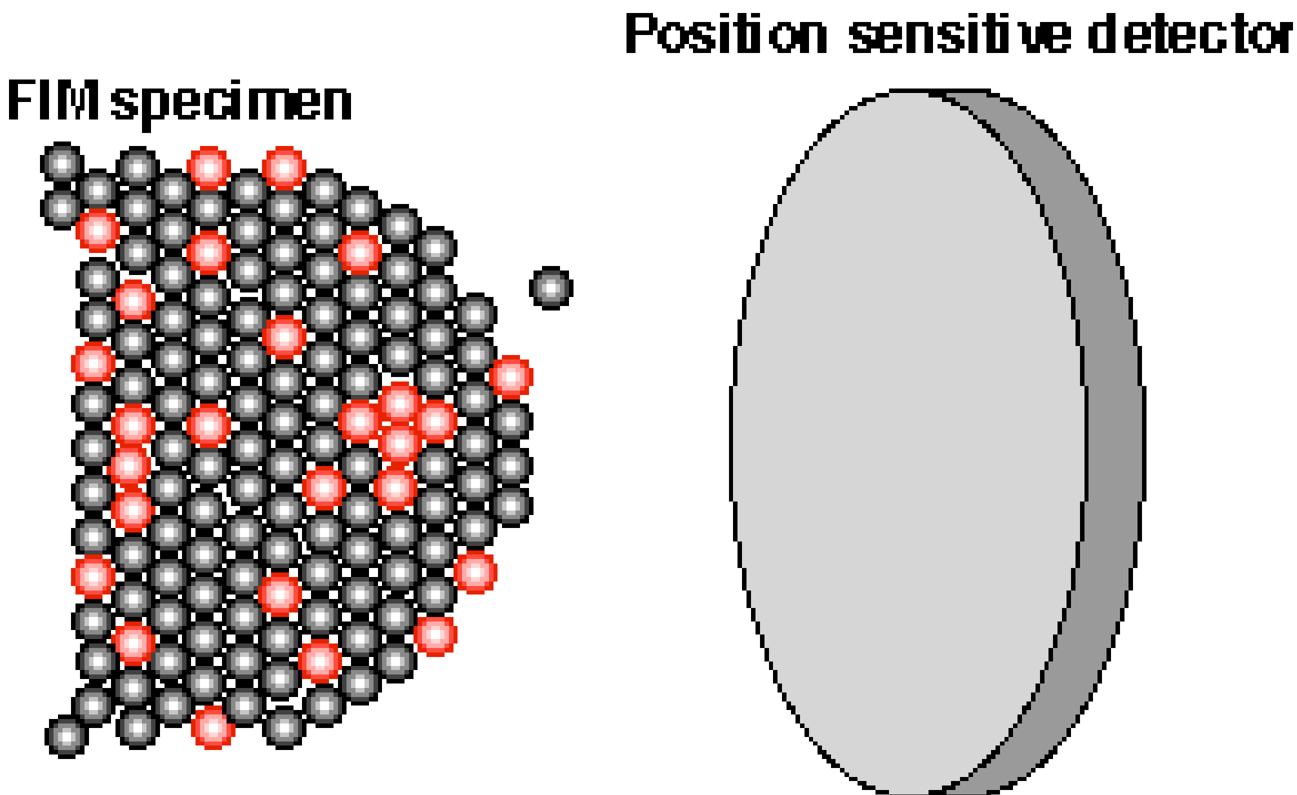
- ***Tendency to form stray grains and weld cracks was reduced with a reduction in welding speed.***

Chromium atom image obtained from atom probe tomography revealed both □matrix and □ precipitates.



