SAND2006-3822C

Microstructure and Properties of PH13-8Mo Steel Fabricated by LENS®

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Outline

- Objective
- Background on LENS
- Microstructure and mechanical properties evaluation
- Thermal behavior during LENS® processing
- Summary

Objective

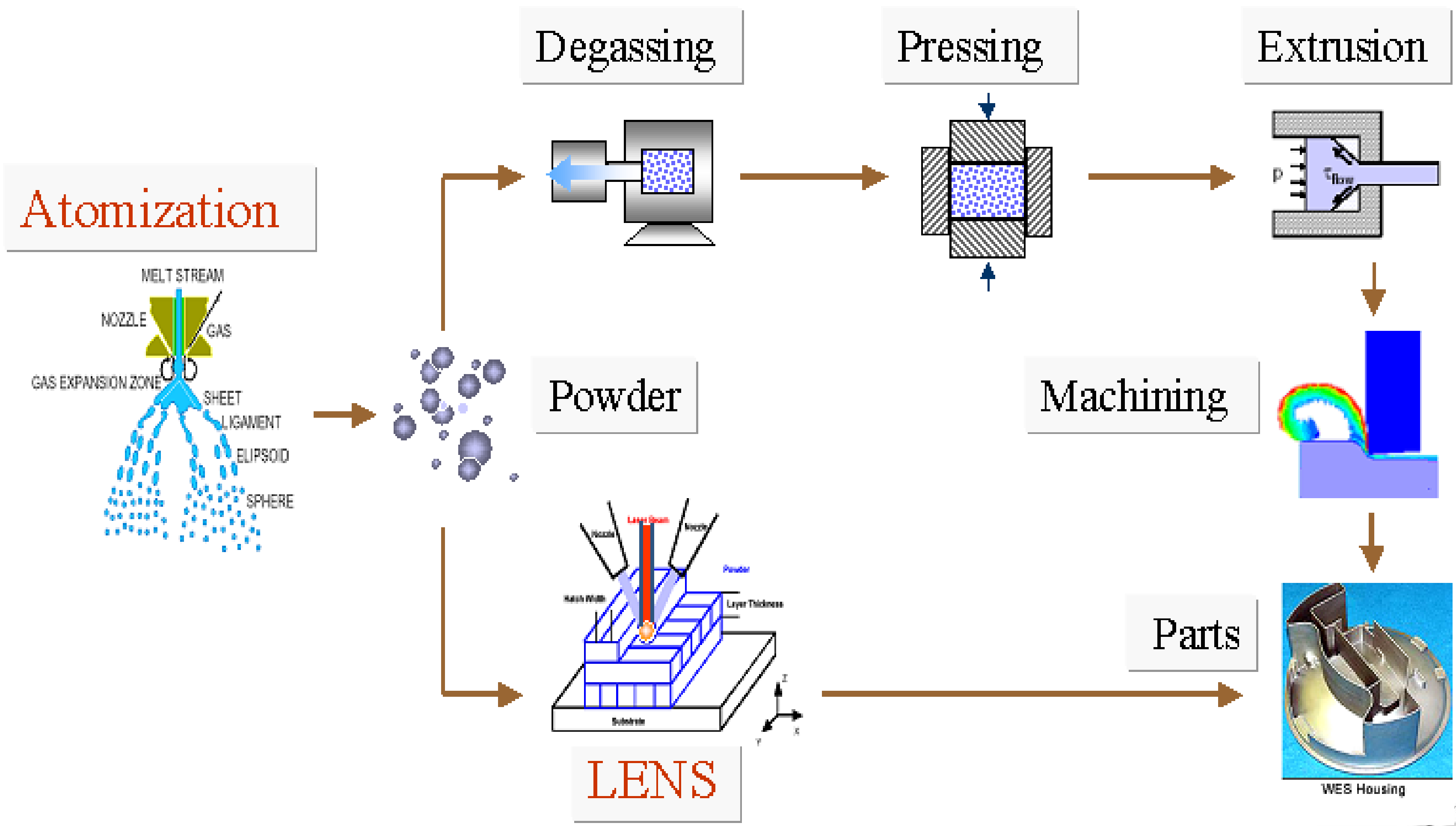
- **Determine and understand microstructure-property relations, and thermal behavior of laser engineered net shaped (LENS®) PH13-8Mo stainless steel.**

- PH13-8Mo Stainless Steel.
  - Is a low carbon (<0.03) precipitation hardenable, martensitic stainless steel.
  - Has the highest combination of corrosion resistance, strength and toughness in all the stainless steels
  - Is an Ideal choice for extreme environmental conditions
- Applications include forged airframe parts, fasteners, undercarriage, petrochemical, and safety and security components.

PH 13-8 Mo stainless is a registered trademark of Armco Inc.

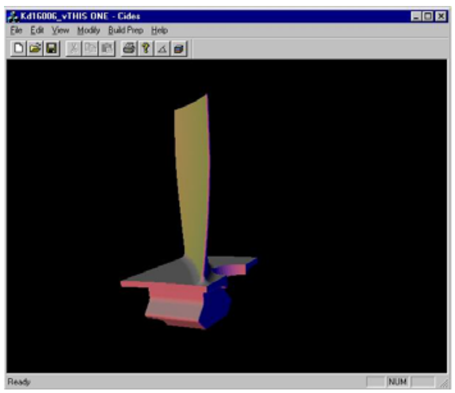
Background on LENS

LENS® Is an alternative technique for consolidating metal powders to net-shape

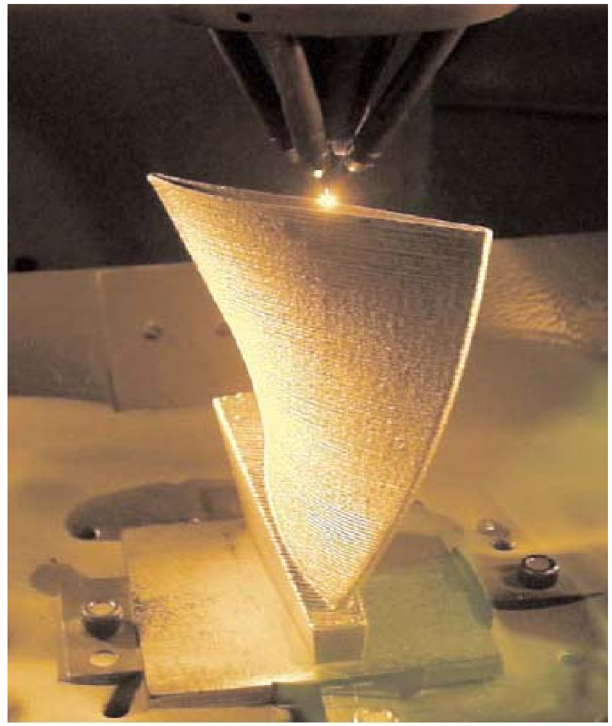


Laser Engineered Net-Shaping (LENS®) Details

- A novel rapid manufacturing process: Using a focused high-powered laser beam to melt the injected powder to net shape components.



- **CAD solid model**
- **Electronically slice to horizontal layers**



- **Automatically controlled laser powder deposition**
- **Forms part line by line, layer by layer**
- **Without tooling**

- **Full dense**
- **Net-shaped**
- **Finished functional blade**

SNL, 2001

Advantages & Applications

Advantages:

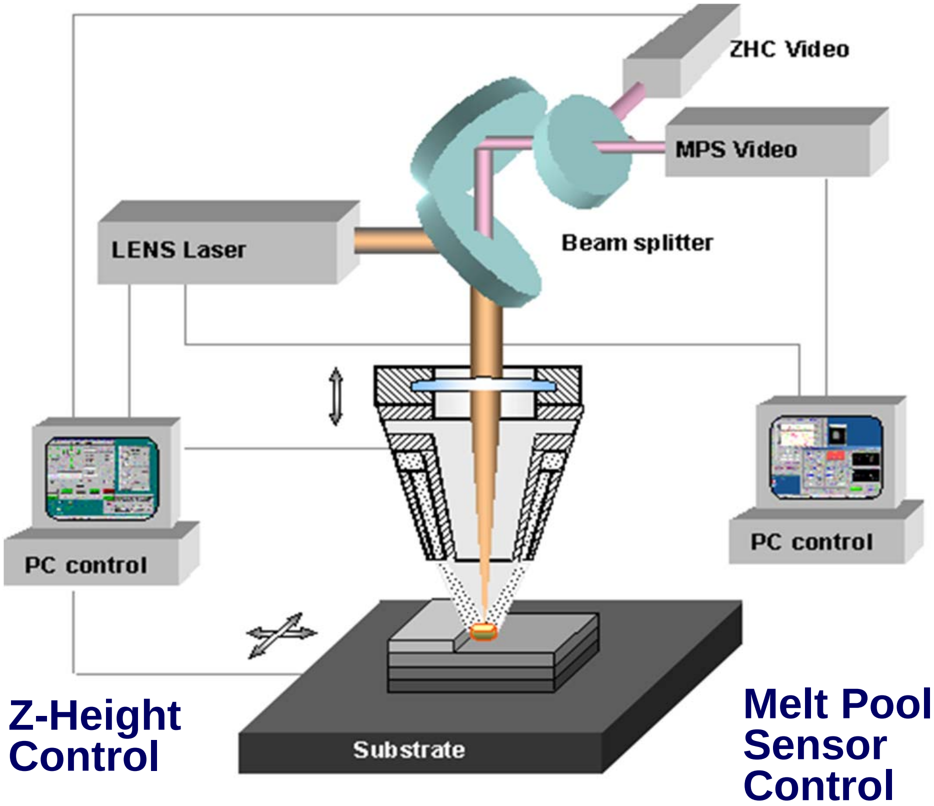
- Small heat affected zone with high cooling rate.
- Excellent material properties due to fine microstructure features.
- Easy composite and functionally graded material deposition with high accuracy.
- Fully dense net shape part deposition bypassing initial forming operation .
- Flexibility and accurate manufacturing.
- Minimal material waste.

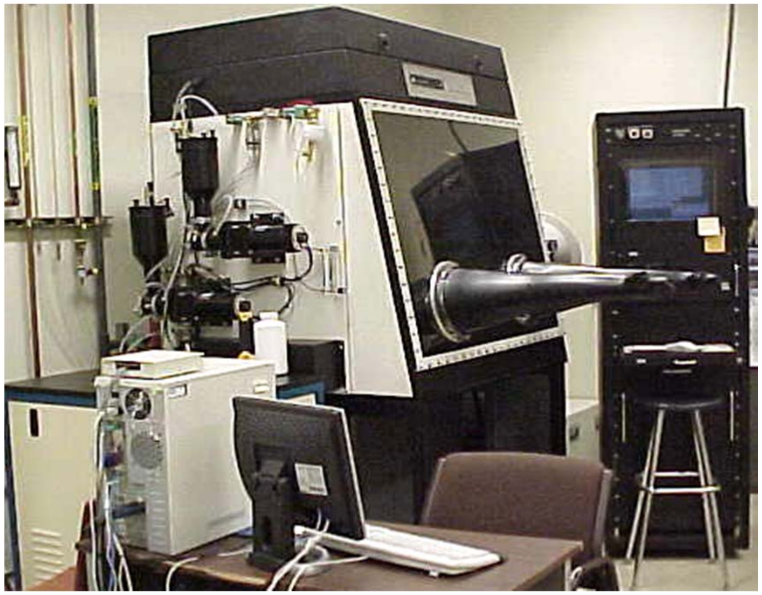
Applications:

- **Rapid prototypes**
  - Functional, smart
- **Modification & repair**
  - Failures in field , fabrication
- **Small lot production**
  - Spare parts, new / development parts
- **Improve properties of existing alloys and composites**
- **Develop new alloys and composites**

Components of LENS® System used for This Study

- LENS® workstation 750 equipped with in-situ melt pool size sensor (MPS) control and Z-height sensor control (ZHC) close-loop subsystems.





