

# 융복합소재연구실

(Convergence & composite Materials Lab.)



**1. Name : Prof. Jo, Ilguk (ijo@deu.ac.kr)**



## **2. Education**

- Ph.D., (2009-2014):  
Metallurgical Materials and Engineering, Colorado School of Mines, Golden, USA
- Bachelors and Masters of Science (2001-2009):  
School of Materials Science and Engineering, Pusan National University, South Korea

## **3. Research area**

- Casting of Al / Mg / steel based MMCs and its evaluation
- Development of composite armor module
- Additive manufacturing

## **4. Research experience**

- 2019.03 ~ current: Assistant Professor, Dong-Eui University
- 2015.01 ~ 2019.02: Senior researcher, Korea Institute of Materials Science (KIMS)
- 2014.09 ~ 2014.12: Post-doctoral fellow, Colorado School of Mines
- 2009.08 ~ 2014.05: Research & teaching assistant, Colorado School of Mines

## **5. Publication (2019 ~ current)**

- SCI(E) 40, KCI 7, Book chapter 1

# Lab. Members & Alumni

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## Graduate



**Yujin Im**

## Undergraduate



**Hyun Jun Shin**



**Minhyeok Bae**

# Alumni

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**Jungyu Park**



**Chami Jeon**



**Heejeong Kim**



**Nayoung Kim**



**Nawon Gwak**



**Seokha Heo**



# Research highlights

## • Magnesium based composites

- In-situ combustion synthesis of TiC/Mg
- High pressure die casting
- Reaction mechanism in Al-Ti-C system
- Automotive components  
(Belt tensioner brackets)

## • Aluminum based composites

- Casting, Liquid pressing process
- Strengthening mechanism, wear
- Armor plate for defense module
- Military truck brake caliper

### Metal Matrix Composites

## • Steel based composites

- Isothermal melt infiltration
- Strengthening mechanism
- Neutron absorbing material
- Wear resistant bearing
- High hardness tool steel

## • Additive manufacturing

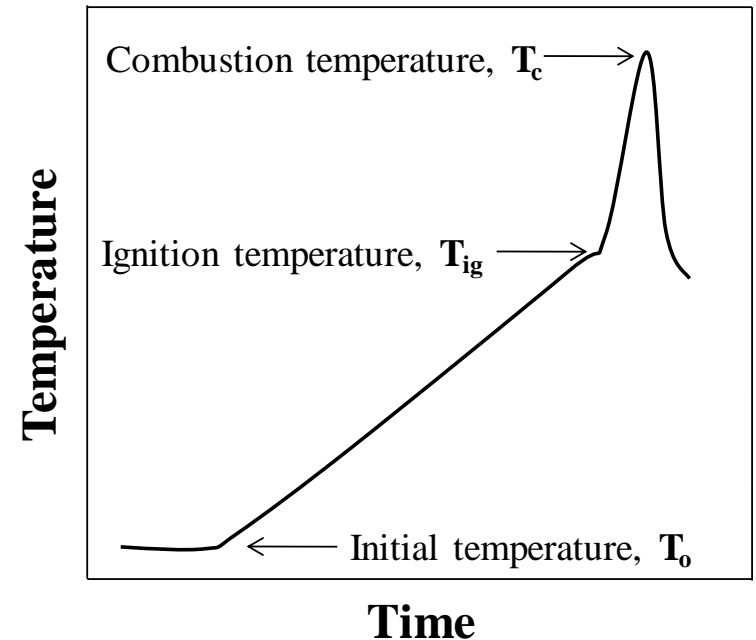
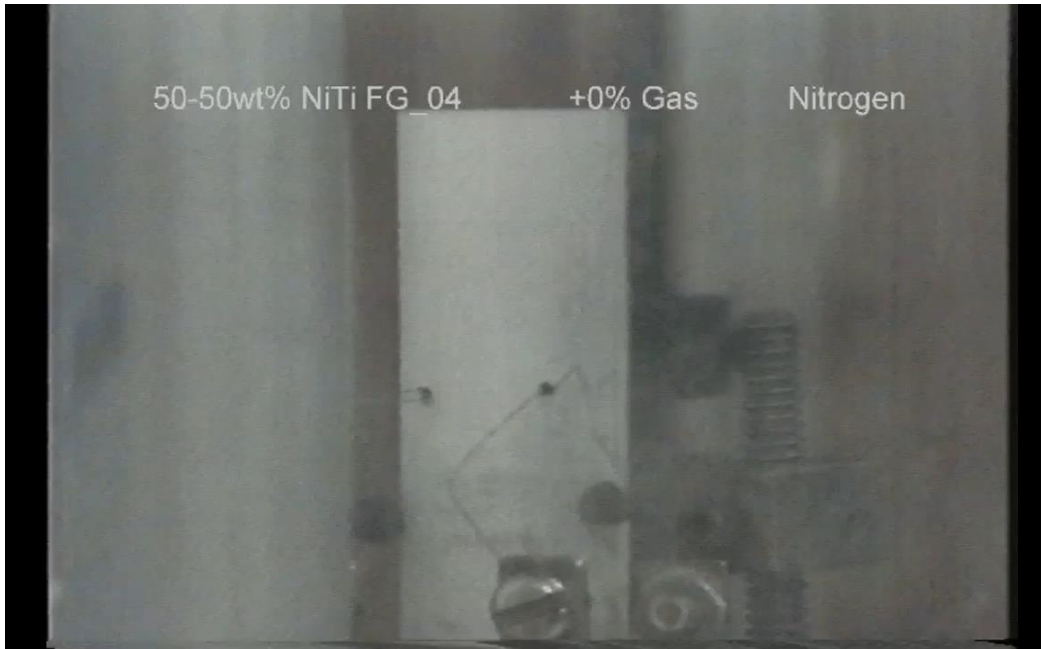
- Powder Bed Fusion
- STS316, Inconel718
- Simulation/Process/Surface treatment/Characterization

# Mg based composites

# What is Combustion Synthesis?

## □ Fundamentals of Combustion Synthesis (CS)

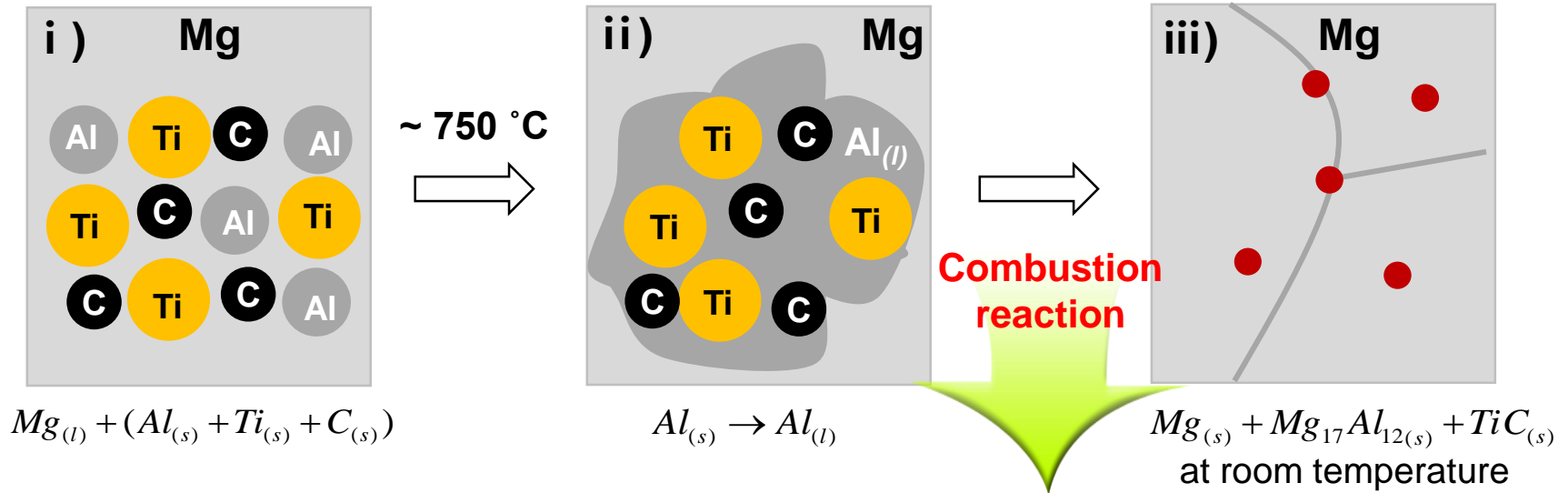
: reactants pressed into a pellet → heated by an external source → initiate an **exothermic reaction**



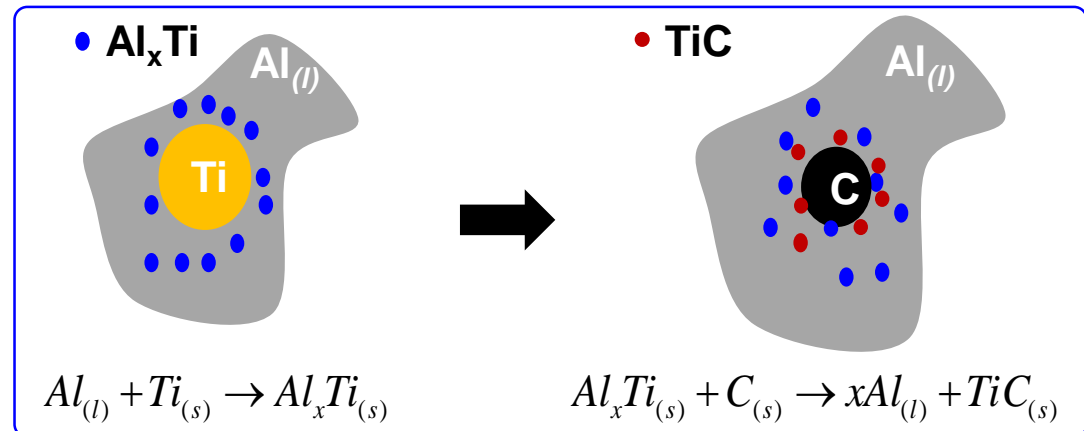
- Low processing temperature
  - **Less contamination** of reinforcement
  - **Thermodynamically stable** reinforcement
  - Near net shape products → reducing processing time and cost
- } **clean interface and good interfacial bonding**

# Why in-situ combustion synthesis?

□ In-situ model of **TiC/Mg composite** including Al + Ti + C reaction mechanism



- Contact with air is minimized
  - TiC formation in the Al
- : clean interfaces, wettability ↑

