# Special Projects and Applications

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# Special Projects and Applications

**Flow Forming (FF) of PM2000 tubes**

- Cold FF
- Warm FF
- Grain structures and properties

**Selective Laser Melting (SLM) PM2000 powder**

- SLM build process
- Build microstructures
- Potential applications

# Biomass HTHE Feasibility Study

*Heat transfer:* *12.5 MW*

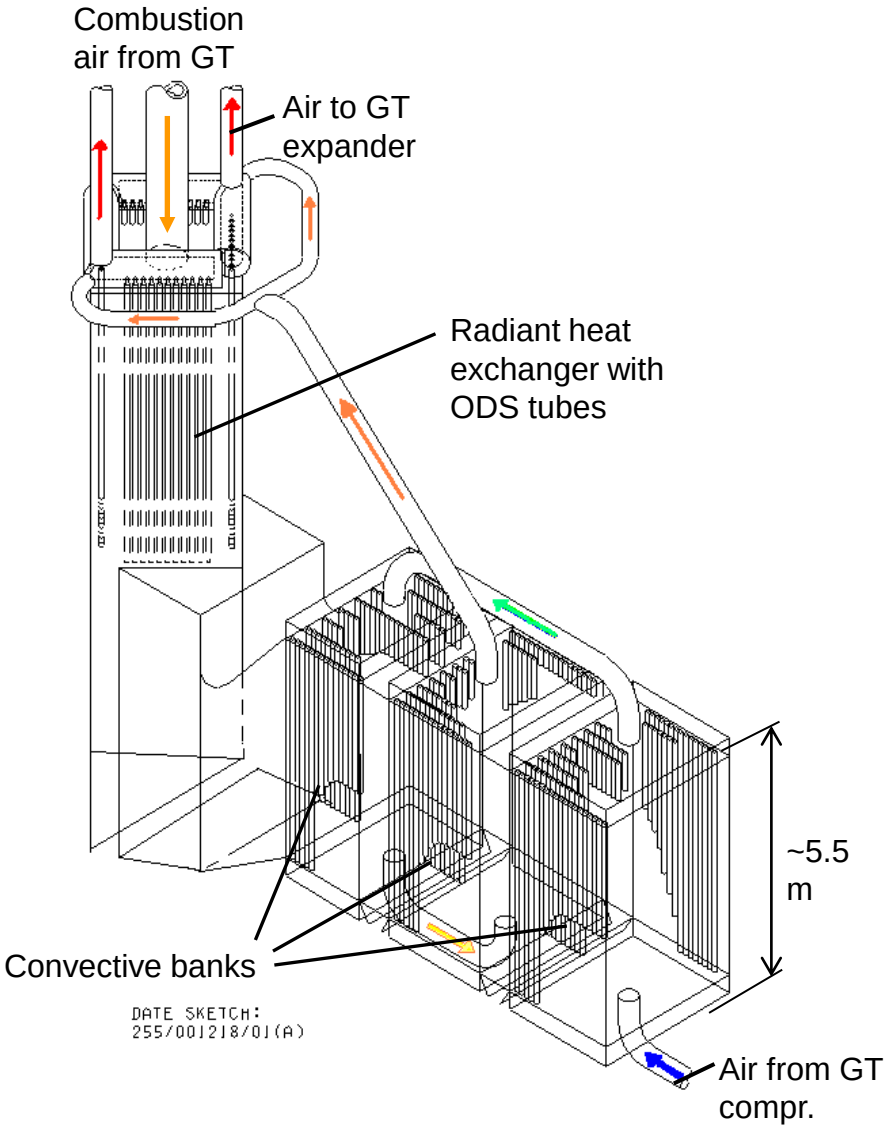
*Air flow:* *17.5 kg/s*

*Pressure:* *11.3 bar*

*Air temp:* *1013°C*

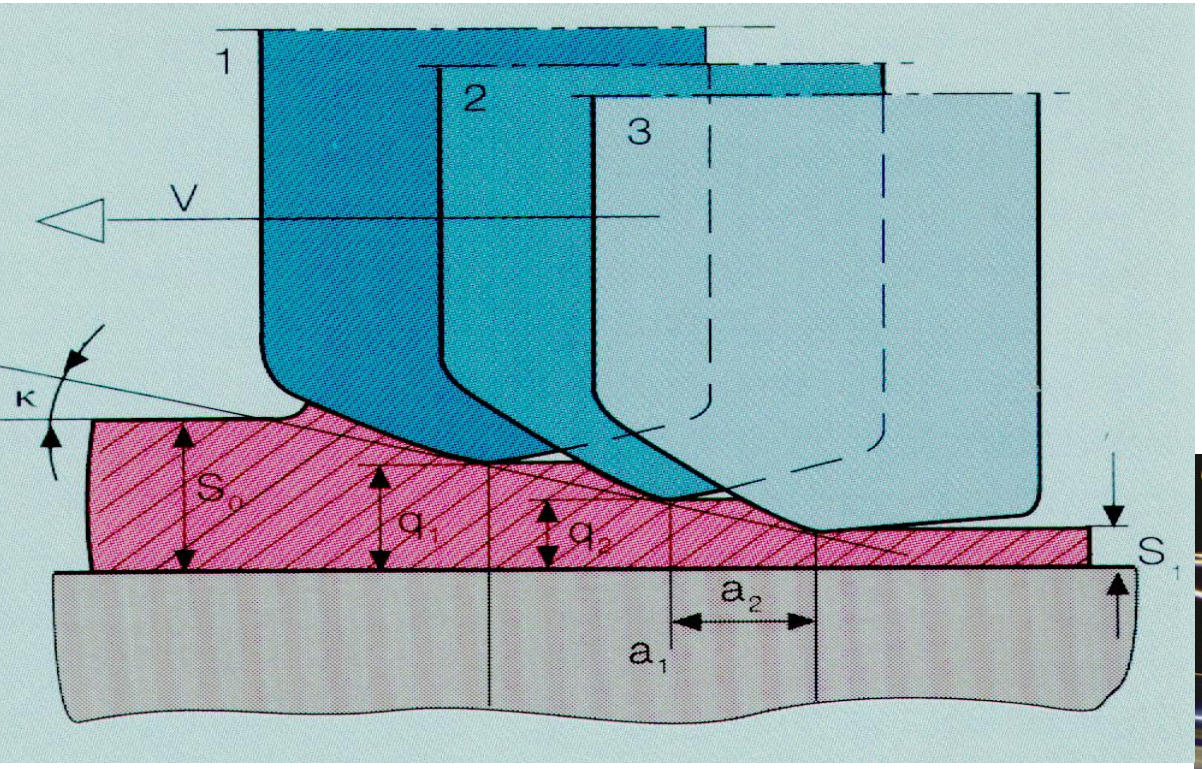
*ODS temp:* *1090°C*

*No.of ODS tubes:* *80*

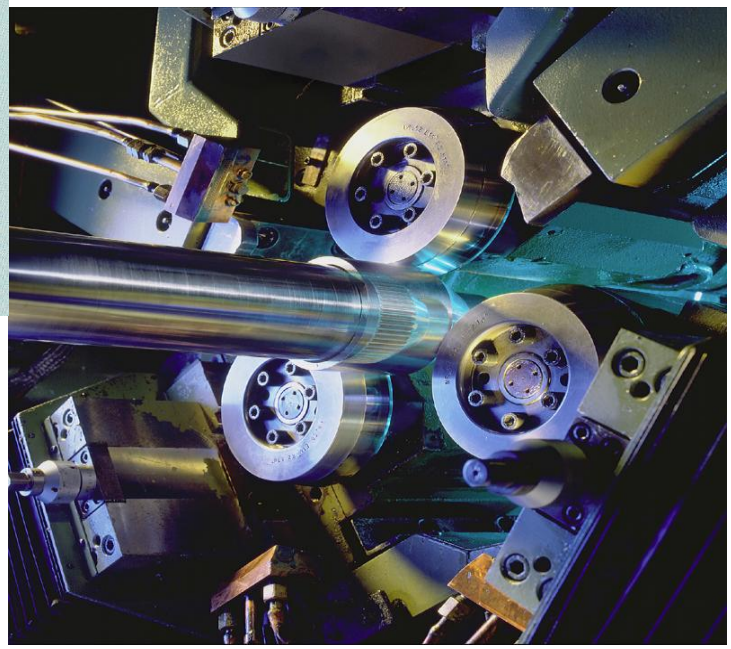


# Flow Forming of PM2000 tubes

## Three -Roller Flow Forming




| | |
|---|---|
| Plansee GmbH / Lechbruck | DE |
| Metall Spezialrohr GmbH | DE |
| Mitsui Babcock Energy Ltd | GB |
| Sydkraft Konsult AB | SE |
| University of Liverpool | UK |
| Risoe National Laboratory | DK |
| University of Cambridge | UK |



