SINGLE CRYSTAL SURFACE ENGINEERING

W. Kurz
C. Bezençon
S. Mokadem
J.-D. Wagnière

J.-M. Drezet

M. Hoebel
M. Konter

Swiss Federal Institute of Technology Lausanne (EPFL)
CALCOM Lausanne
ALSTOM Power Baden

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) ↓
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.

\[ E_{[100]} \sim 125 \text{ [GPa]} \]
\[ E_{[111]} \sim 310 \text{ [GPa]} \]
LASER CLADDING PROCESS

- Laser Beam
- \( P, D_b \)
- Injection Nozzle
- \( V_b \)
- Clad
- Molten pool
- \( \Delta y \)
- \( m \)
- Substrate
- \( T_o \)
MICROSTRUCTURES / DEFECTS

Columnar
Epitaxial growth
Equiaxed grains
Non-epitaxial columnar grains

SX - Substrate
SX - Deposit

[001]

Ideal case
Defects to avoid

EPFL
EPITAXY

Ensure at the surface
• metallic contact with the substrate
• similar crystal structure of primary phases
LASER CLADDING PROCESS

- **Deposit**
- **Remelted zone**
- **Liquid**
- **Mushy zone**
- **Solid**
- **Substrate**

Symbols:
- $V_b$
- $G, V_S$
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

CMSX-4

MCrAlY

EPFL
Dendrites grow along \langle 100 \rangle 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
COLUMNS TO EQUIAxed TRANSITION

Process
- Temperature Gradient
- Solidification Velocity

Alloy
- Growth Undercooling
- Nucleation Site Density
- Nucleation Undercooling

Constitutional Undercooling

EPFL
COLUMNAR TO EQUIAXED TRANSITION

Effect of $G$ and $V$

High $G$

Low $V$

$G_1$

$G_2$

$\Delta T_c$

$\Delta T_c$

$z$

$T$

$z$

$T$

$T$

$V_1$

$V_2$

COLUMNAR TO EQUIAXED TRANSITION

Effect of $G$ and $V$
COLUMNAR TO EQUIAXED TRANSITION

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

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

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

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

\[ \frac{G^n}{V} > K \]

, for a columnar structure

EPFL
MICROSTRUCTURE SELECTION MAP

Equiaxed Dendritic

Columnar Dendritic

Planar Front

$G^n / V > K$

Solidification Velocity [m/s] vs. Temperature Gradient [K/m]
PROCESSING PARAMETERS

Calculation of

- temperature gradient, $G$
- interface velocity, $V$

as a function of position in the melt pool
SOLIDIFICATION CONDITIONS

Temperature Gradient

Rosenthal Solution of the Heat-flux equation
SOLIDIFICATION CONDITIONS

Solidification velocity

Isotherm velocity: \( V_{iso} = V_b \cdot \cos \theta \)
SOLIDIFICATION CONDITIONS

Solidification velocity

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

Dendrite velocity: \( V_{hkl} = \frac{V_{iso}}{\cos \psi} \)
SOLIDIFICATION CONDITIONS

Temperature Gradient [K/m] vs. Solidification Velocity [m/s]

- Solidification velocity for $T_o = 1000^\circ$C and $T_o = 20^\circ$C
- Solidification conditions at surface and 50% for $T_o = 1000^\circ$C
- Solidification conditions at bottom for $T_o = 20^\circ$C
COMBINATION OF PARAMETERS CHARACTERISTIC FOR MICROSTRUCTURES & PROCESSING

MICROSTRUCTURE-PROCESSING MAP
$T_0 = 20^\circ C$

$T_0 = 1000^\circ C$

LASER REMELTING

EPFL
LASER CLADDING MCrAlY

Orientation analysis (EBSD)

[100] Pole Figure

EPFL
SX CLADDING OF MECH. TEST SPECIMEN

Transverse Section

MCrAlY - 0.3 mm

EPFL
MICROSTRUCTURE OF TEST SPECIMEN

[100] [110]
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 weak at grain boundaries:

• avoid formation of g.b.

SOLUTION: SX REPAIR OF SX BLADES

EPFL
Platform crack due to thermo-mechanical fatigue

After cutting/polishing
AFTER LASER METAL FORMING
LASER METAL FORMING

Microstructure Analysis

8 laser traces

0°

deposit

substrate

54°
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.
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.