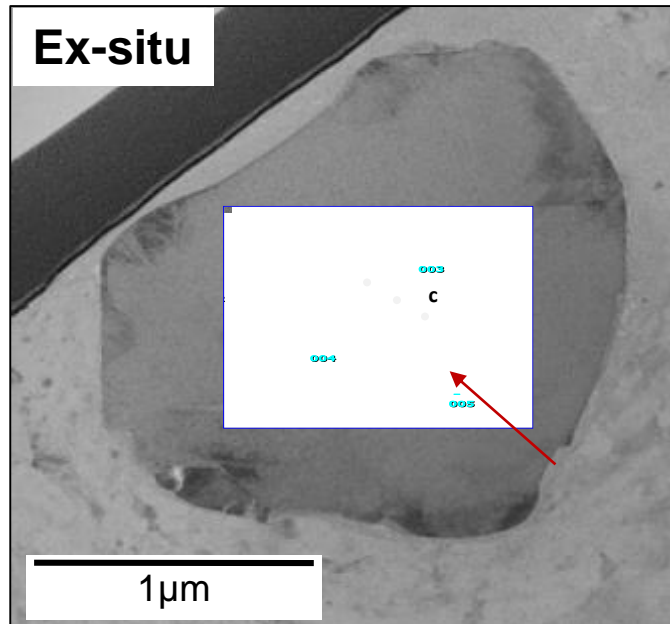


→ Experimentally define reaction mechanism & interfacial characteristics

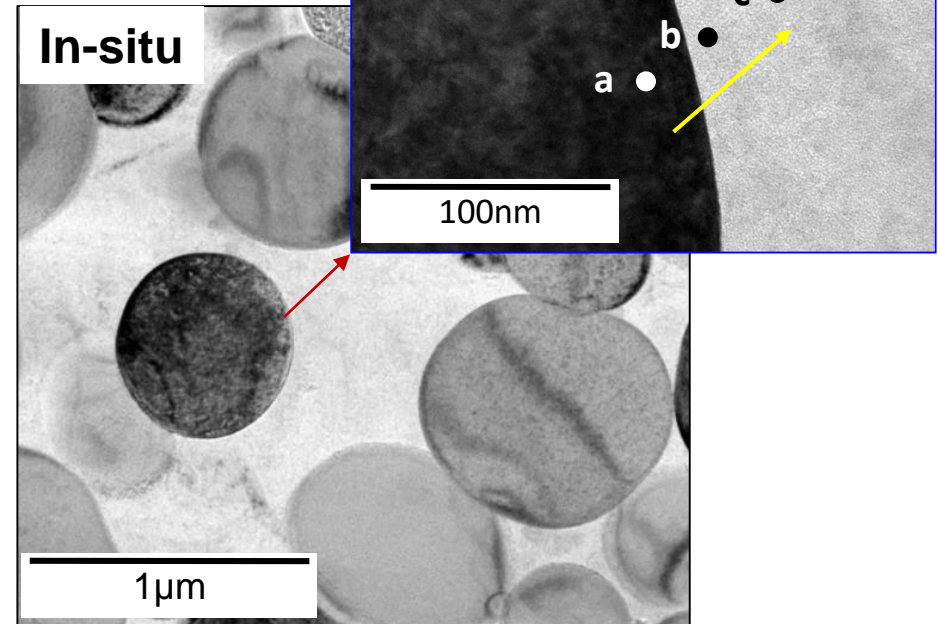


# Interfacial properties of TiC/Mg

## □ TiC morphology and EDS point analysis – TEM analysis



Point		a	b	c
Atomic %	O	0.55	6.5	2.56
	Al	0.01	-	0.09



Point		a	b	c
Atomic %	O	0.25	0.81	1.27
	Al	0.07	1.22	1.11

→ **Low oxygen contents & Al contents increased at the interface : Al layer on TiC**

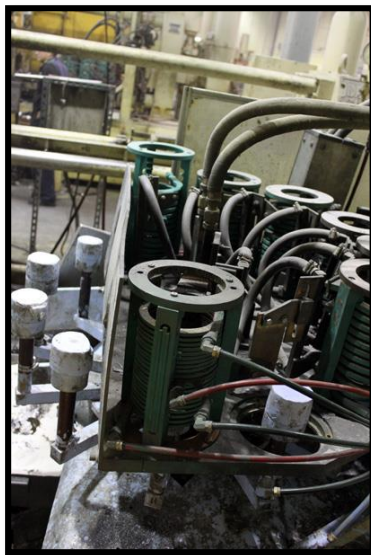
# Die-casting of TiC/Mg composite

## □ High pressure die casting – semi-solid die casting

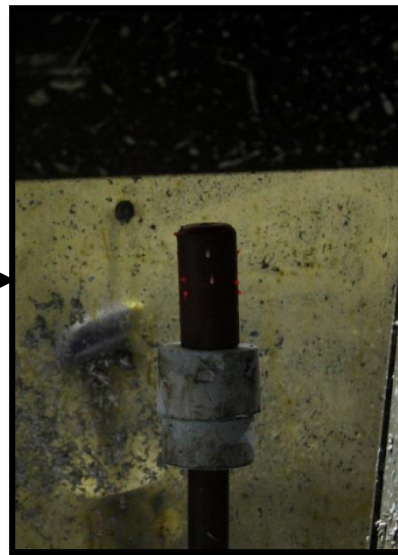
1. Casting has been the **dominant manufacturing process** for Mg components

→ About 98% of structural applications of Mg. [J. Magnesium and Alloys 1 (2013) 2-22]

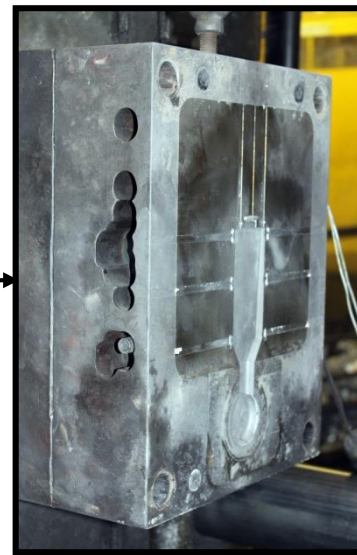
2. High pressure die casting (HPDC) is the **most common method of casting Mg alloys**



Induction coil



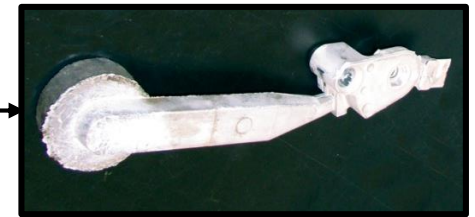
Reheating billet



Casting die



Wedge sample



Automotive part

- 400 US ton hydraulic manufacturing cell with 100 kW induction heating system were used.

# Overall mechanical properties

- Overall mechanical properties of HPDC parts compared to real automotive part

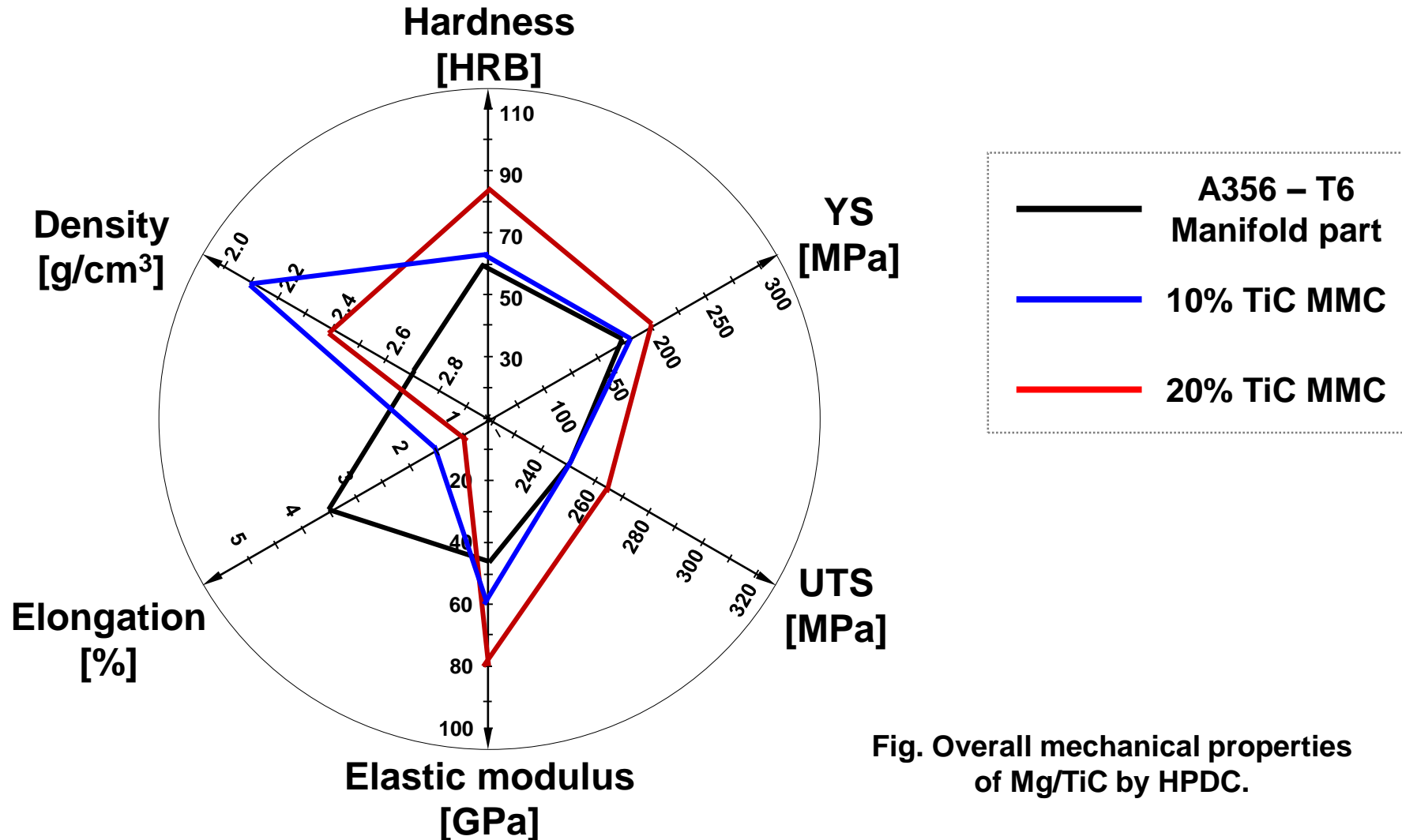


Fig. Overall mechanical properties of Mg/TiC by HPDC.