- CW Nd:YAG laser (1064 nm) to create a melt pool
- 4-nozzle coaxial powder feed system
- 5-axis positioning control system assisted by CAD model
- Controlled environment glove box
- Energy density in the range of 30,000-100,000W/cm^2

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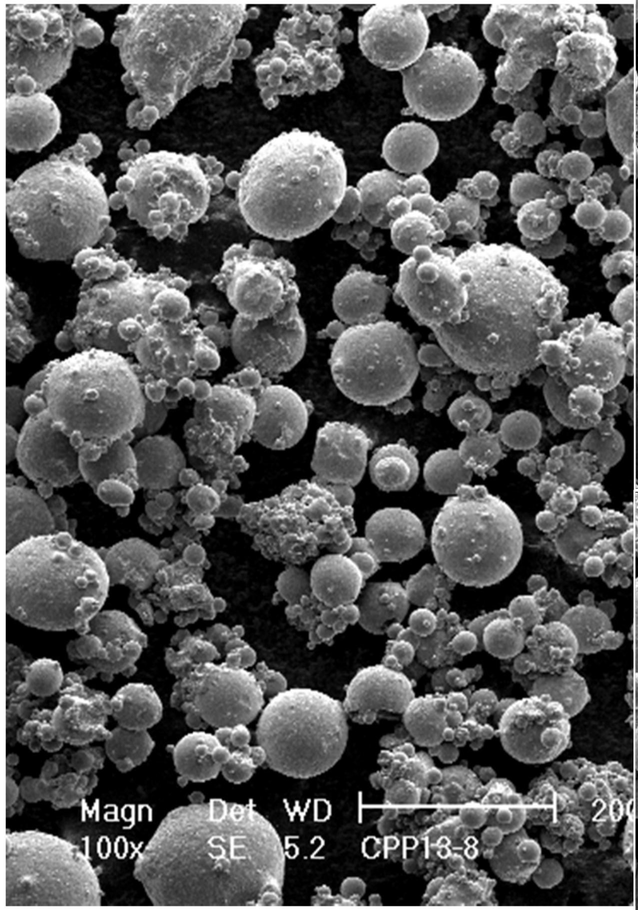
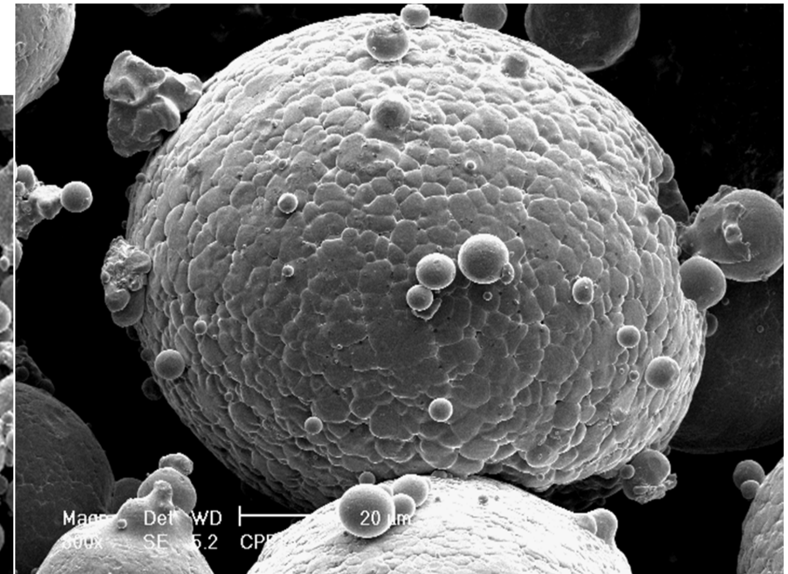
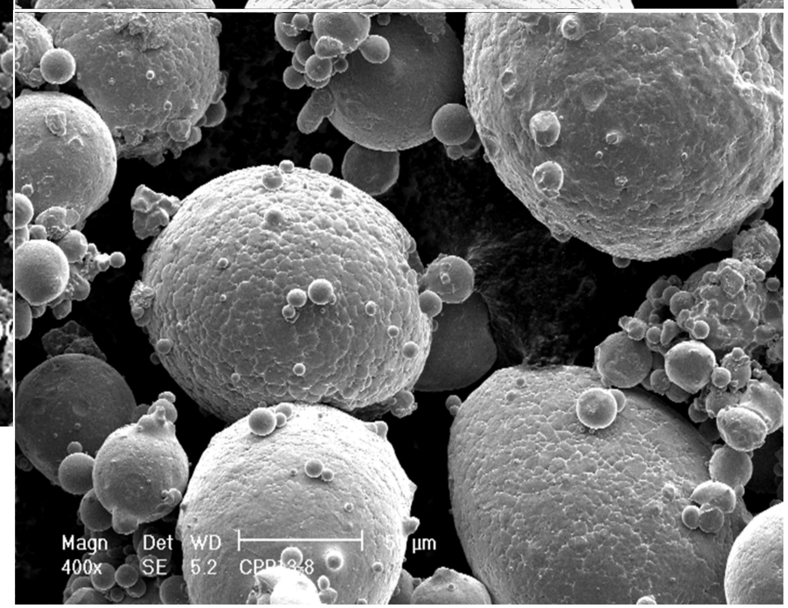
PH13-8Mo Powder

Chemical Composition

Sym.	wt% in Product
Fe	Balance
Cr	12.6
Ni	8.2
Mo	2.2
Al	1.1
C	0.026
Mn	0.01
Si	0.02
P	<0.005

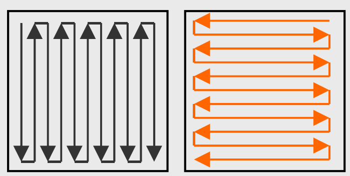


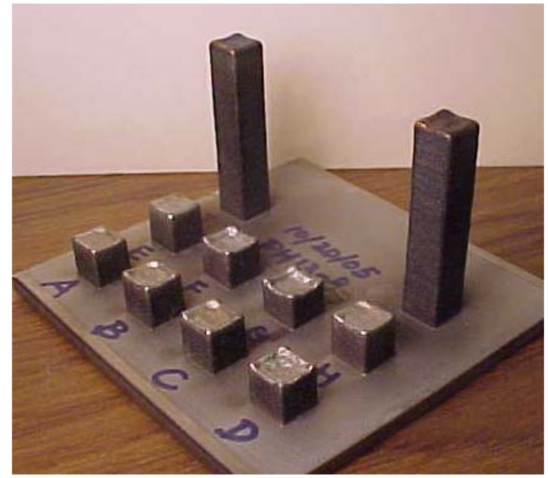


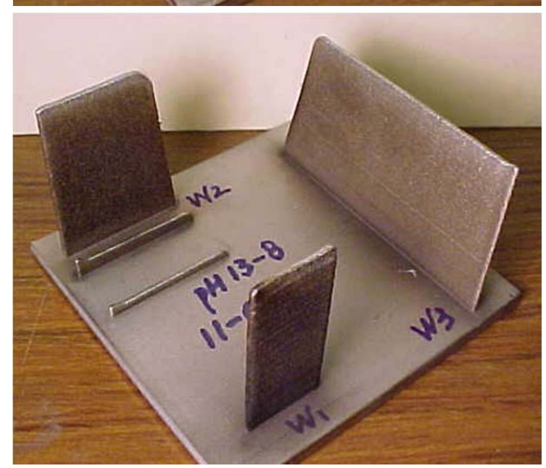


Gas atomized powder
-100+325mesh (45-150μm)