**'Graintwist' - European BRITE project**

- Background – ODS tubed heat exchanger
- Tube Flow forming: change GAR in PM2000
- Hoop creep properties
- 3 years / $3.2m

# Flow Forming of PM2000[1] tubes

## Cold (water cooled) reverse flow formed tubes produced

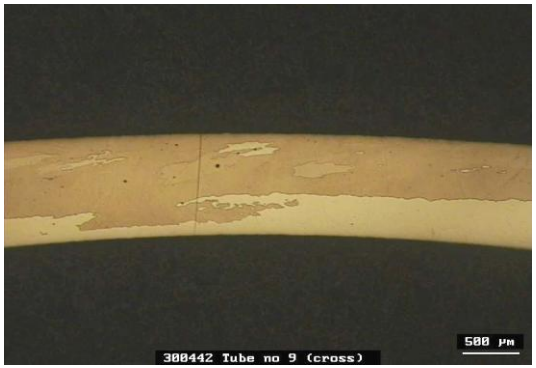
| Tube | Total cold deformation | Passes | End.OD x WT [(2)] |
|---|---|---|---|
| No. 1 | 74% | 1 | 46,8 x 1,30 |
| No. 2 | 76% | 1 | 46,6 x 1,20 |
| No. 3 | 72% (41+62) | 2 | 47,2 x 1,40 |
| No. 4 | 74% | 1 | 46,8 x 1,30 |
| No. 5 | 73% | 1 | 47,0 x 1,30 |
| No. 6 | 47% | 1 | 49,4 x 2,60 |
| No. 7 | 92% (43+70+56) | 3 | 45,2 x 0,50 |
| No. 8 | 83% (47+72) | 2 | 46,0 x 0,90 |
| No. 9 | 81% (43+76) | 2 | 46,2 x 1,00 |
| No. 10 | 90% (54+72) | 2 | 45,4 x 0,60 |

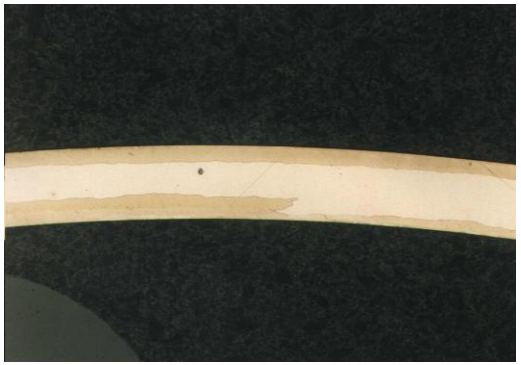
(1) Fine grained condition

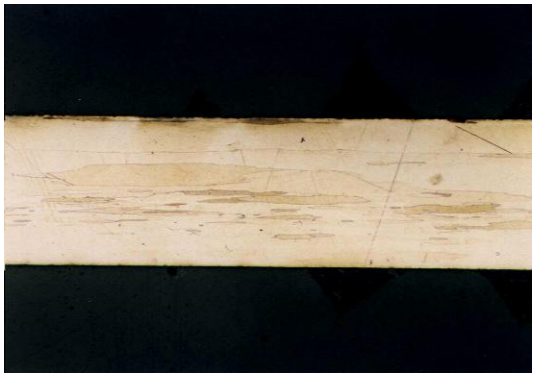
(2) Start dimensions 53.3mm OD, 4.55mm wall

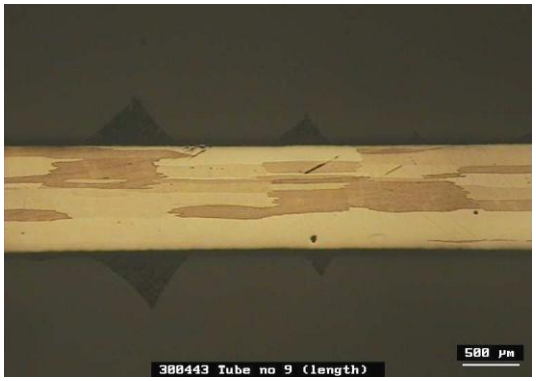
# Flow Forming of PM2000 tubes

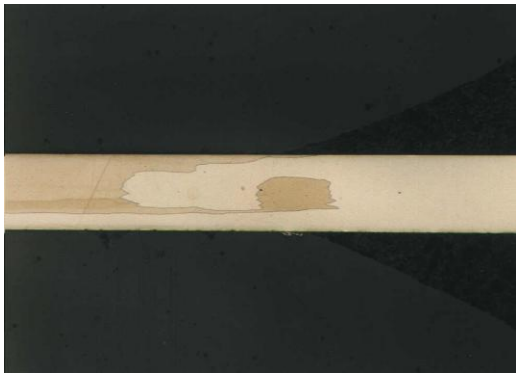
## PM2000 Tubes Cold Flow formed [1,2] + Secondary Recrystallised [3]







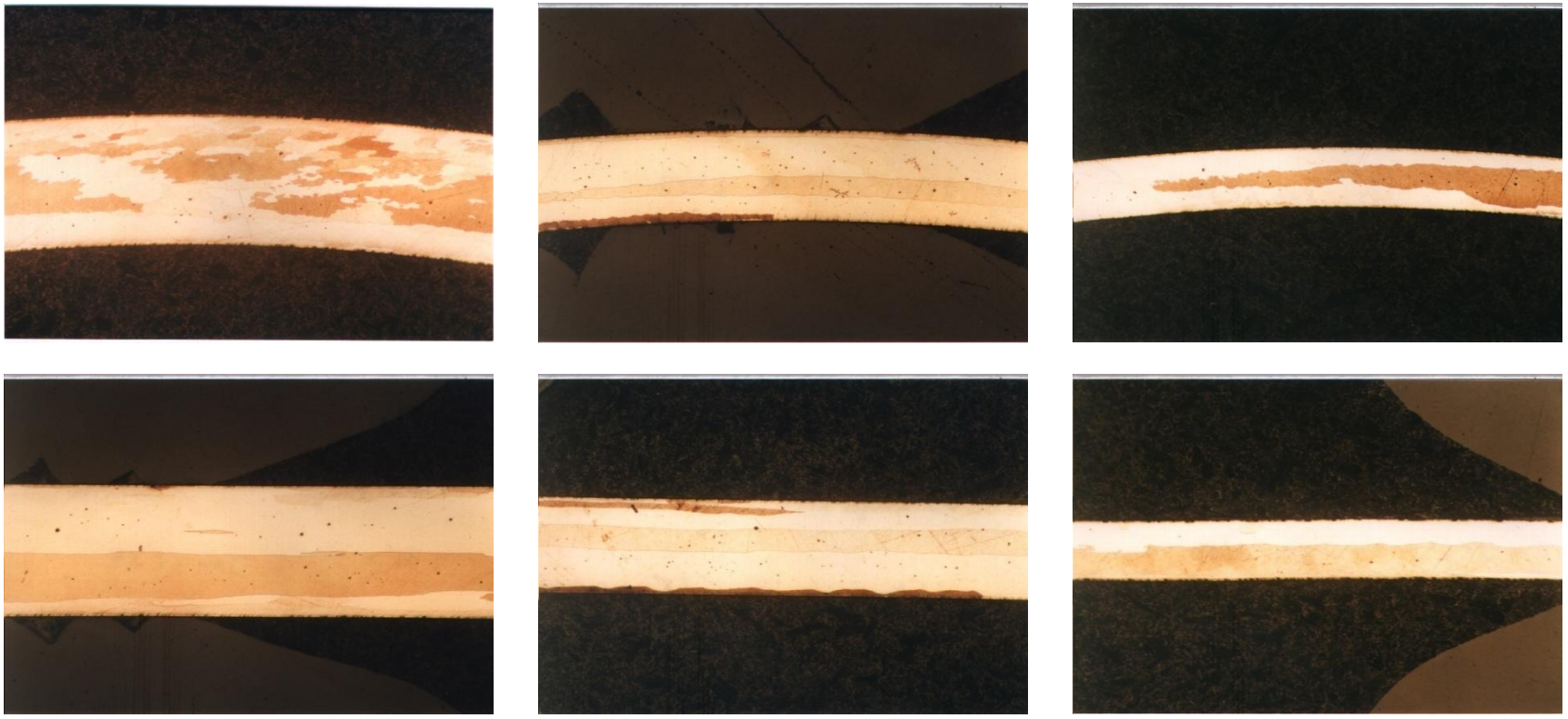



**Tube 1 ( 74%)** **Tube 9 ( 81%)** **Tube 10 ( 90%)**

[1] Water cooled reverse flow forming.
[2] PM2000 preforms (53.3mm OD/4.55mm wall).
[3] $1320^0$C / 1.5h

