SINGLE CRYSTAL SURFACE ENGINEERING

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Physical Metallurgy - EPFL

SX - SURFACE ENGINEERING

- What is SX surface engineering ?
- Why ?
- How does it work ?

THE CONCEPT OF
SX - SURFACE ENGINEERING

- SX superalloys are generally used for HPT turbine blades.
- Mechanical properties ↑ when

1. Cr (oxidation) ↓
2. C, B, Zr (grain boundaries) ↓

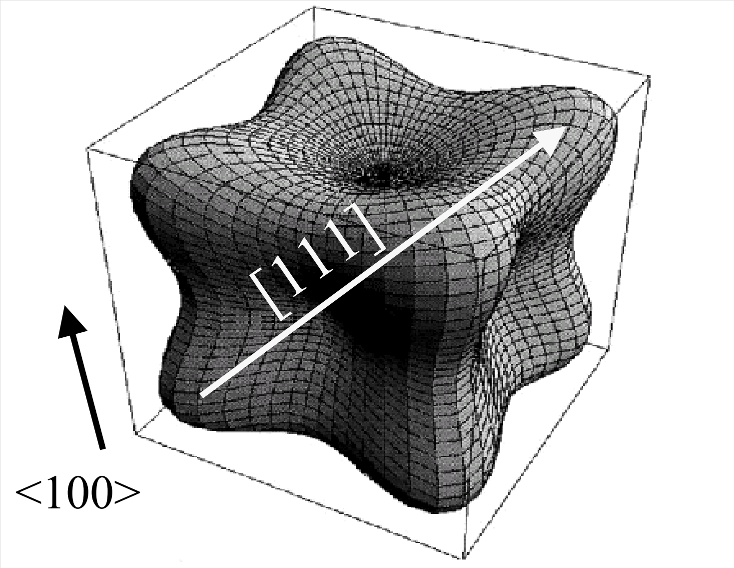
THE CONCEPT OF
SX - SURFACE ENGINEERING - I
COATING

Low Cr superalloys require protection against oxidation and corrosion :

- Present day technique: plasma spray Cr rich polycrystalline NiCrAlY coating.
- Ni has high crystal (E) anisotropy → incompatibility stresses in thermal cycling → premature cracking.

SOLUTION: SX COATING ON SX BLADE

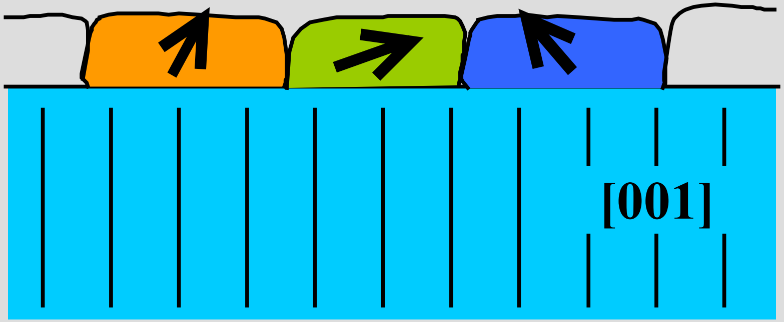
E-MODULUS ANISOTROPY OF Ni



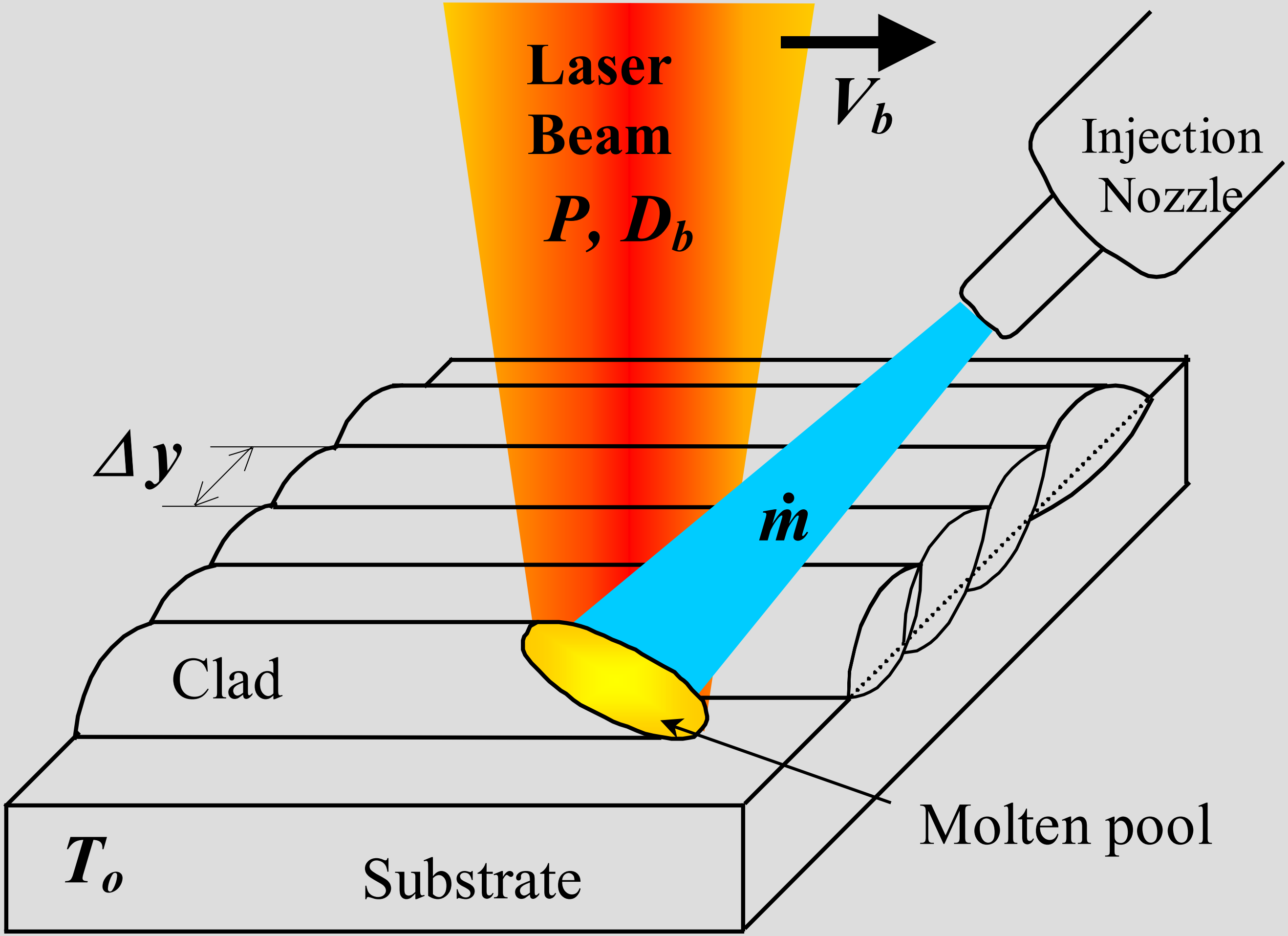
Phase γ - Siebörger et al.

$E_{[100]} \sim 125$ [GPa]

$E_{[111]} \sim 310$ [GPa]



LASER CLADDING PROCESS



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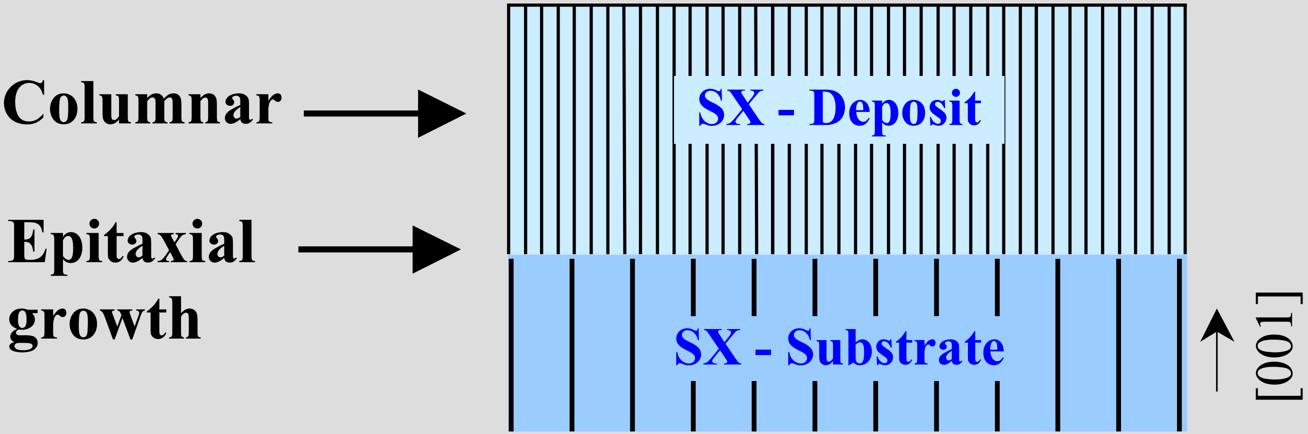
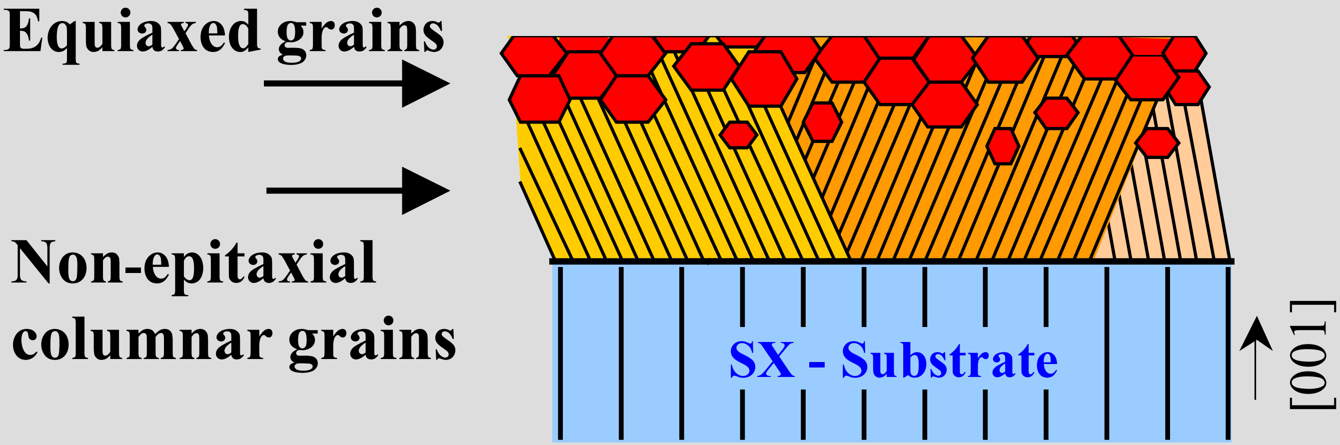
MICROSTRUCTURES / DEFECTS