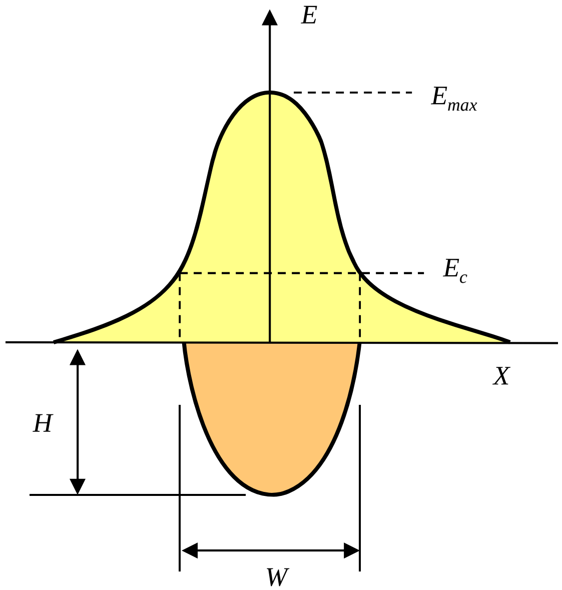
Samples & Process Parameters

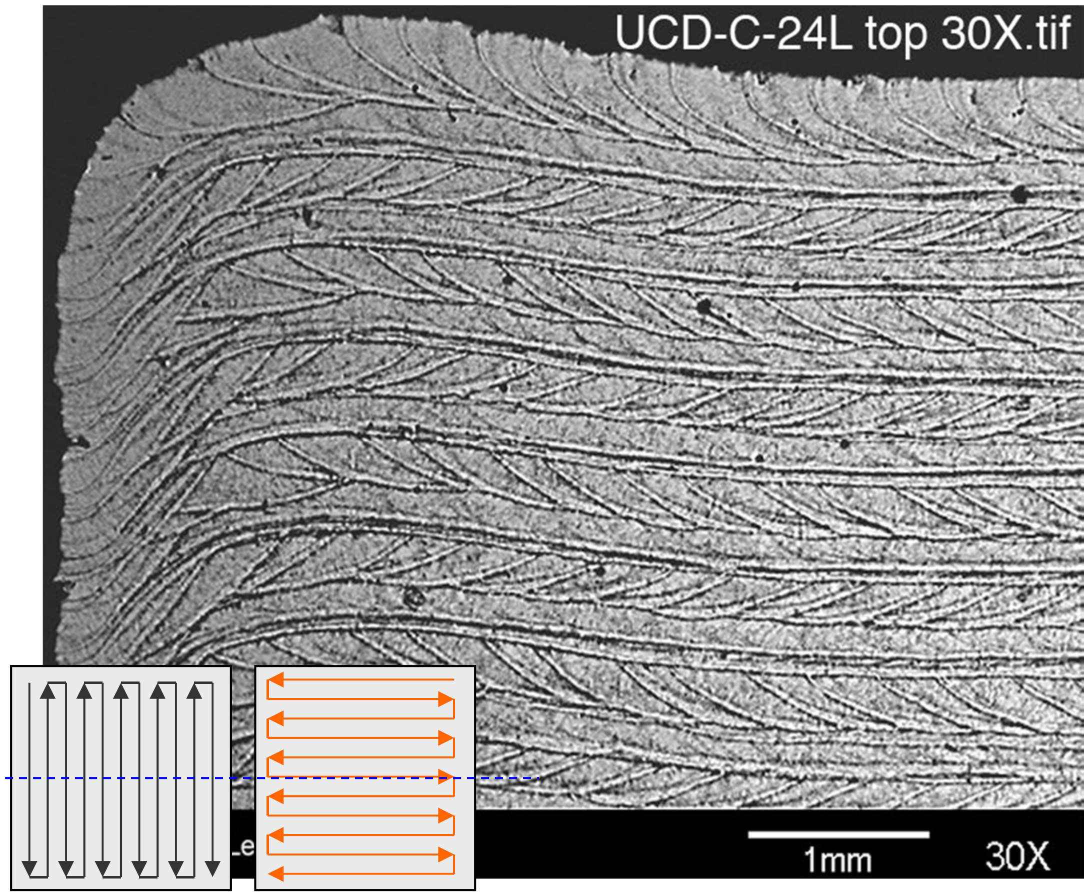
Shape	No.	Power (W)	Speed (mm/s)	Others
Cubic 10x10 x10 mm	A	355	14.8	**A/Deceleration = 847mm/s^2**
	B	355	14.8	**A/Deceleration = 212mm/s^2**
	C	355	14.8	**Shutter Delay 100 ms**
	D	**270**	**12.7**	
	E	**440**	**16.9**	
	F	355	14.8	**Hatch: 0. 51 mm**
	G	355	14.8	**Lay thickness: 0.38 mm**
	H	355	14.8	Normal condition *
Cubic 10x10 x51 mm	I	355	14.8	
	J	355	**16.9**	
	K**	355	14.8	
	L	355	**12.7**	
	M	**440**	**16.9**	
	N	**270**	**12.7**	
Thin wall	W1	355	14.8	**Contour 22x51x0.25 mm**
	W2	355	14.8	**Single 38mm x 51mm**
	W3	355	14.8	**Single 83mm x 51mm**

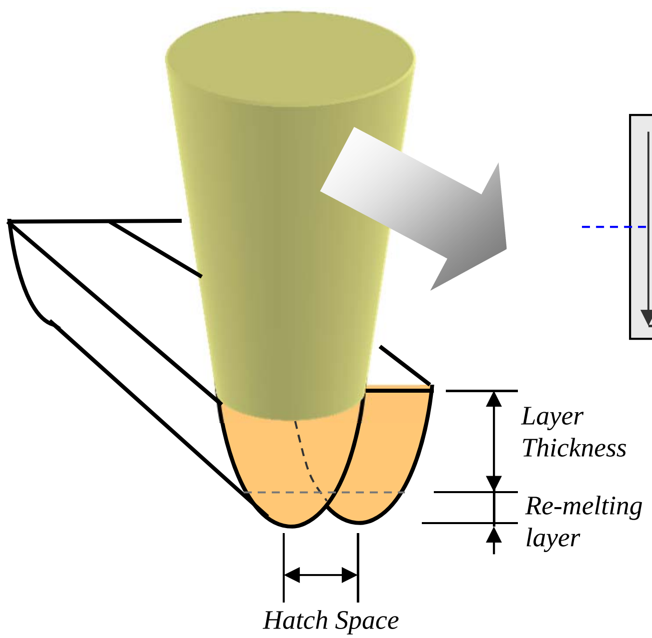




Laser Beam and Melt Pool Track

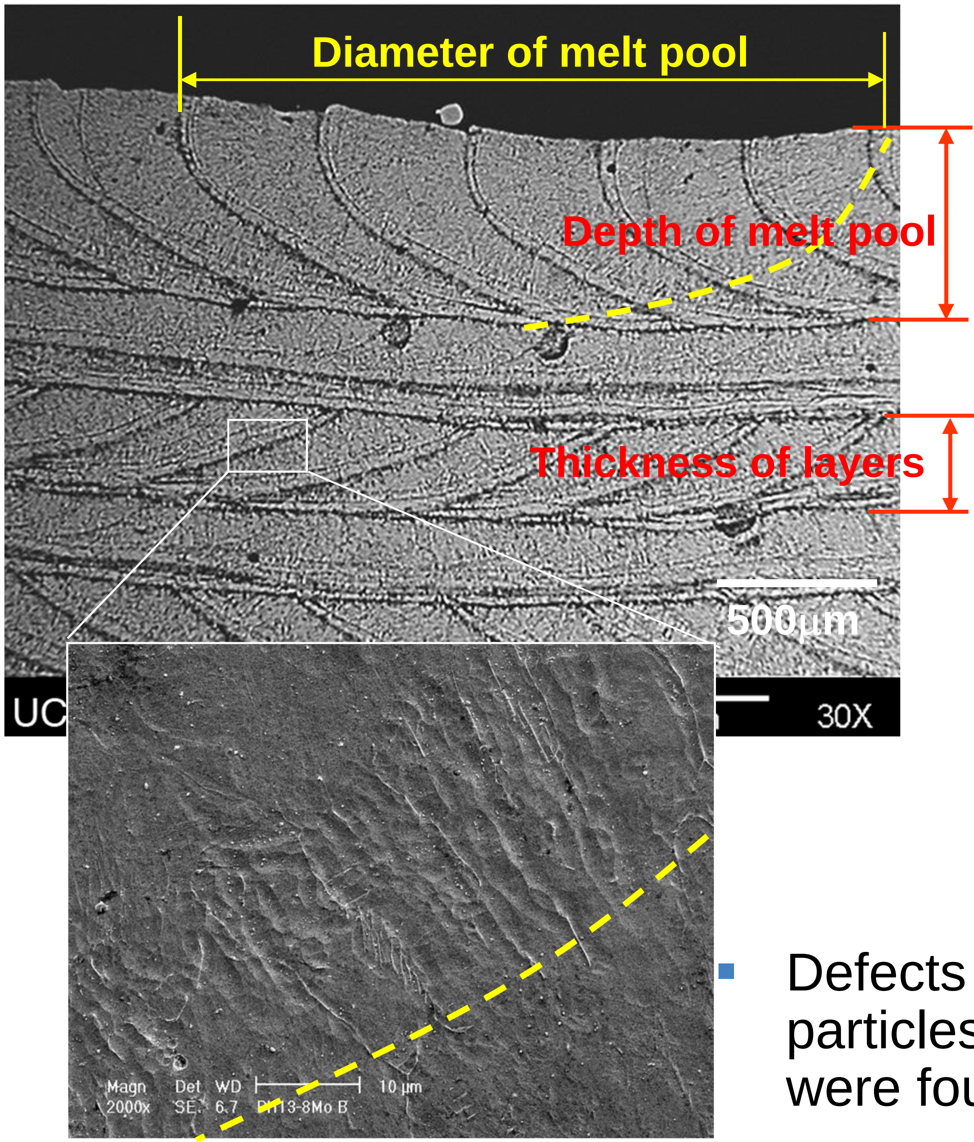


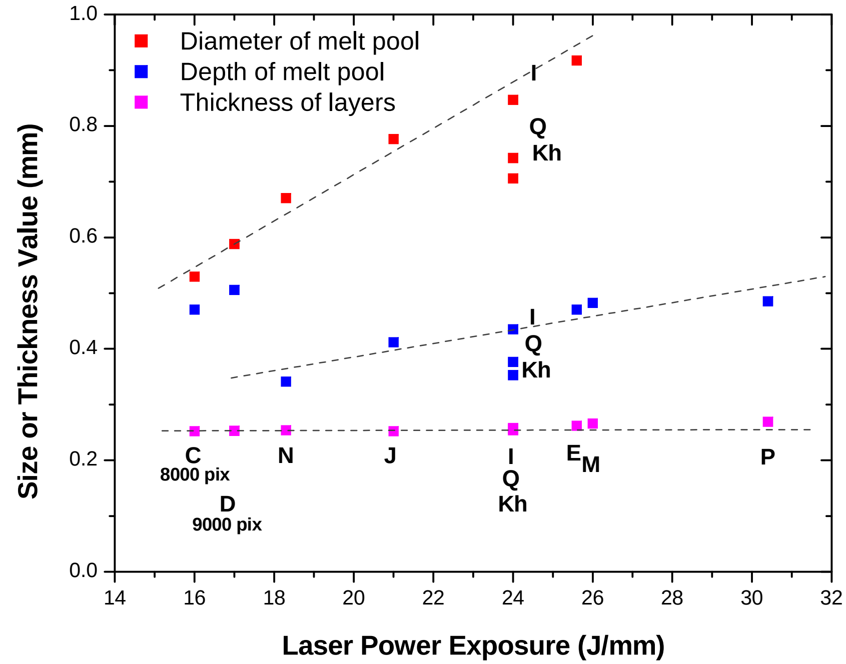




- Melt Pool Track of overlap between adjacent lines and re-melting previous deposited layer

Layer Features and Microstructure





Dependence of melt pool diameter and depth on laser power exposure (power/speed).