# Flow Forming of PM2000 tubes

## PM2000 Tubes Warm Flow formed [1] + Secondary Recrystallised [2]



W 4 (72%) W 5 (80%) W 8 (88%)

[1] Warm flow forming: 600-650$^0$C. Preheated tube / mandrel (gas burners)
[2] 1320$^0$C / 1.5h

# Flow Forming of PM2000 tubes

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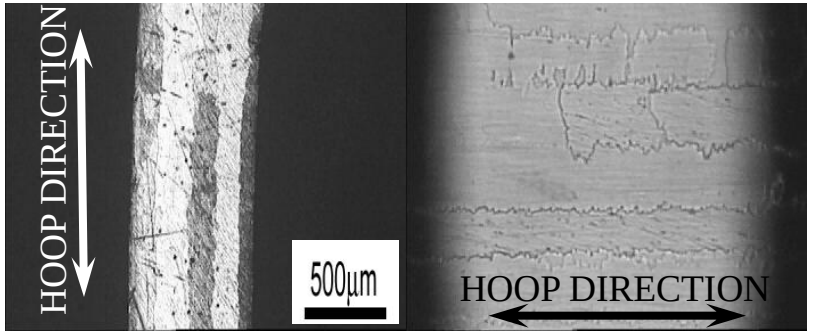
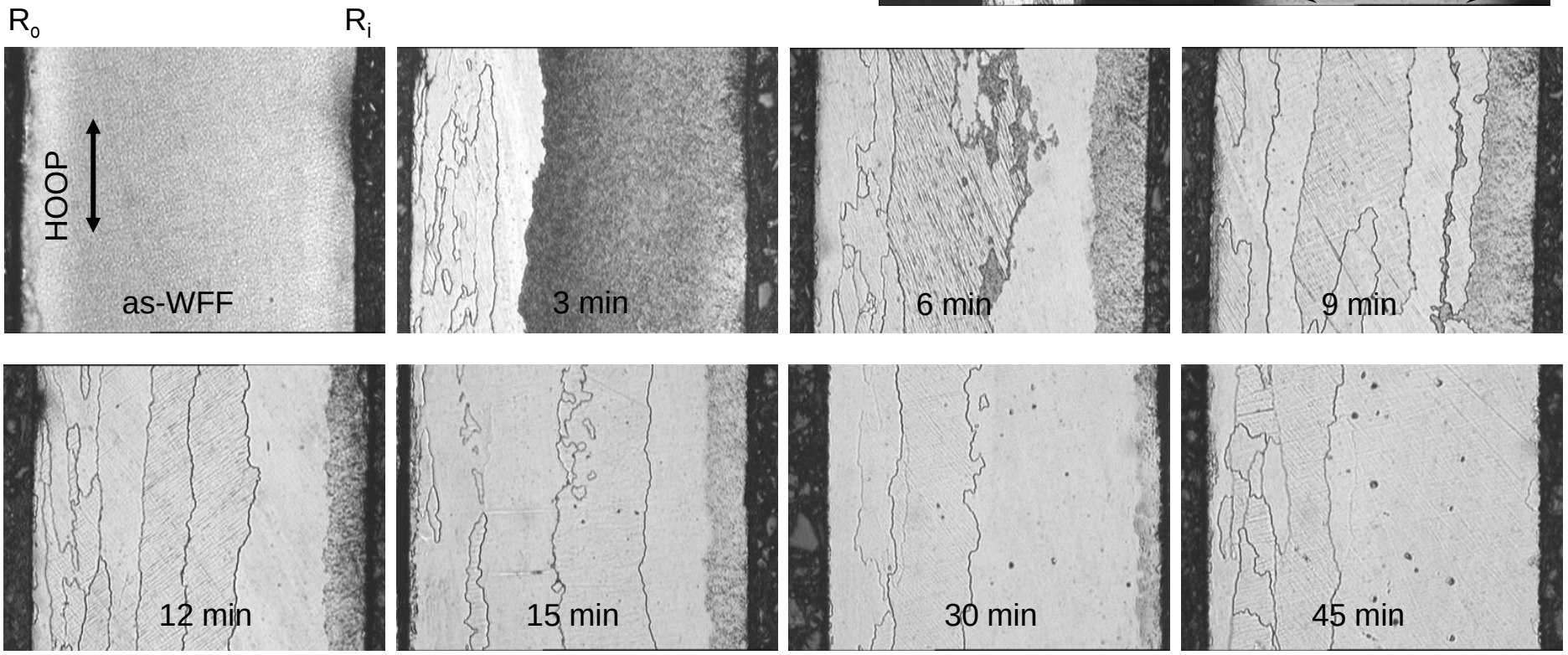
Secondary Recrystallisation:

tube – W7 (86%)