# **AI based composites**



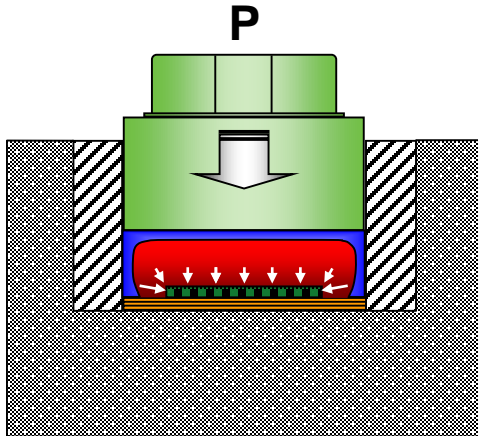
# Squeeze casting vs. Liquid pressing process

## □ Liquid pressing process : pressure infiltration casting

- Molten metal is infiltrated by the **hydrostatic force** to the reinforcement particles  
→ Uniform force yield uniform distribution / distribution of particles
- Lower pressure than squeeze casting process : large scale component

### Squeeze casting

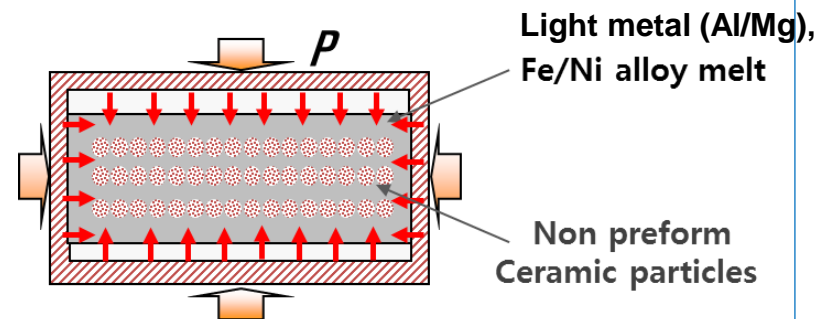
- **Semi-solid** state pressurization  
⇒ **High pressure** process (>45~60 MPa)
- Disadvantage on large composite



•  $\Phi 350$  component : over 4,000ton large press

### Liquid pressing process

- Isothermal hydrostatic principle ⇒ **Non-preform** / uniform distribution
- Pressurized metal melt  
⇒ **Low pressure process** (<10 MPa)
- Possible to produce large component



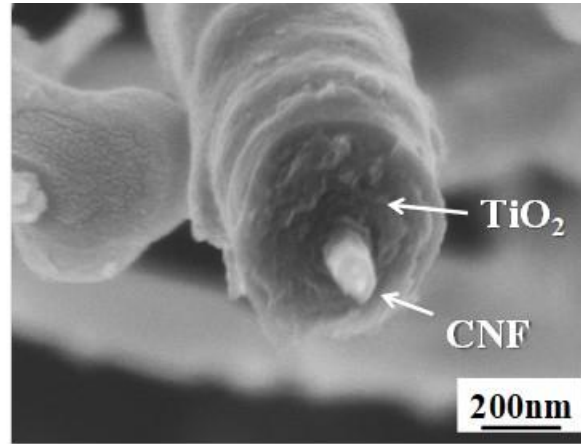
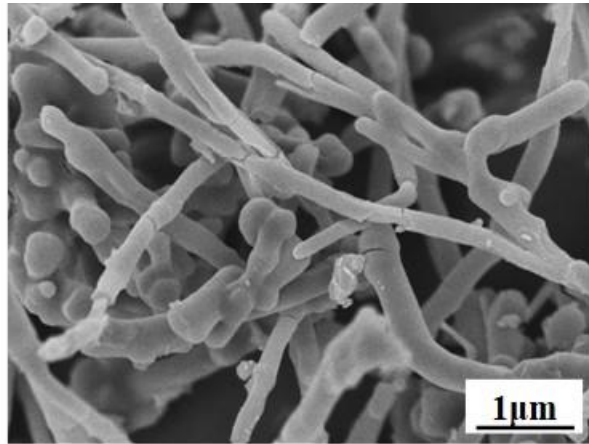
Isotropic Pressure

•  $\Phi 350$  component : less than 500ton press

# Nano-carbon reinforced Al composite

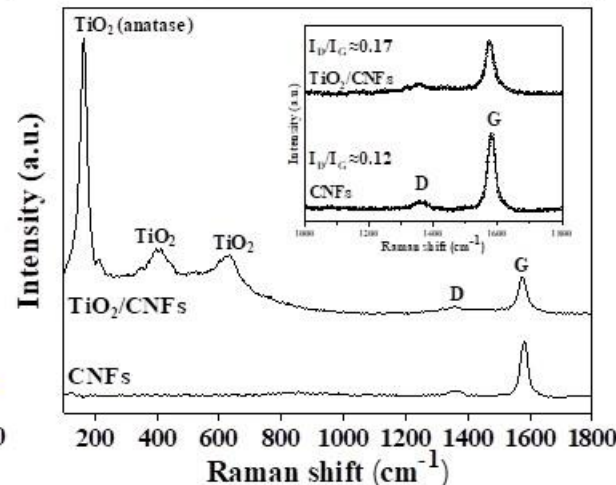
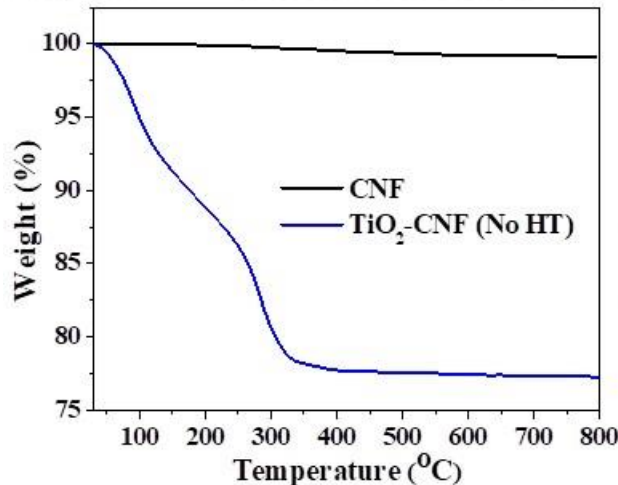
## ❑ Challenges in nano-carbon reinforced metal composites

- **Hard to incorporate** nano-carbon due to the density difference
- **Interfacial reaction** between the nano-carbon and the reactive metal matrix



## Approaches

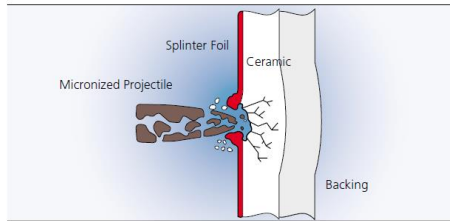
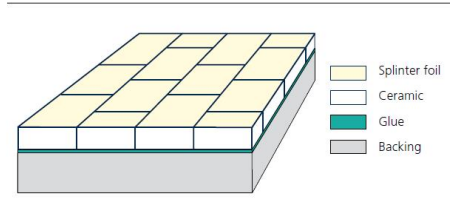
1. **CNFs coated by TiO<sub>2</sub>** by sol-gel to improve wettability and interrupt unwanted interfacial reaction → **maximize the load transfer** from the Al matrix to the CNFs via the TiO<sub>2</sub> coating layer
2. Molten Al infiltrated into reinforcement by liquid pressing process : **pressure infiltration casting**



# Al composites for armor application

[CeramTec – ETEC / Mater Sci Eng A 259 (1999) 155-161]

## □ Weight reduction in armored vehicle



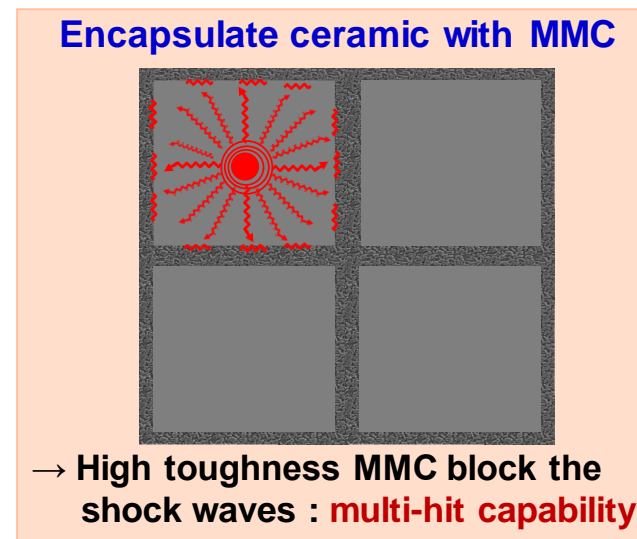
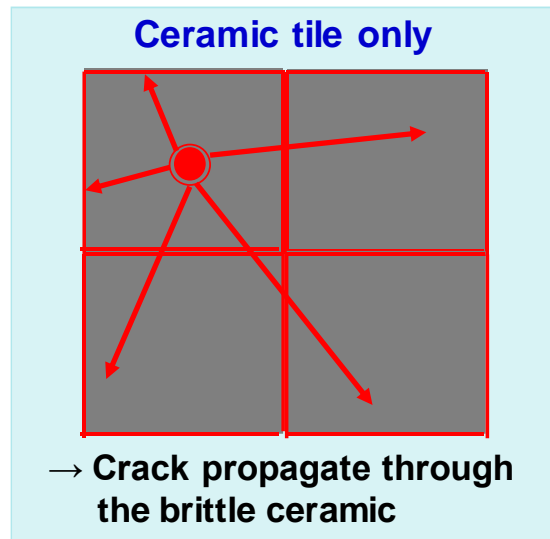
### Hard ceramic front :

blunt and to induce a destructive shock wave on to the projectile

### Soft metal backing :

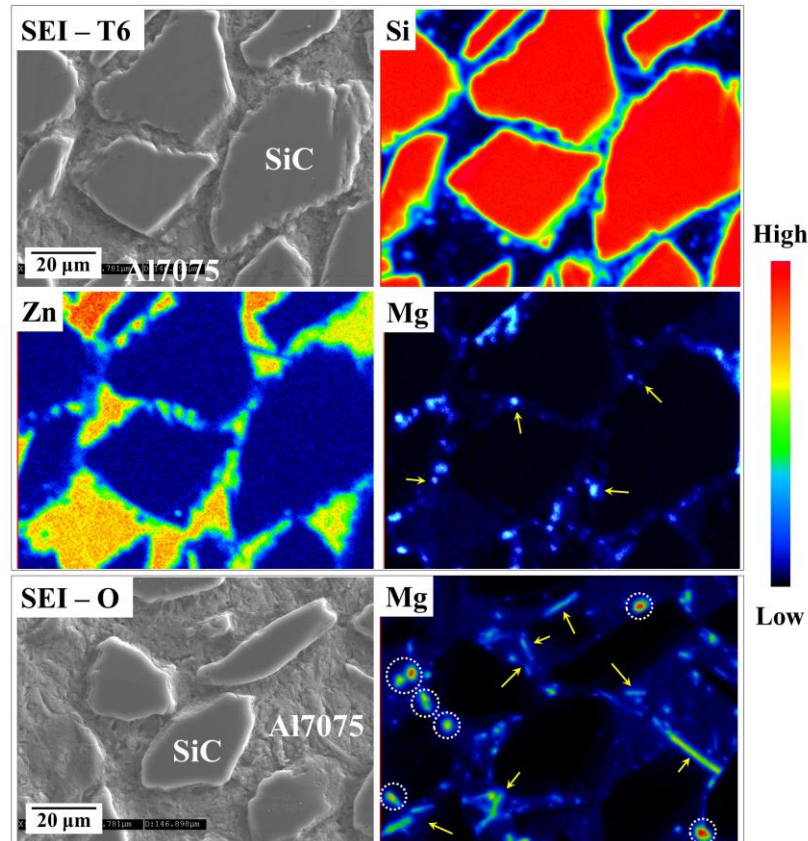
‘catcher’ for residual broken fragments in preventing target penetration