Ideal case



Defects to avoid

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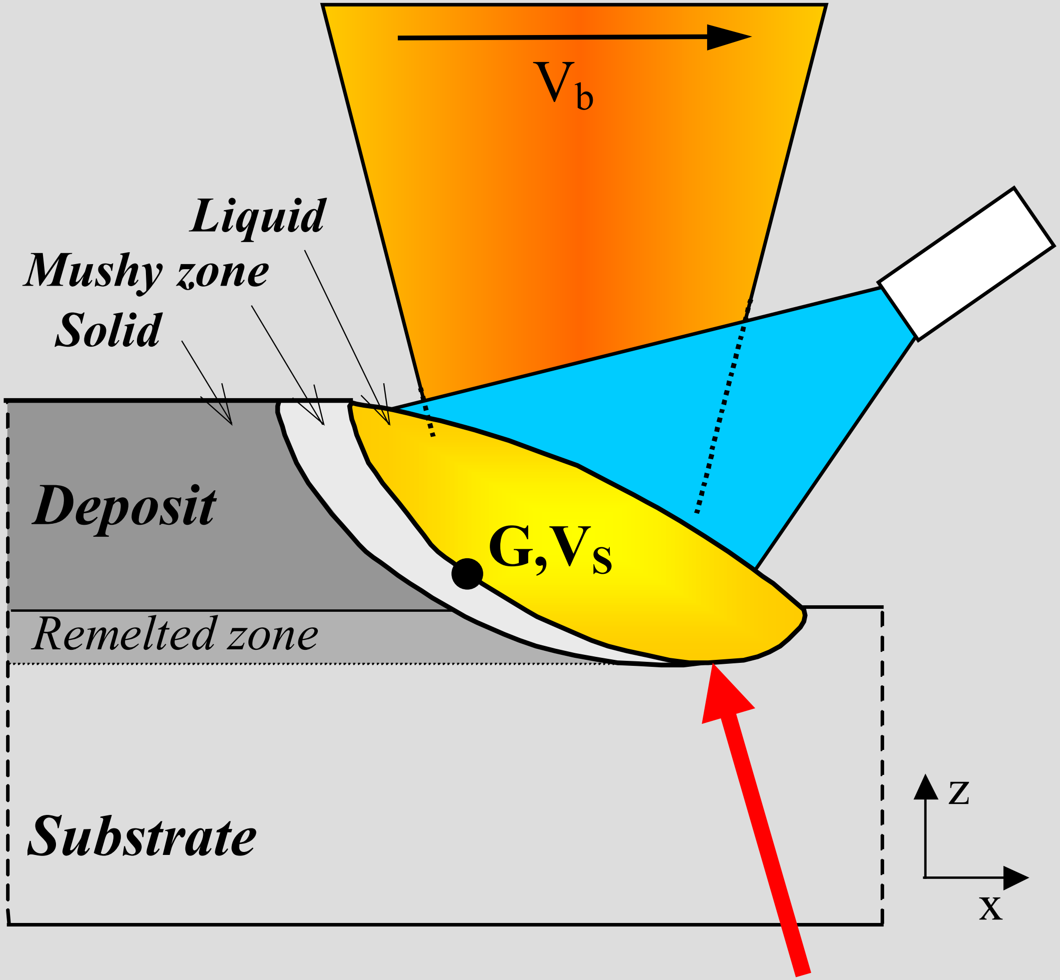
EPITAXY

Ensure at the surface

- metallic contact with the substrate
- similar crystal structure of primary phases

LASER CLADDING PROCESS



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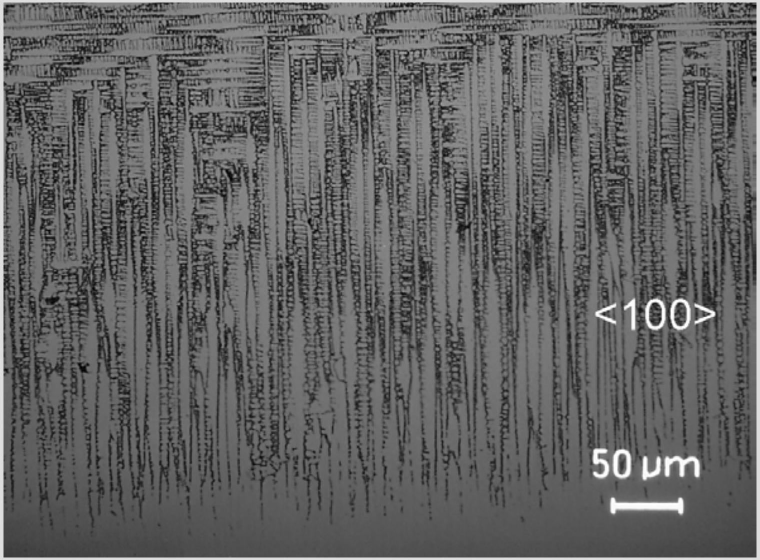
EPITAXY