- Defects of porosity and un-melted particles of around 100µm in size were found

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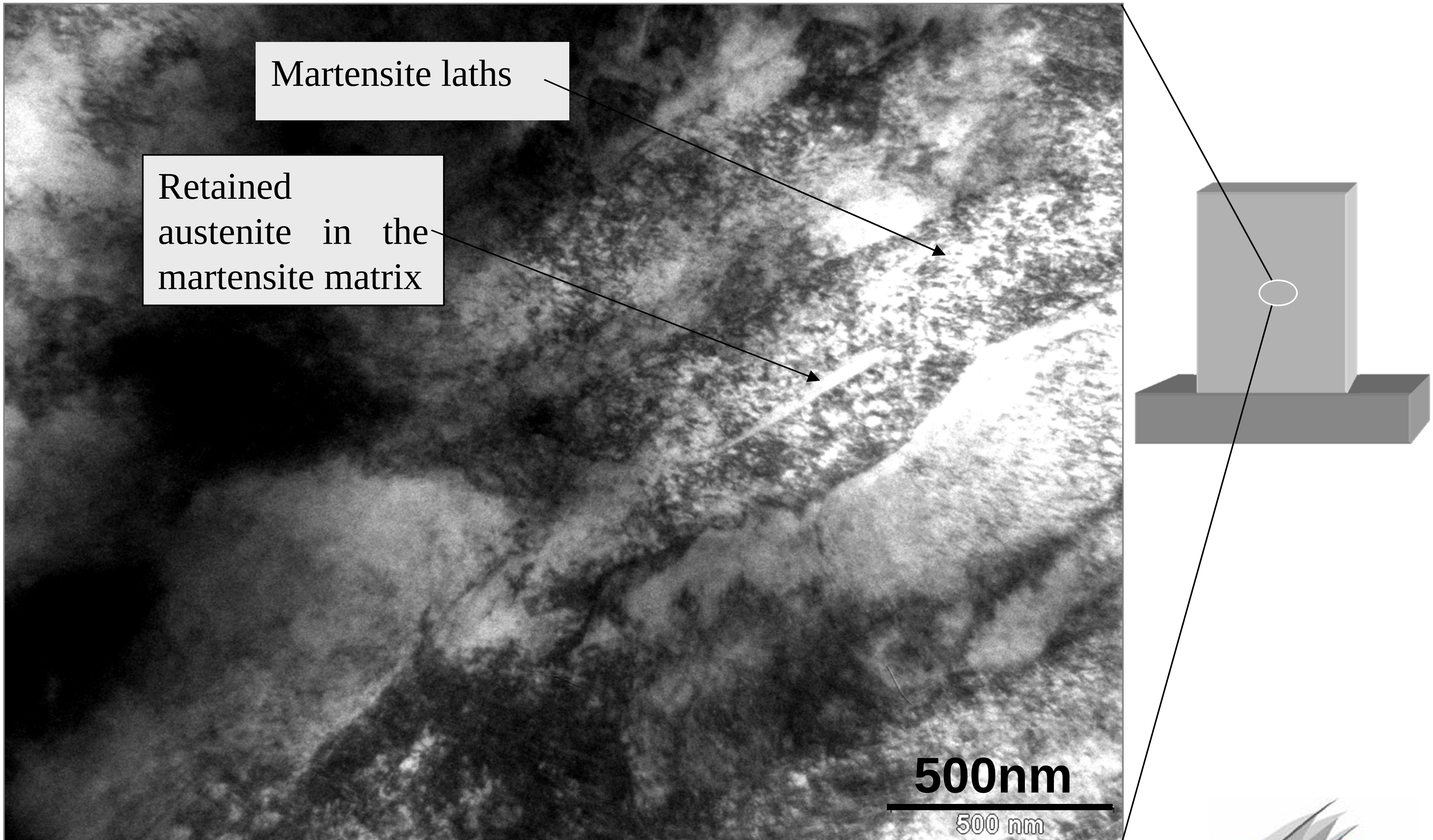
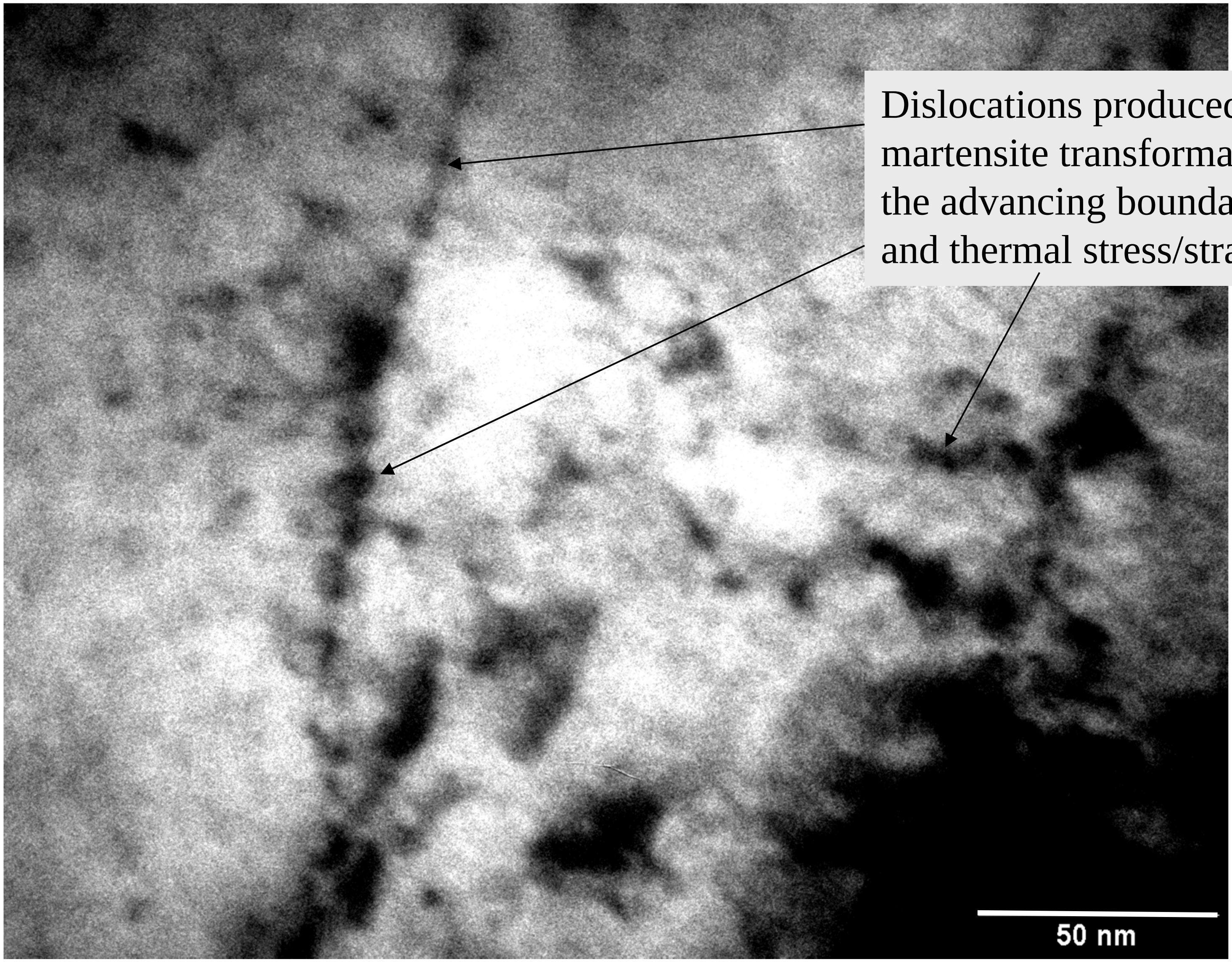
Martensite Phase



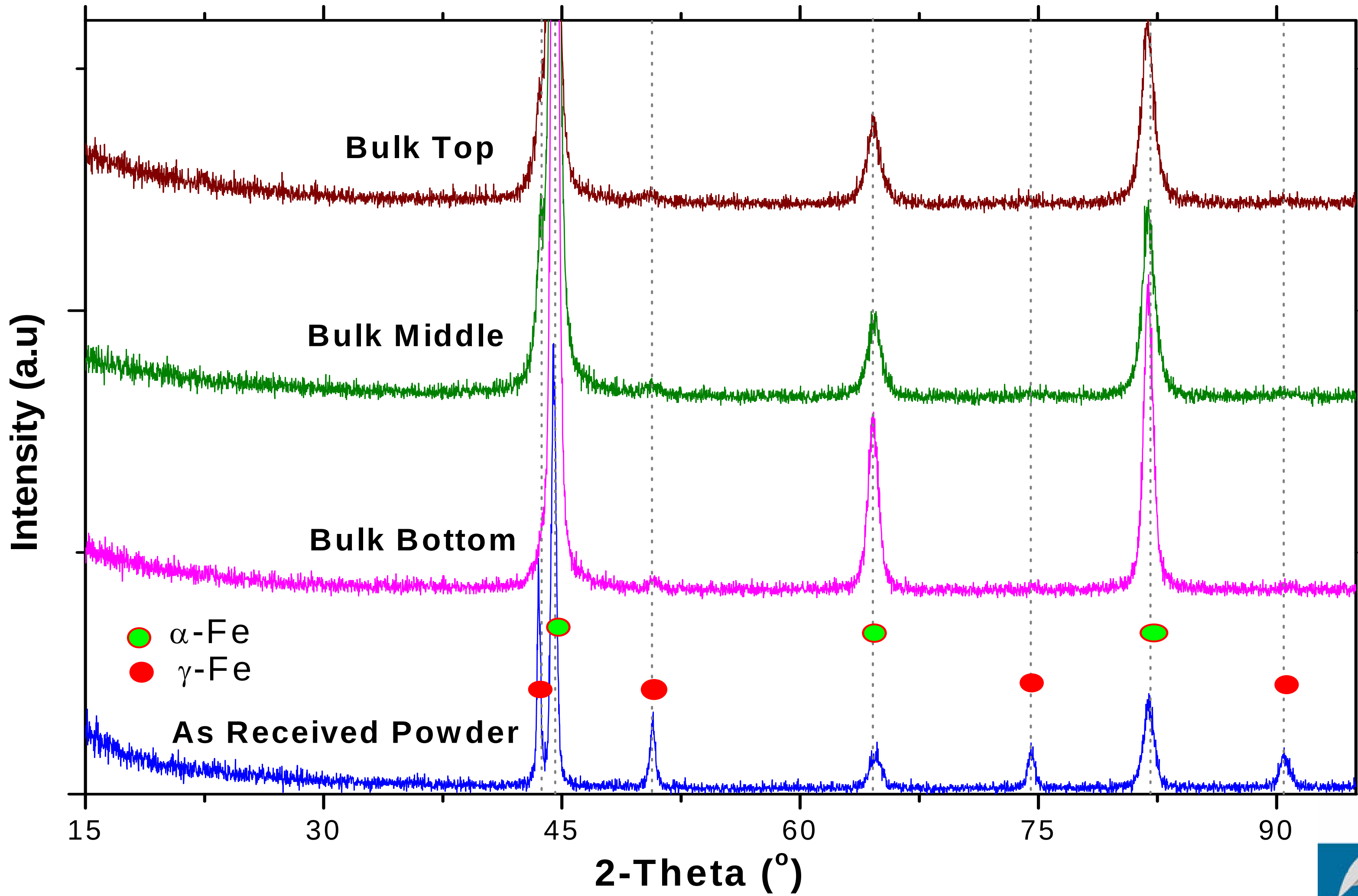
Dislocations



Dislocations produced by austenite-martensite transformation and left by the advancing boundary, and thermal stress/strain

XRD Diffraction

of LENS® deposited PH13-8Mo components and the gas atomized powder.