## □ New concept : encapsulate ceramic tile with MMC by pressure infiltration casting

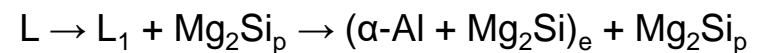
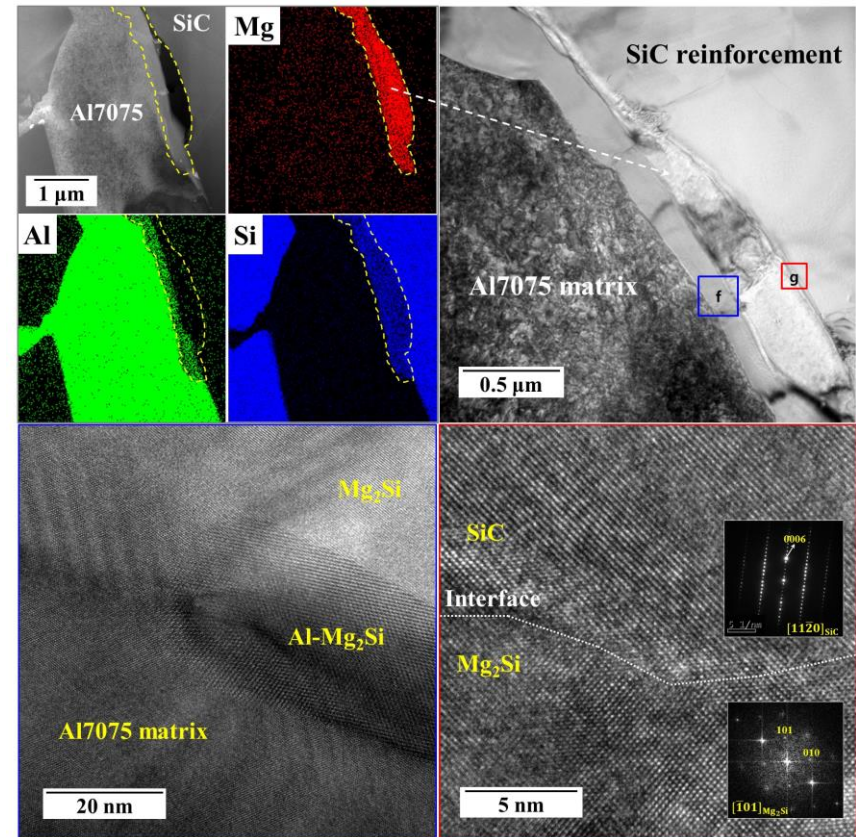


# Al composites for armor application

## □ Study of strengthening mechanism of SiC/Al7075 composite



Formation of a smaller and spherical Mg<sub>2</sub>Si phase in the T6 heat-treated composite

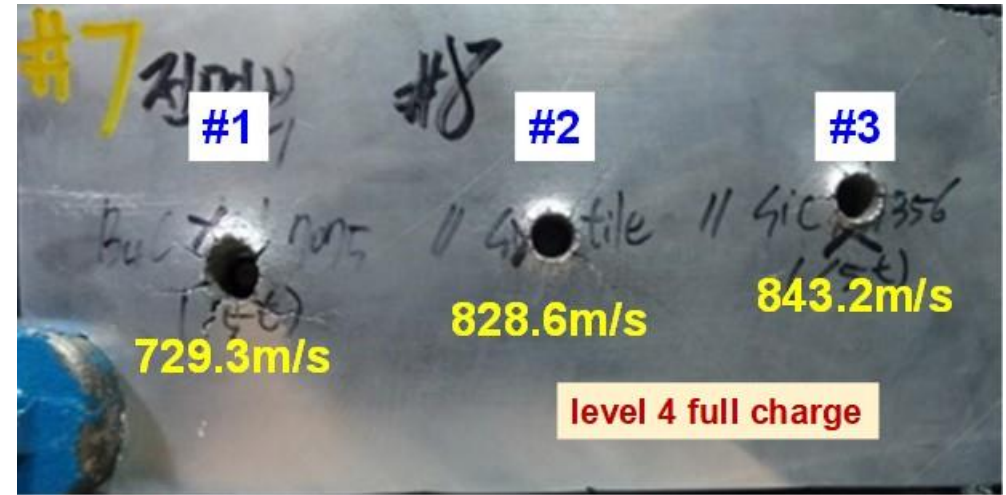
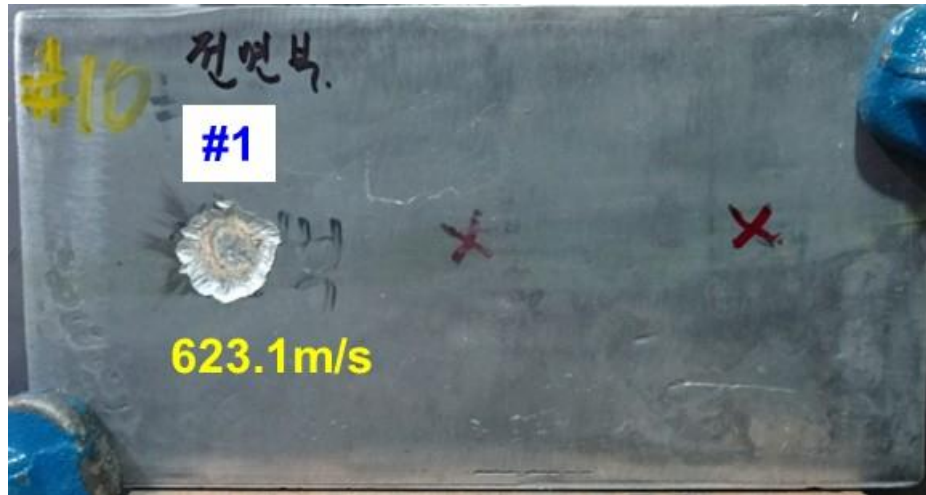


→ Suggest new strengthening mechanism of SiC/Al7075 composite!

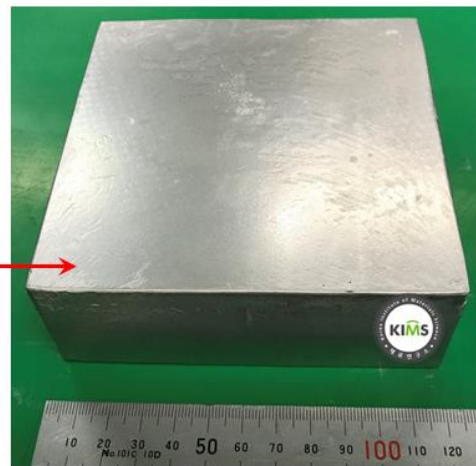


# Al composites for armor application

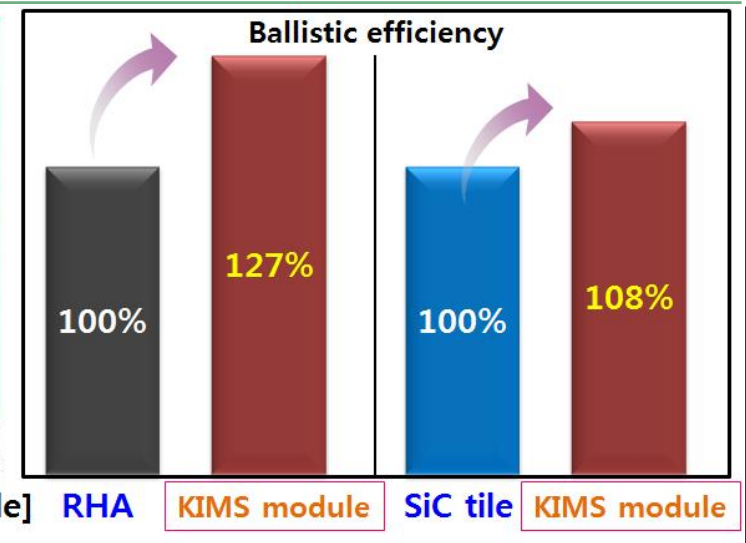
## □ Ballistic properties of armor module for AP projectile & 30SPG



[Ballistic module in tank]



[KIMS ballistic protection module]

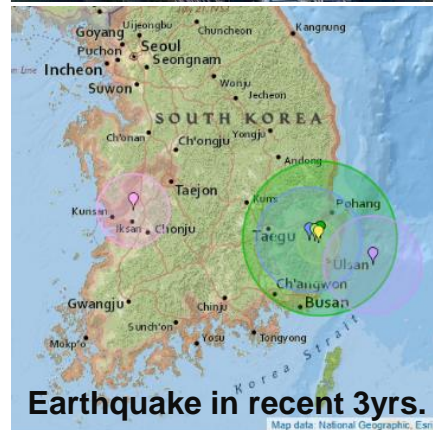


# Neutron absorbing Al composites

## □ Nuclear power plant in Korea & recent safety issues

In Operation	Under Construction	Planning
25Units (23,116MW)	5Units (7,000MW)	4Units (5,800MW)