MCrAlY with

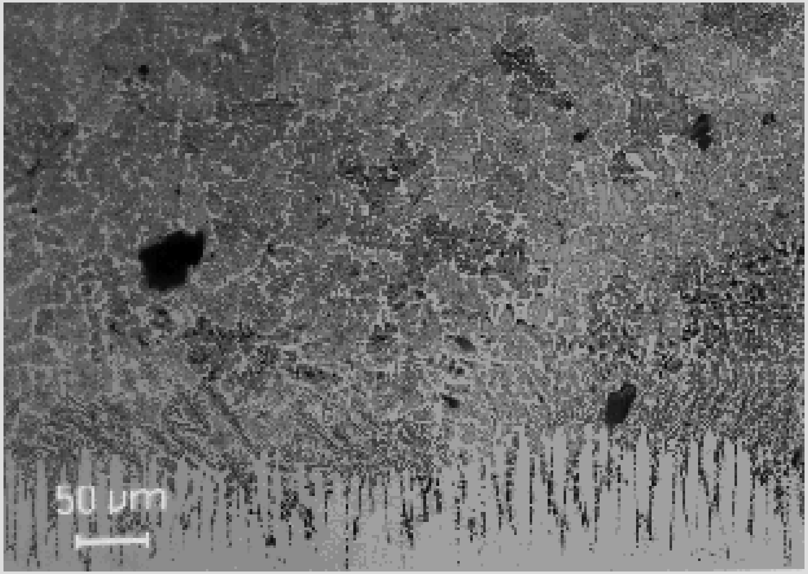
low Al

γ primary phase



high Al

β primary phase

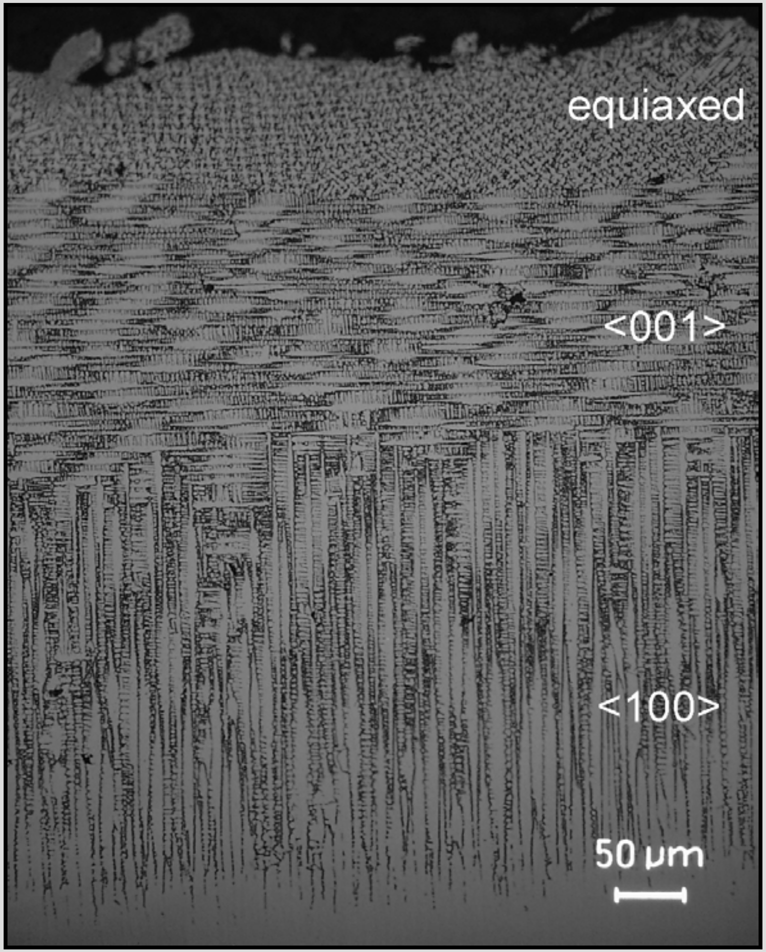


SINGLE CRYSTAL LASER CLADDING OF MCrAlY ON CMSX 4

Equiaxed

Columnar Dendritic Growth

Epitaxy



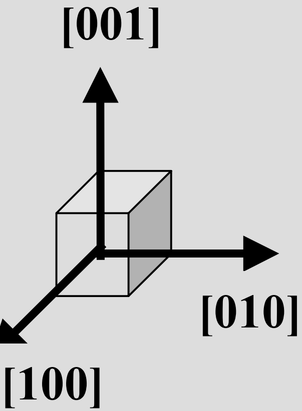
MCrAlY

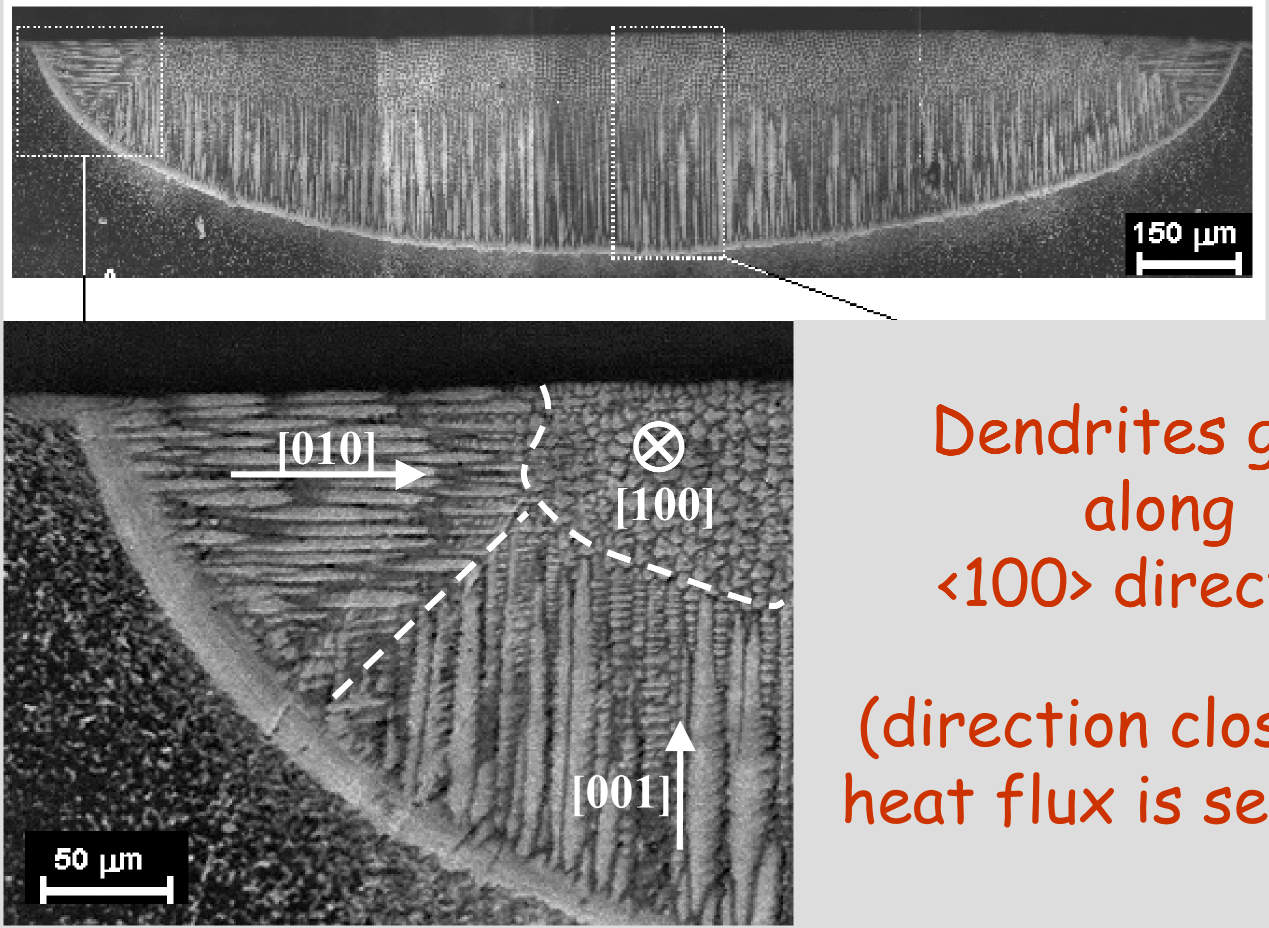
CMSX-4

DENDRITE BRANCH SELECTION

Laser Remelting

⊗ $\vec{V}_b$





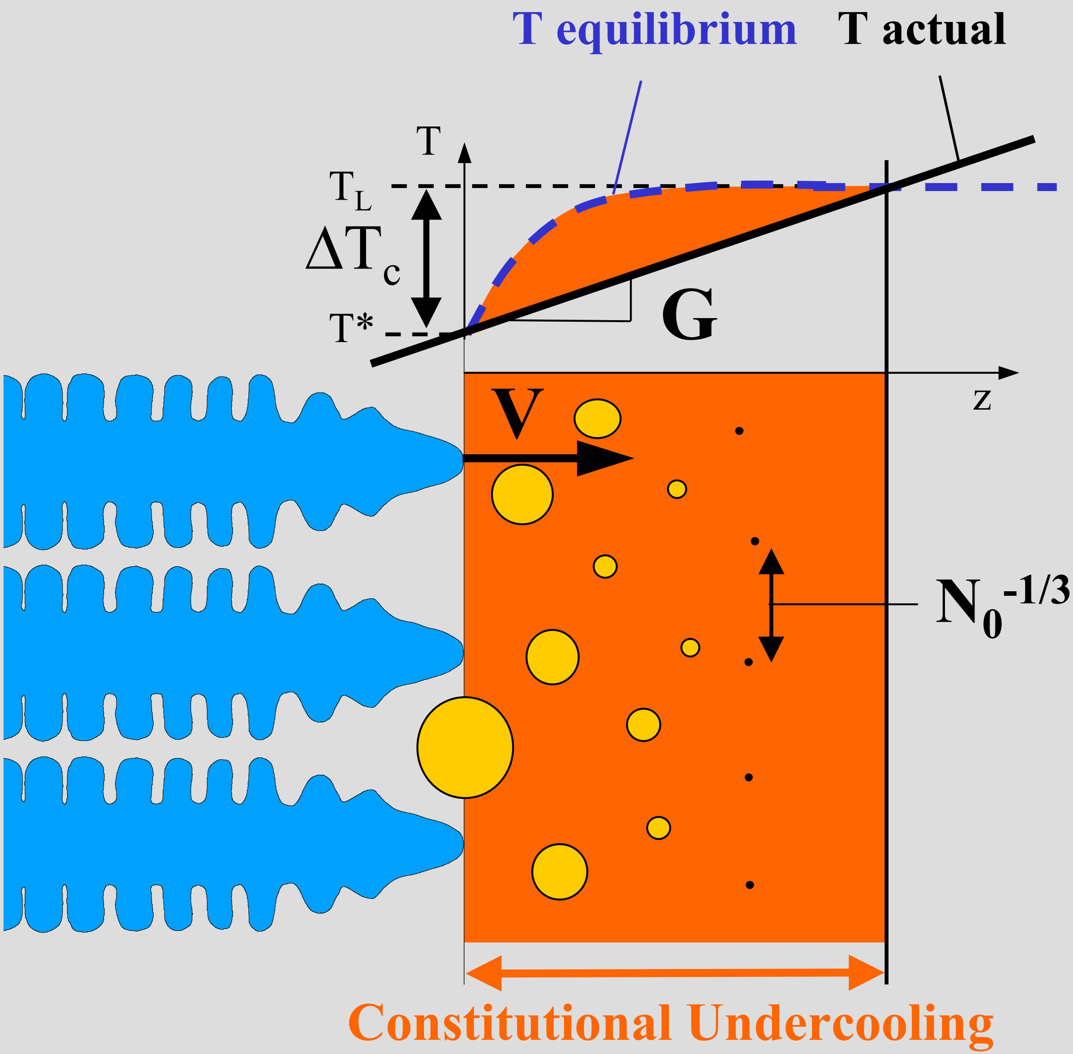
Dendrites grow along <100> direction

(direction closest to heat flux is selected)

COLUMNAR-EQUIAXED TRANSITION
CET

Avoid nucleation and growth in the constitutionally undercooled region ahead of the columnar dendritic zone

COLUMNAR TO EQUIAXED TRANSITION



Constitutional Undercooling

Process

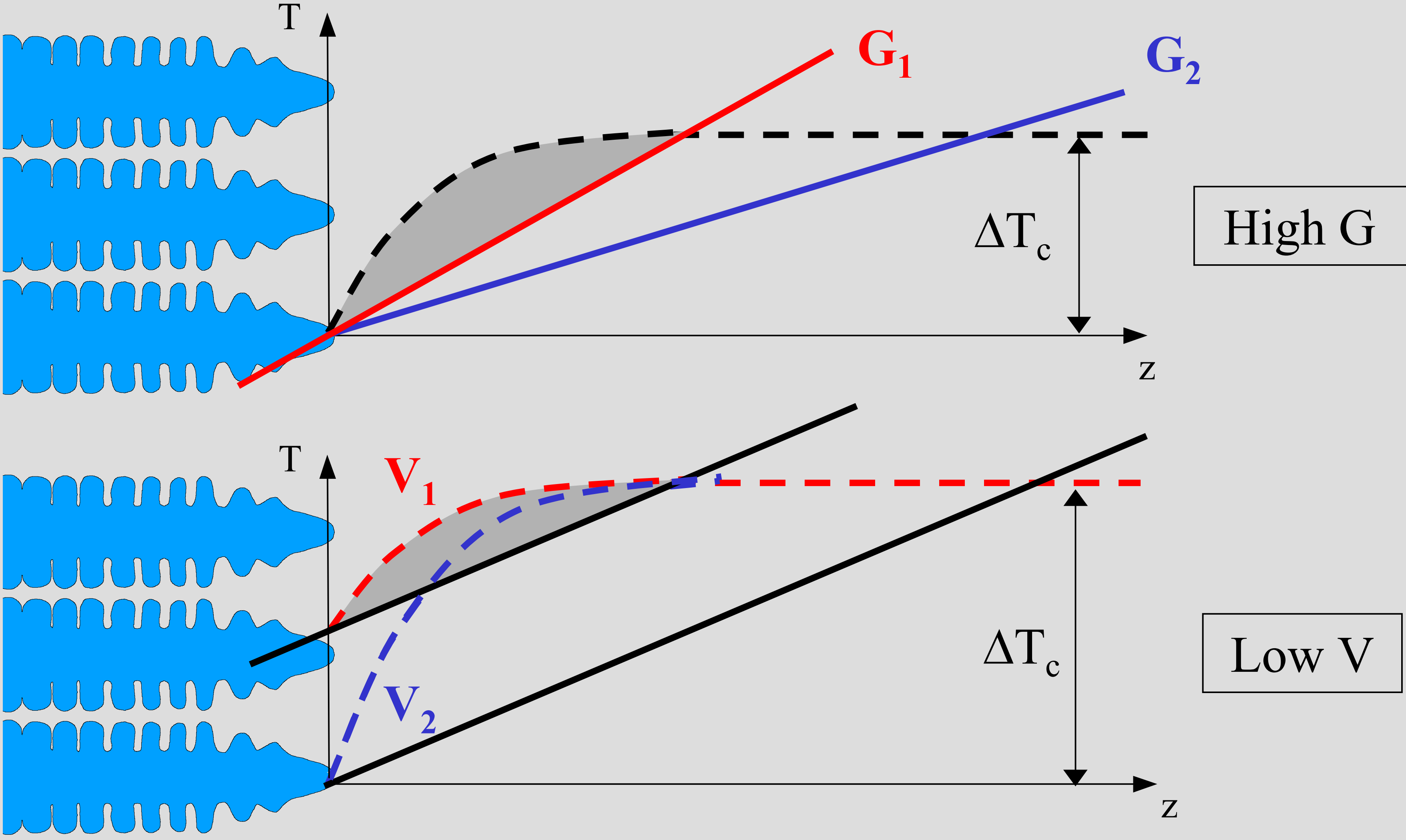
- Temperature Gradient **G**
- Solidification Velocity **V**

Alloy

- Growth Undercooling **ΔT_c**
- Nucleation Site Density **N_0**
- Nucleation Undercooling **ΔT_n**

COLUMNAR TO EQUIAXED TRANSITION

Effect of G and V



High G

Low V

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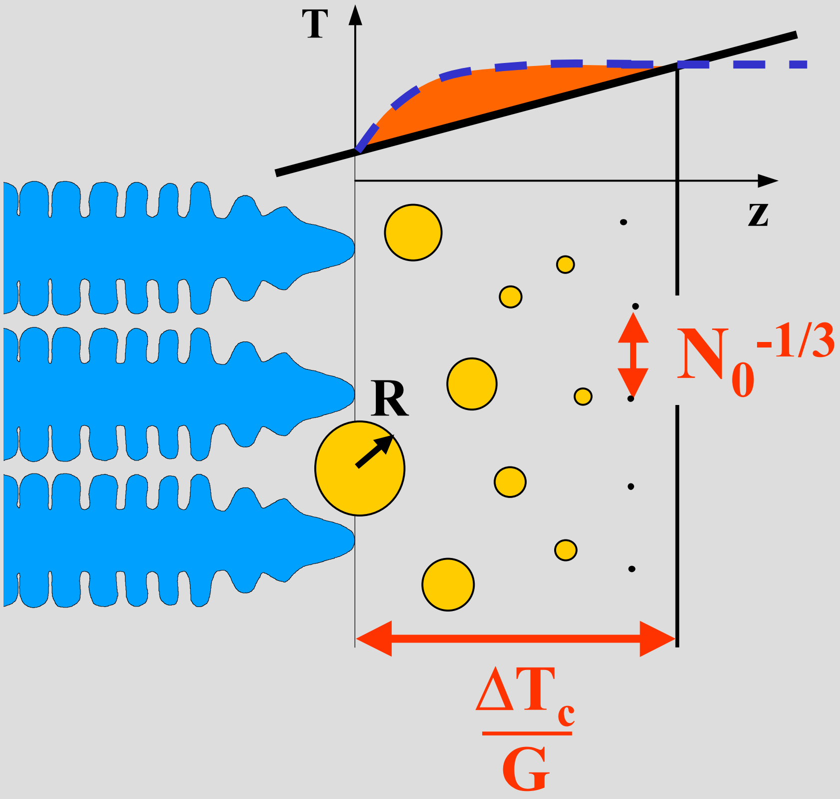
COLUMNAR TO EQUIAXED TRANSITION



