Manufacturing: Optimal Integration of Engineering Endeavors
제조: 공학기술의 최적화를 위한 통합

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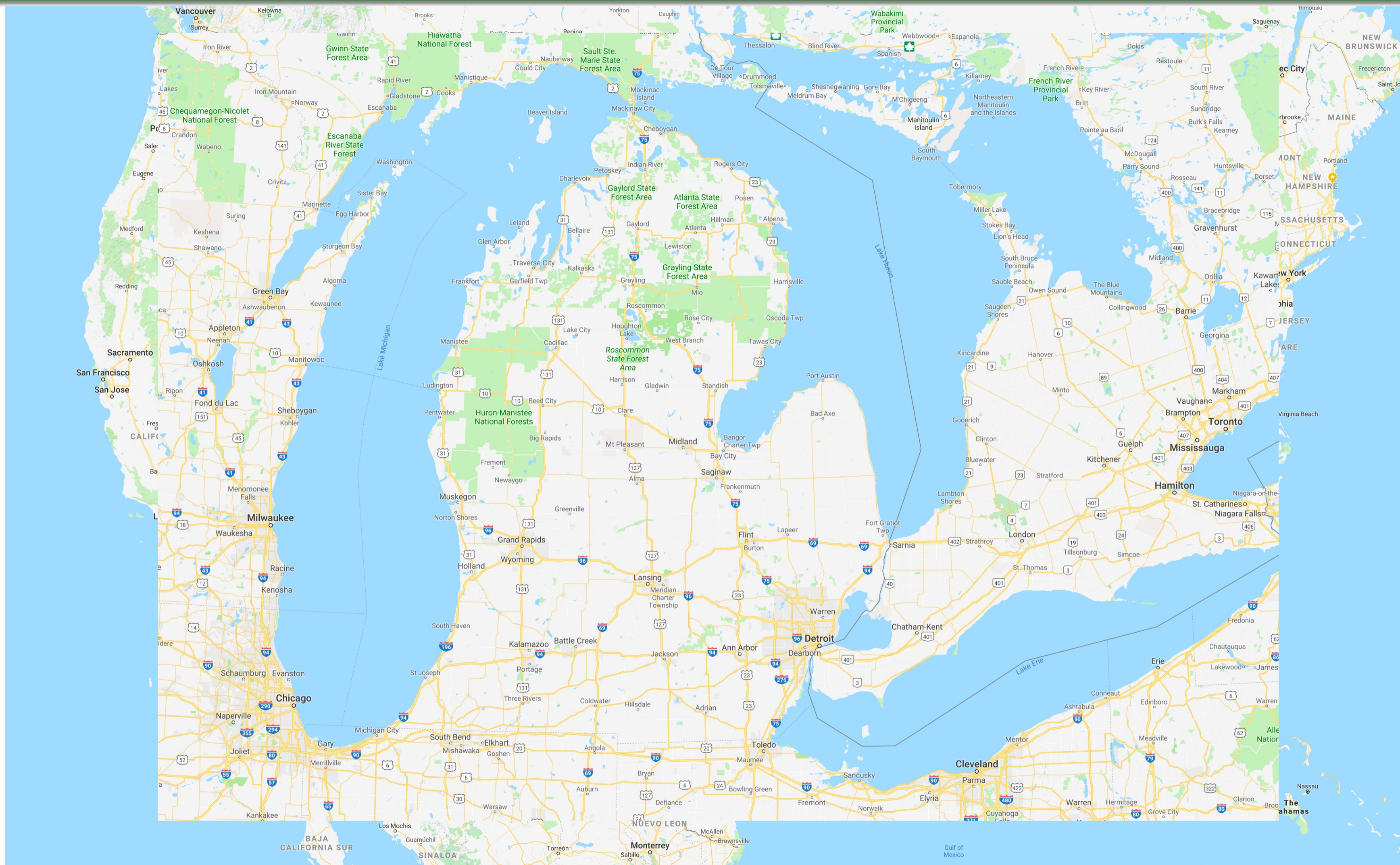

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Huron-Manistee National Forests
Hiawatha National Forest
Chequamegon-Nicolet National Forest

Historical Note in relation to MFG

- Artisan
  - Tools in Stone age
  - Powder processing (Clay) (4000BC)
  - Metals - Casting, Forging & Heat Treating (2500BC-1850)
- The First Industrial Revolution (1760-1830)
  - John Wilkinson (1774) - Machine tools
  - Thomas Newcomen & James Watt (1776) - Steam Engine
  - **Eli Whitney** (1797) - Interchangeable parts
  - Adam Smith (1776) - "The Wealth of Nations" - Free Enterprise
  - **Henry Ford (1913) - Assembly line**
- The Second Industrial Revolution (1950-1970s)
  - Computers & Microchip – CNC machine
- The Third Industrial or Information Revolution (1980s) - Internet
- The Fourth Industrial Revolution? Additive Manufacturing (AM), Industry 4.0,
  - Can AM produce a part with the required tolerances and surface finish that a modern product demands?

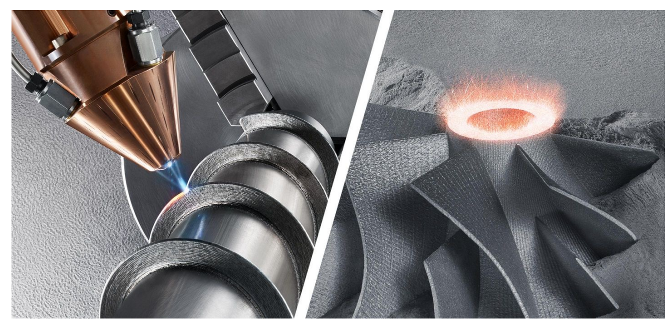
Manufacturing

- **Manufacturing is the creation or production of goods with the help of equipment, labor, machines, tools, and chemical or biological processing or formulation.**
  - **Materials**
  - **Quantity**
  - **Quality - geometric attributes (precision & surface finish), ma terial specs**
- Manufacturing Engineering – efficient & effective manufacturing enterprise
- Materials Science background to deal with materials

Laboratory of Advanced Manufacturing Processes (LAMP@MSU)

- Advanced Machining
  - Deformation mechanisms (Prof. Guo)
  - Tool wear mechanisms (Prof. Kwon)
  - Enhancement Techniques (MQL and MAM) (Profs. Guo & Kwon)
  - Stability (Chatter) (Prof. Khasawneh)
  - Sensor monitoring (Machining Ti alloys - Profs. Khasawneh & Kwon)
  - Magnetic Assisted Finish (Profs. Chung & Kwon)

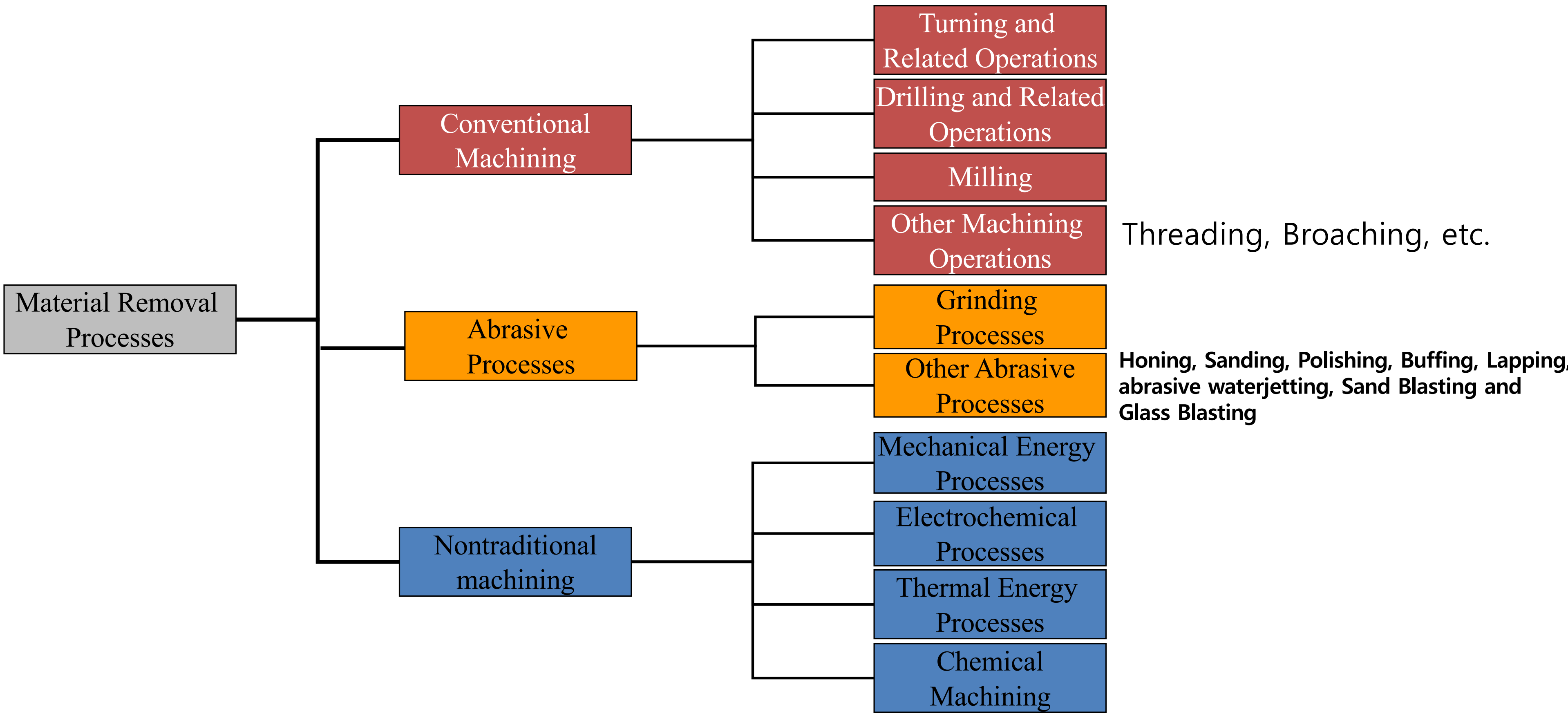
- Additive Manufacturing (3DP)
  - Binder Jet Printing (Prof. Kwon)
  - Electron Beam Melting (Prof. Kwon)
  - Laser Beam Melting (Prof. Chung)
  - Directed Energy (Profs. Chung & Sahasrabudhe)
  - Hybrid System (Prof. Chung)
  - Scalable & Expeditious Additive Manufacturing (SEAM) (Profs. Chung & Kwon)