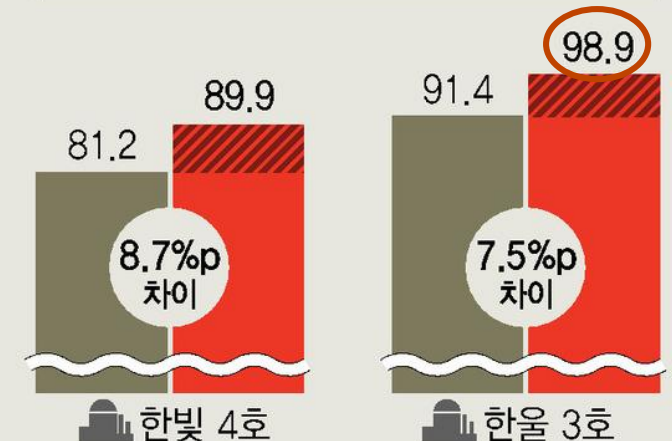
● In Operation  
● Under Operation



## 국내 경수로 원전 사용후핵연료 포화도

■ 한수원 발표 포화도:  
비연료물질 제외 저장량/비가용셀 포함 저장용량

■ 실제 포화도:  
비연료물질 포함 저장량/비가용셀을 뺀 저장용량

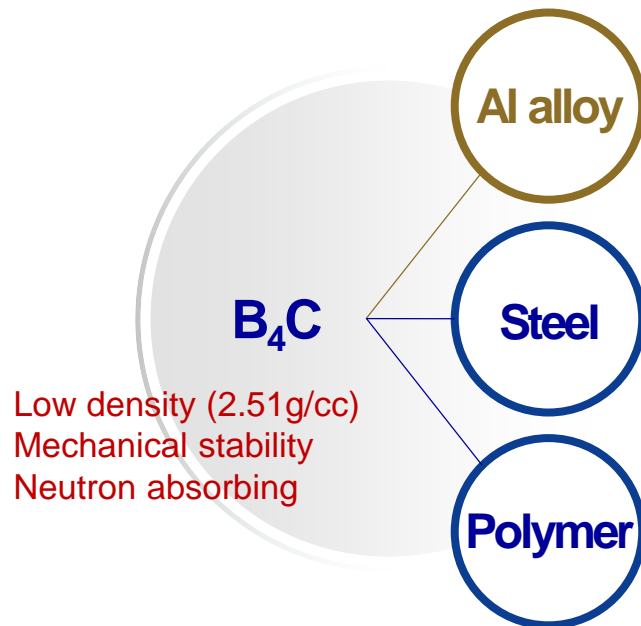


- Social safety issues due to the recent earthquake near nuclear power plant area
- Problems in spent fuel management (storage/transport)
- **Need to develop neutron absorbing material**

# Neutron absorbing Al composites

## Neutron absorbing capabilities of boron & various materials

Material	Neutron absorption cross section (barn)	Material	Neutron absorption cross section (barn)	Material	Neutron absorption cross section (barn)
Natural Boron	750	Aluminum	0.233	Nickel	4.43
<b>B-10</b> / B-11	3,850 / 0.005	Copper	3.79	H <sub>2</sub> O	0.66
Fe (Iron)	2.4	Silicone	0.52	D <sub>2</sub> O	0.003
Gd	44,000	Sm	6,500	Cd	2,400



## Challenges in neutron absorbing B<sub>4</sub>C/Al

- Complex process : powder metallurgy
- Difficult to uniformly disperse B<sub>4</sub>C particle in a matrix
- Difficult to extrude due to deformation resistance
- Easy to crack by rolling process
- Development of commercial neutron absorbing materials are not tried yet

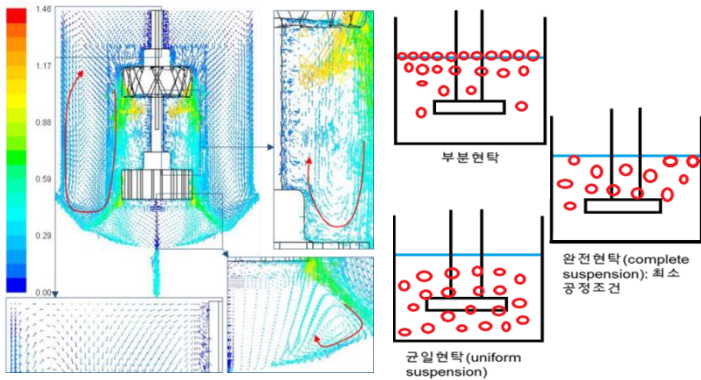


# Neutron absorbing Al composites

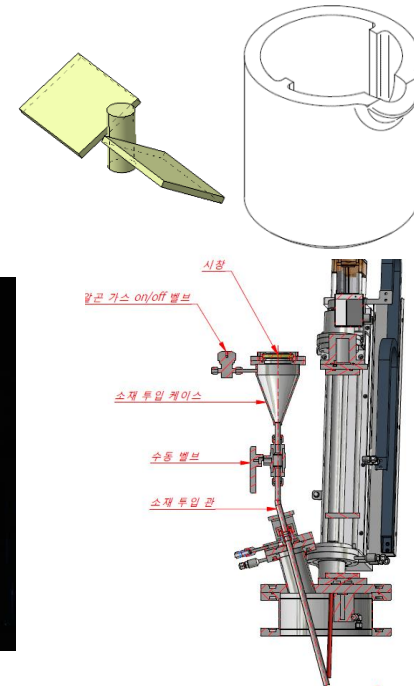
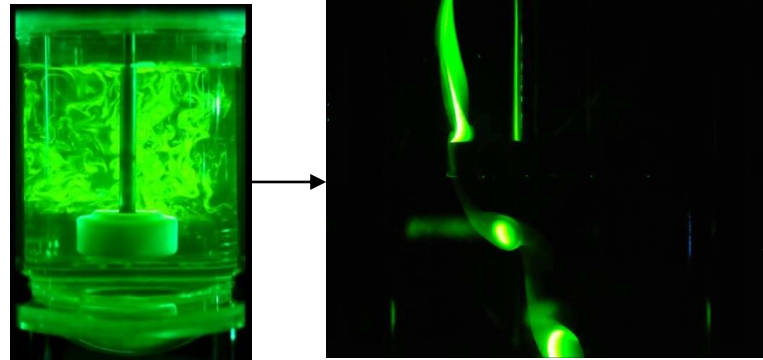
## Approaches

- Optimize manufacturing of composite : **stir casting process**
- Design of mold, impeller, process window based on the **flow analysis**

### Turbulent flow field analysis



### Flow visualization



### Stirring



### Reinforcement incorporation



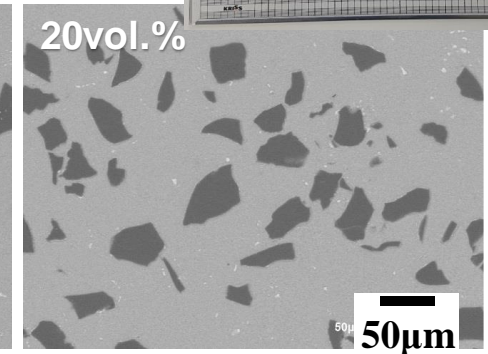
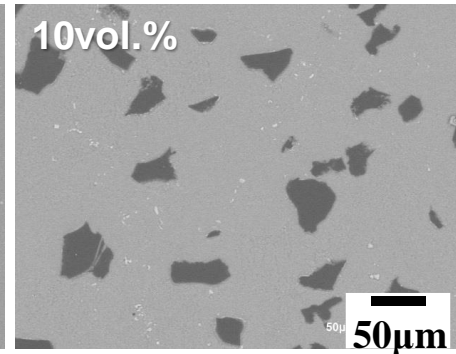
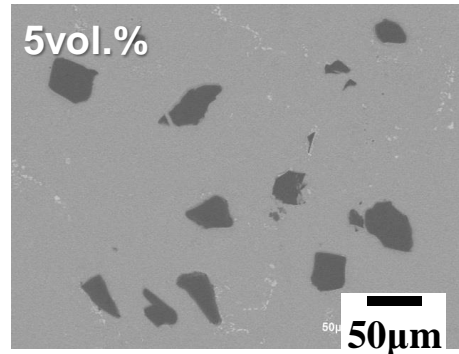
### Casting



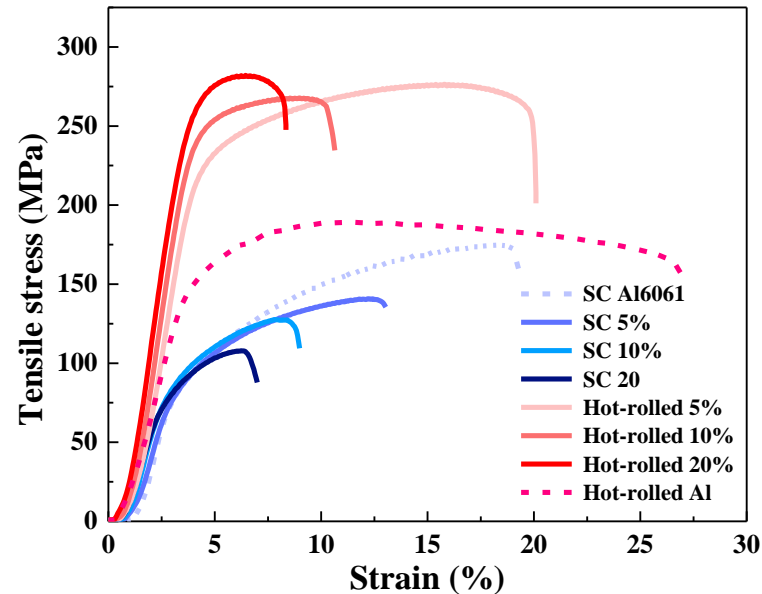


# Neutron absorbing Al composites

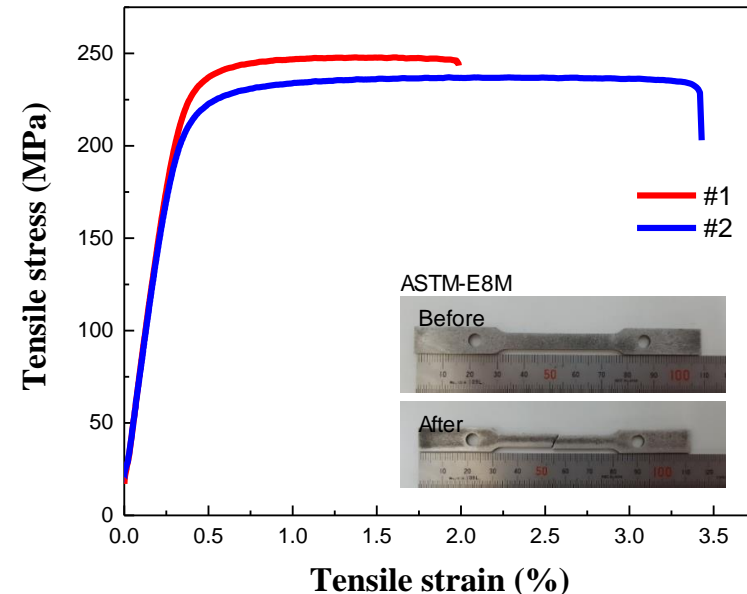
## Hot rolling of stir-cast composite



Tensile tests before and after rolling



0.2% offset high temp. tensile test (@200°C)