warm flow formed + 1h / 1380ºC

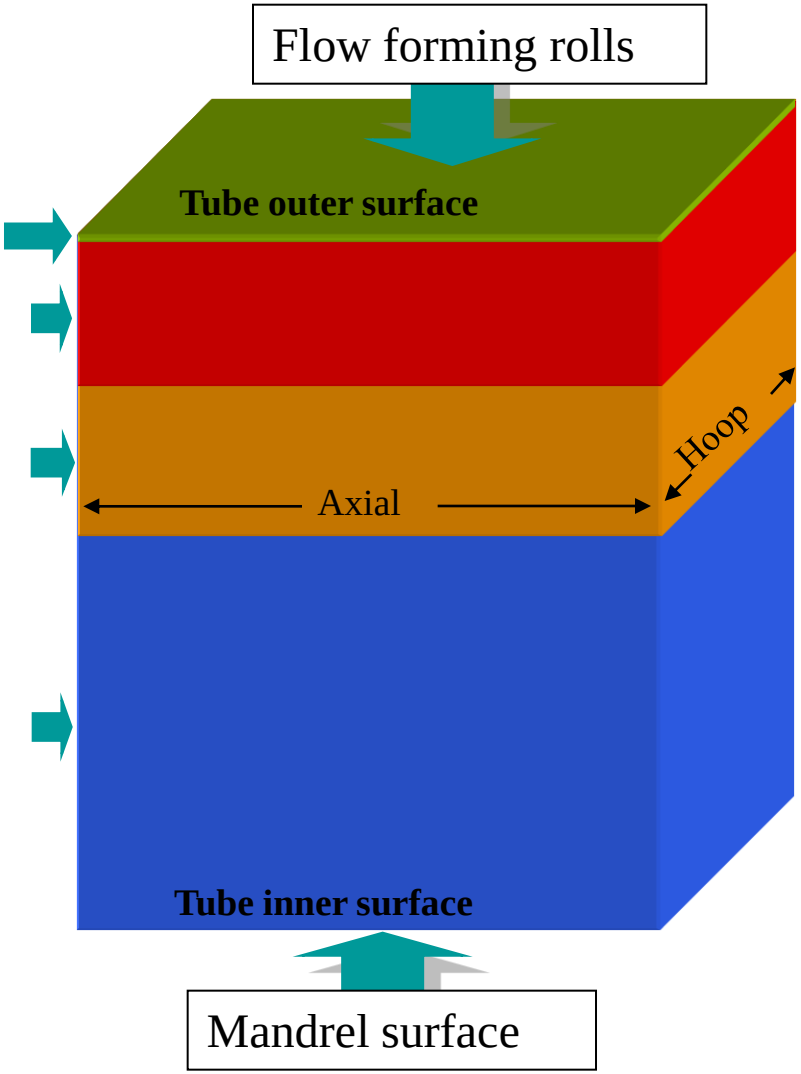



Annealing Time @ 1380ºC

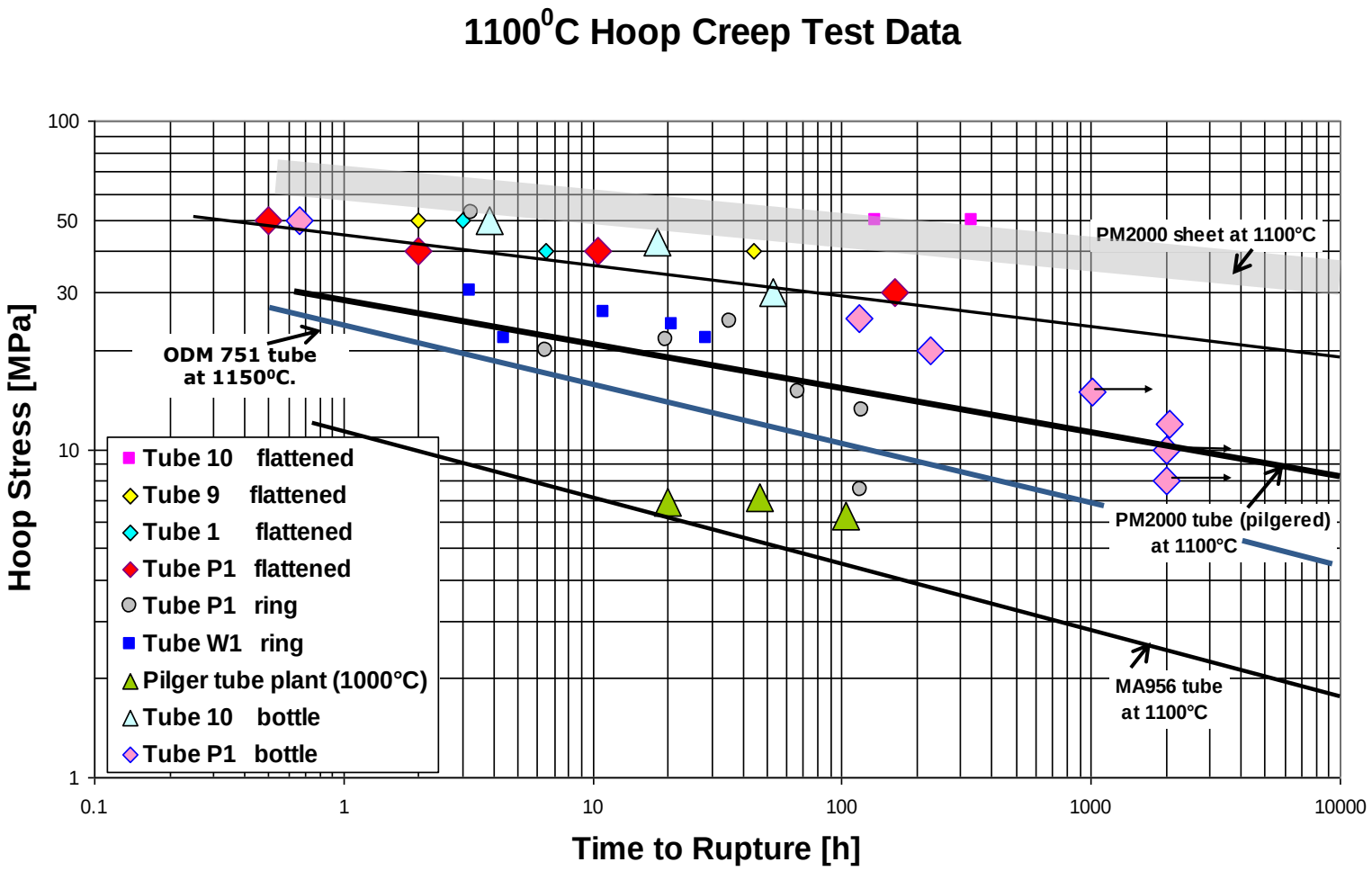
# Flow Forming of PM2000 tubes

**SR Microstructural zones in Warm deformed tube – W7 (86%)**




| | Grain Size [μm] | | |
|---|---|---|---|
| | Axial | Radial | Hoop |
| A | 600 | 10 | 50000 |
| B | 650 | 90 | 100 |
| C | 2500 | 150 | 1500 |
| D | 10000 | 350 | 7500 |

# Flow Formed + SR tube Creep Test Data



# Flow forming of PM2000 tube: outcomes

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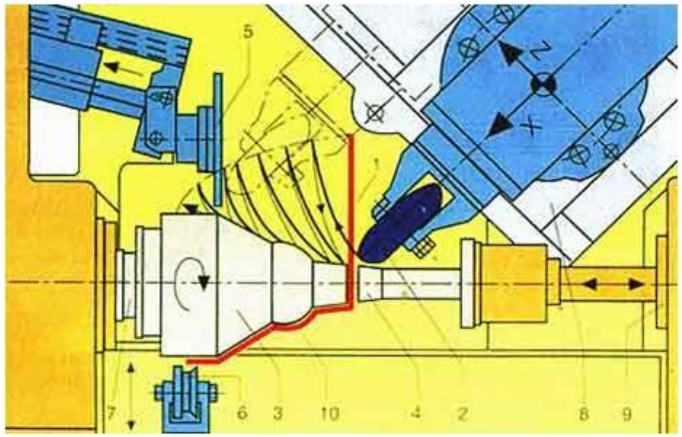
- Flow Formed (FF) tube can exhibit large hoop creep strength increment c.f. Pilger tube
- FF deformation > 80% required to achieve useful (coarse) SR grain structures
- 'Warm' FF may offer certain advantages over 'cold' FF
- Commercial FF produce complex *deformation patterns* in tube:
  - axially periodic (reflect roller positions)
  - vary significantly through tube wall thickness
  - influenced by number of passes/roller geometry
- FF produces a wide range of *SR microstructures* in tube:
  - grain size
  - GAR (and orientation)
  - $T_{Rex}$
  - texture type/strength

  } vary through wall thickness

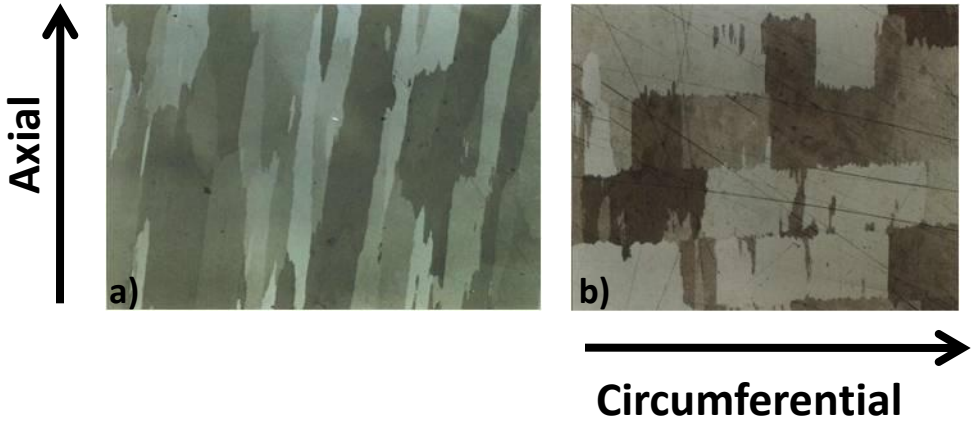
  - grain size varied with total level of FF deformation (50-90%)

# Metal Spinning for Combustor Cans




Schematic showing a CNC metal spinning process.

Example of a conventional combustor can (Typhoon DLE). Courtesy of Siemens




Metal spinning imparts tangential material flow: influences circumferential grain structures after SR.

Different grain morphologies can be produced depending on the combination of forming parameters.