Manufacturing Processes -Classification

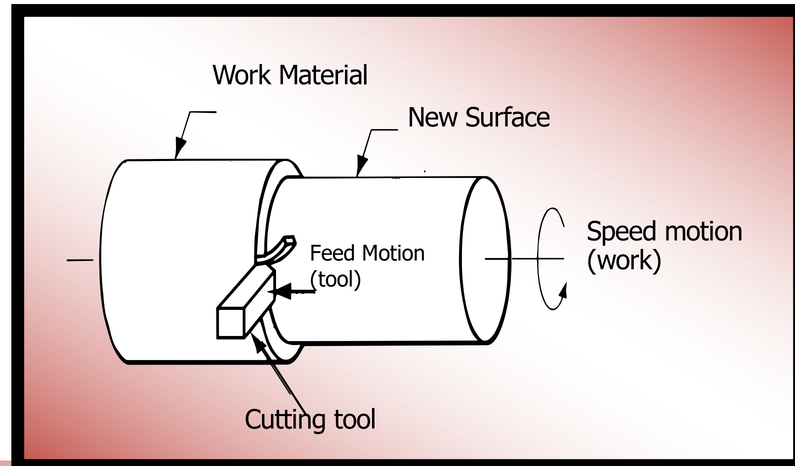
- Process Operation
  - Shaping
    - Casting — Liquid or semifluid
    - Particulate — Powder
    - Deformation — Ductile Solid
    - Material Removal — Solid - Molding
  - Property Enhancing
    - Heat Treating
  - Surface Enhancing
    - Surface Treatment
    - Coating
- Assembly Operation — Permanent joining & Mechanical fastening

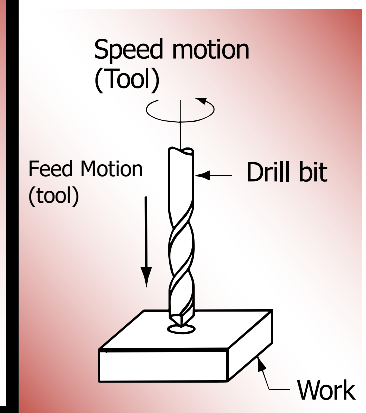
Machining: Material Removal Processes

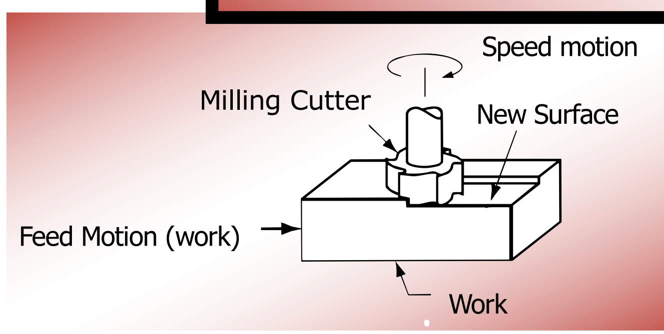


Conventional Machining

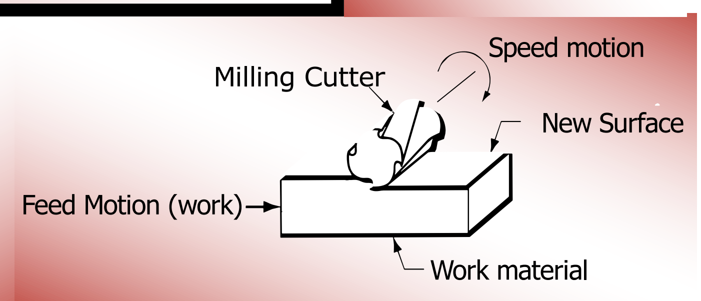
- Subtractive - Removes undesired sections of workpiece while being efficient
- Types
  - Turning - Lathe
  - Drilling – Drill press
  - Milling – Milling Machine
    - Peripheral & Face
- Work piece & Cutting Tool





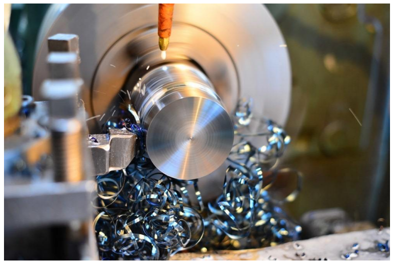


Peripheral (End) Milling

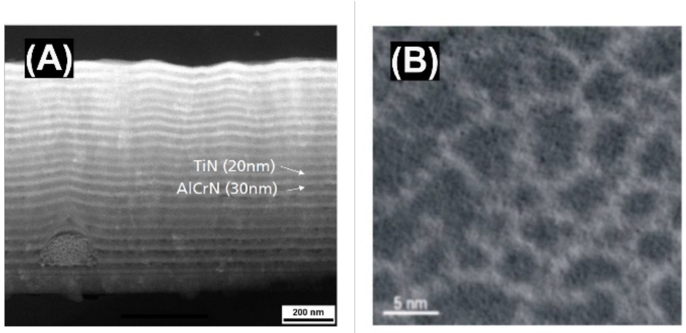


Face (Slab) Milling

Key Issues in Machining



- Many research works were done on turning.
  - Cutting tools depending on the material being cut (new materials)
    - Improve productivity
    - Tool wear to change tools
  - Chatter – Machine stability
  - Monitoring
    - Motor power and current
    - Measuring forces and torques using piezoelectric, strain gage
    - Acoustic emission sensor
    - Audible sound

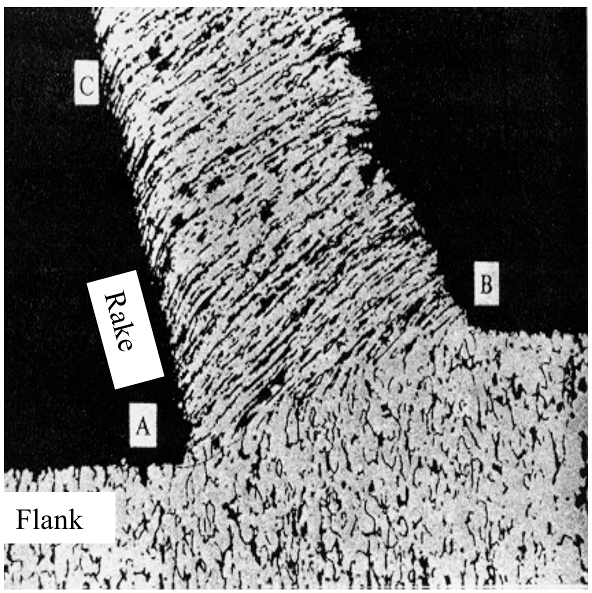


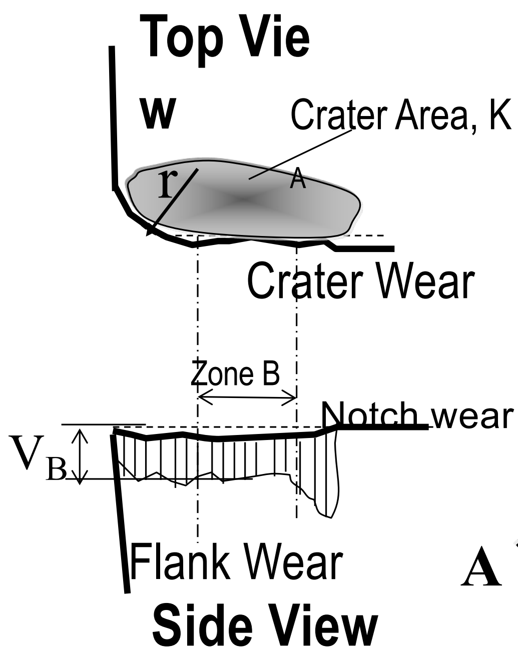
Nano-composite coating

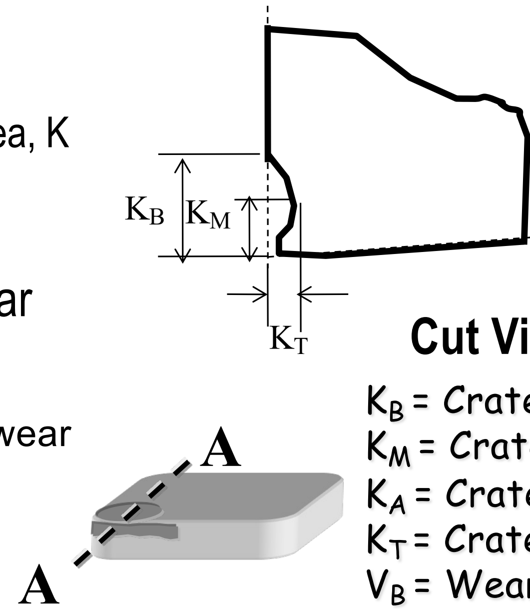
Tool Wear

Still, an empirical approach to predict tool wear

$$Taylor's\ Model: V^a d^b f^c = \text{constant}$$







Cut View Section A-A

K_B = Crater Width
K_M = Crater Center Distance
K_A = Crater Area
K_T = Crater Depth
V_B = Wear Land Width
r =Radius of Cutting Edge

Cause of Tool Wear (Wear Mechanisms)

Mechanical wear

- **Abrasive wear**

- The sliding and rolling of hard second phase on the work/tool materials interface

- Erosion Wear
- Delamination Wear

- Continual loading leads to subsurface cracks pr opagation

- **Adhesion** (Ti)