$$\frac{\Delta T_c}{G} < N_0^{-1/3}$$

$$\Delta T_c = \Delta T_0 (a \cdot V)^{1/n}$$

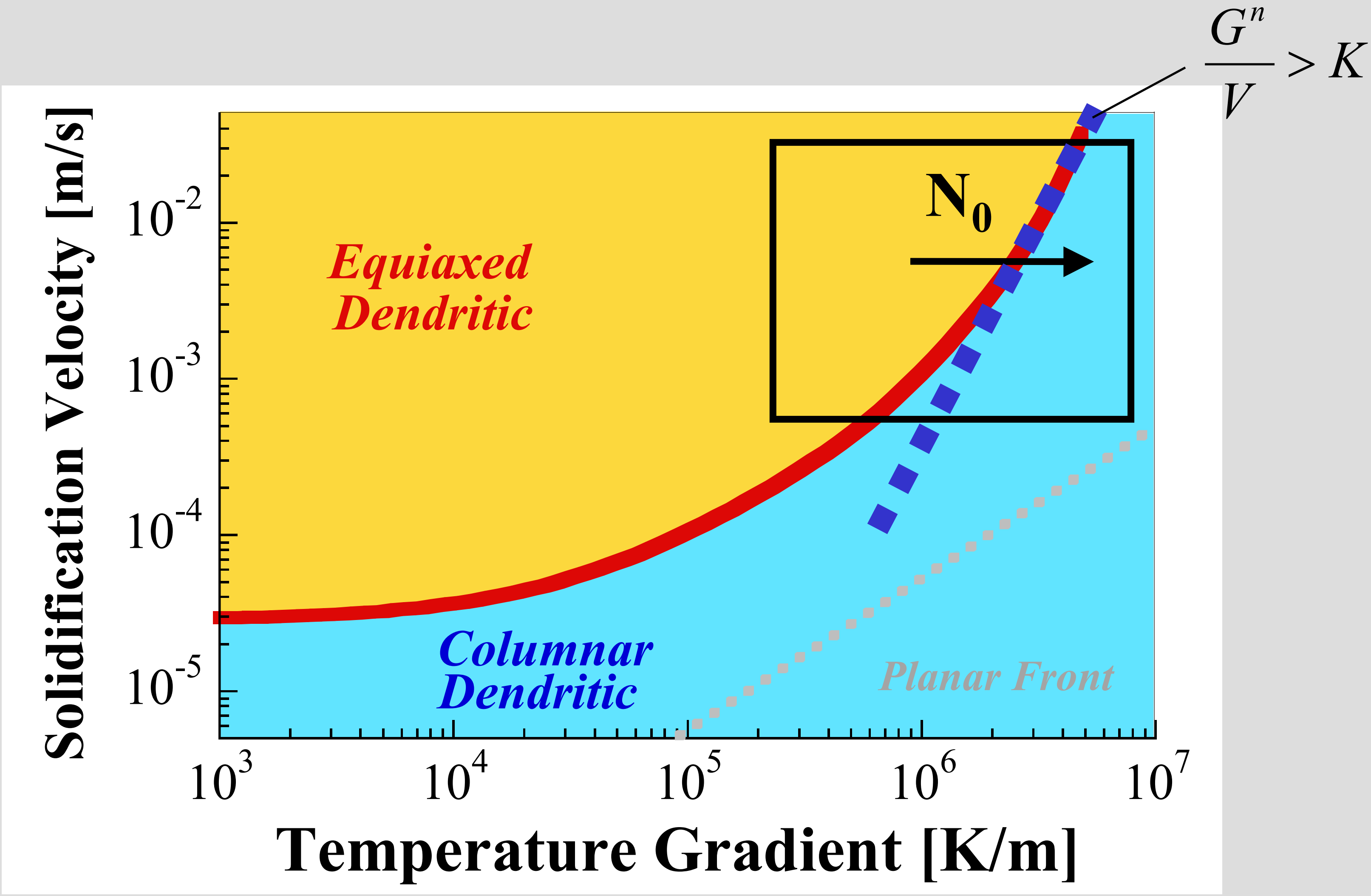
$$\Delta T_0 (a \cdot V)^{1/n} < G \cdot N_0^{-1/3}$$

$$\frac{G^n}{V} > a \cdot (\sqrt[3]{N_0} \cdot \Delta T_0)^n$$

$$\frac{G^n}{V} > a \cdot \left\{ \sqrt[3]{\frac{4\pi \cdot N_0}{3\phi_c}} \cdot \frac{\Delta T_0}{1+n} \right\}^n \Rightarrow \boxed{\frac{G^n}{V} > K}$$

, for a columnar structure

MICROSTRUCTURE SELECTION MAP



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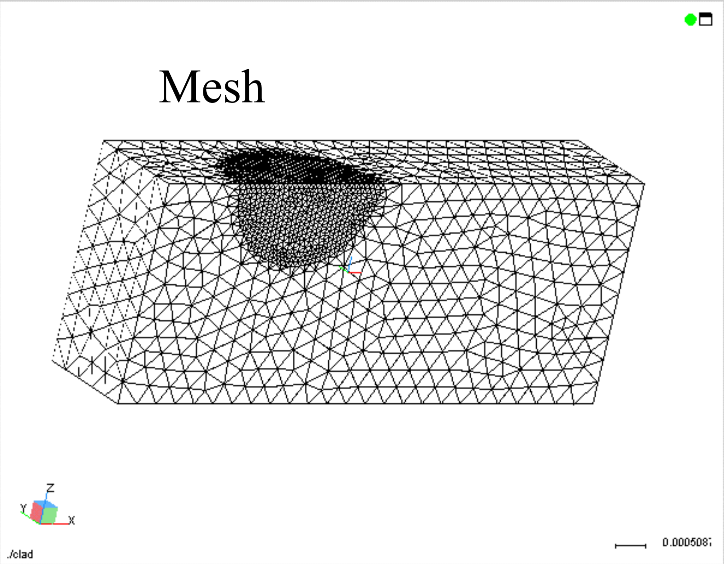
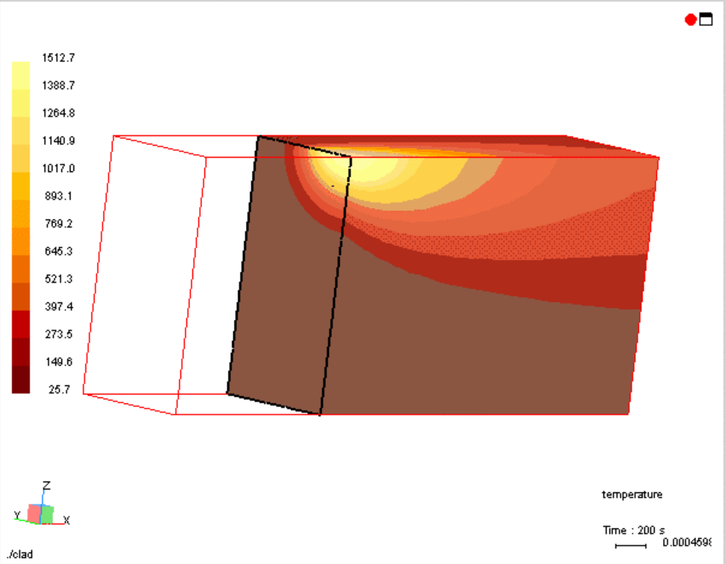
PROCESSING PARAMETERS

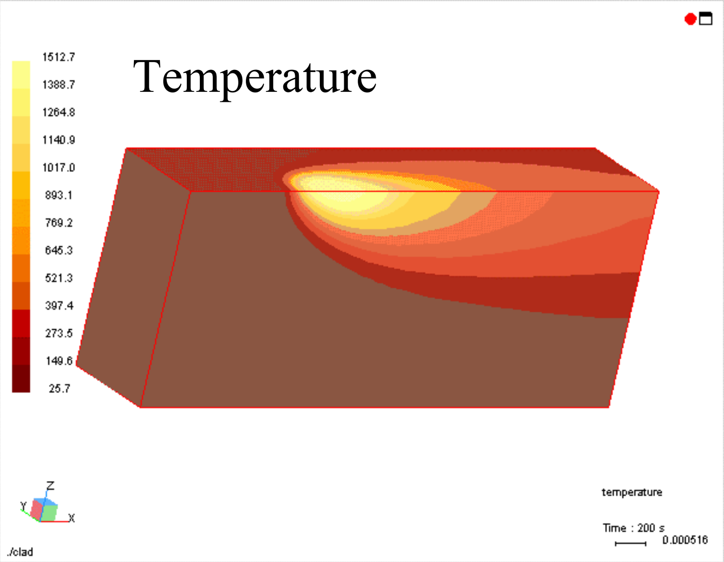
Calculation of

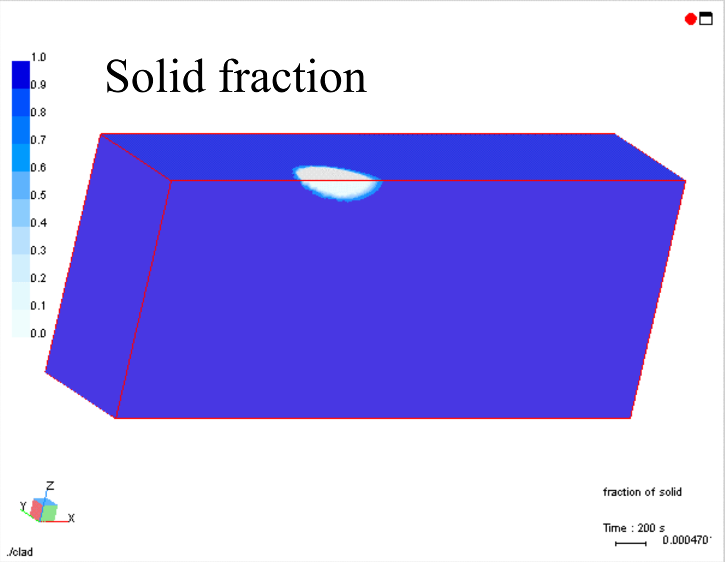
- temperature gradient, G
- interface velocity, V

as a function of position in the melt pool


Mesh




Temperature


Solid fraction

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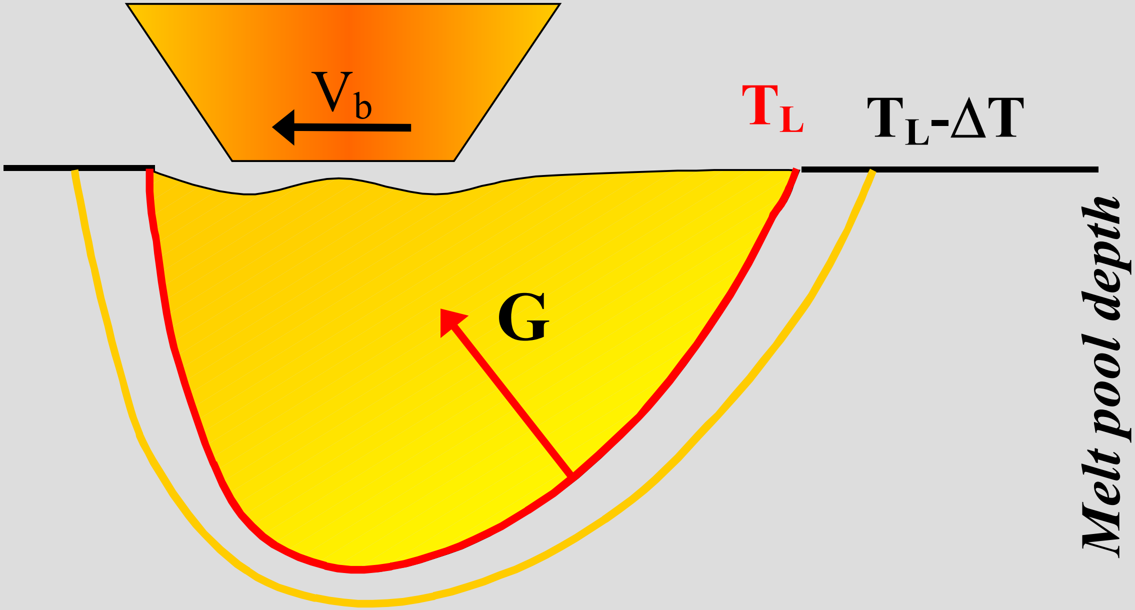
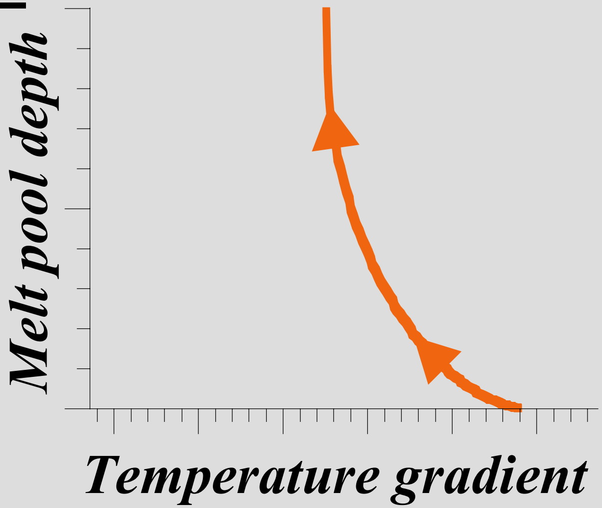
SOLIDIFICATION CONDITIONS