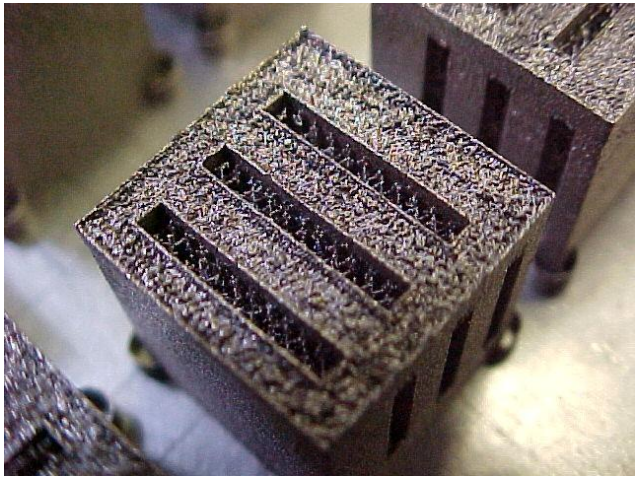
Figures show plan views of grain structures in different PM2000 spun cans.

Grain morphology relative to the component varies from almost fully axial (a) to fully circumferential (b).

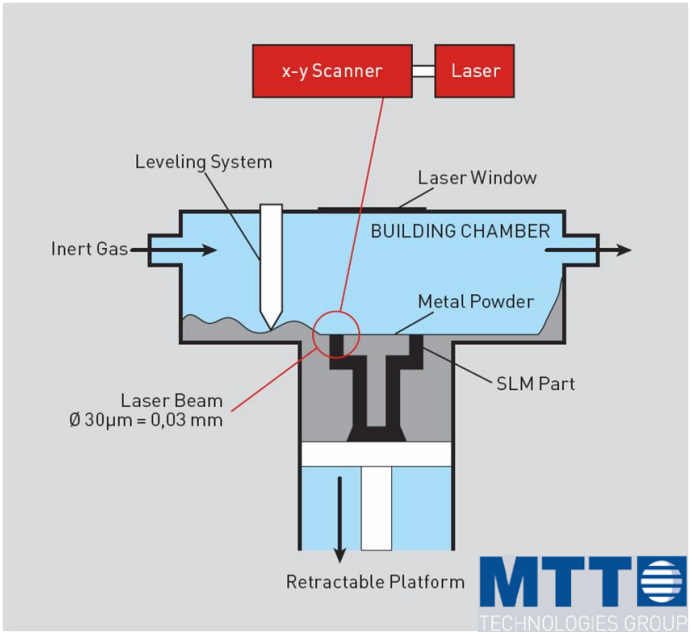
# Selective Laser Melting (SLM) PM2000 powder

**PM 2000 Thermocouple Sleeves**
Application: e.g. in Gas Turbines; temperature measurement close to combustion chamber

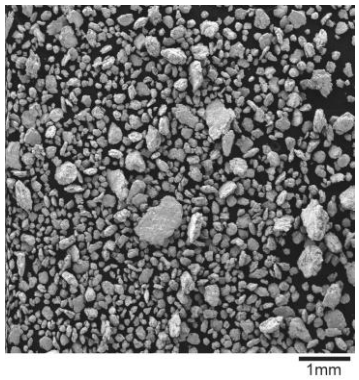
**PM 2000 low $NO_x$ burner nozzles**

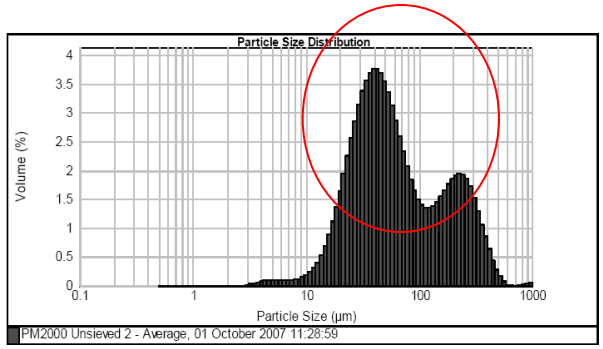


**Micro-heat exchanger** by SLM (20mm cube)

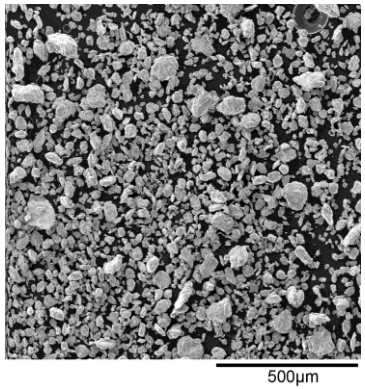


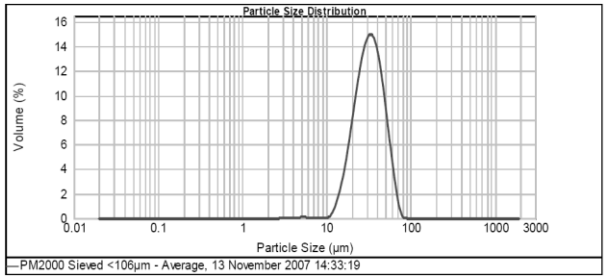
# Selective Laser Melting (SLM) PM2000 powder