- *Nonequilibrium concentration of Co in □ and Al in □phase was observed.*

Atom Probe Tomography



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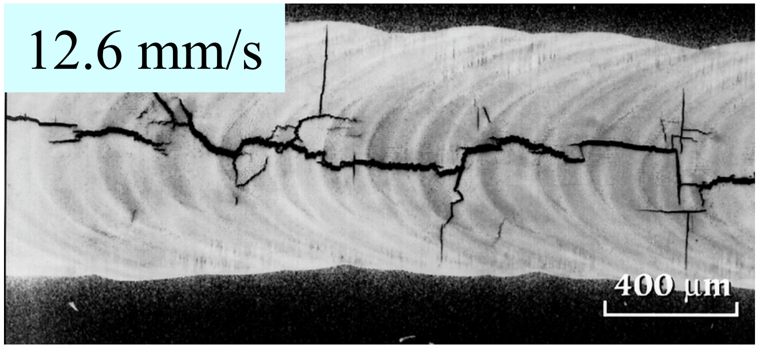
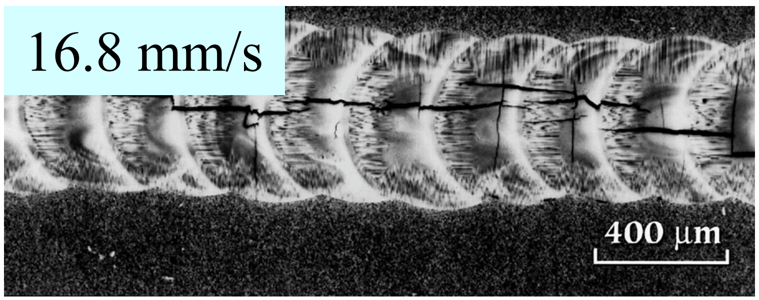
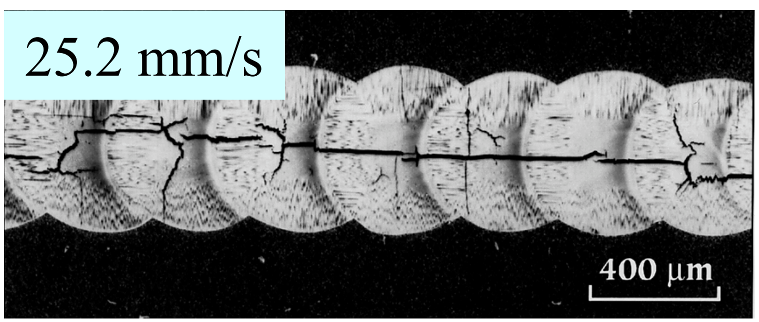
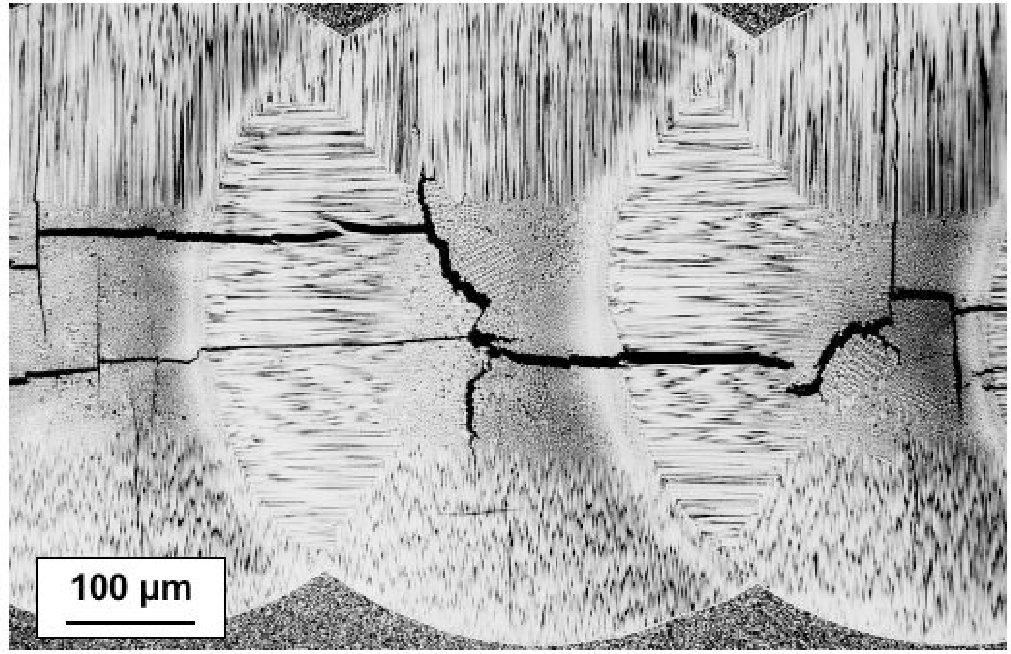
- ***Three dimensional compositional differences and precipitate morphology can be analyzed.***