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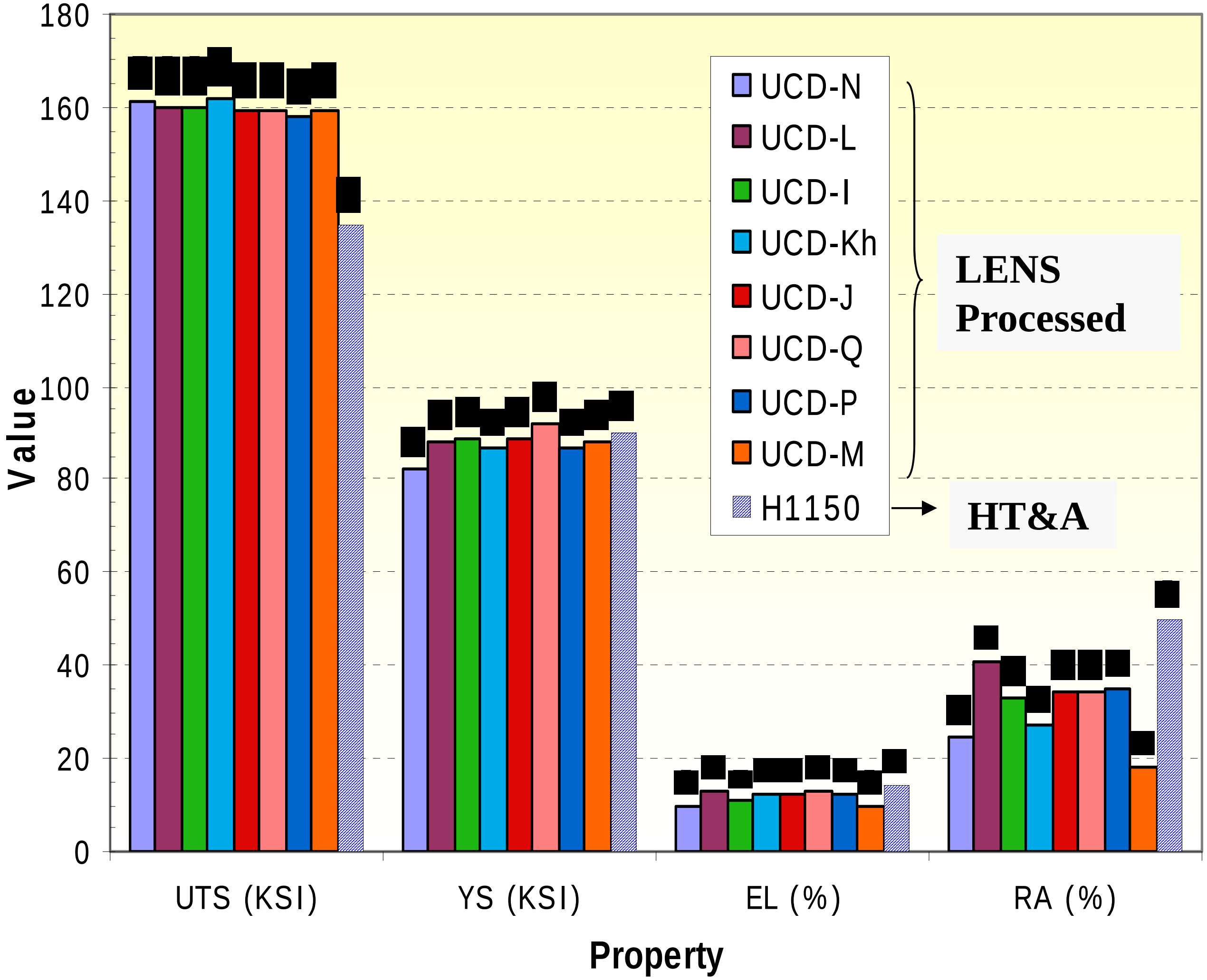
Mechanical Properties of Cube Samples

Summary of LENS processed PH13-8Mo samples



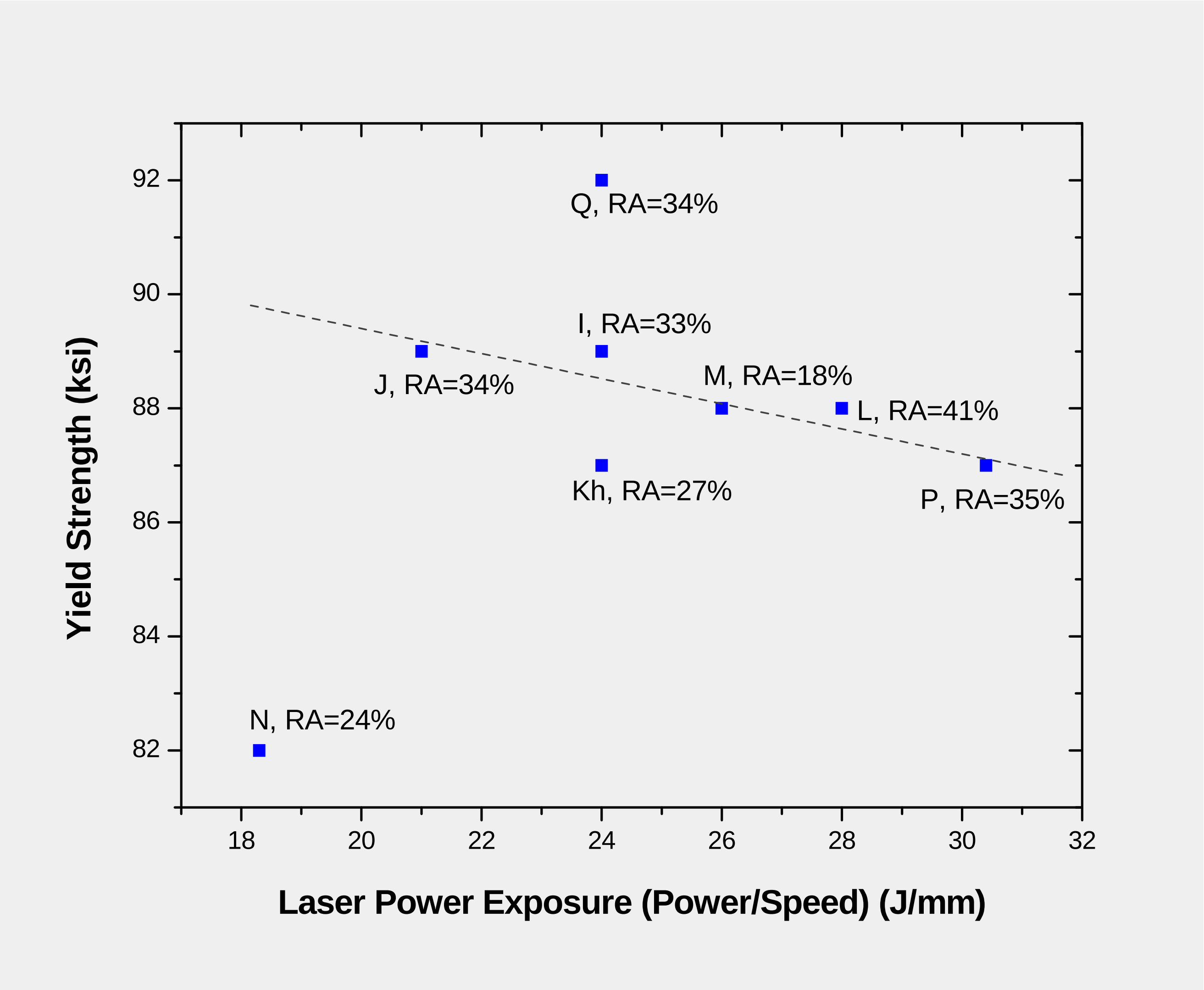
Proper-ties	LENS processed	Conventional HT&A
UTS (ksi)	158–162	120–135
YS (ksi)	82–92	80–90
EL (%)	10–13	14–16
RA (%)	24–41	50–55

H1150:

Homogenization: 1038° C(1900° F), 1.5hr;

Aging: 621° C (1150° F), 4hr

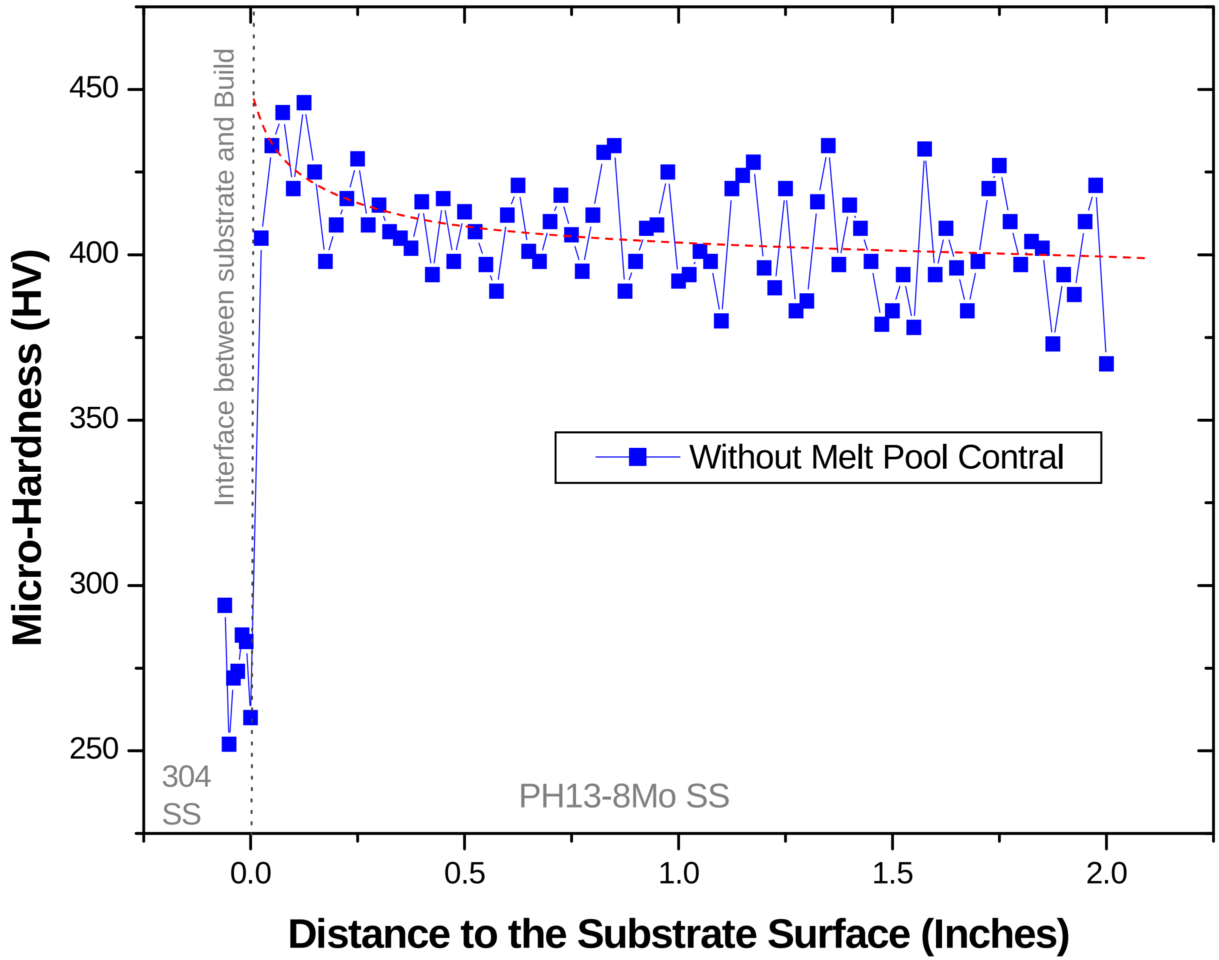
Effects of Process Parameters on YS



Yield strength vs. laser power exposure

(power/speed).