- Welding of asperity junctions

Thermochemical wear

- **Dissolution Wear**

- Thermally activated mechanisms - Ato mic transport across the interface

- **Diffusion wear**

- The component of tool materials can be diffused into chips

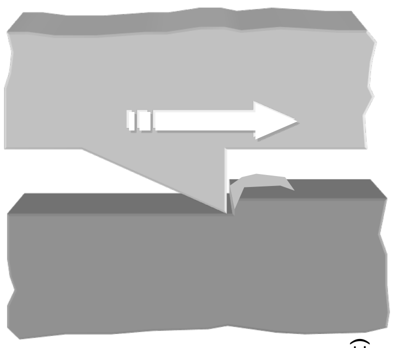
- **Chemical reaction** (Ti)

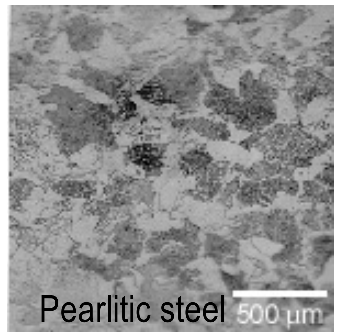
- Chemical reaction between tool and work material

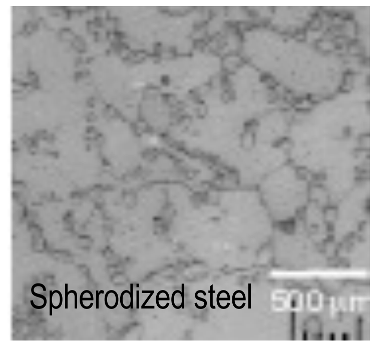
- Thermomechanical fatigue - Milling

Prediction by Abrasive Models

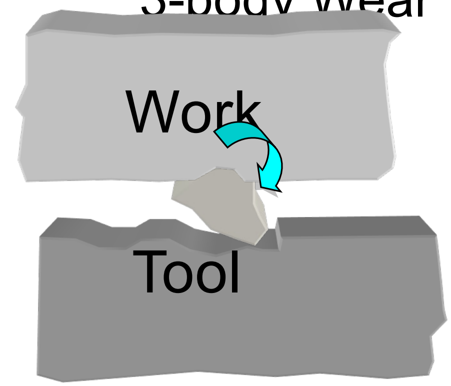
2-body Wear

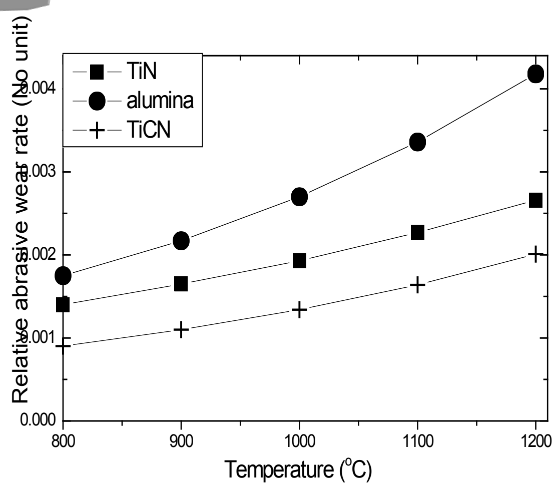




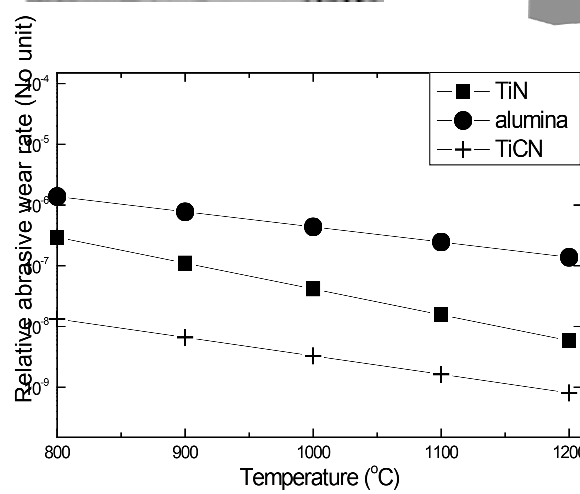


3-body Wear





2-body Abrasive Model



3-body Abrasive Model

Compositions of Steels

(All in wt%)

	C	Mn	P	S	Si	Ni	Cr	Mo
1018	0.21	0.70	0.02	0.03	0.21	0.07	0.13	0.02
1045	0.48	0.74	0.01	0.04	0.27	0.05	0.08	0.02
1070	0.68	0.78	0.01	0.02	0.22	0.04	0.17	0.02
1018 (S)	0.16	0.83	0.01	0.03	0.20	0.01	0.08	0.01
1045 (S)	0.48	0.74	0.01	0.04	0.27	0.05	0.08	0.02
1065 (S)	0.64	0.80	0.01	0.01	0.28	0.07	0.15	0.02
1095 (S)	0.89	1.02	0.02	0.03	0.31	0.15	0.32	0.14
4340	0.41	0.70	0.04	0.04	0.27	1.83	0.80	0.25

- Round Bar stocks: nominally of diameters between 3” and 6” and length about 2-1/2' initially.

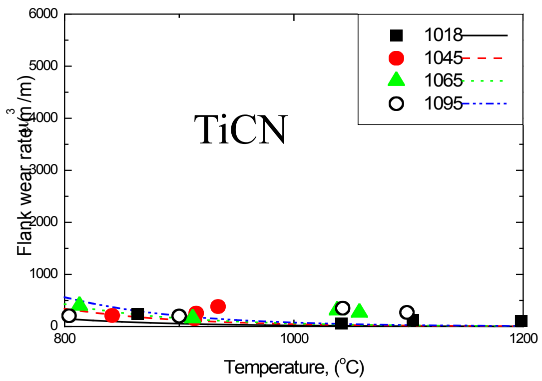
Flank Wear - Spherodized

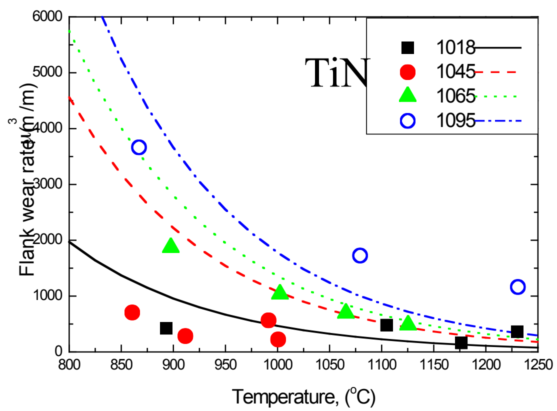
Flank Wear Rate

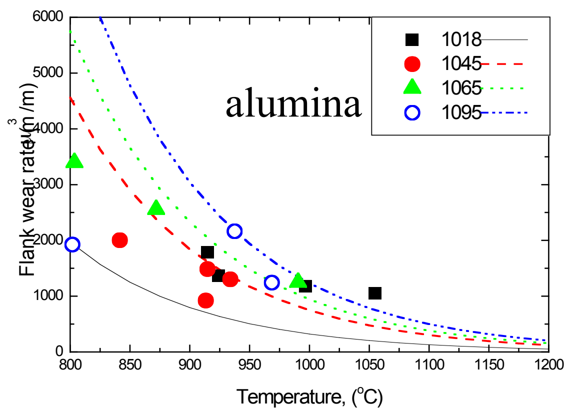
$= 1.166A(P_a^{(n-1)})/P_t^n$

Area fraction, A

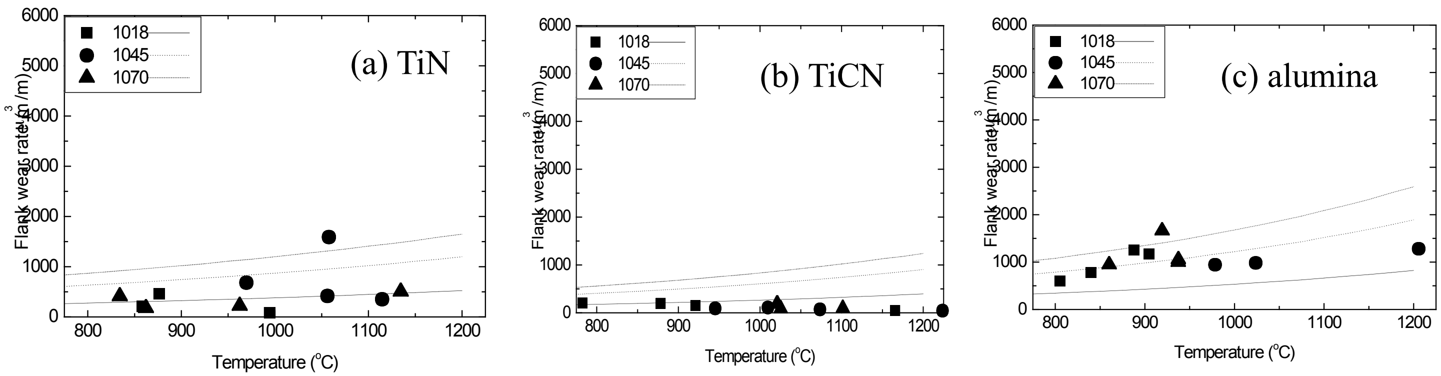
steel	A
1018	0.07
1045	0.16
1065	0.21
1095	0.27