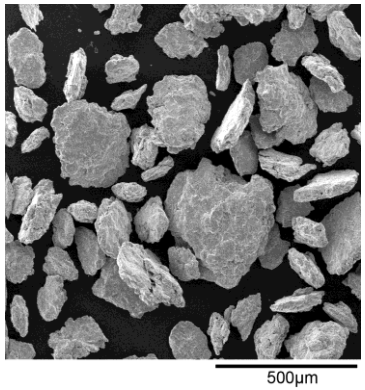



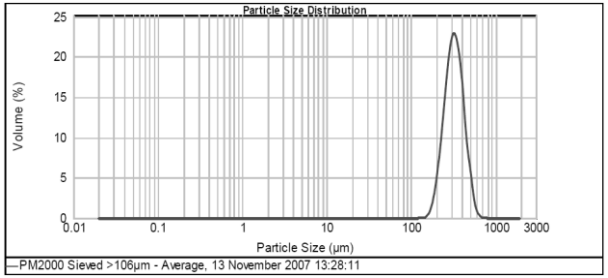

As-received powder




Smaller fraction <106µm



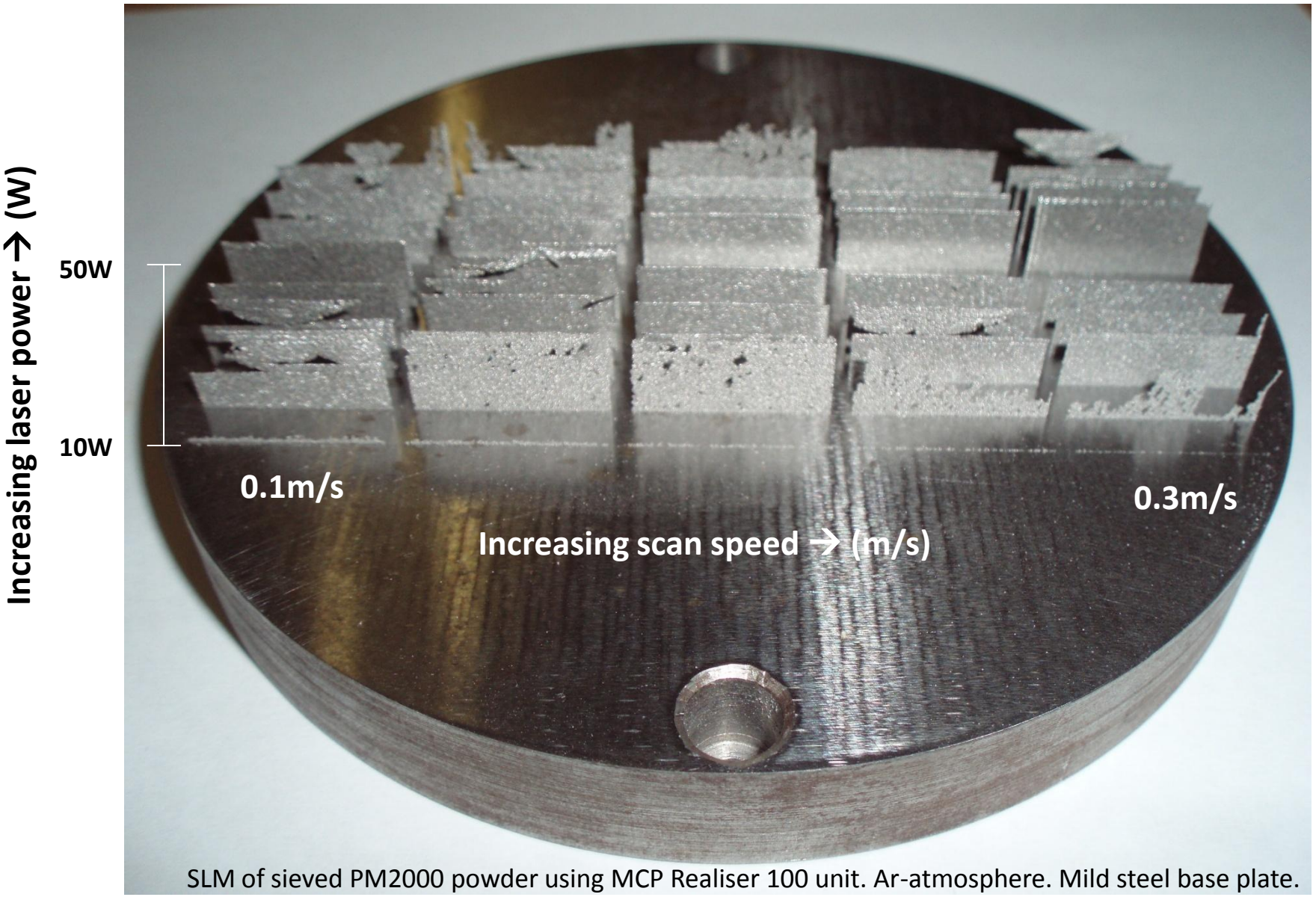




Larger fraction >106µm

**PM2000 Particle size analysis**

- The PM2000 MA powder exhibited a bi-modal particle size distribution.
- Powders were sieved to remove large particles that would impede flow/disturb the powder bed.

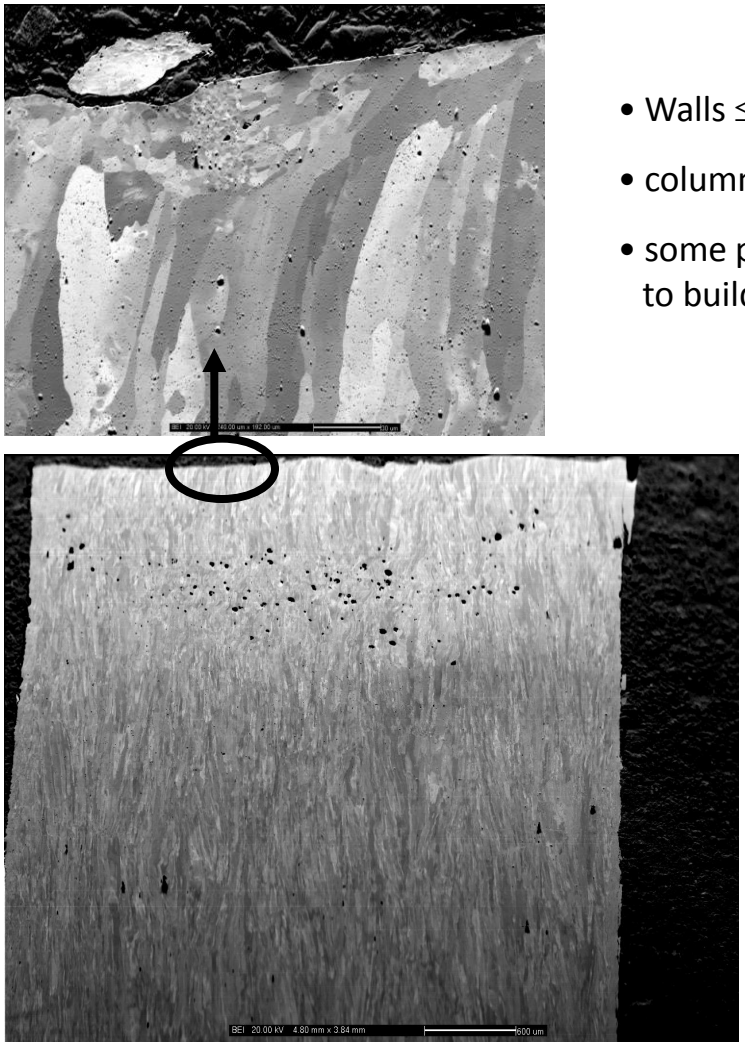
# Selective Laser Melting (SLM) PM2000 powder




SLM of sieved PM2000 powder using MCP Realiser 100 unit. Ar-atmosphere. Mild steel base plate.

# Selective Laser Melting (SLM) PM2000 powder

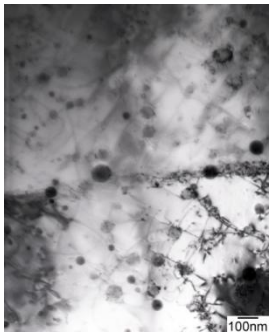

50W, 0.1m/s wall



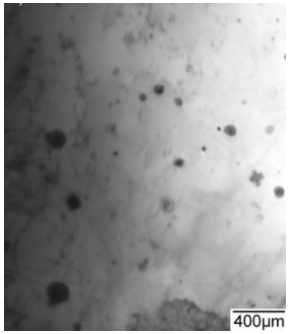
PM2000 SLM wall, side view, 50w, 0.1m/s.
Electron channelling contrast images.

- Walls ≤ 200μm thickness
- columnar grain structure
- some porosity; sensitive to build parameters

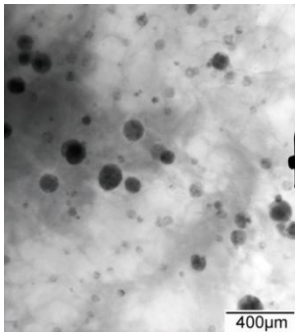
# Selective Laser Melting (SLM) PM2000 powder