Temperature Gradient

Rosenthal Solution of the Heat-flux equation

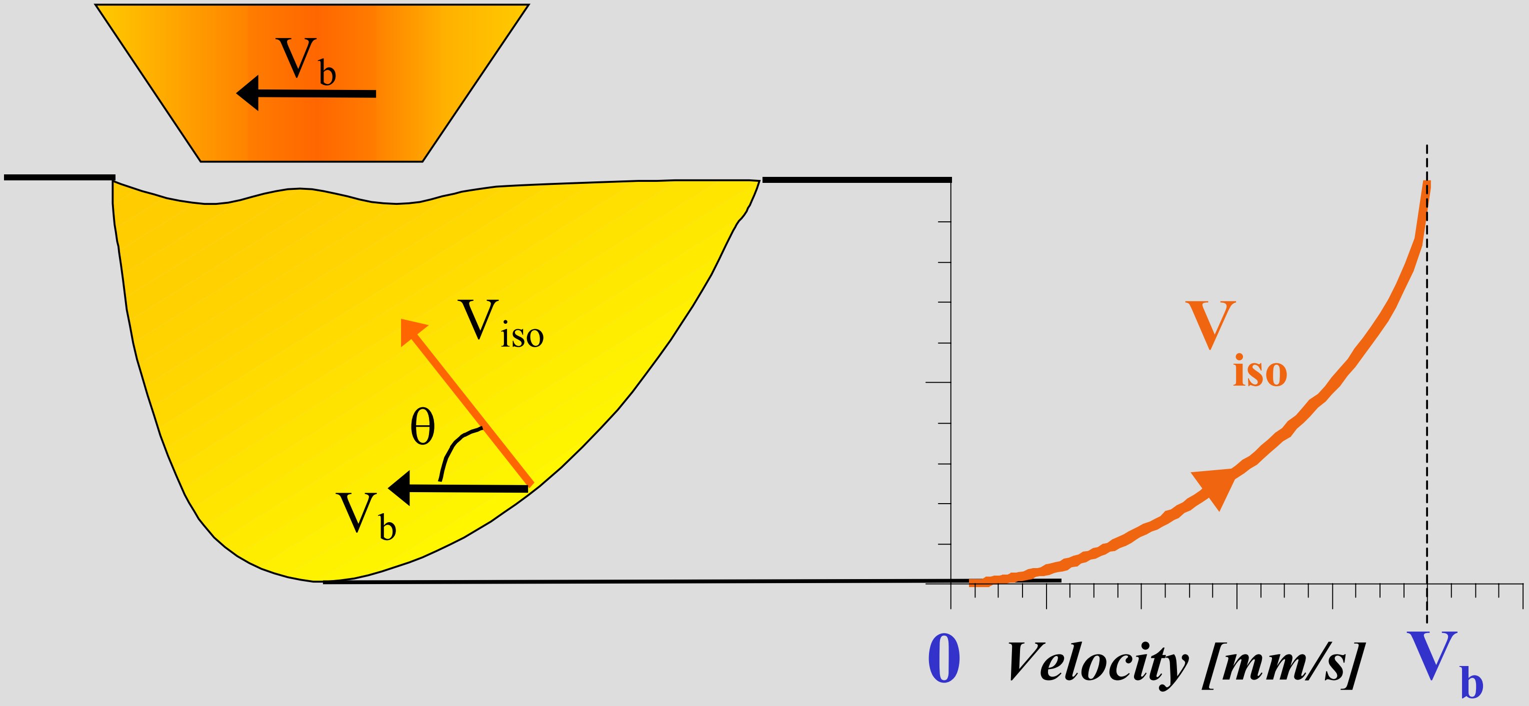




SOLIDIFICATION CONDITIONS

Solidification velocity

Isotherm velocity : $V_{iso} = V_b \cdot \cos\theta$



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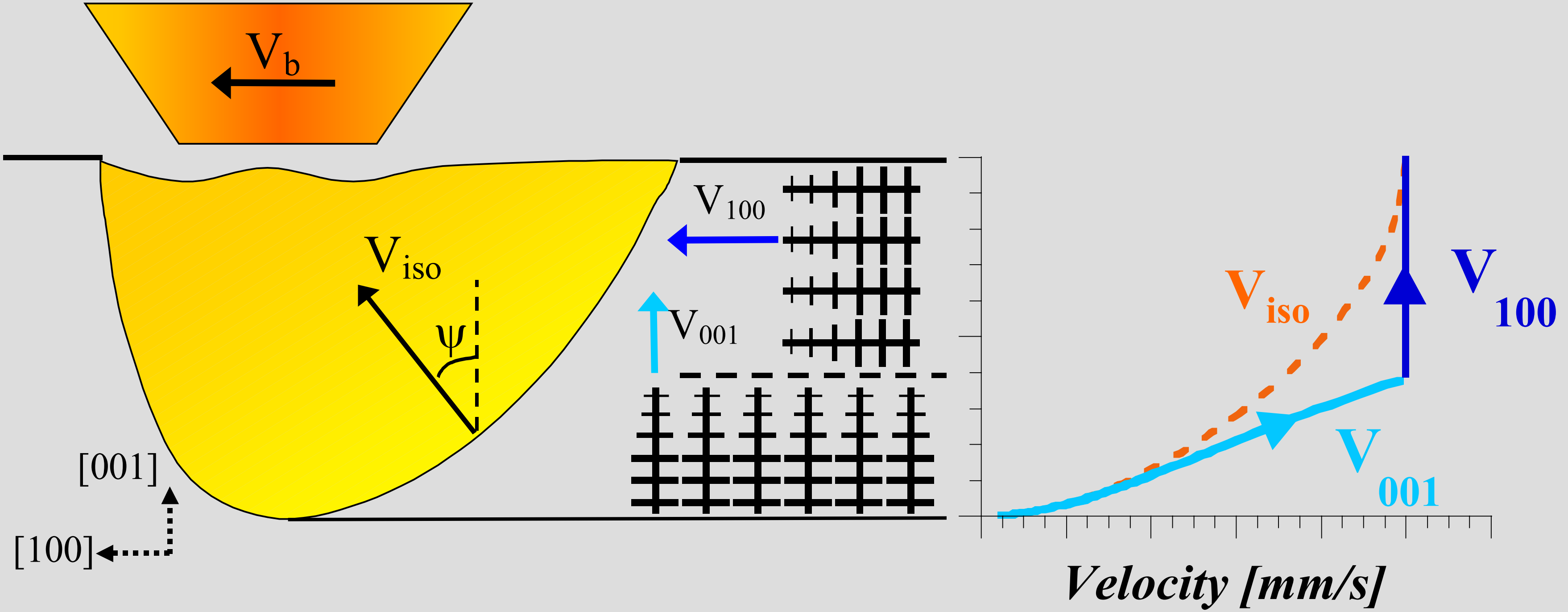
SOLIDIFICATION CONDITIONS

Solidification velocity

Isotherm velocity : $V_{iso} = V_b \cdot \cos\theta$

Dendrite velocity : $V_{hkl} = \dfrac{V_{iso}}{\cos\psi}$



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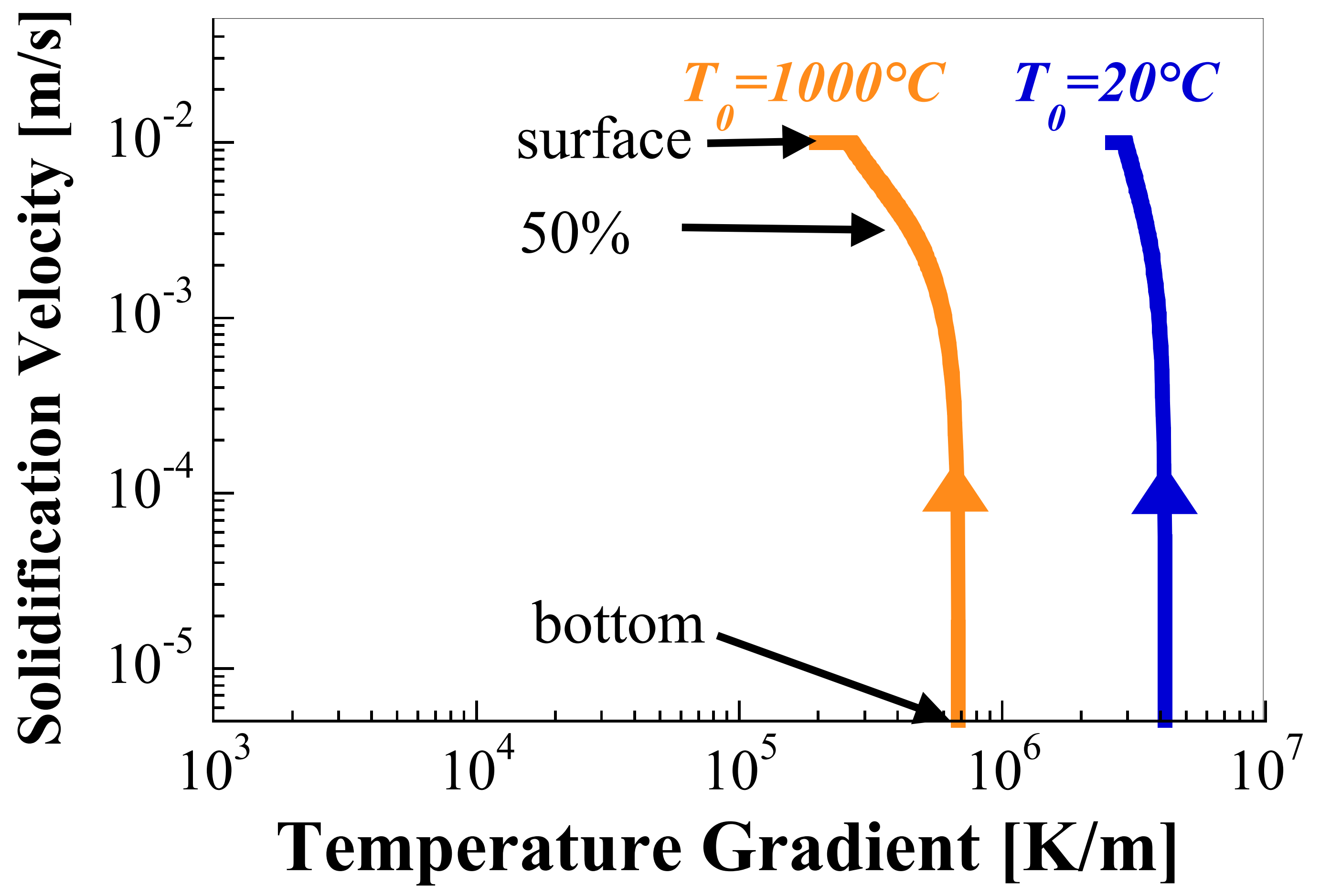
SOLIDIFICATION CONDITIONS