Flank Wear - Pearlitic

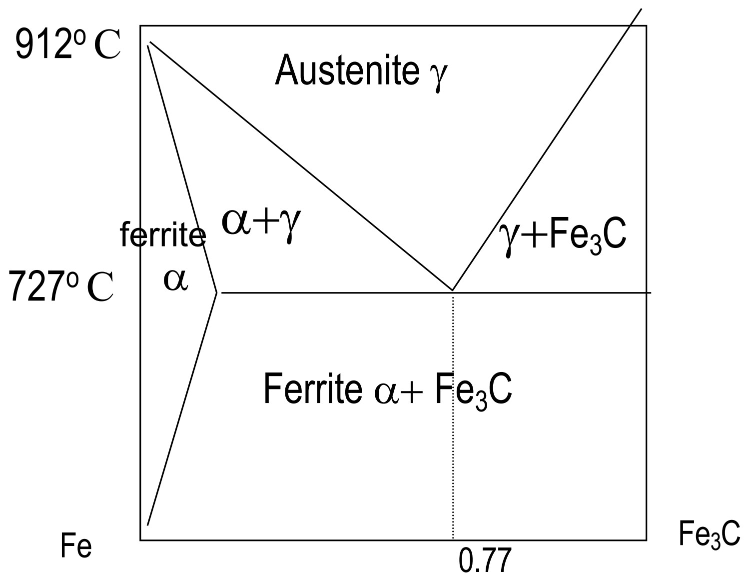


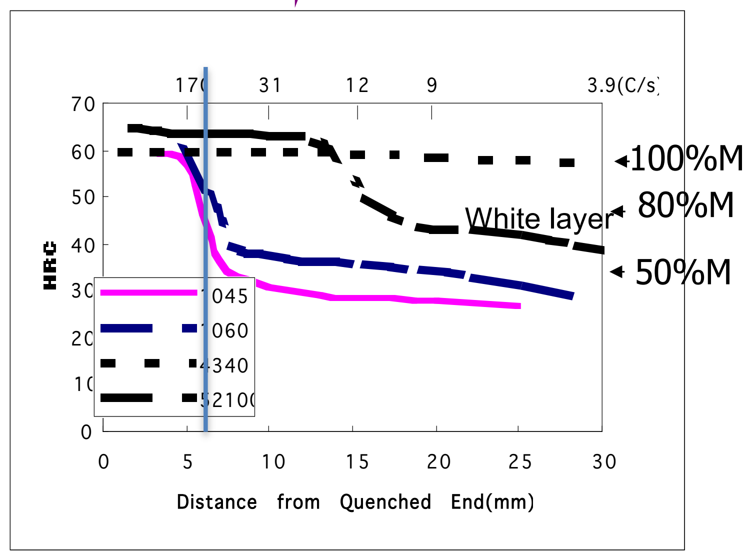
- Problems
  - The Inadequacy of 2-body Abrasive Wear Model
    - TiCN – too low wear
    - No cementire effect - Phase Transformation

Phase Transformation

Interface Temperature: lower than 727 °C due to pressure
(Clapeyron's equation)

➡ Phase transformation ➡ Wear behavior

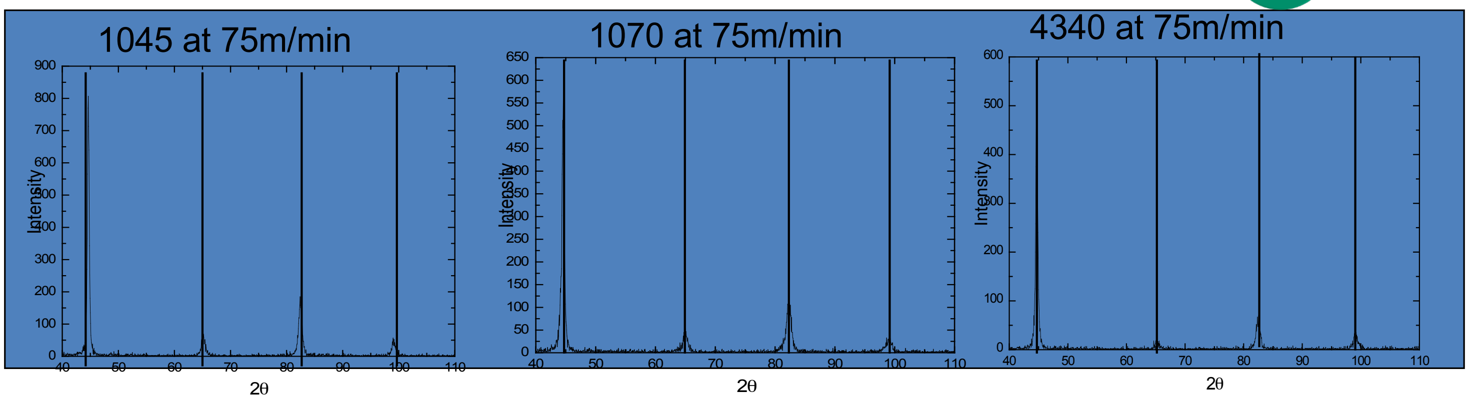


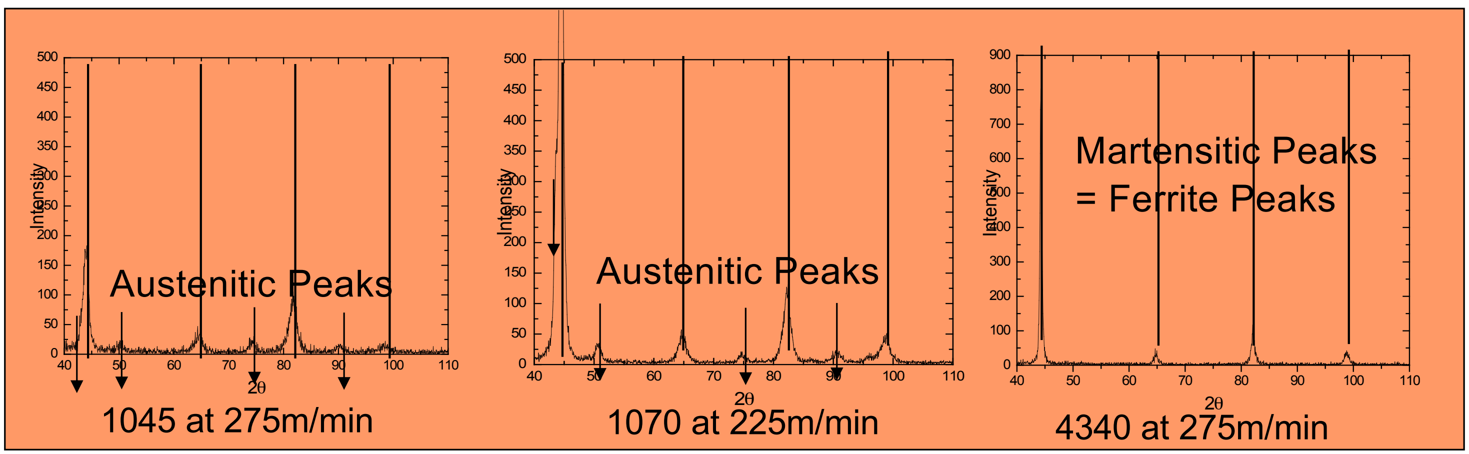


Abrasives: Fe_3C

Phase transformation temperature changes wit h composition variation & pressure.

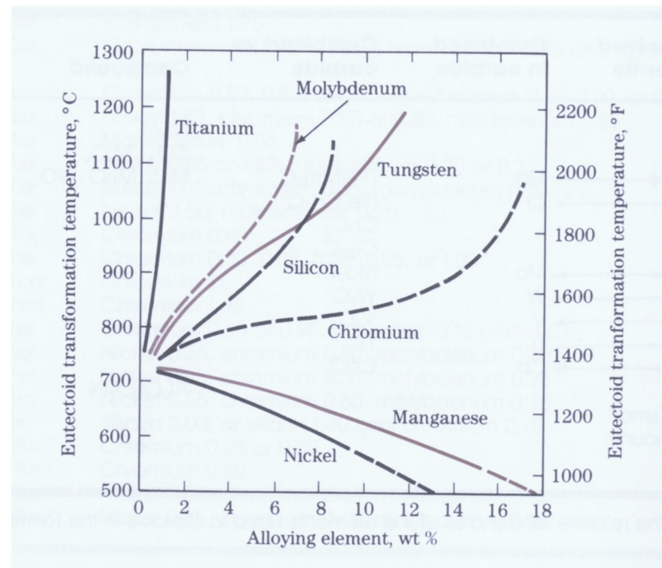
Results of X-ray diffraction





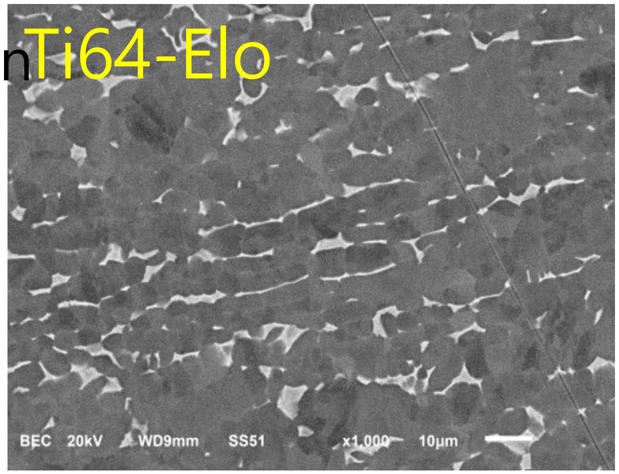
Practical Applications

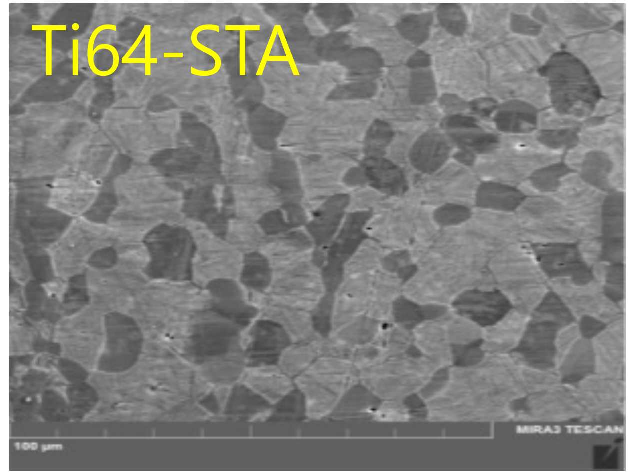
- Phase Transformation
  - High Pressure – Decrease the Transformation Temperature based on Clayperon's Equation
  - Variations in Tool Life even for the same work material
    - Compositional differences – Increase or decrease Friction & Temperature
  - Cutting at higher speeds could improve the machinability for most ferrous materials