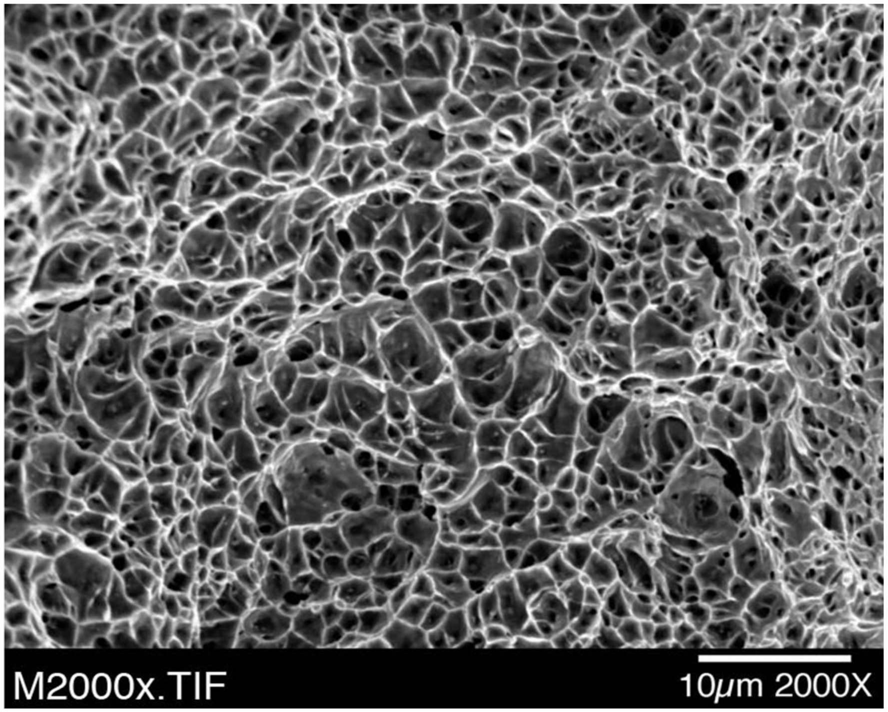
Micro-Hardness



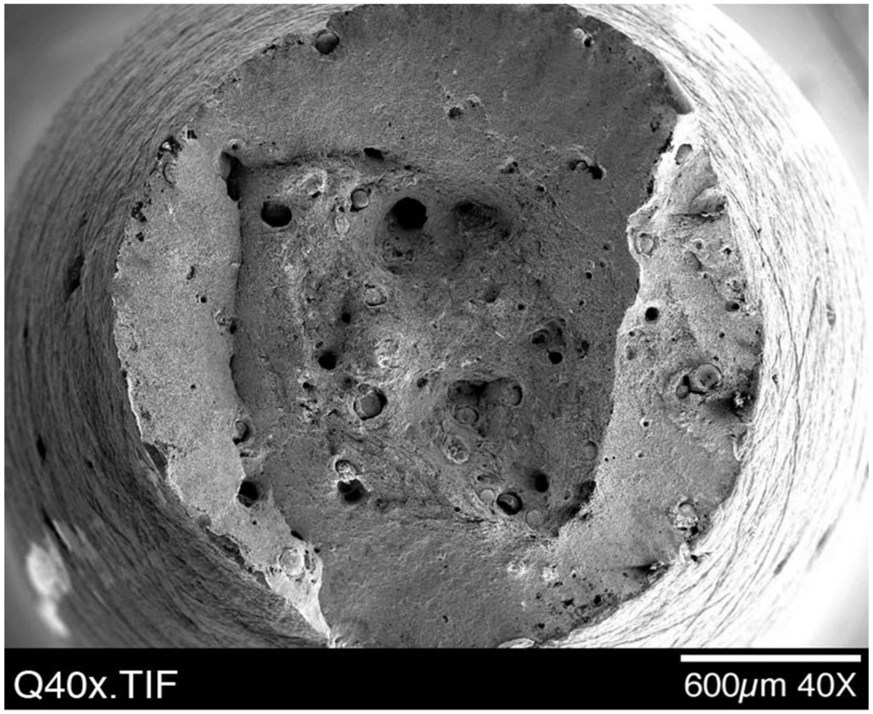
Tensile strength ≅ 0.33 x hardness, the mean tensile strength should be 200ksi (1373MPa).

LOP = 355 W
LTS = 14.8 mm/s
PFR = 10 g/min

Defects Initiated Ductile Fracture



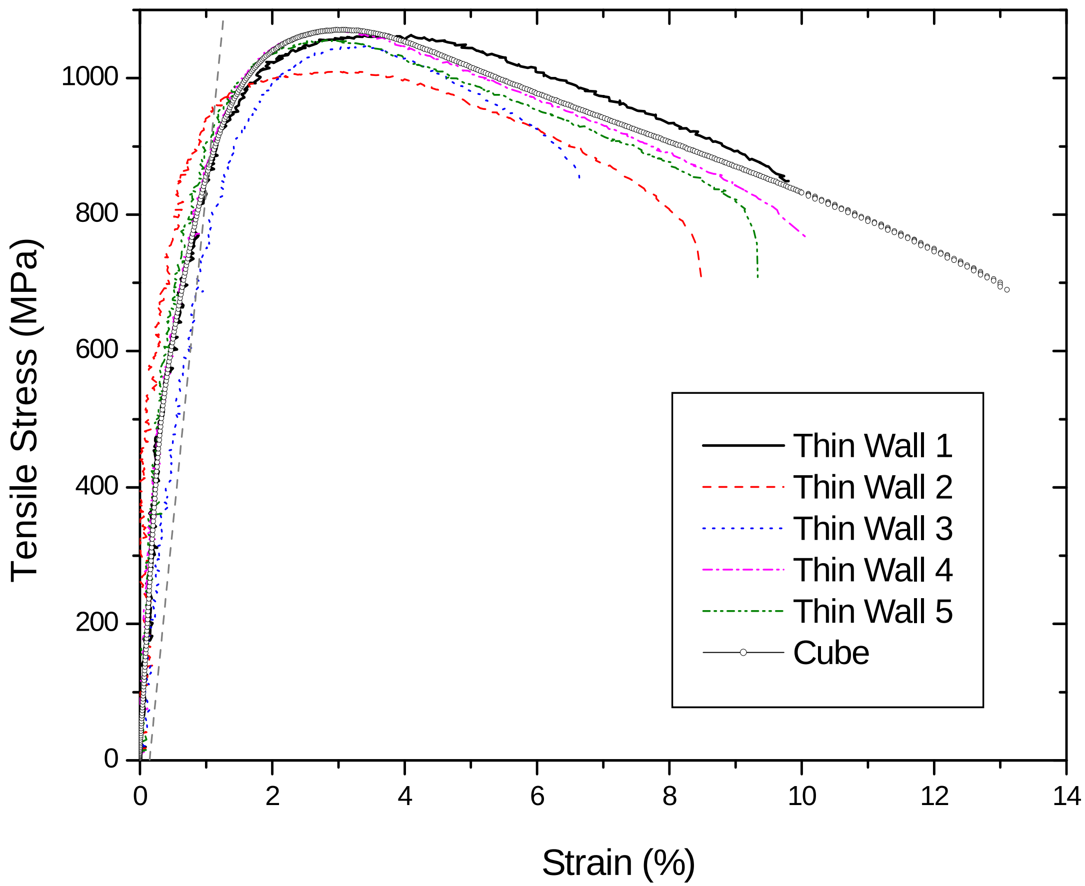
- Micro-dimple morphology
- Ductile fracture
- Crack initiation from particles at the bottom of dimples



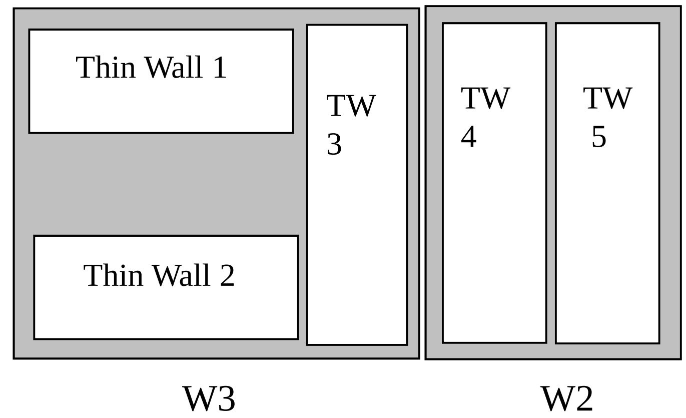
- Porosity and unmelted particles in the material, and observed on the fracture surface, affect strength

Premature fracture due to defects is the reason for low ductility

Mechanical Properties of Thin Wall Samples



Stress-strain curves for LENS® deposited PH13-8Mo samples



No.	YS (ksi)	UTS (ksi)	EL (%)
1	84	154	9.8
2	80	146	8.5
3	78	152	6.7
4	85	155	10.1
5	82	153	9.4
C	87	157	13.2

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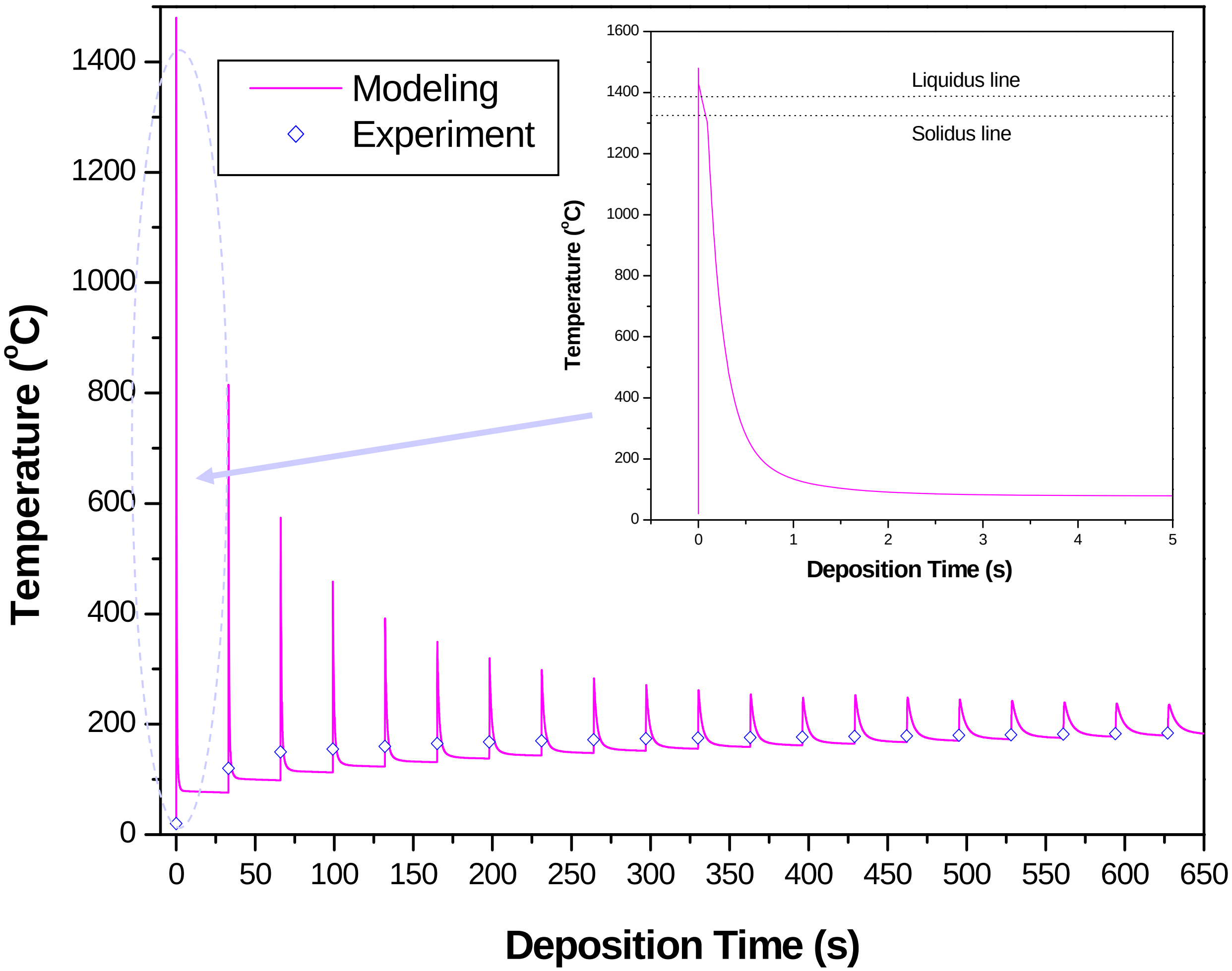
Thermal History during LENS® Processing