Cracking was observed even in pulsed laser welds



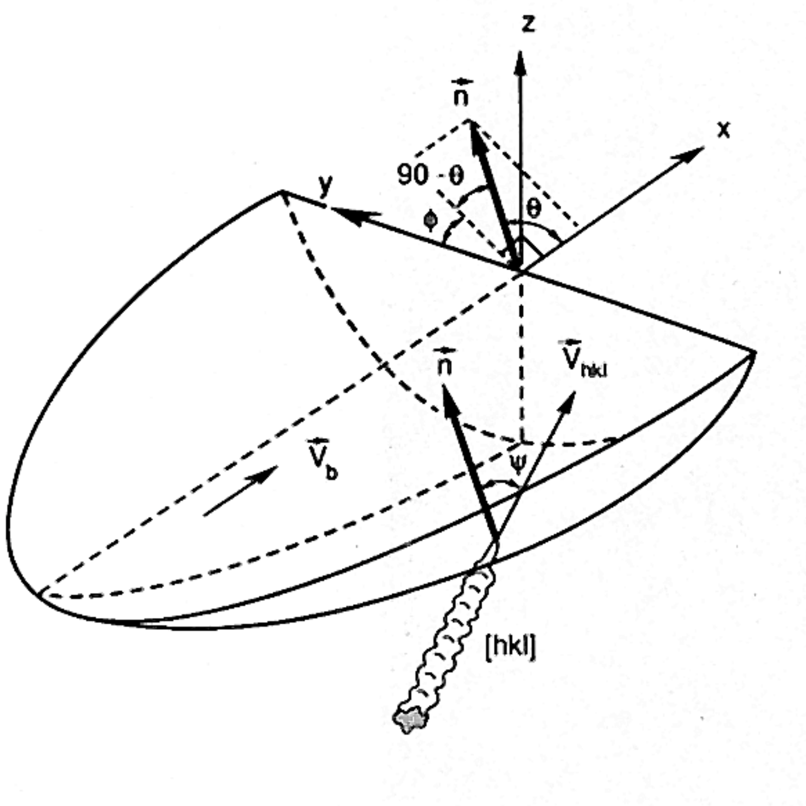


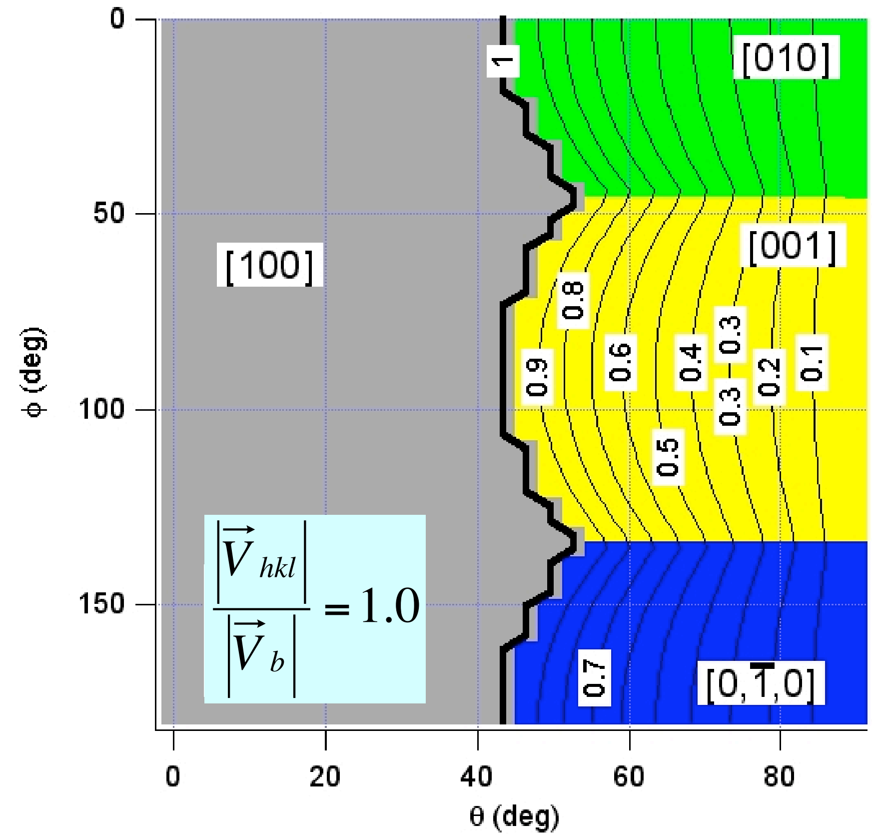




- ***Stray grains formed in the last stages of solidification.***