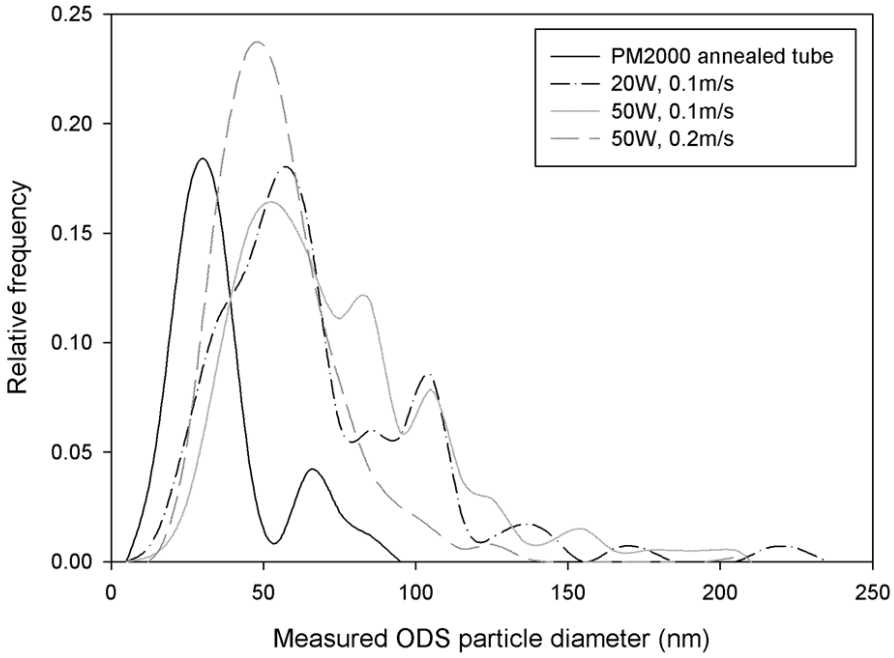

SLM: 50W,0.2ms$^{-1}$
$r_m$ = 24.2±12.6nm




SLM: 50W,0.1ms$^{-1}$
$r_m$ = 30.3±11.5nm




SLM: 20W,0.1ms$^{-1}$
$r_m$ = 26.9±8.7nm

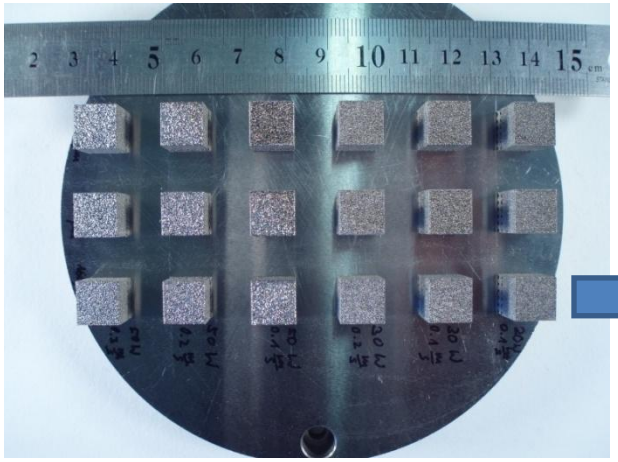



TEM revealed nano-particles present in all SLM PM2000 builds

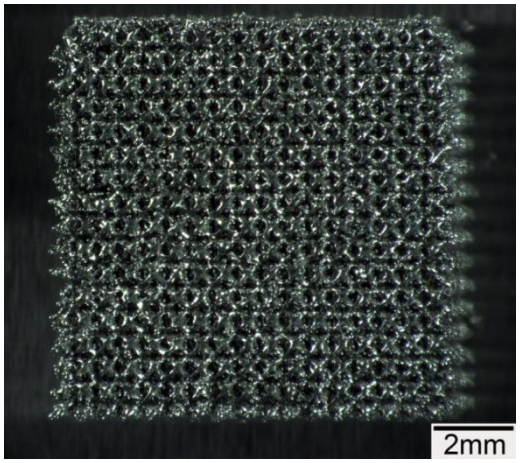
c.f. $r_m$ = 15.0±4.5nm for ODS particles in PM2000 tube annealed 1h/1380$^0$C

# Selective Laser Melting (SLM) PM2000 powder

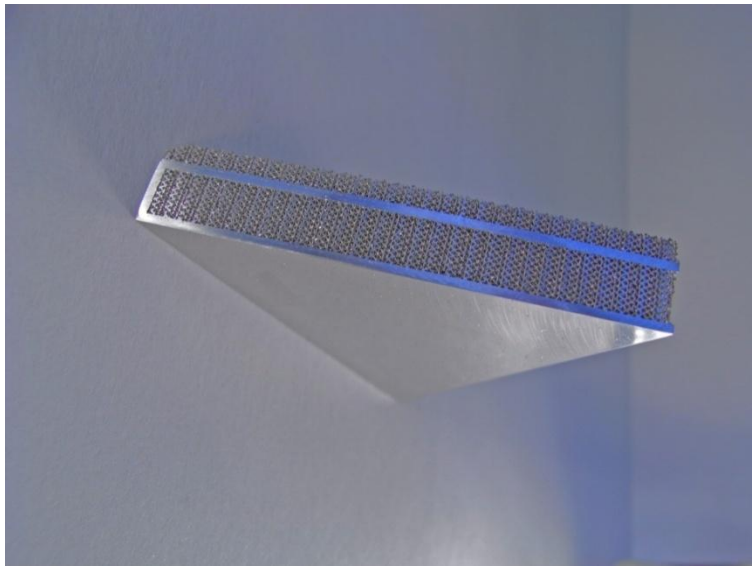
SLM build in progress
50W/0.2ms$^{-1}$



SLM array of 1cm$^3$ PM2000 mesh cubes




PM2000 SLM 1cm$^3$ mesh
0.6mm octahedral cell



SLM build using a Co-Cr alloy powder

SLM used to fabricate:

- walls and mesh arrays using as-MA PM2000 ODS alloy feed powders.
- demonstrator, fabricated with a CoCr alloy, to show how SLM can direct build enclosed, mesh filled parts.

# SIEMENS SLM of PM2000 powder on IN939

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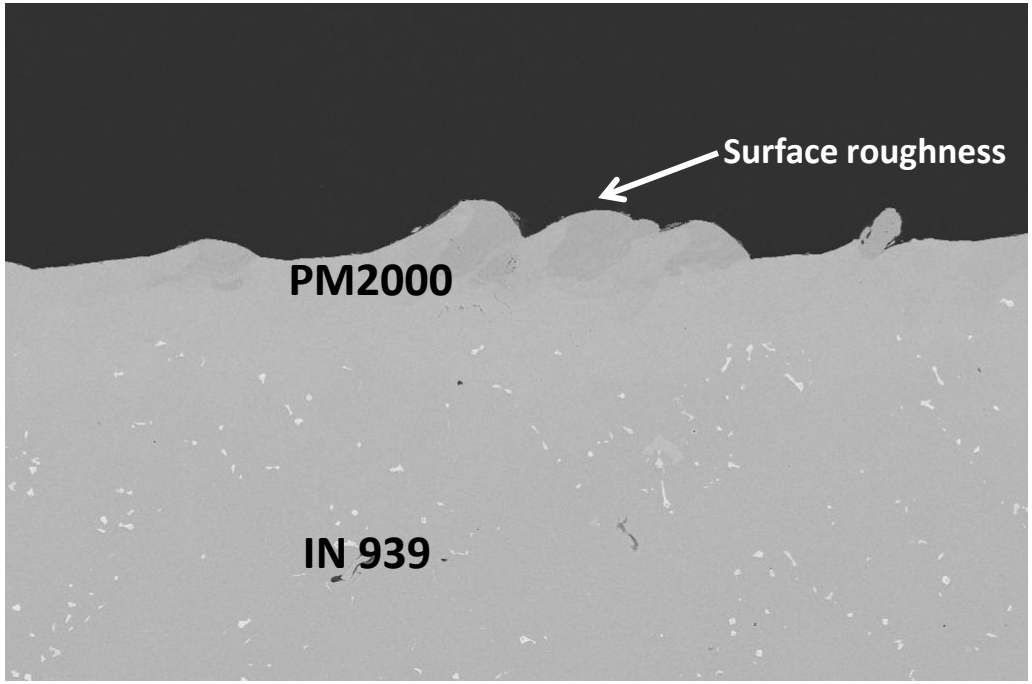