Four Microstructures of Ti64s: α & β phases

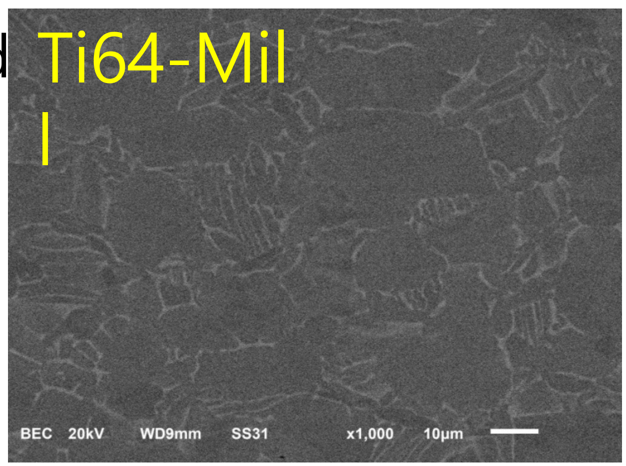
Equiaxed Grain (Elongated)

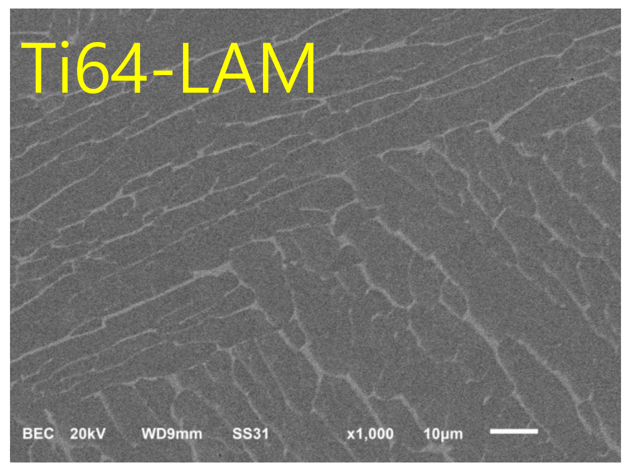




Solution Treated & Aged (STA)

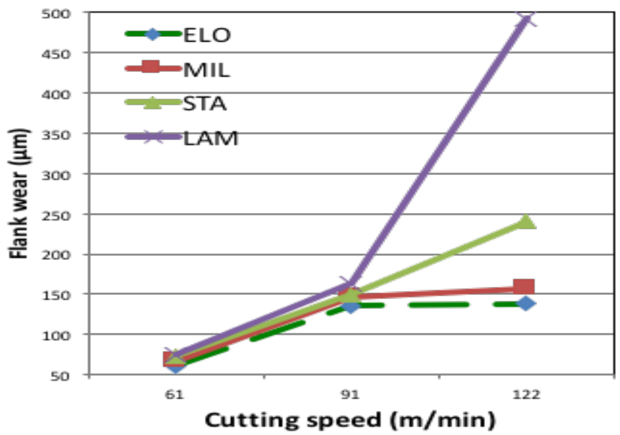
Mill Annealed (MIL)



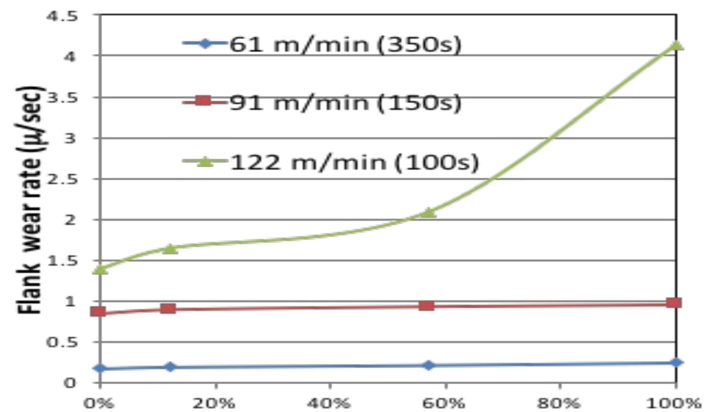


Lamellar

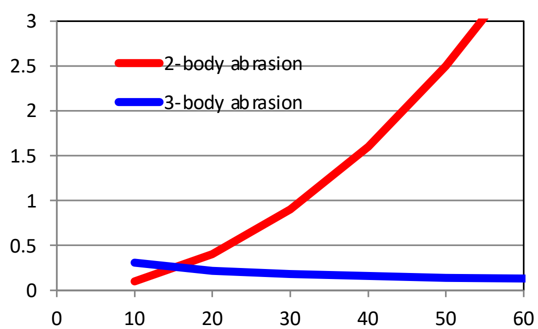
Discussion On Flank Wear



Flank Wear vs. Cutting Speed



Flank Wear vs. Lamellar content



Predictions by 2- & 3-body abrasions (Kwon, 2000)

Root Cause for flank wear in machining Ti alloys[14]

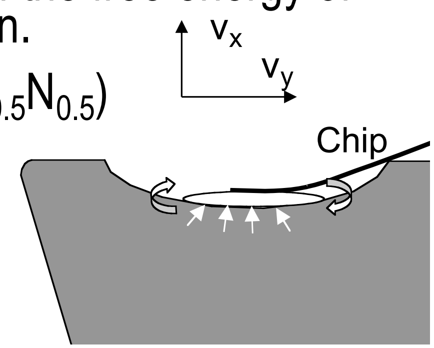
1. The hard direction of HCP clusters (Hard α-cluster)
2. Lamellar phase

- Flank wear rapidly increased with high cutting speed (122 m/min) with the lamellar content
- Lamellar colonies with the constrained (alternate) α- and β-phase exhibiting 2-body abrasion whereas hard α-clusters are not as well constrained among other α-clusters exhibiting less 2-body abrasion.

Dissolution/Diffusion Wear Model

The material pair in sliding will dissolve to each other if the free energy of the material pair decreases by the formation of solution.

Dissolution wear rate for tertiary coating, $A_xB_yC_z$ ($Ti_1C_{0.5}N_{0.5}$) (Kramer & Suh, 1980; Kramer & Kwon, 1985)



Atomic transport across the interface

$$BMV^{0.5}\,C_{AxByCz}$$

B = the dissolution wear coefficient

M =molar volume of the coating material in cm^3/mol

V =cutting speed (m/min)

Solubility $$C_{A_xB_yC_z} = \exp\left[\frac{\Delta G_{A_xB_yC_z} - x\Delta G_A^{xs} - y\Delta G_B^{xs} - z\Delta G_C^{xs} - RT(x\ln x + y\ln y + z\ln z)}{(x+y+z)RT}\right]$$

$\Delta G_{A_xB_yC_z}$ = free energy of formation

ΔG_i^{xs} = excess free energy of i component

R = gas constant

T = temperature (K)

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Dissolution Prediction

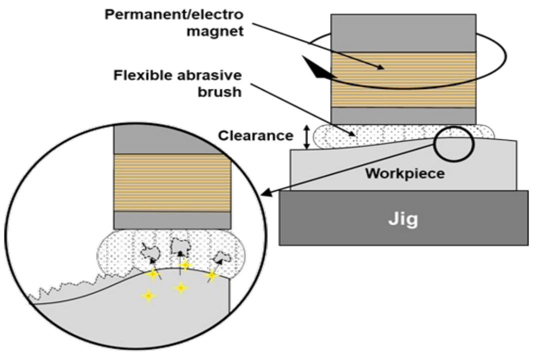
Tool Materials	Relative Wear Rate	Relative Wear Rate	Time for 25μm of wear
ZrO_2	0.0000367	26.053	26 month
Al_2O_3	0.00124	27.051	23 days
TiO_2	0.00313		21 hr
HfN	0.680		60 min
HfC	1.	1	41 min
TiN	5.92		6.9 min
TiC	12.8		3.2 min
BN	57.0		43 sec
WC	332.	0.824	7.4 sec
Diamond	445	0.227	5.5 sec
	At 1300° C **Into Fe**	At 1100° C **Into Ti**	

Surface Finish

- After Grinding, polishing is needed after machining
- Some techniques in machining can also work in grinding
- Polishing is done manually
  - Automation possibility with Magnetic-Assisted Finishing (MAF)

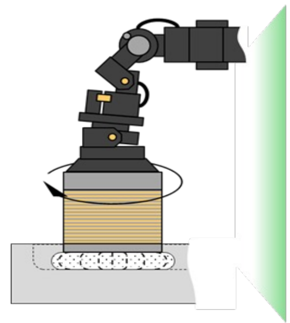
Magnetic-field Assisted Finishing (MAF)

MAF process



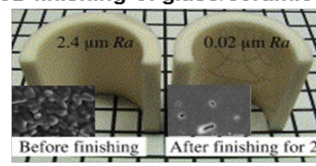
Applications

: 3D printed parts, fine pattern, mold surface, etc.

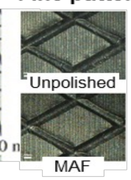


3D printed parts

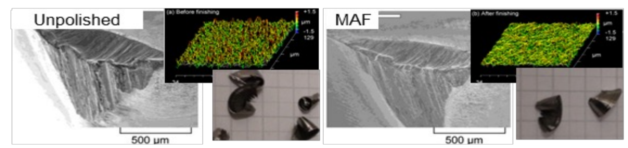
3D finishing of glass/ceramic



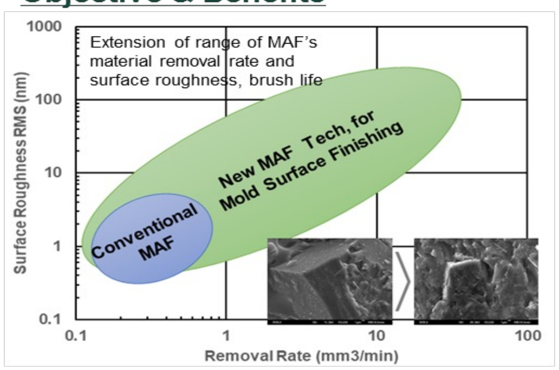
Fine pattern



Treatment of tool surf.