- ***Complex cracking tendencies with both longitudinal and transverse cracking were observed.***

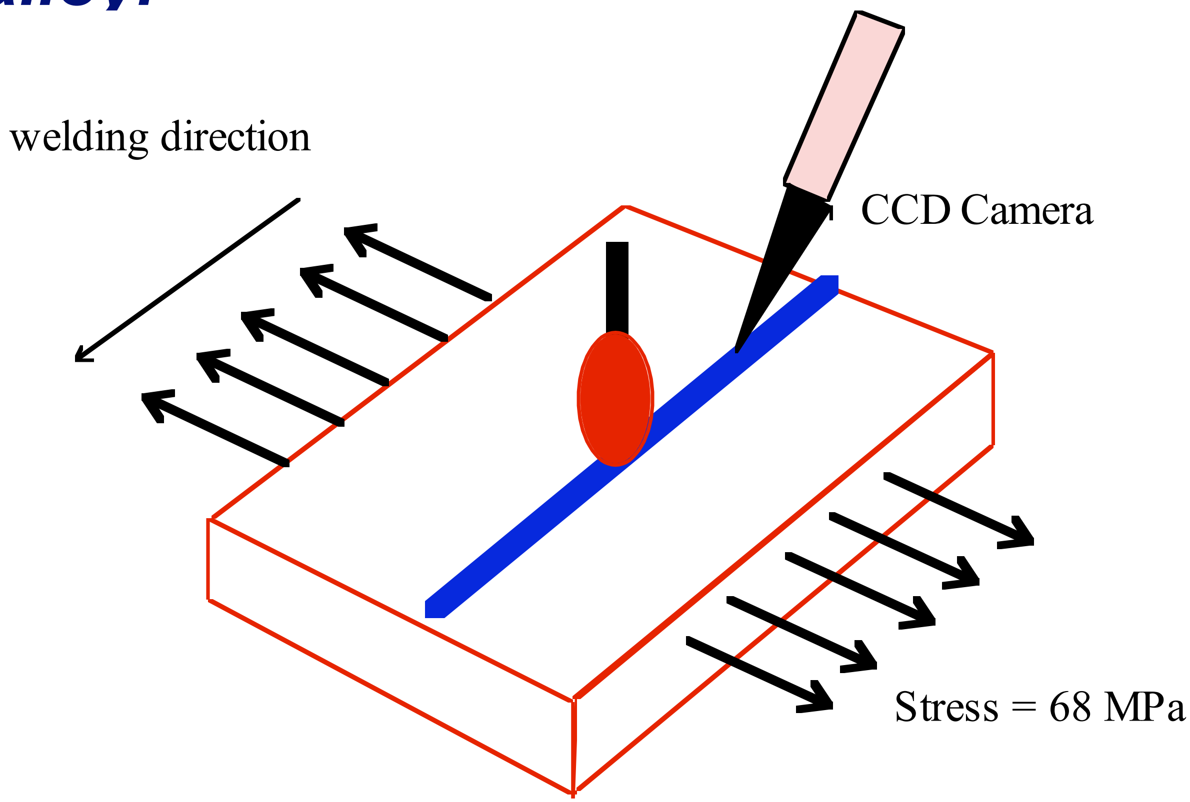
A geometrical model was developed to predict the dendritic microstructure in single crystal welds.