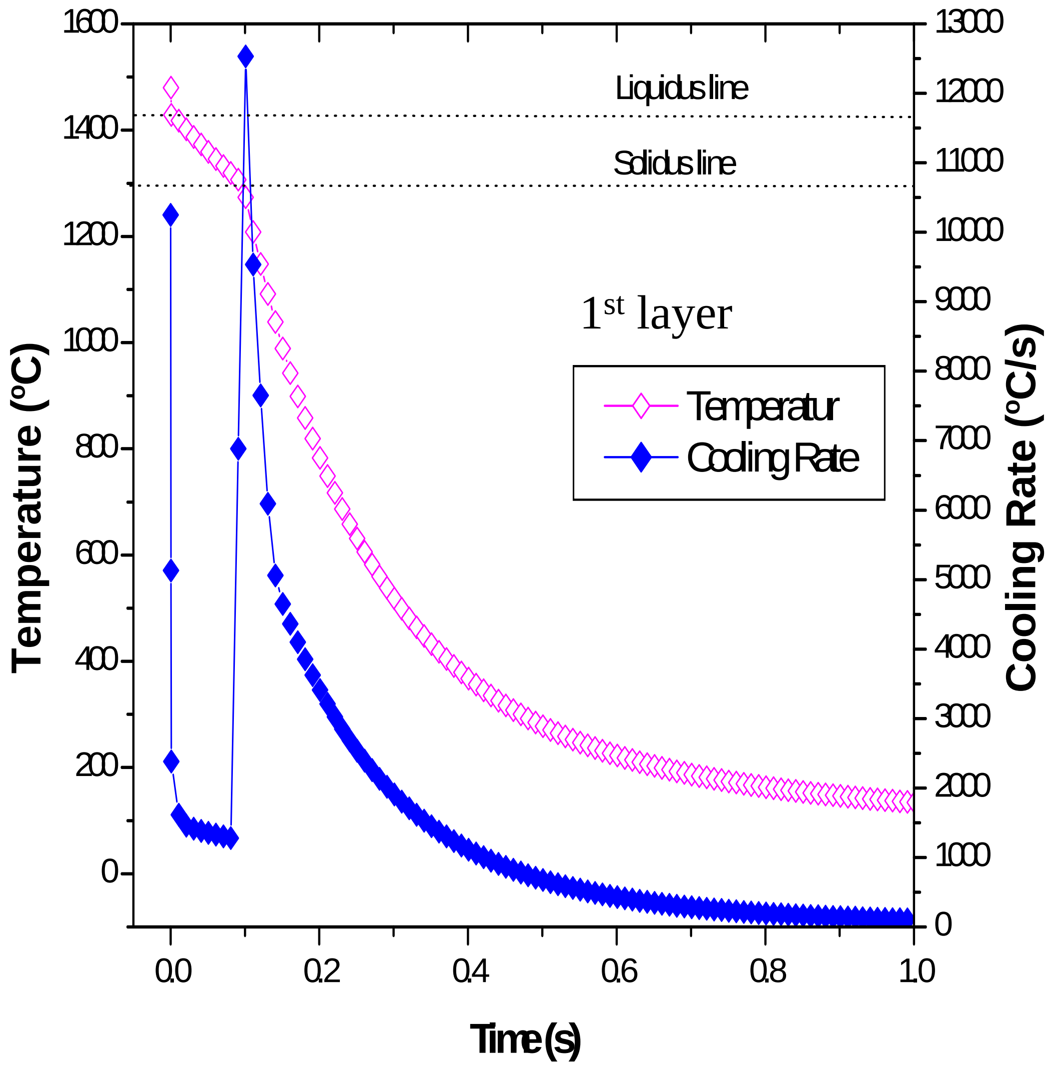
Thermal behavior associated with the LENS process involves numerous reheating cycles.

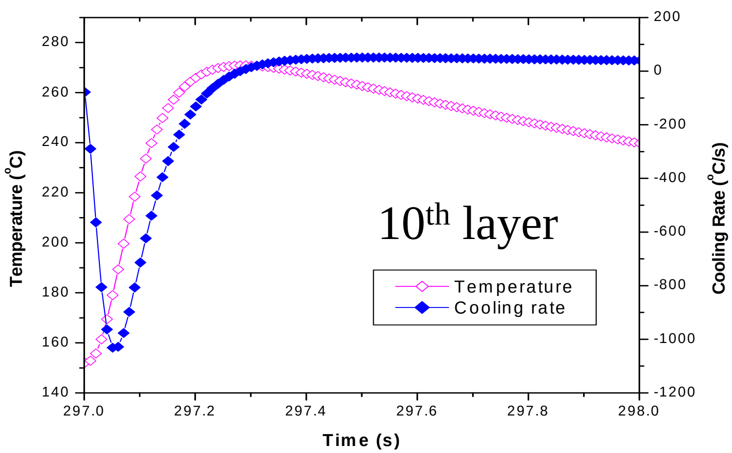
As a result, the temperature history of the deposited materials is a dampen pulse wave.

T_{mp} = 1480°C
T_s = 20°C
$\triangle t$ = 33s

Variation of Temp. and Cooling Rate

during early stage of 1st and 10th layer deposition

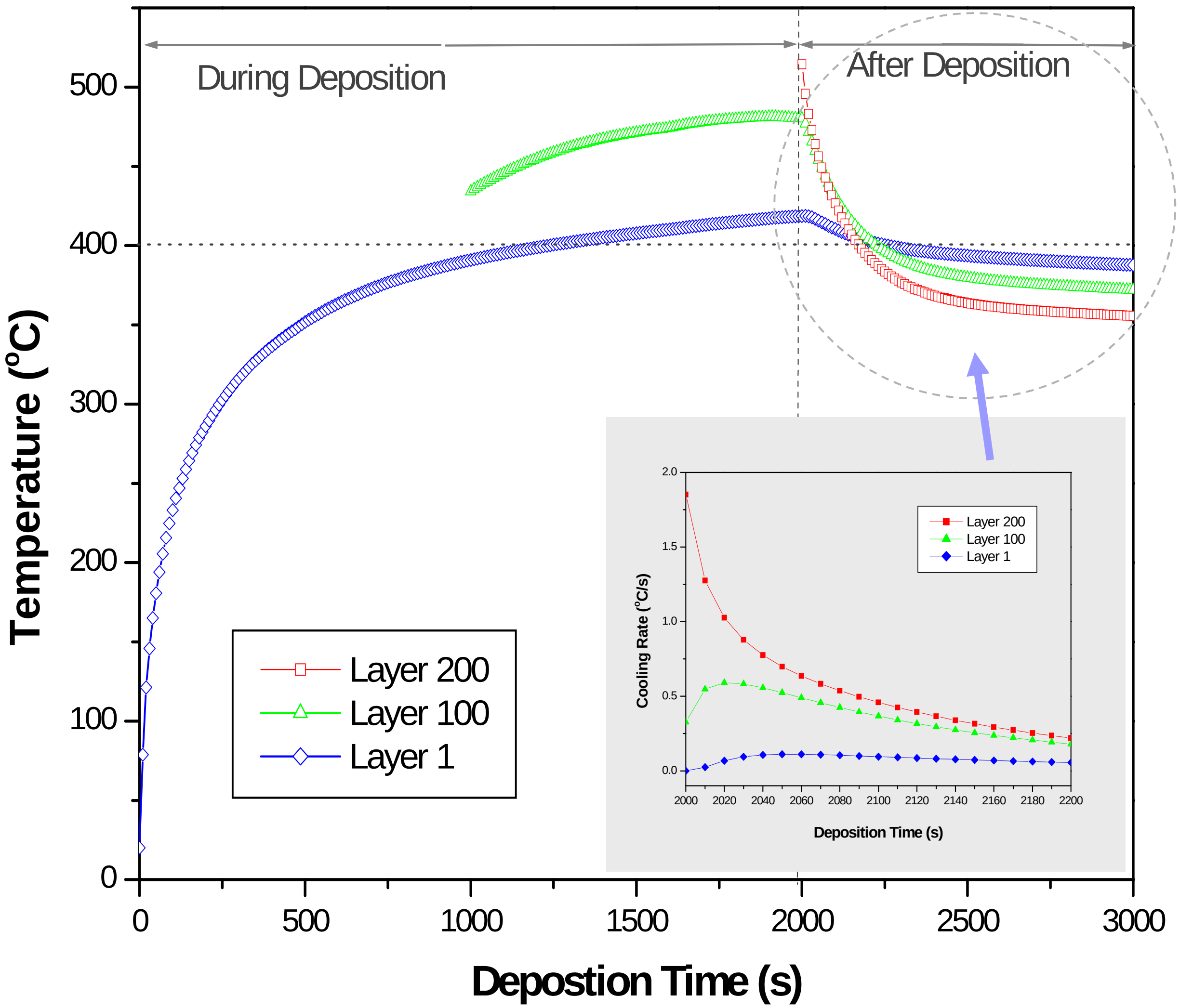




In the initial stages of deposition, the deposited materials experience a significant rapid cooling effect, and can attain a very high cooling rate, ~10^4K/s.

In the later deposition, the rapid cooling effect decreases and even disappears.

During and After Deposition



Variation of temperature at different position during and after deposition

T_{mp} = 1480°C
T_s = 20°C
$\triangle t$ = 10 s

Reheating cycles have tempering and aging effects;

When temperature > 400°C, NiAl particles will precipitate coherently with the matrix, leading to strengthening.