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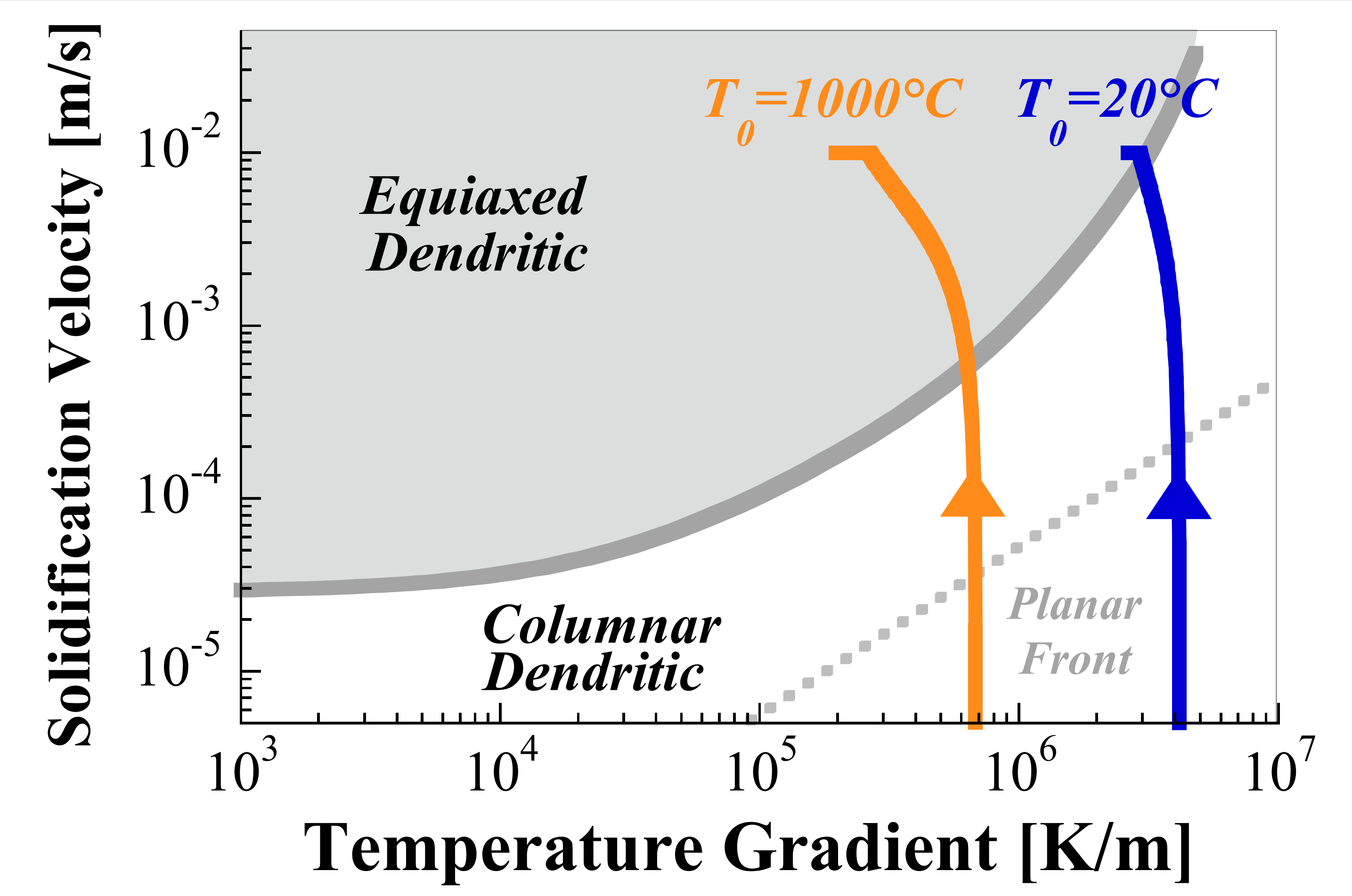
COMBINATION OF PARAMETERS CHARACTERISTIC FOR MICROSTRUCTURES
&
PROCESSING

MICROSTRUCTURE-PROCESSING MAP

PROCESSING-MICROSTRUCTURE MAP



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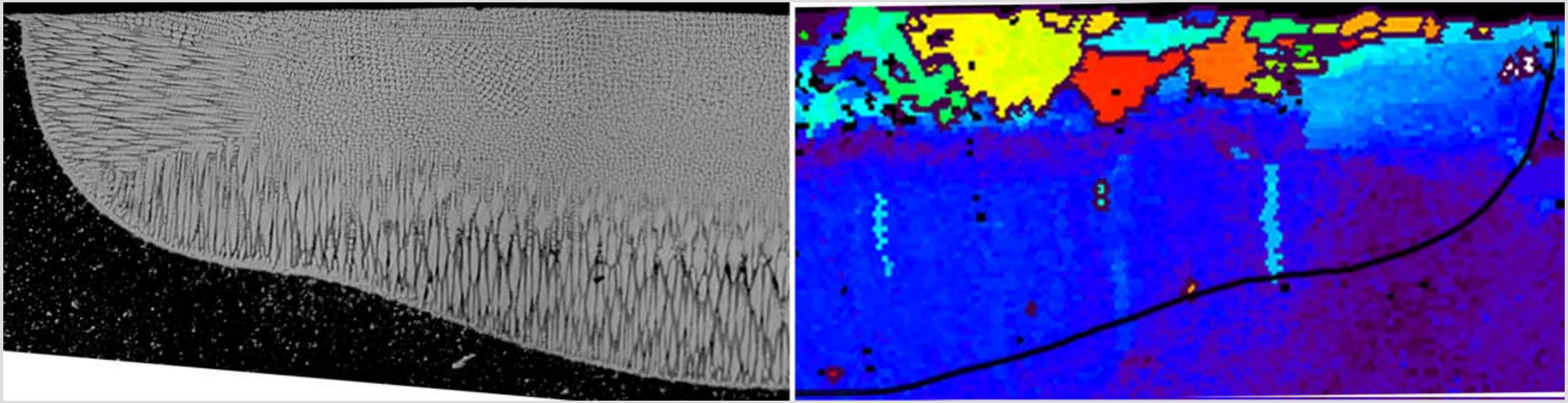
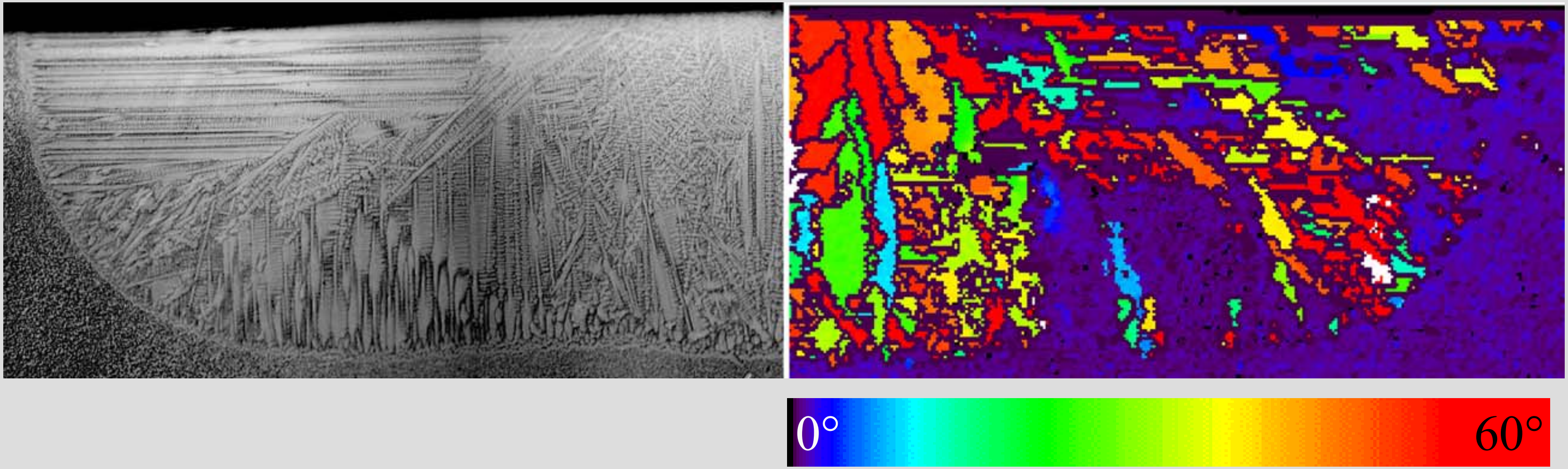
$T_0 = 20°C$



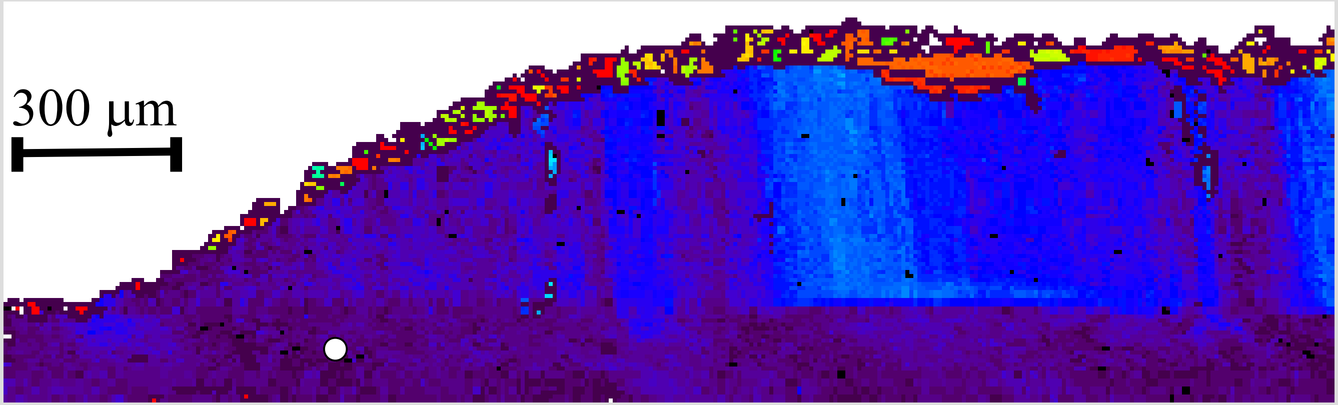
$T_0 = 1000°C$

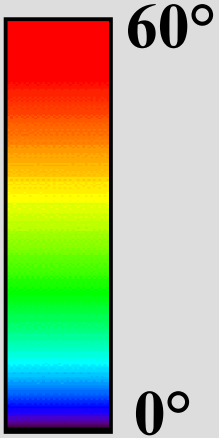


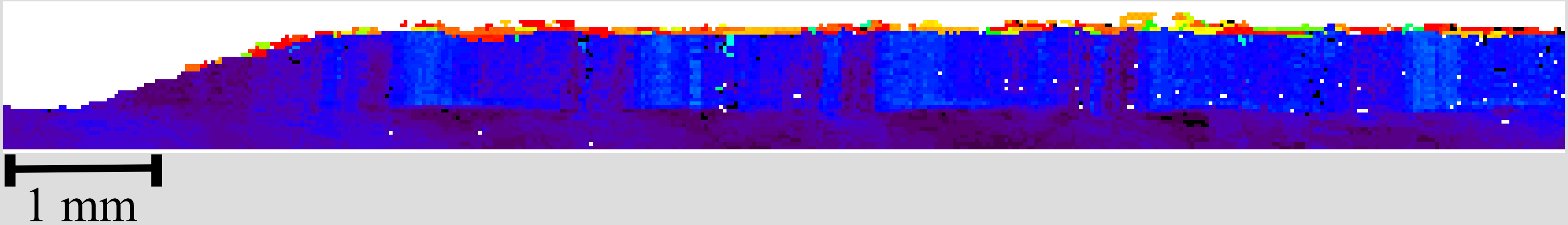
LASER REMELTING

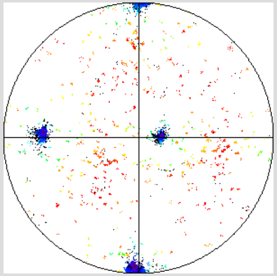
LASER CLADDING MCrAlY

Orientation analysis (EBSD)