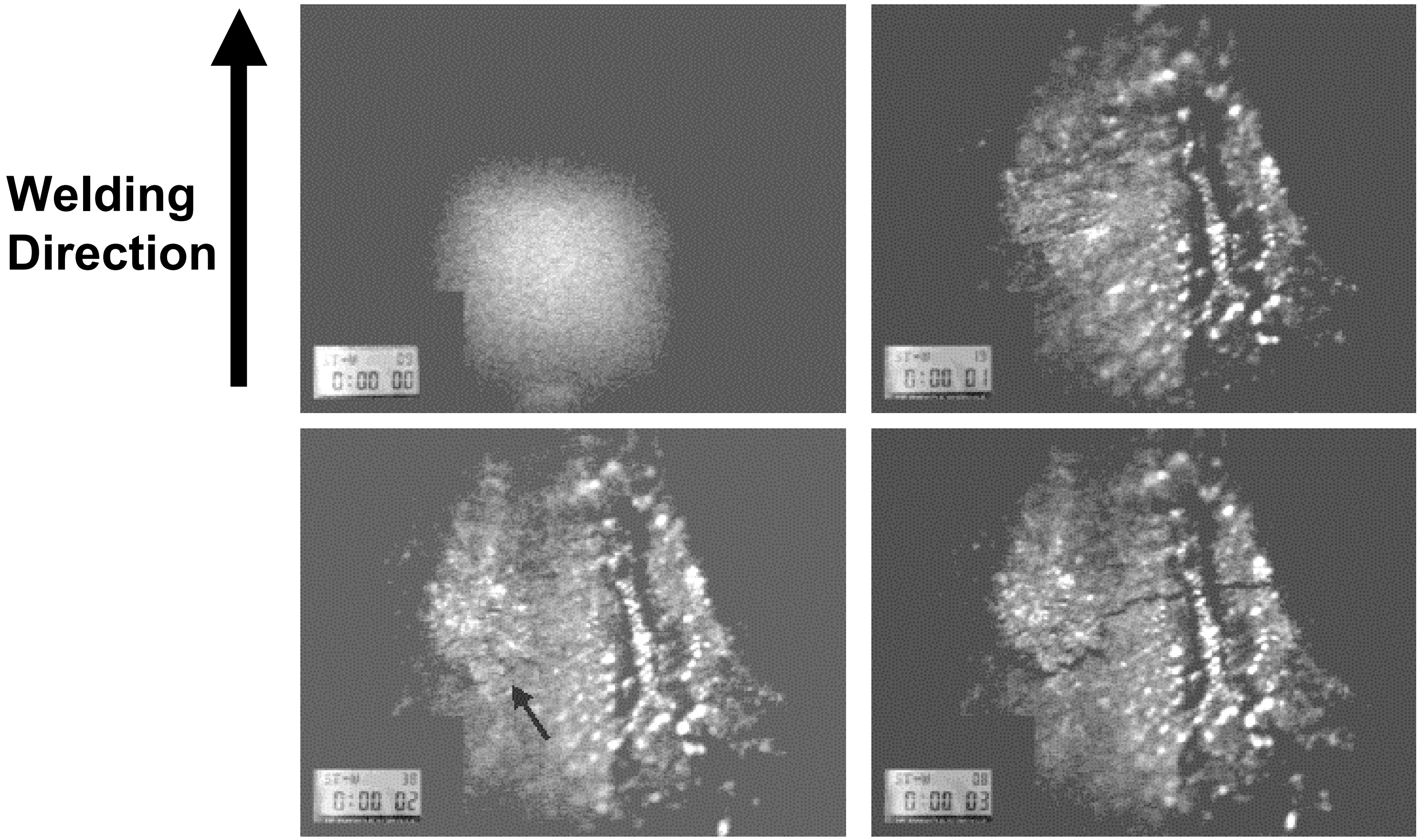
- ***The preferred growth direction can be calculated as a function of the solidification front orientation and weld pool shape***