# Neutron absorbing Al composites

## Neutron shielding rate measurement

- Korea Research Institute of Standards and Science

- P : transmission rate

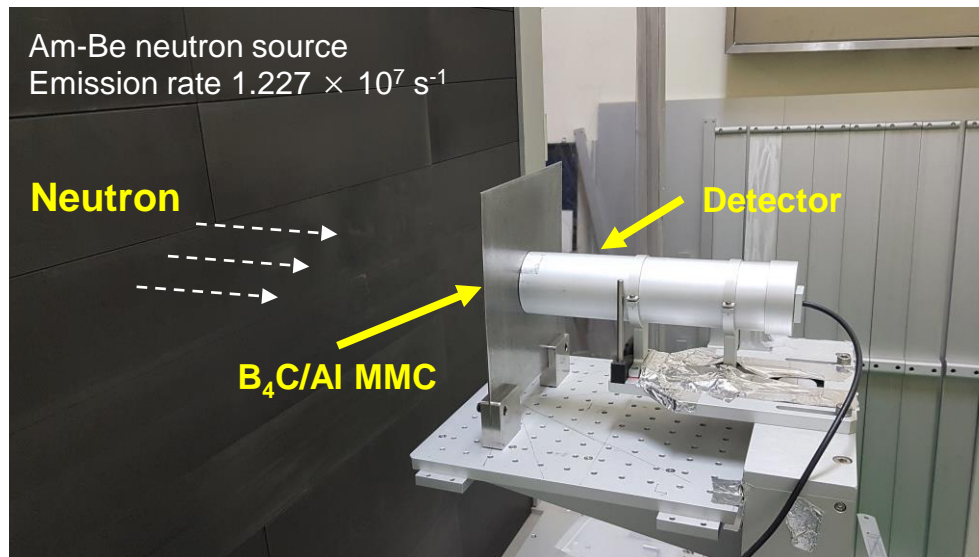
$u(P)$  : uncertainty of measurement

Absorption capacity =  $(1 - P) \times 100$

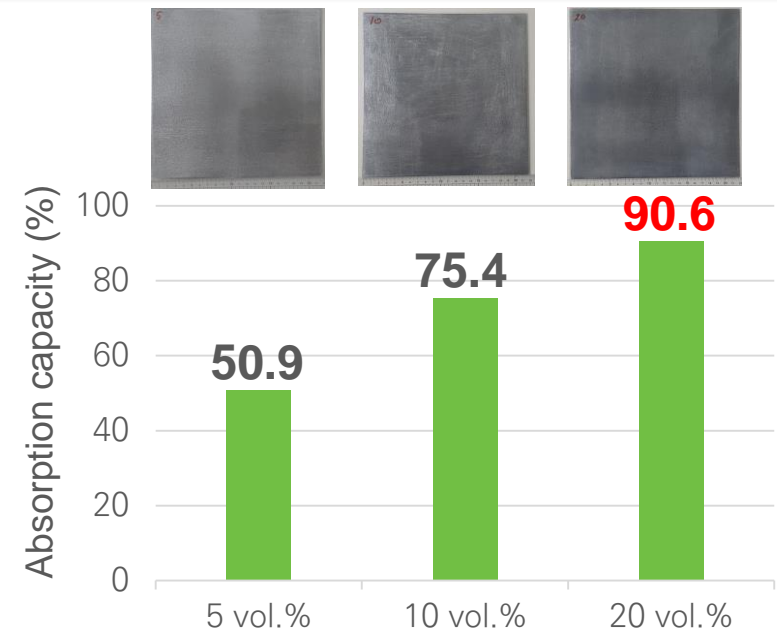
- 20 vol.% B<sub>4</sub>C/Al6061 : 90.6% neutron shield

\* Metamic neutron shielding rate: 93.07% (@t 1.58mm)

Transmission rate		
B <sub>4</sub> C-Al	$P$	$u(P)$
5 vol.%	0.491	0.004
10 vol.%	0.246	0.002
20 vol.%	0.094	0.001



Neutron shielding rate measurement tester (KRIS)

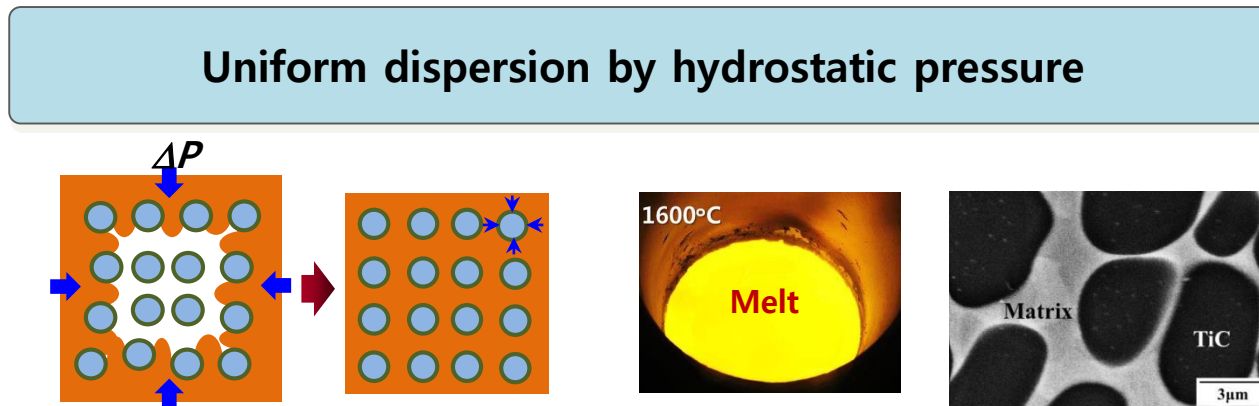


# **Steel based composites**

# What is Liquid Pressing Infiltration ?

## ◉ Liquid Pressing Infiltration (LPI) process

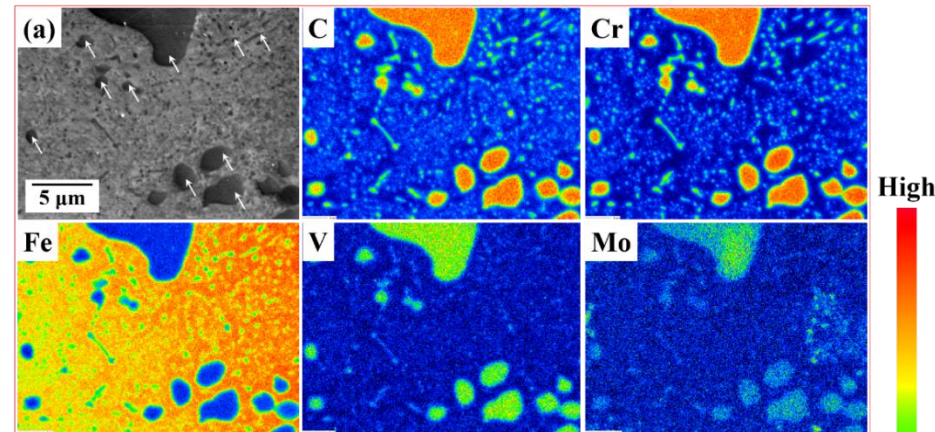
- Infiltrate **molten metal** into TiC preform using **hydrostatic pressure**,
  - which allows **uniform pressure distribution** on reinforcements
  - leading to **uniform dispersion** of TiC particles in steel matrix



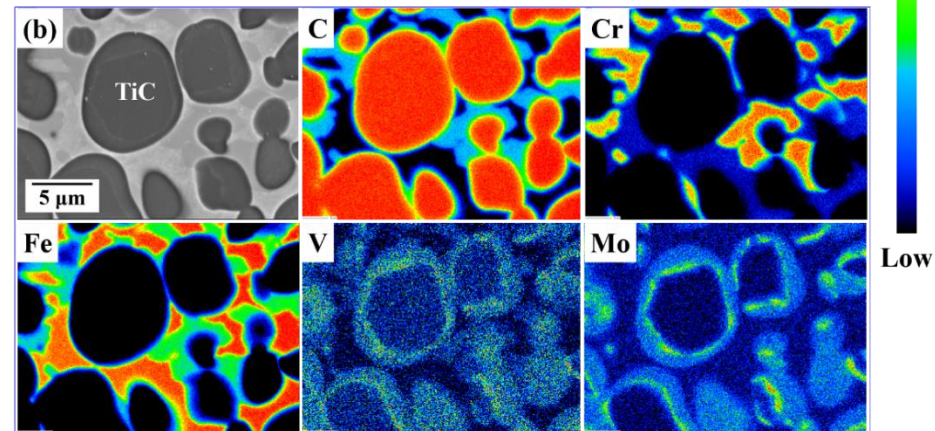
- The key process parameters are
  - i) **Pressure**, ii) **Temperature**, and iii) **Time**
- In order to successfully fabricate steel composites, it is necessary to precisely control those parameters