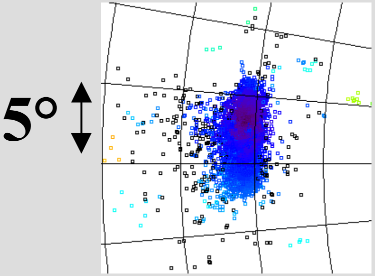








[100] Pole Figure



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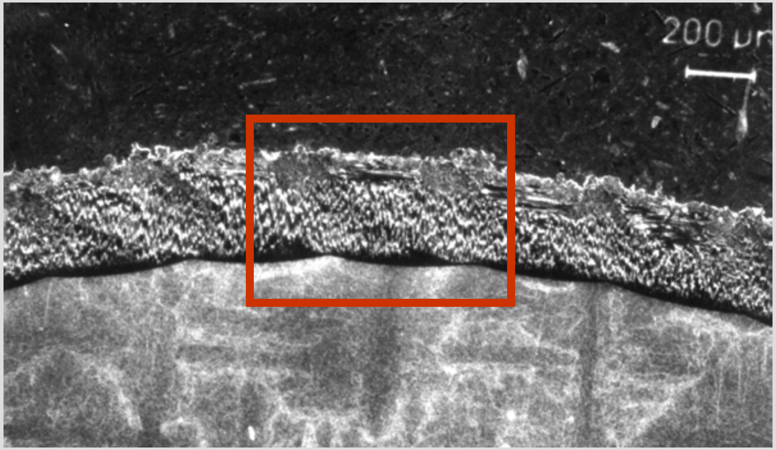
SX CLADDING OF MECH. TEST SPECIMEN

Transverse Section



MCrAlY - 0,3 mm

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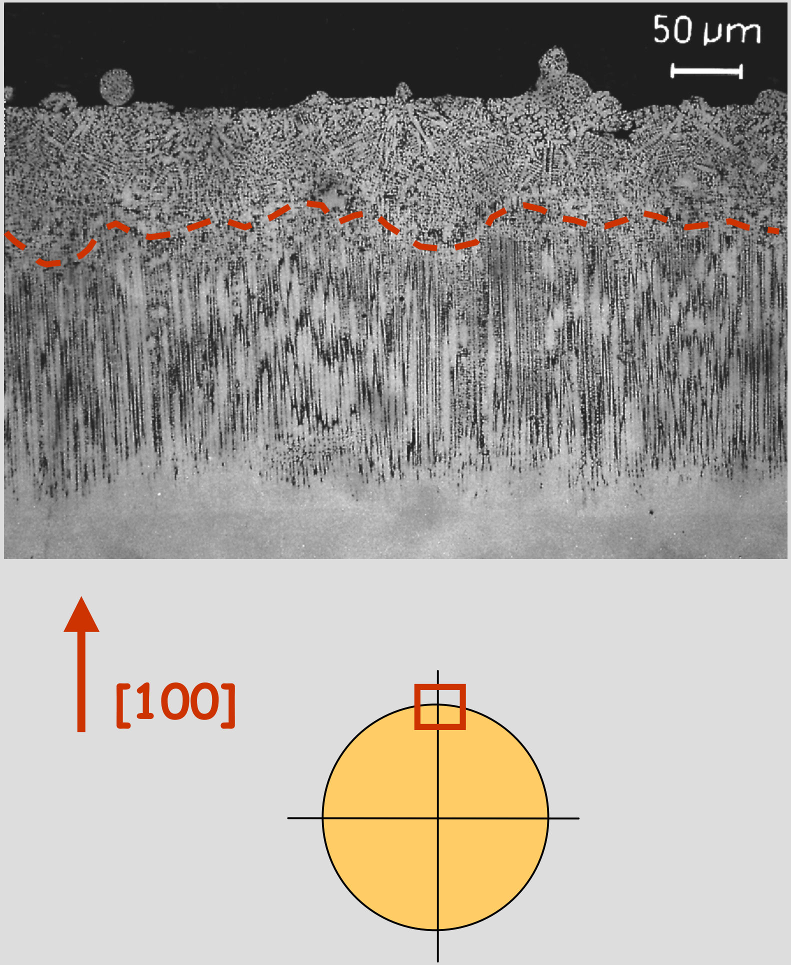
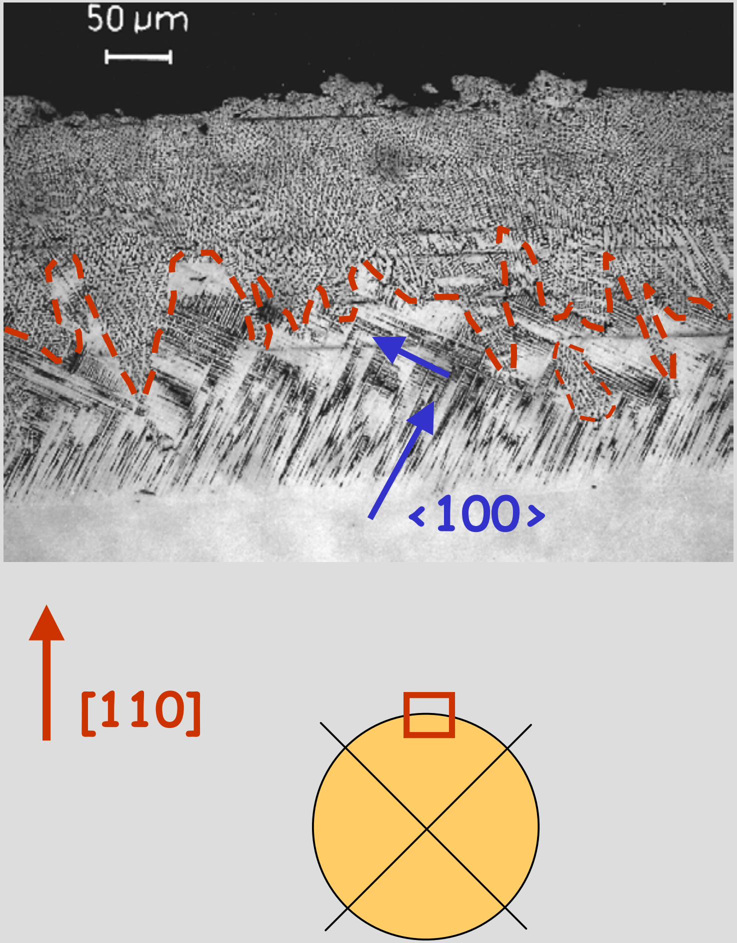
MICROSTRUCTURE OF TEST SPECIMEN





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REPAIR ENGINEERING

High price of SX components,
typically 5 k€ per blade,
asks for life time extension techniques

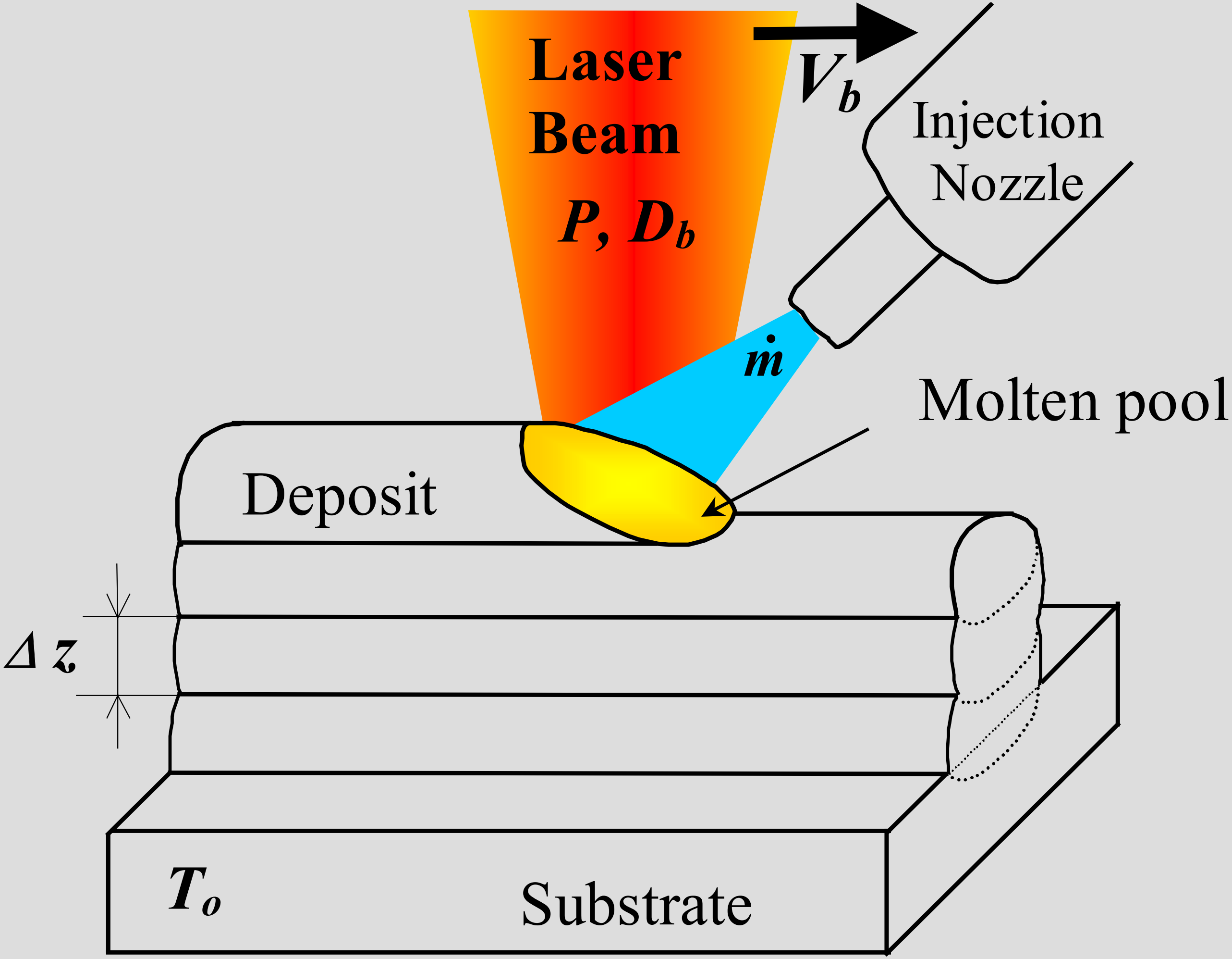
THE CONCEPT OF
SX - SURFACE ENGINEERING - II
REPAIR ENGINEERING

Low C, B, Zr superalloys form (at high T) mechanically strong crystals - but are very week at grain boundaries:

- avoid formation of g.b.