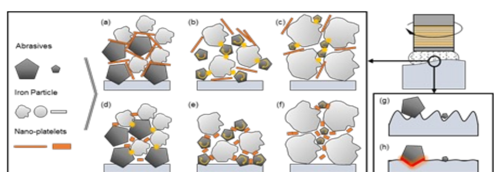
Objective & Benefits

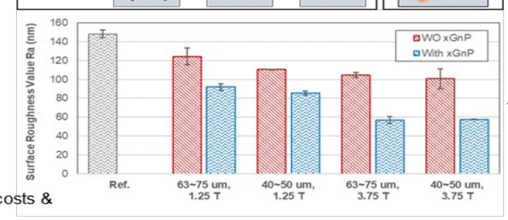


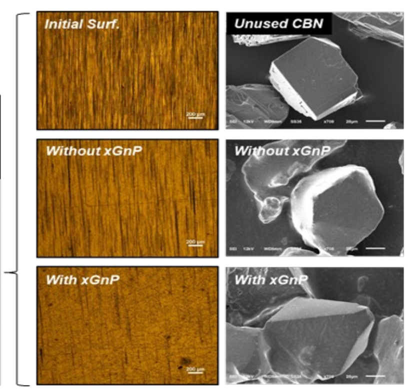
Reduction of processing costs & delivery time, Prediction / management of finishing quality

Experiments

: Improvement of workpiece surface roughness and tool life

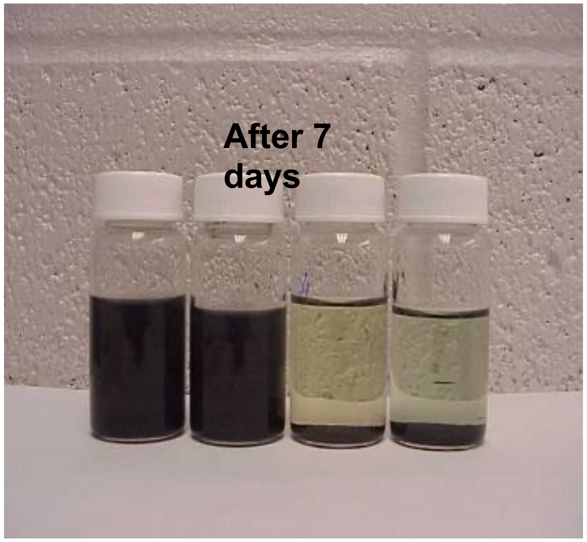


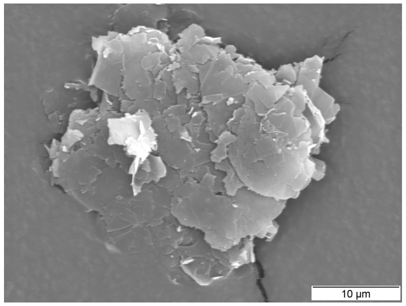


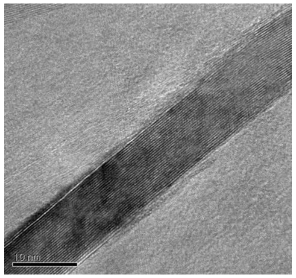


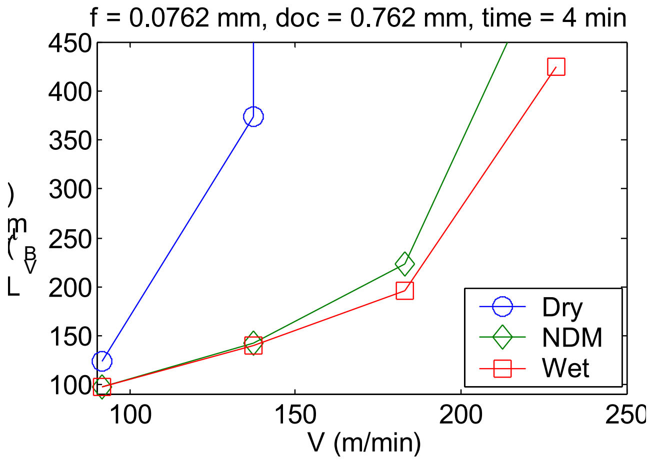
Minimum Quantity Lubrication

- MQL Parameters which significantly influence on the effectiveness of MQL machining
- x-GNP modified MQL oil









Magnetic Field Assisted Finishing (MAF)

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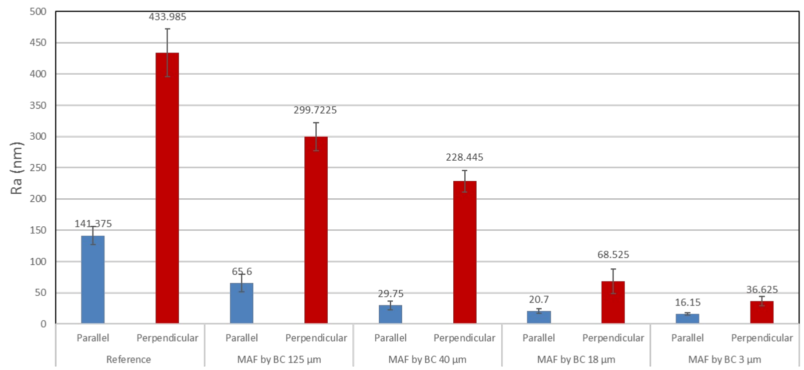
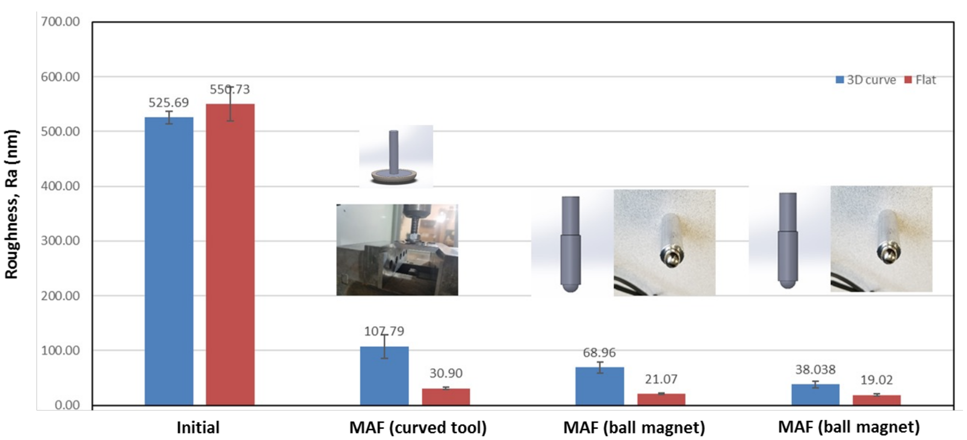
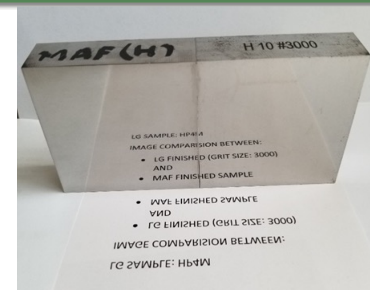
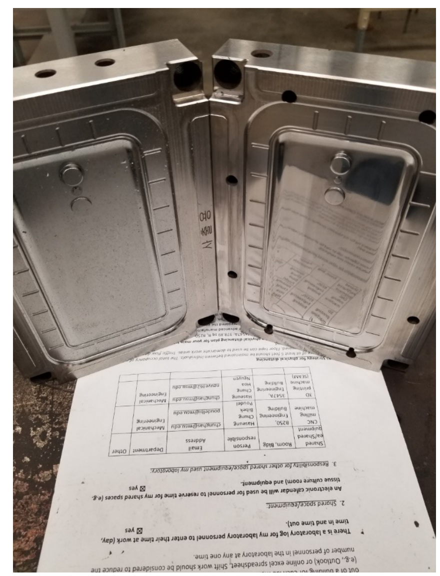
Mold steel (HP4M)







Comparison between MAF sample (left) and manually finished sample (right)



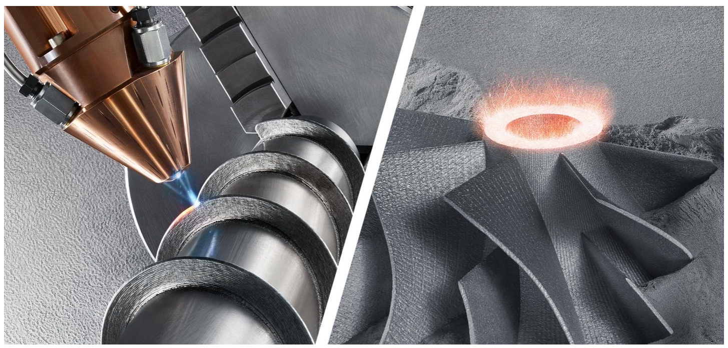
Collaborative project (mold finishing) with ***LG electronics* (Chung & Kwon)**

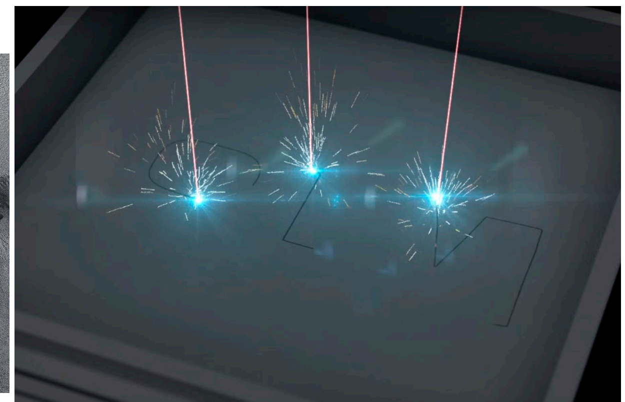
Advantages & Applications

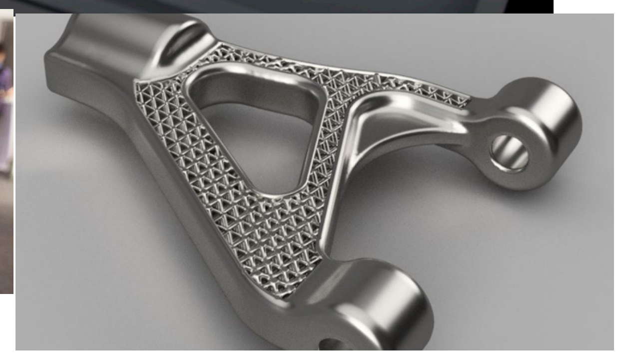
: *“Metal AM reduced the total part count and replaced more complex brazing of multiple components to create a lighter, simpler, and more durable product!”*

: Aerospace, Biomedical, Automotive Parts, etc.