# Microstructure of TiC/SKD11 - EPMA

SKD11 matrix



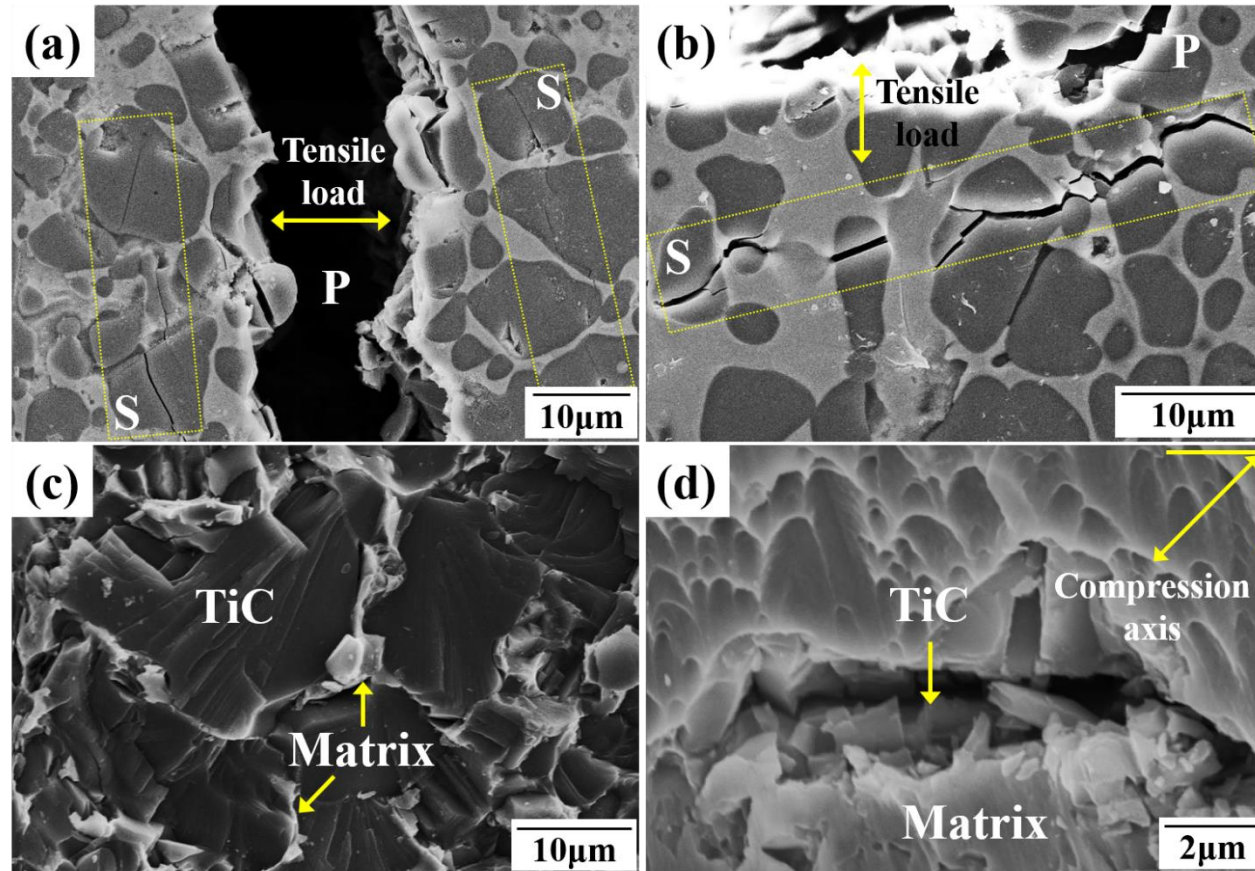
TiC/SKD11 composite



- Carbides :  $\text{M}_7\text{C}_3$ ,  $\text{M}_{23}\text{C}_6$  type carbide
- TiC 입자의 partial dissolution  $\rightarrow$  matrix의 V, Mo 원소가 TiC 입자로 확산  $\rightarrow$  (Ti, Mo, V)C 생성
- 강화재 입자의 dissolution  $\rightarrow$  interfacial energy 감소  $\rightarrow$  기지-강화재간 젖음성 증가  
 $\rightarrow$  계면결합력 증가  $\rightarrow$  기계적 특성 증가



# Fracture morphologies



- TiC fracture was observed in the fractured surface after tensile test.
- effective load transfer at the interface → good interfacial bonding



# Mechanical properties - Nano Indentation

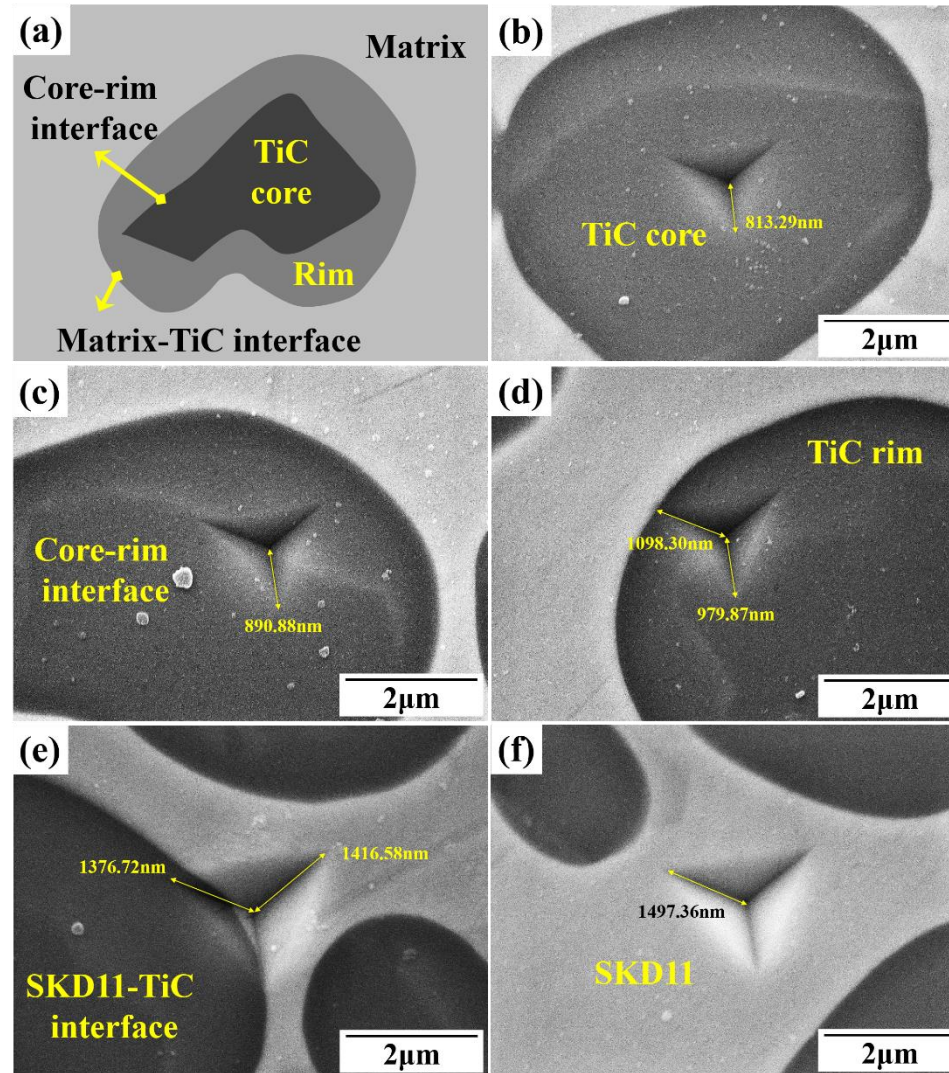
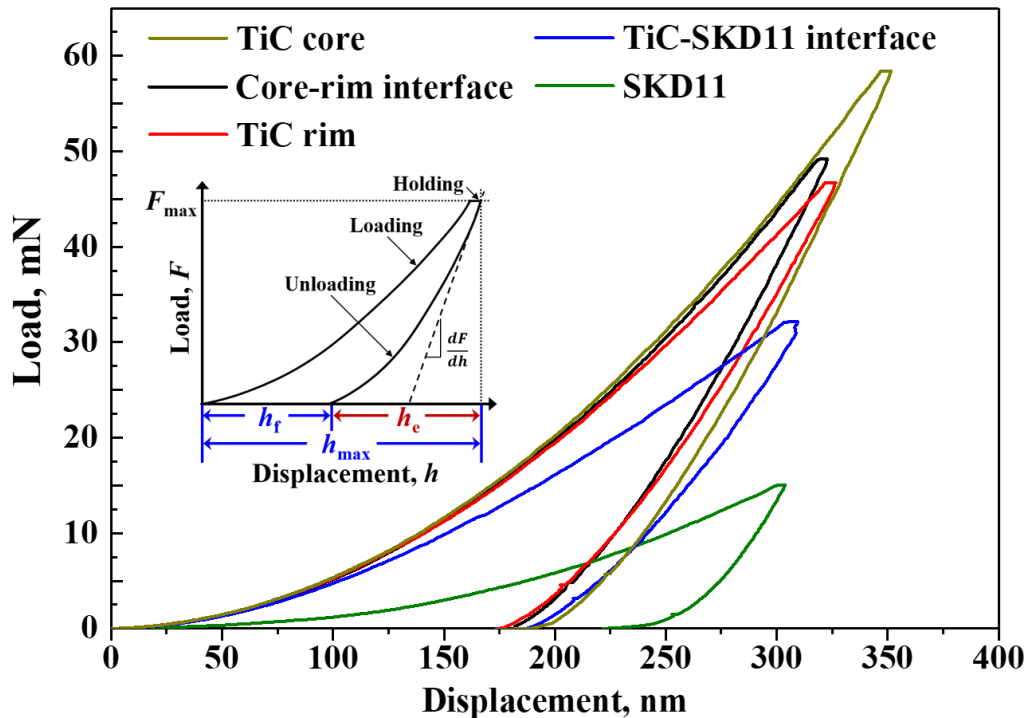
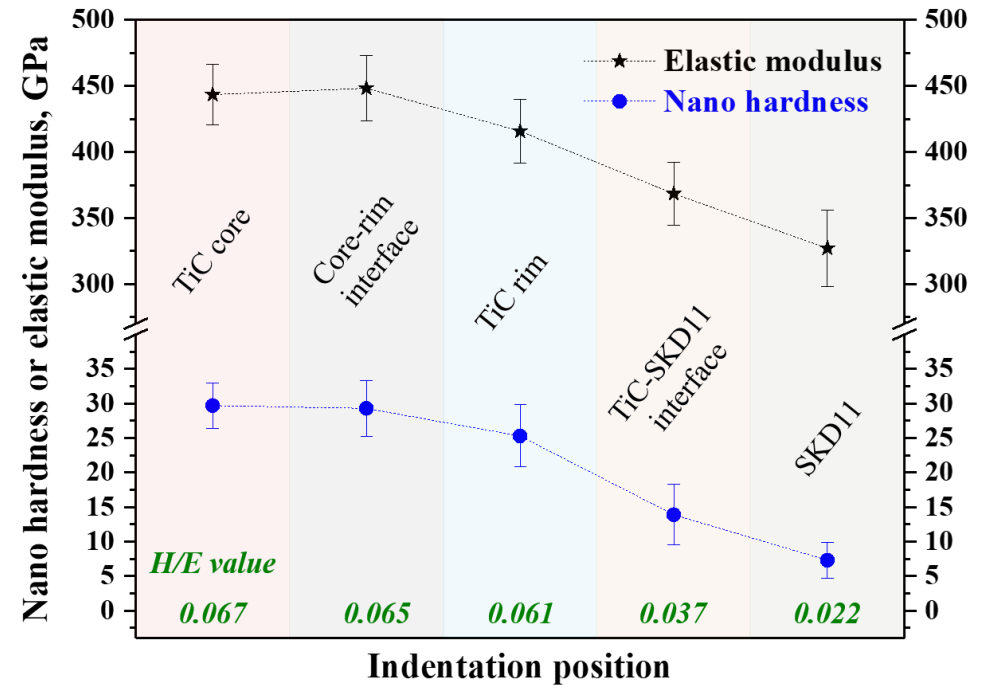


Fig. (a) Schematics and detailed microstructure of impression after nano-indentation on (b) TiC core; (c) TiC core-rim interface; (d) TiC rim; (e) TiC/SKD11 matrix interface; and (f) matrix alloy.