In-situ weld crack monitoring was used to track cracking tendencies in an experimental M738 single-crystal alloy.



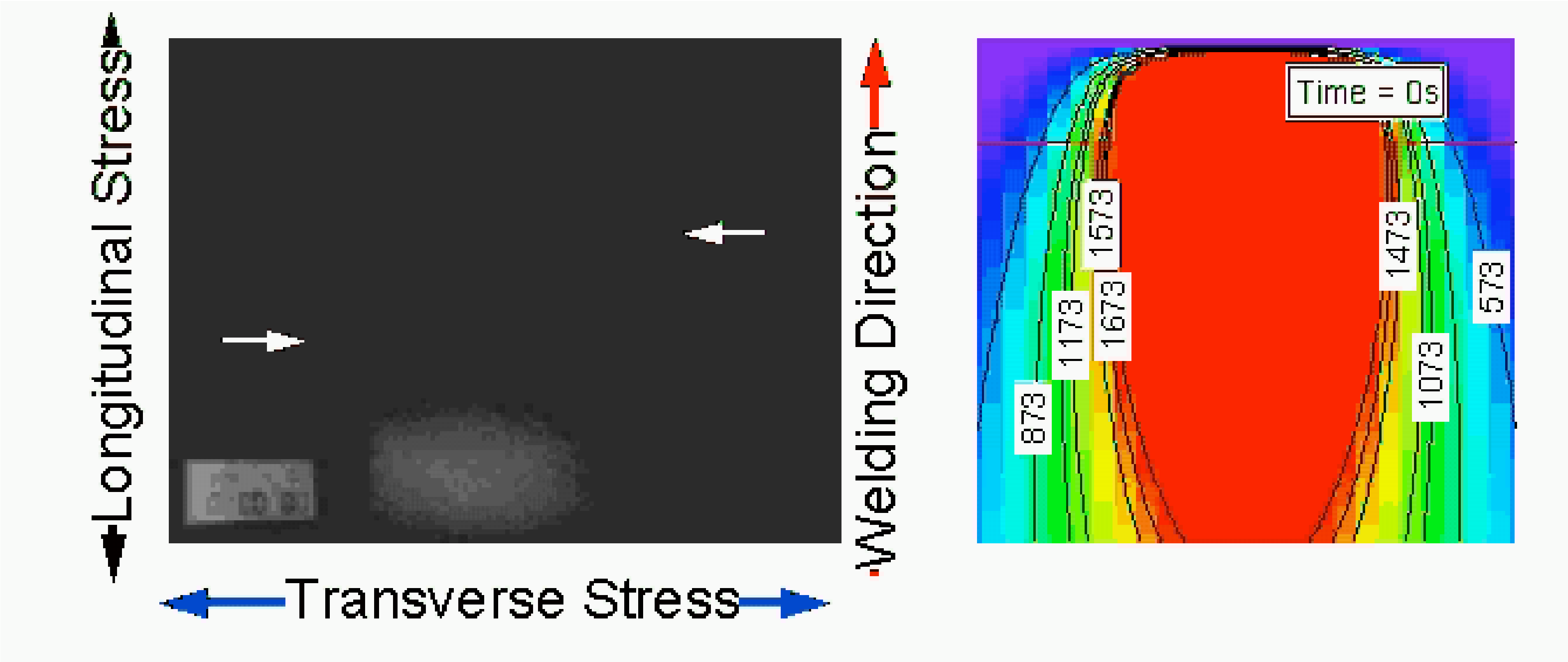
- ***"Vision-Systems" applies stroboscopic light to record the weld surface features.***

Sub-solidus crack formation in a stressed weldment was observed.