Process development & Material Integrity

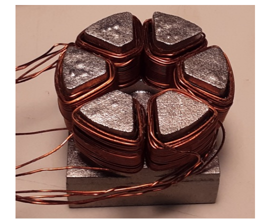






Additive Manufacturing (AM)

- Various AM manufacturing techniques such as selective laser melting (SLM), electron beam melting (EBM), binder jet printing (BJP), directed energy deposition (DED), and a new patent-pending scalable and expeditious additive manufacturing (SEAM). Main efforts are
  - Motor - Electric steels (BJP with S. Foster) - New material Development
  - Introducing multi-functionalities (e.g.: nitinol) (Kwon, Chung, Lee & Baek)
  - The development of SEAM using photopolymer to fabricate supercritical CO_2 heat exchanger (Benard, Chung & Kwon),
  - The modification of SEAM using hydrogel for ceramic materials (Lin, Chung & Kwon).



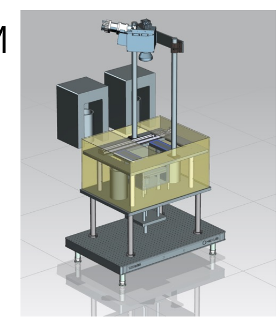
BJP

Hybrid-DED

SLM

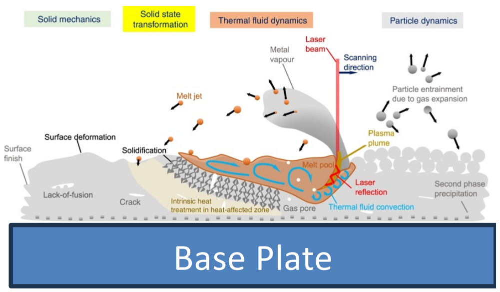
EBM

SEAM

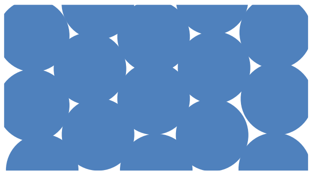


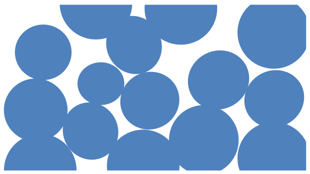
Types of AM Techniques

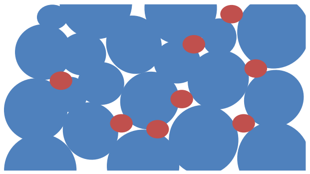
- Powder Feed System - Directed Energy Deposition (Laser cladding)
- Powder Bed Fusion
  - near net shape, but distortion, residual stress, heterogeneity
  - Selective Laser Melting (SLM)
  - Electron Beam Melting (EBM)



- Powder Bed
  - Hard to achieve full dense but homogeneous, no residual stress
  - Binder Jet Printing (BJP) – sintering additive to form liquid phase
  - Scalable & Expeditious Additive Manufacturing (SEAM)


ideal

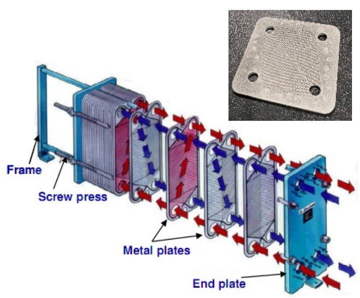

Real


Engineered

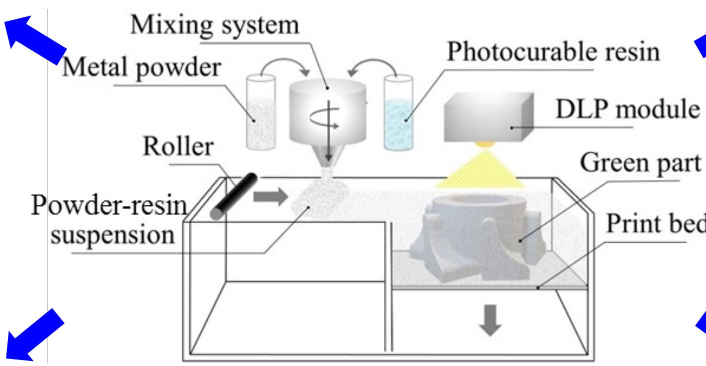

Full density

Scalable & Expeditious Additive Manufacturing (SEAM)

Collaborative project with ***Hyundai Motor Company*** (Chung & Kwon)

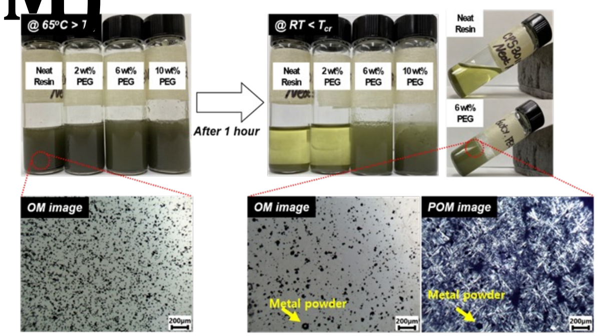


ARPA E Project: Fabrication of heat exchanger assembly (Chung & Kwon w/ Benard)

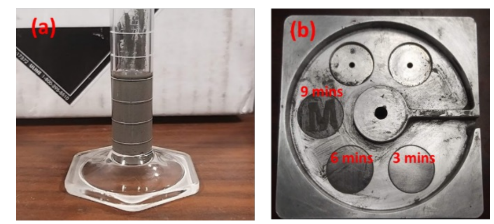


New additive manufacturing process developed at MSU
(Chung & Kwon)

Few issues: Segregation



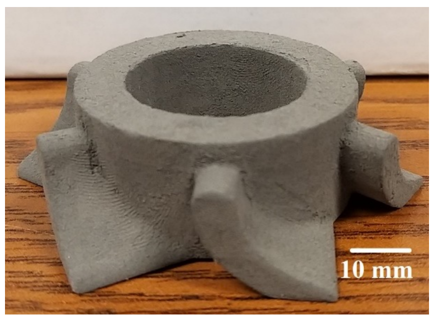
NSF CAREER Project: Development of viscosity tunable photopolymer (Chung)



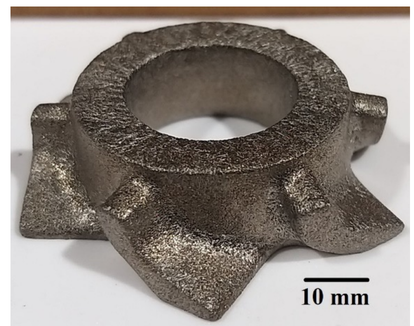
MTRAC Project: New photopolymer formula for recycling the material (Chung & Kwon)

Scalable and Expeditious Additive Manufacturing (SEAM)

- Green turbine with 50 mm diameter and 20 mm height was fabricated
- Processing parameters
  - Powder: Stainless steel 420 with size 55/22 µm
  - Suspension: 0.56 powder volume fraction – 87.5% wt%
  - Layer thickness: 100 µm
  - Layer curing time: 40 seconds



Green part



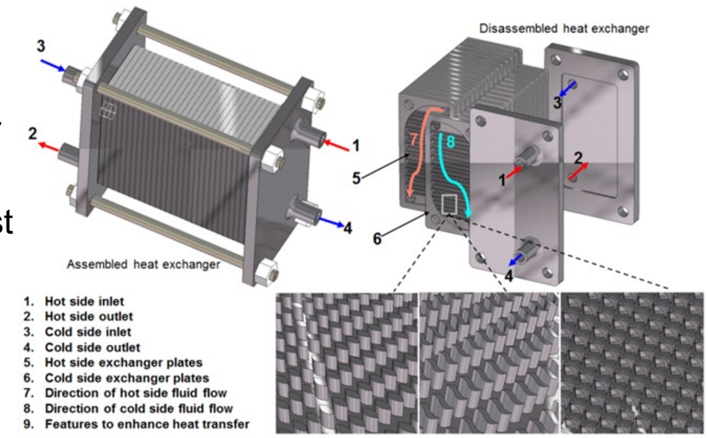
Sintered part

- Binder burn-out & Sintering
- With the new process, three dimensional objects were successfully fabricated on a powder bed system, and sequentially sintered to a relative density of 99.5%.