Summary

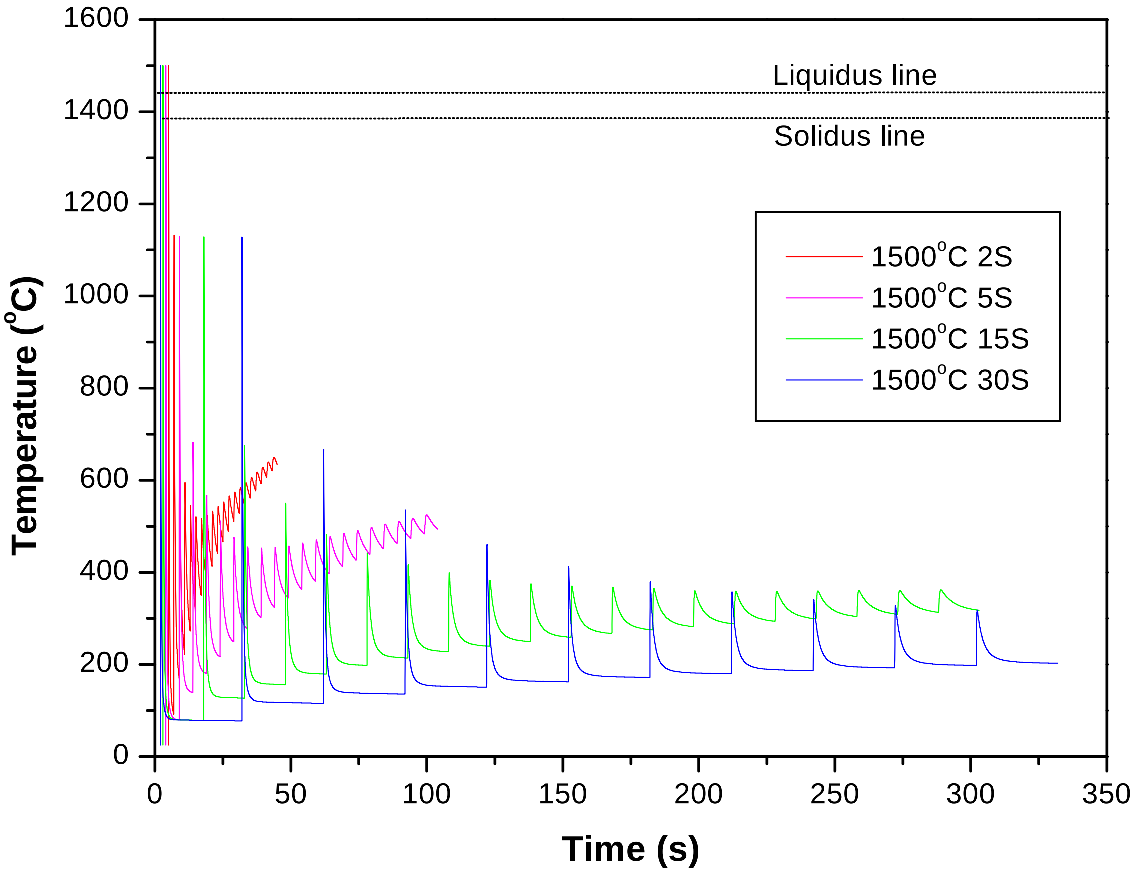
- LENS® process evaluated for making net shaped components from gas atomized PH13-8Mo powder;
- The mechanical strengths of the LENS® deposited PH13-8Mo material were equivalent to the heat treated and aged wrought materials;
- Microstructure contains 0.2μm wide martensite laths nearly parallel with retained austenite. High density of dislocation and fine lath size is responsible for the high hardness
- Porosity and un-melted particles in the laser deposited materials caused reduced ductility, despite presence of a ductile dimple fracture mode;
- Thermal behavior associated with the LENS process involved numerous reheating cycles, which may have temper and aging effects, and may promote NiAl particle precipitation.

Acknowledgments

- Work at UCDavis is partially supported by the U.S. National Science Foundation under grant DMI-0423695.
- Work at Sandia National Laboratories is supported by the U. S. Department of Energy under contract DE-AC04-94AL85000.
- Metallography and fractography were performed by A. Gardea and J. Chames respectively; Tensile tests were performed by M. Tootle and Dr. Bing Q. Han.

Thanks for Your Attention

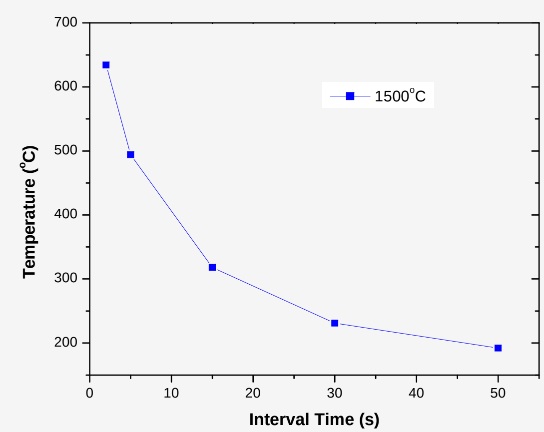
Effects of Interval Time



Variation of thermal behavior with change of interval time

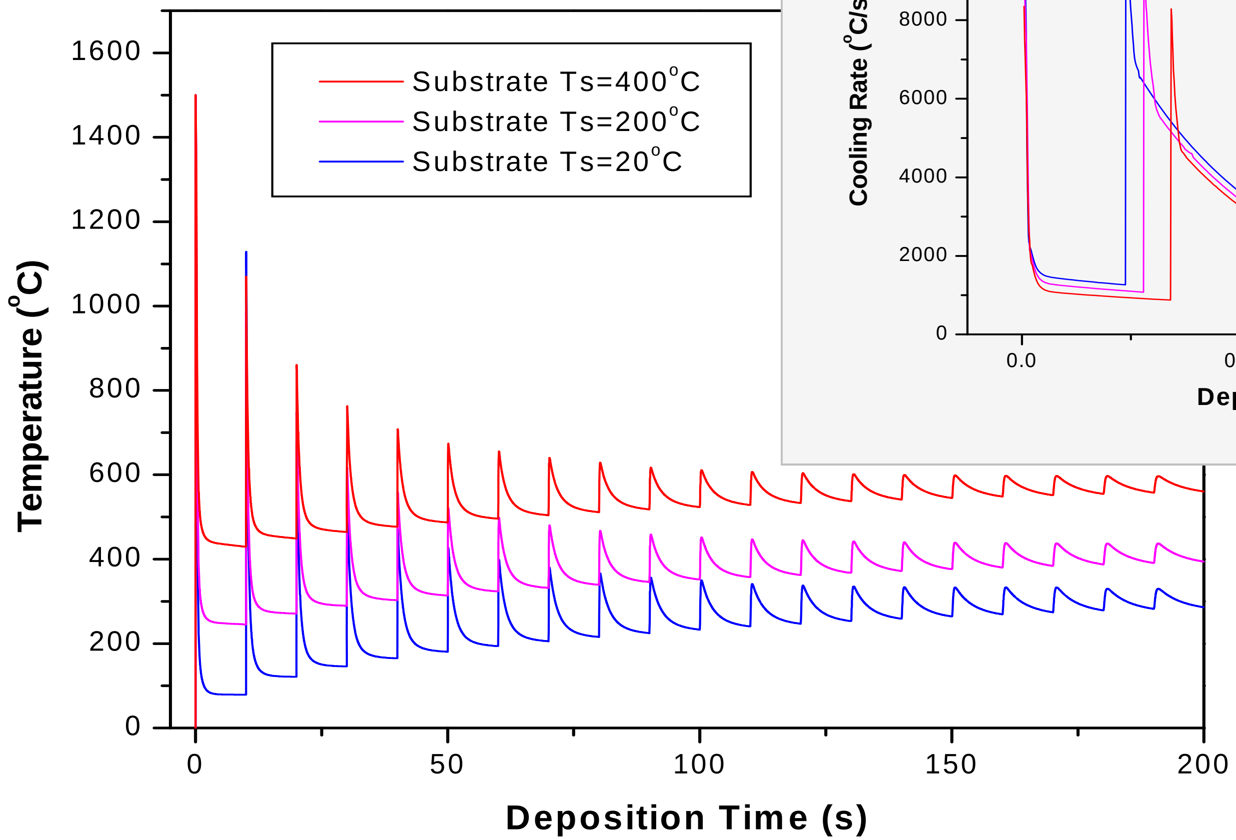
- **Travel speed**
- **Part dimension**
- **Laser stay time between layer**

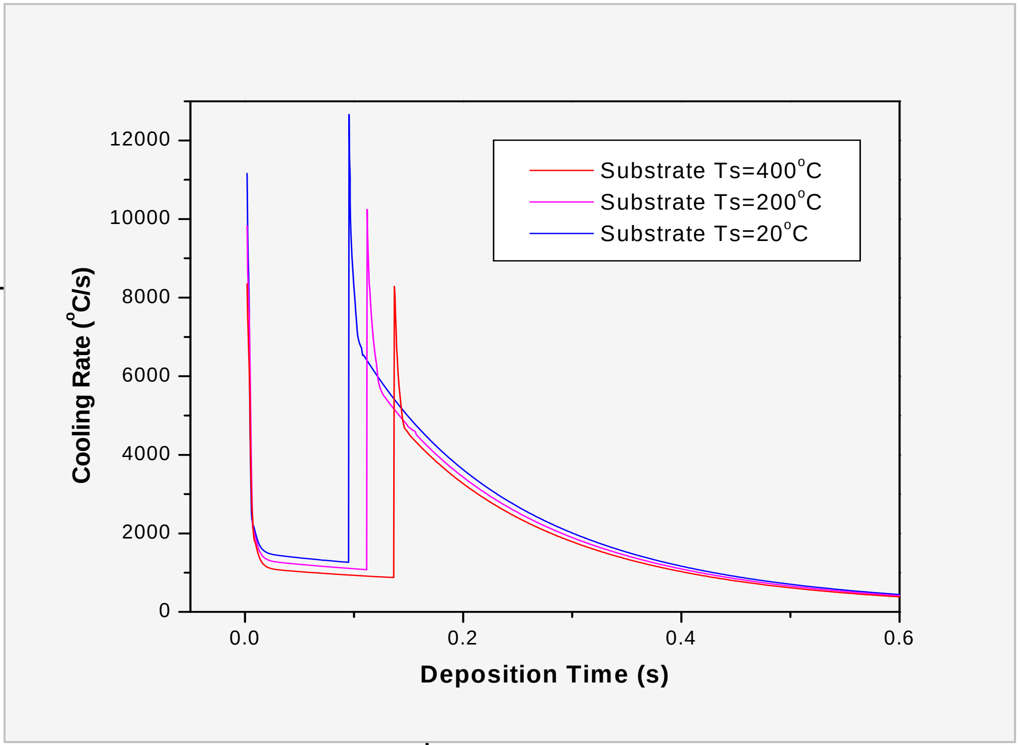
- Interval time



Effects of Initial Temp. of Substrate

Variation of thermal behavior with initial temperature of the substrate





T_{mp} = 1500ºC

$\triangle t$ = 10 s

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