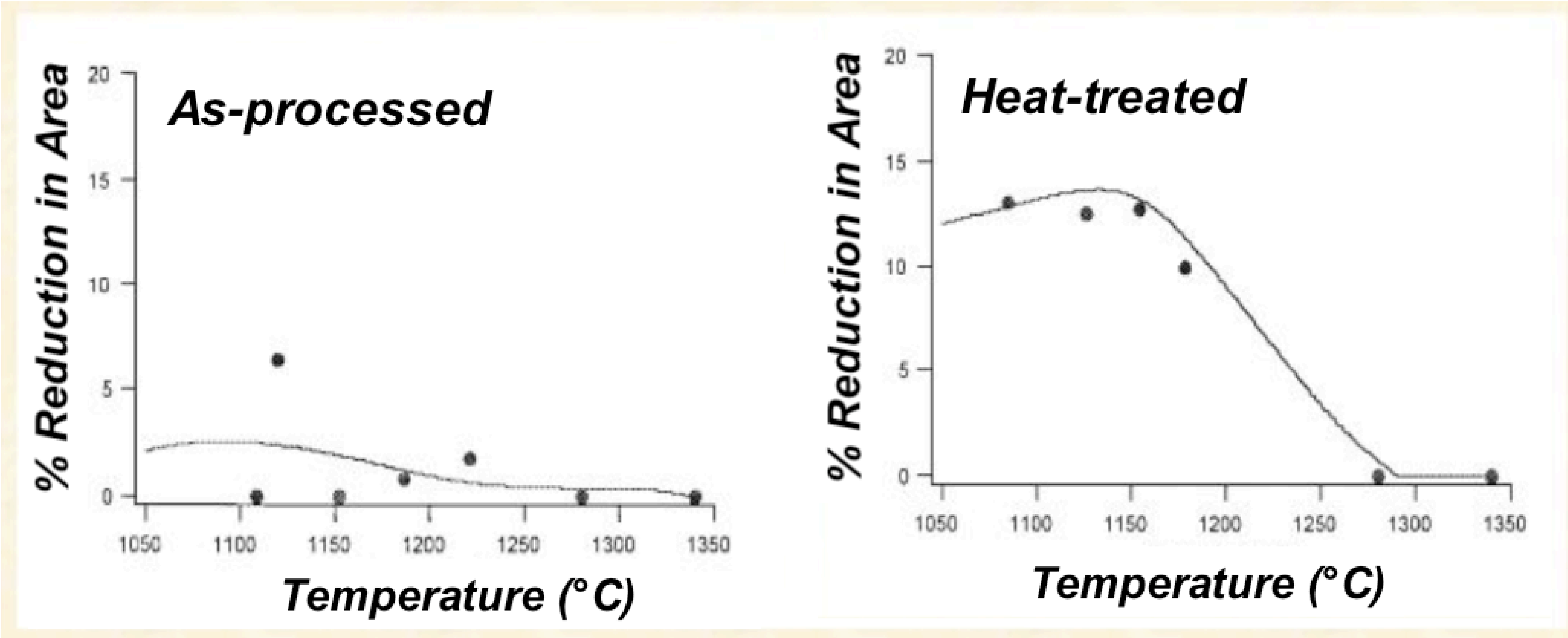
- ***Weld cracks in M738 (~IN738) was transverse in nature.***

Transverse cracking occurred after the completion of weld solidification. Analytical heat-transfer model suggests the cracking occurs at very low temperature compared to solidus.



- ***Is there any relation to the high temperature stress-strain characteristics of this alloy?***

Gleeble® hot ductility measurements show low ductility at temperatures below solidus.



- *However, properly heat-treated alloy can reduce cracking behavior.*
- *The above results showed in some single crystal alloys, the cracking may occur in the solid-state condition too.*