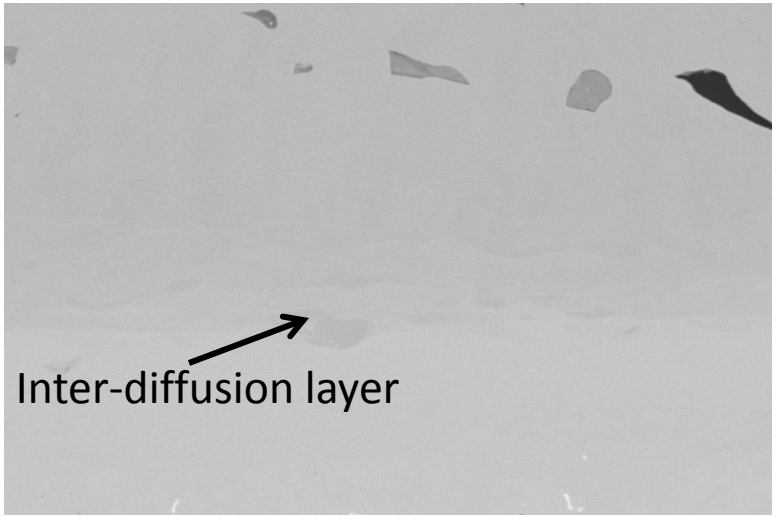


**SLM deposition of PM2000 surface layer (~150μm) on IN939 (Co-Cr Ni-base superalloy) substrate**

# Selective Laser Melting (SLM) PM2000 powder

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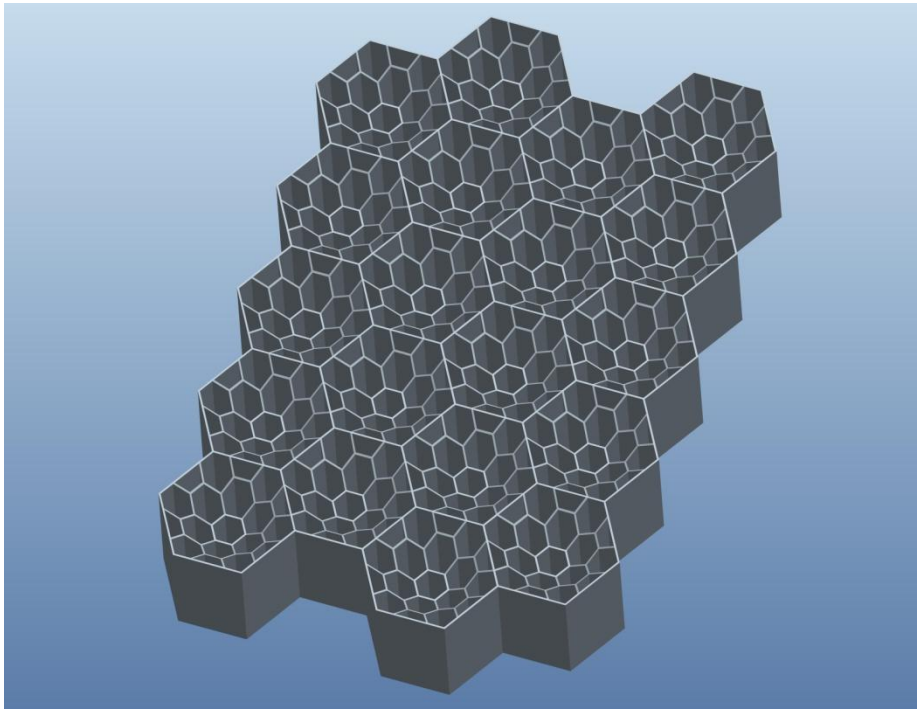
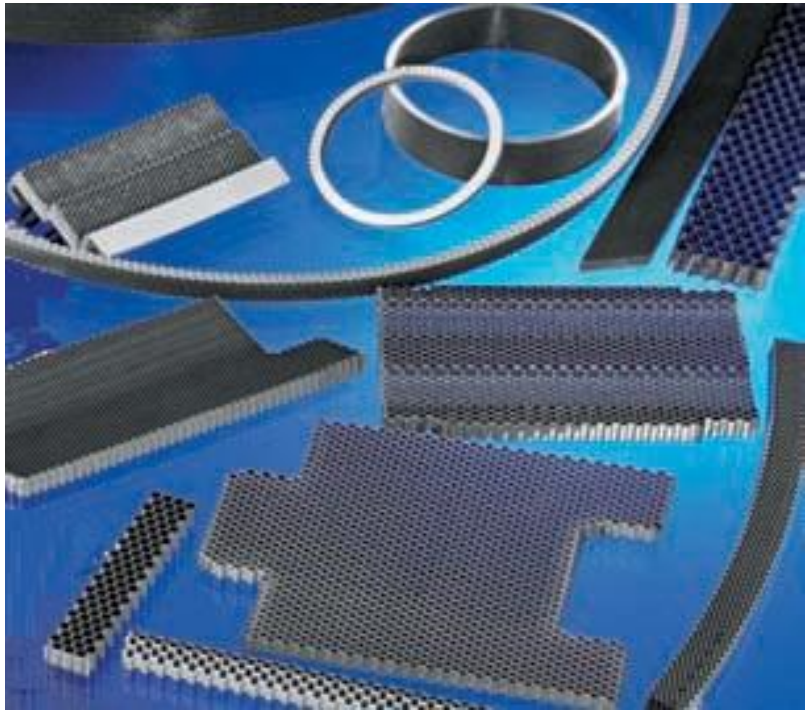
**SLM of PM2000 alloy**

PM2000: 25mm OD, 15mm height , 3mm ‘wall’, 0.25mm thick uniform shell.

# Selective Laser Melting (SLM) PM2000 powder



Design for honeycombe within honeycombe SLM PM2000 Build



Sulzer Neomet products: typical honeycombs – labyrinth air seals for aero gas turbines.

# Selective Laser Melting (SLM) PM2000 powder

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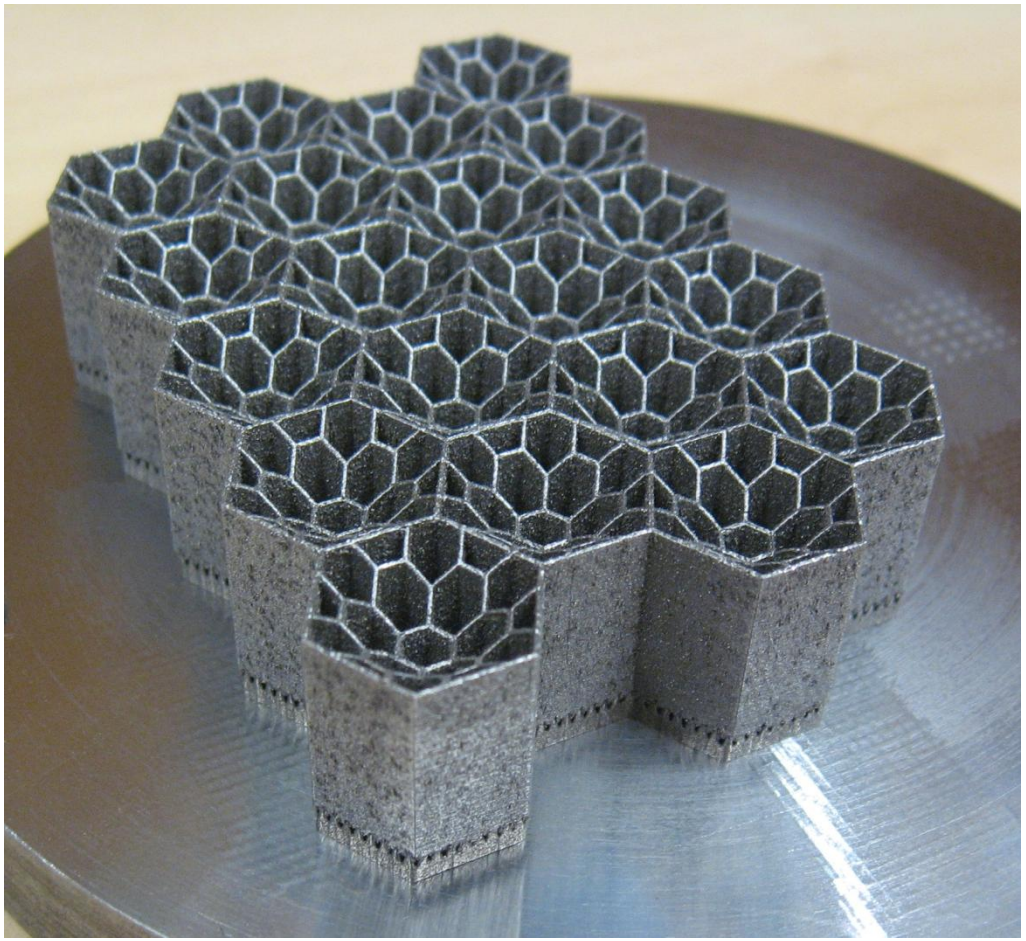
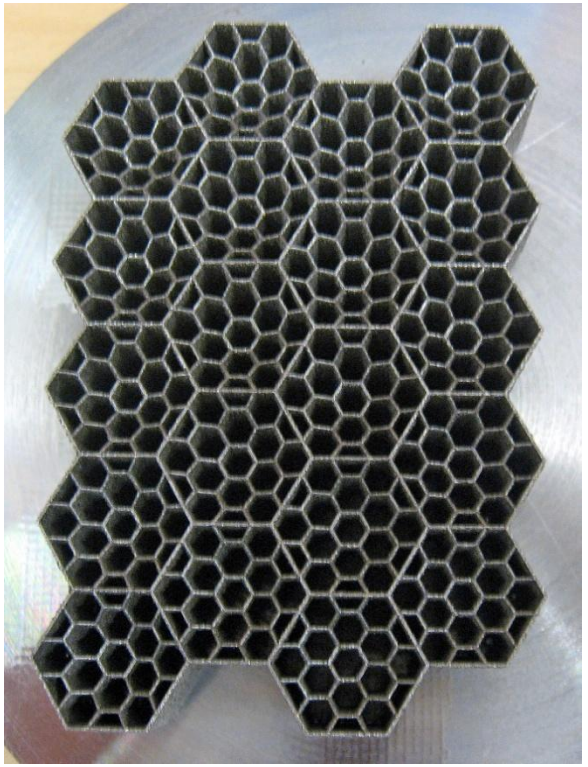


SLM PM2000 honeycombe within honeycombe



| | |
|---|---|
| Small hexagon side | 2 mm |
| Large hexagon side | 8 mm |
| Wall thickness | 0.2 mm |
| Hexagon build height | 15 mm |
| Height rebate (centre to edge) | 4 mm |

# SLM of PM2000 powder: outcomes

**SLM:**

**Direct build from PM2000 powders feasible**

**Retention of ODS particulate**

**Possible applications include:**

- Complex shapes
- Self canning
- coatings