SOLUTION: SX REPAIR OF SX BLADES

LASER METAL FORMING



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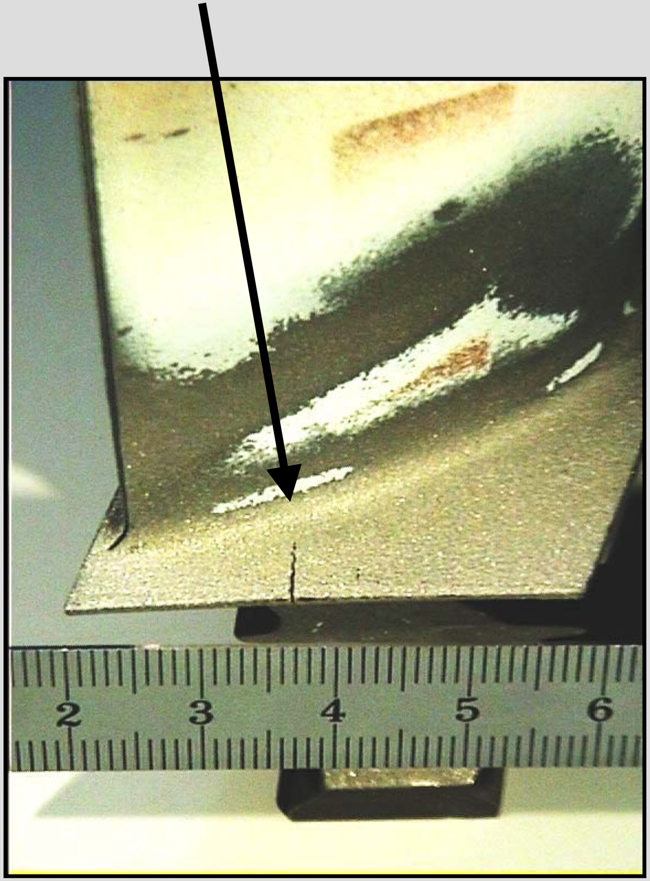
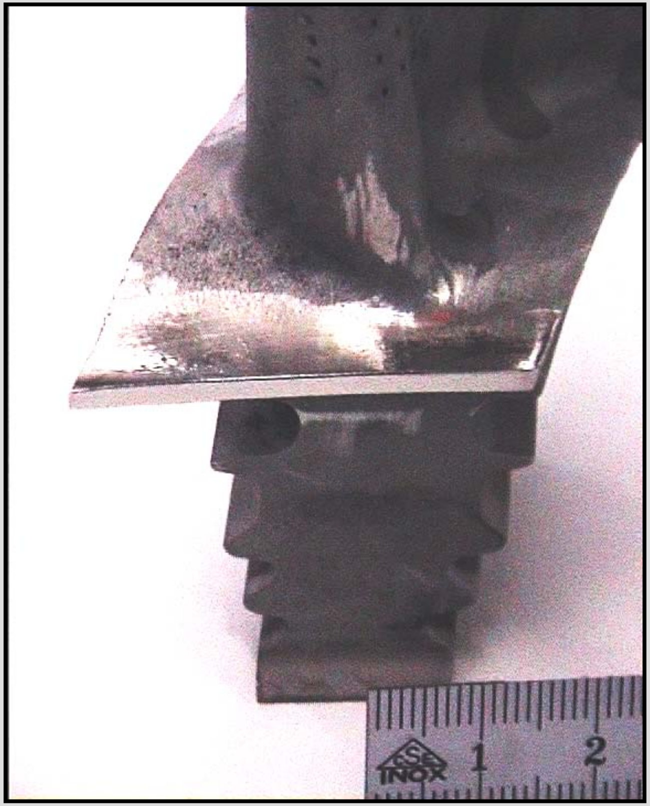
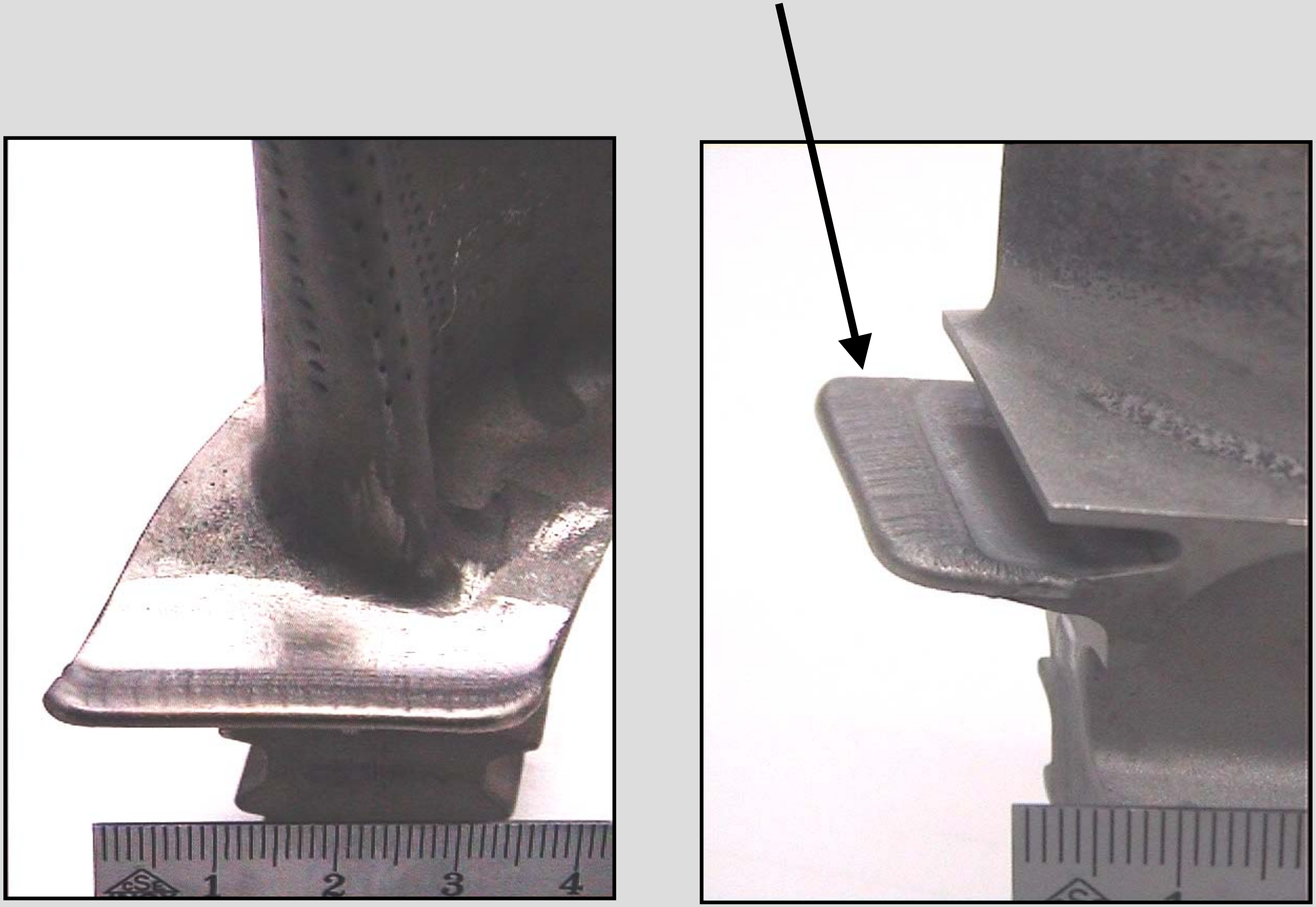
Platform crack due to thermo-mechanical fatigue





After cutting/polishing

AFTER LASER METAL FORMING



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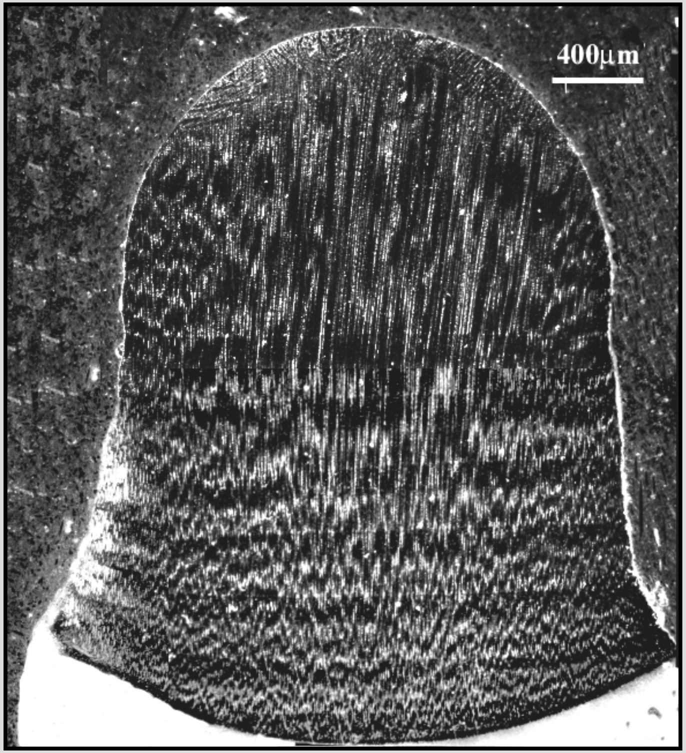
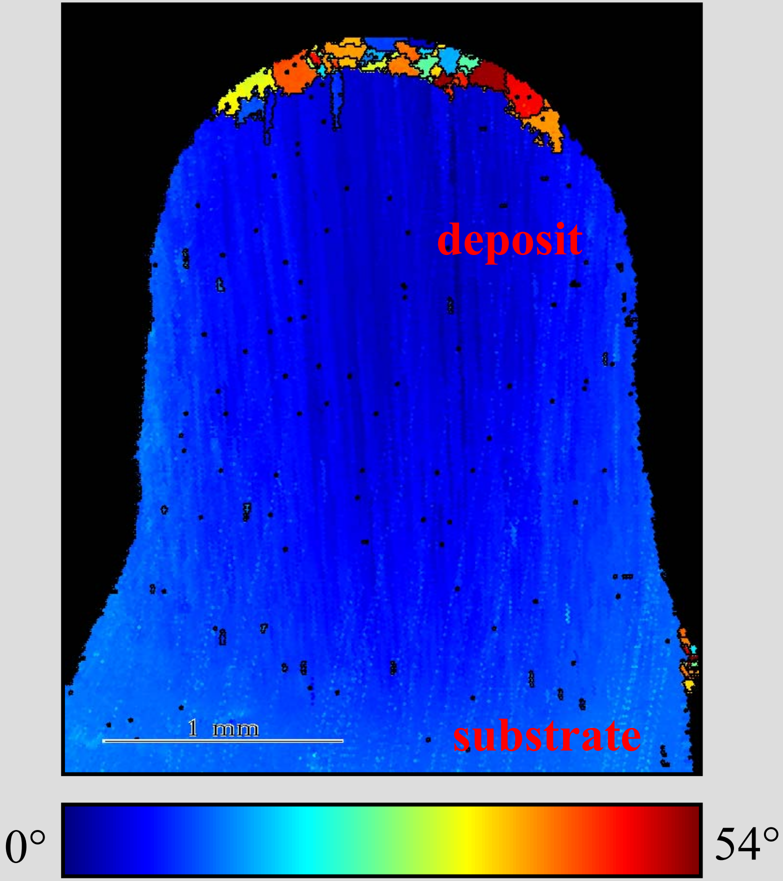
LASER METAL FORMING

Microstructure Analysis



8 laser traces



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CONCLUSIONS

- Epitaxial Cladding,
- Epitaxial Laser Forming,
- (also Epitaxial Welding),

can be achieved on SX components. It requires solidification theory for a close control of

- macroscopic heat flux (epitaxy) and
- microstructure development to control CET.

CONCLUSIONS

Today there is industrial activity to transfer the concepts into production for stationary gas turbines and aircraft engines.

Ideal ground for application of long term university research to industrial problems.