Heat-Exchanger Intensification through Enhanced Design

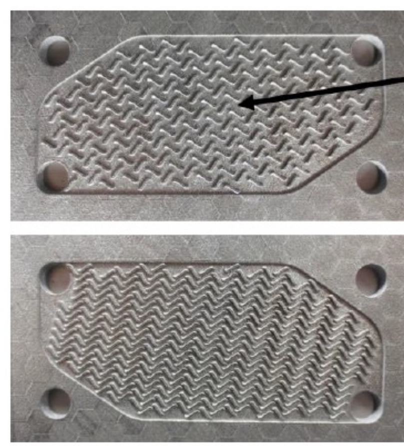
MICHIGAN STATE UNIVERSITY

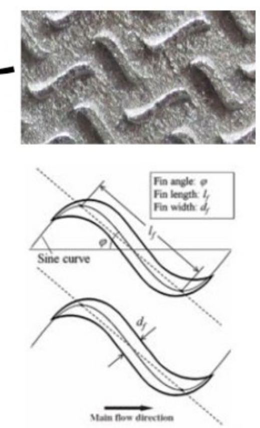
- Technology Summary
  - Transformative high temperature (1100°C), high pres sure (250 Bar) compact HX for sCO2 power gener ation systems
  - Super-alloy compositions provide corrosion resist ance



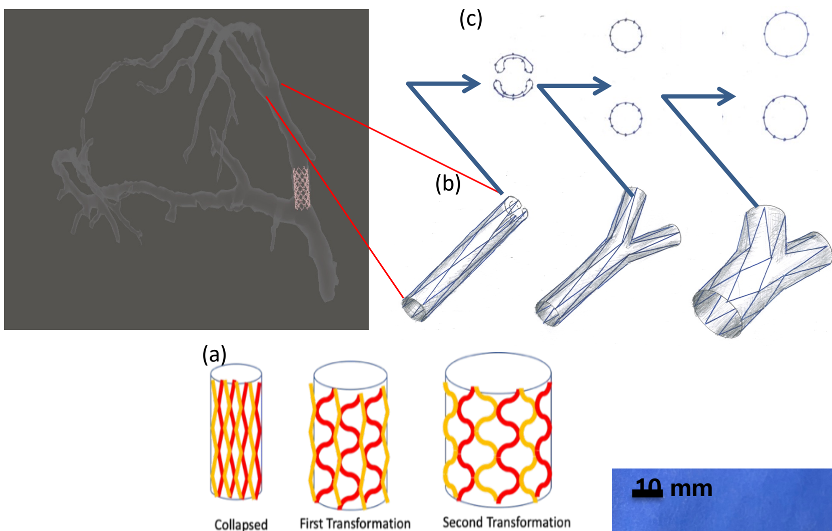
- Prototype of heat exchange cold and hot plates manufactured by selective laser melting (SLM) process

Prox DMP 200 (3D Systems)





Advanced NiTi Stent (Helen Devos Children's Hospital)



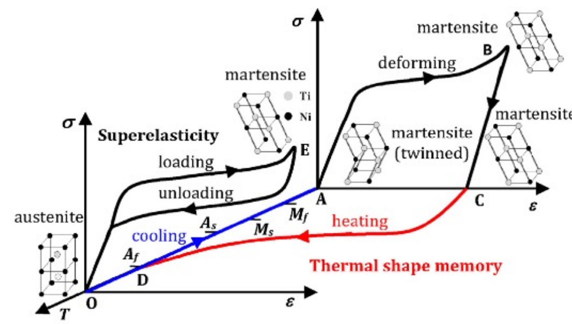
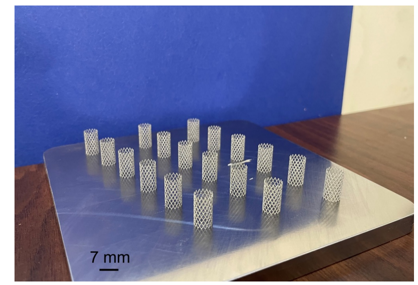
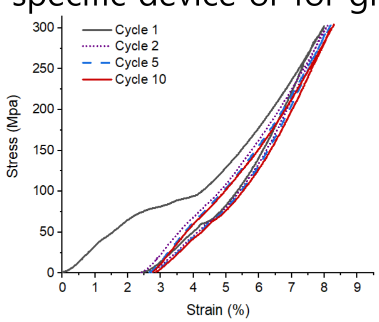


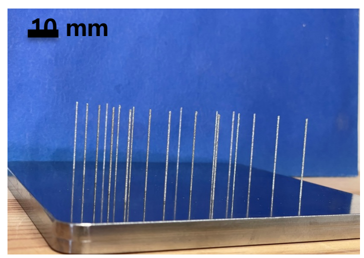
Figure: Stress-strain –temperature diagram of nit inol. (Guo et al. 2013)

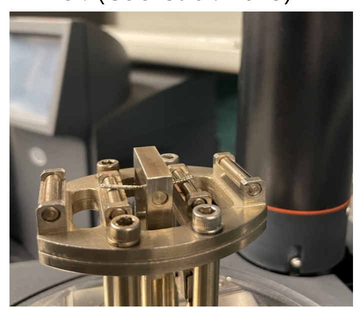


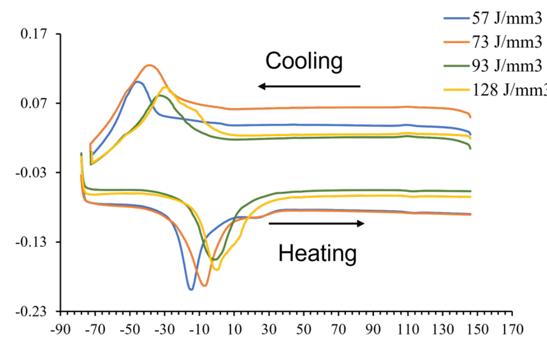
Patient-specific device or for growth



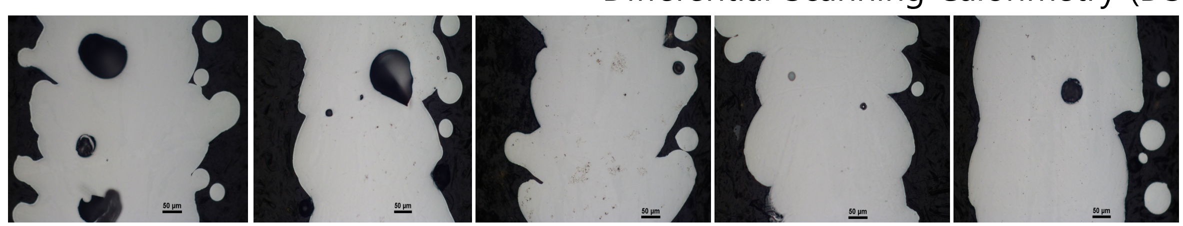
Superelasticity test: Cyclic load-unload test







Differential Scanning Calorimetry (DSC)



Representative AM Technology

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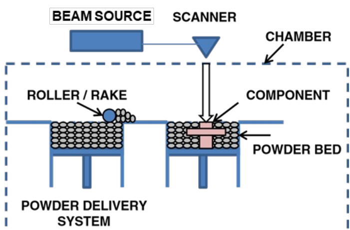
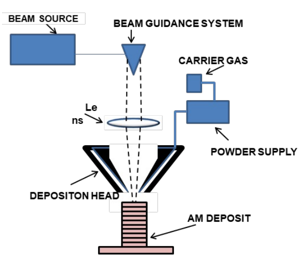
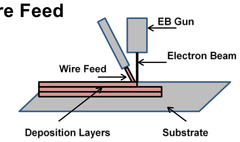
European Countries Focus on PBF & The U.S. Companies Focus on DED

System	Company (Equipment Name)	MFG Country	Process	Build Volume (mm)	Energy Source
Powder Bed Fusion (PBF) 	ARCAM (A2)	Sweden (now GE)	EBM	200 x 200 x 350	7 kW electron beam
	EOS (M280)	Germany	DMLS	250 x 250 x 325	200-400 W Yb-fiber laser
	Concept laser cusing (M3)	**USA**	SLM	300 x 350 x 300	200 W fiber laser
	MTT (SLM 250)	Germany	SLM	250 x 250 x 300	100-400 W Yb-fiber laser
	Phenix system group (PXL)	France	SLM	250 x 250 x 300	500 W fiber laser
	Renishaw (AM 250)	UK	SLM	245 x 245 x 360	200 or 400 W laser
	Realizer (SLM 250)	Germany	SLM	250 x 250 x 220	100, 200, or 400 W laser
	Matsuura (Lumex Advanced 25)	Japan	SLM	250 x 250 diameter	400 W Yb fiber laser; hybrid additive/subtractive system
	3D Systems (ProX DMP)	**USA**	SLM	250 x 250 x 330	50-500 W fiber laser
Directed Energy Deposition (DED) – **Powder Feed** 	Optomec (LENS 850-R)	**USA**	LENS	900 x 1,500 x 900	1 or 2 kW IPG fiber laser
	POM DMD (66R)	**USA**	DMD	3,200ºx3º, 670ºx360º	1-5 kW fiber diode or disk laser
	Accufusion laser consolidation	Canada	LC	1,000 x1,000 x 1,000	Nd:YAG laser
	Irepa laser (LF 6000)	France	LD		Laser cladding
	Trumpf	Germany	LD	600x1,000 long	
	Huffman (HC-205)	**USA**	LD		CO_2 laser cladding
Directed Energy Deposition (DED) – **Wire Feed** 	Sciaky (NG1) EBFFF	**USA**	EBDM	762x483x508	>40 kW @ 60 kV welder
	MER plasma transferred arc select ed FFF	**USA**	PTAS FFF	610x610x5,182	Plasma transferred arc using two 350A DC power supplies
	Honeywell ion fusion formation	**USA**	IFF		Plasma arc-based welding

Metal AM Standard Roadmap (2013~)

Important Technology and Measurement Challenges for Additive Manufacturing

AM Materials
- Characterization Data and Standards for Post Processing
- Robust In Situ Process Monitoring Techniques
- Metals Design Allowables Database

AM Process and Equipment
- Non-Destructive Evaluation Techniques Optimized for Metals AM
- Fast In-Situ Measurements
- Performance Capability Database for AM Technologies
- Sensors for Measuring and Monitoring AM Processes and Products

AM Qualification and Certification
- Closed Loop Process Control
- Standard Guidelines and Methods for Qualification and Certification
- Shared/ Standardized Third-Party Data Repository
- Standards and Protocols for Round-Robin Build and MaterialTesting

AM Modeling and Simulation
- Expert System for AM Design
- Validated Physics- and Properties-Based Models for AM
- Standard Data Structures, Definitions, and Metrics for AM Models

NIST
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Concluding remarks

- Manufacturing is not a traditional subject which delves into deeper understanding but integration of engineering solutions from multidisciplinary approaches.
- Each topic is typically immense, requiring concentrated but multi-discipline efforts.