# Mechanical properties - Nano Indentation



- Indentation depth : 300 nm
- Elastic recovery : 45.9, 44.7, 46.3, 41.8, 27.2% of the maximum penetration depth



elastic recovery of indentation,  $h_e$ ,  

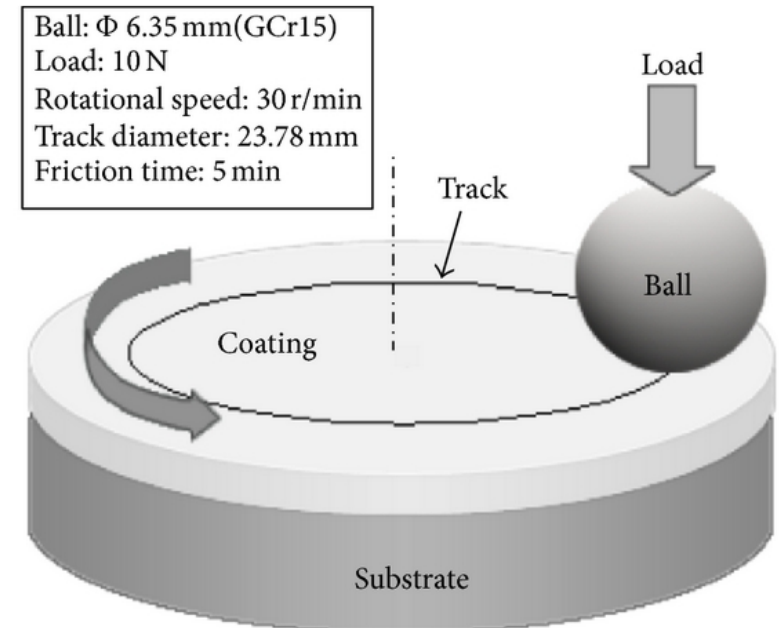
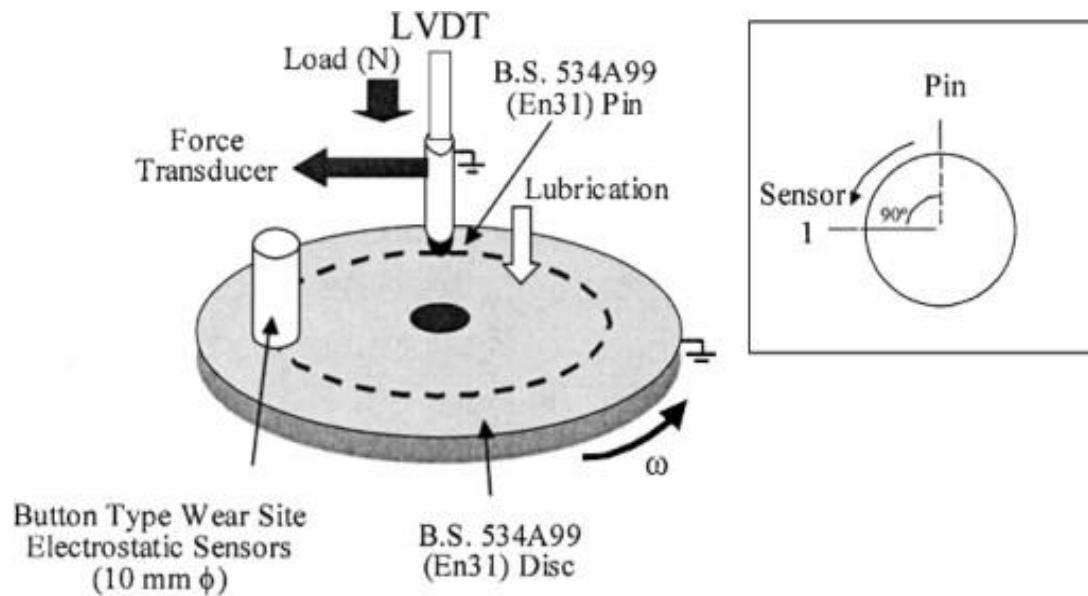
$$h_e = h_{max} - h_f$$

$h_{max}$  : maximum penetration depth  
 $h_f$  : residual penetration depth

# Wear

## □ Evaluation of wear properties and wear mechanism of high-durable convergence materials for bearings

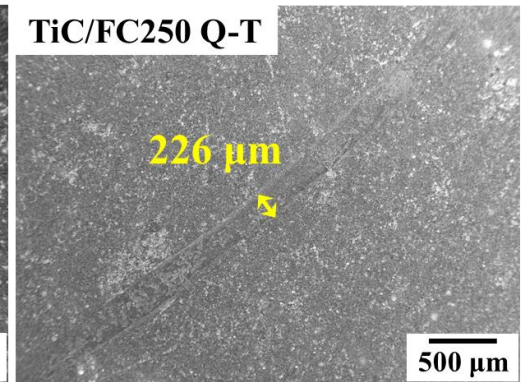
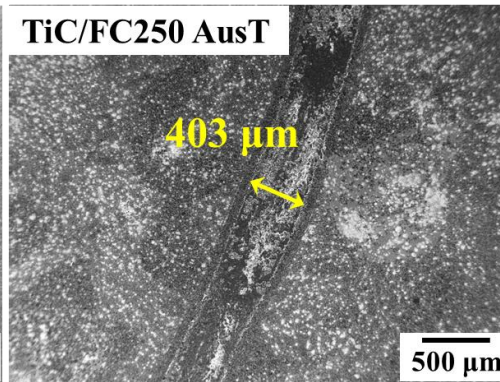
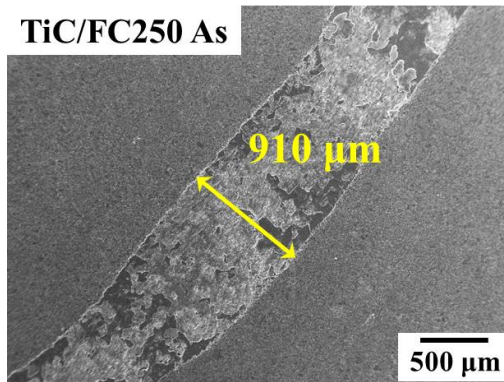
- Metal matrix composites, cast iron
- Pin-on-disk, ball-on-disk test, 3 ball test
- High-temperature wear
- Wear mechanism



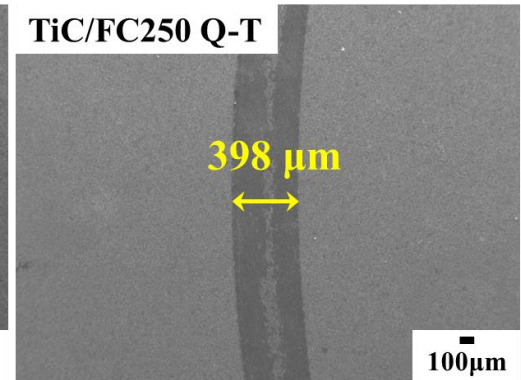
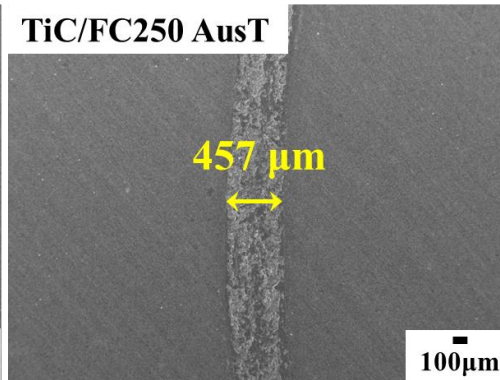
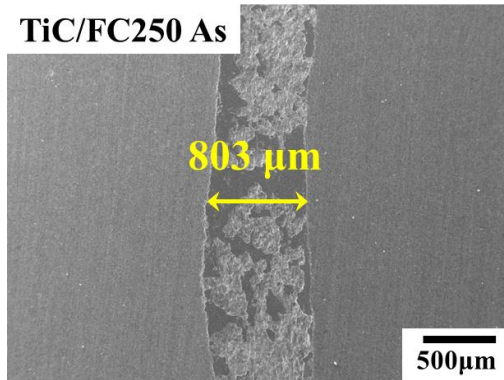


# MMCs wear mechanism

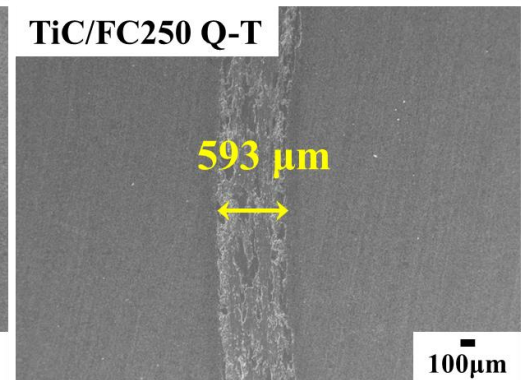
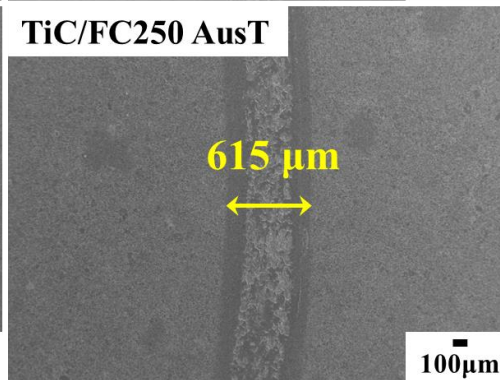
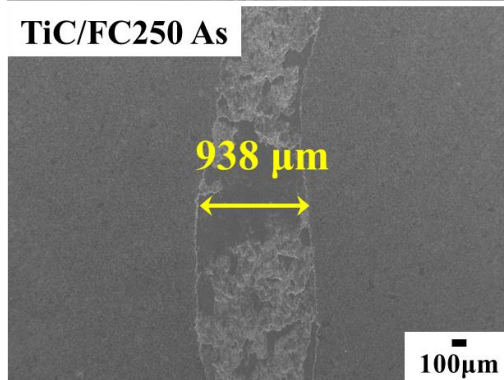
R.T.



50°C



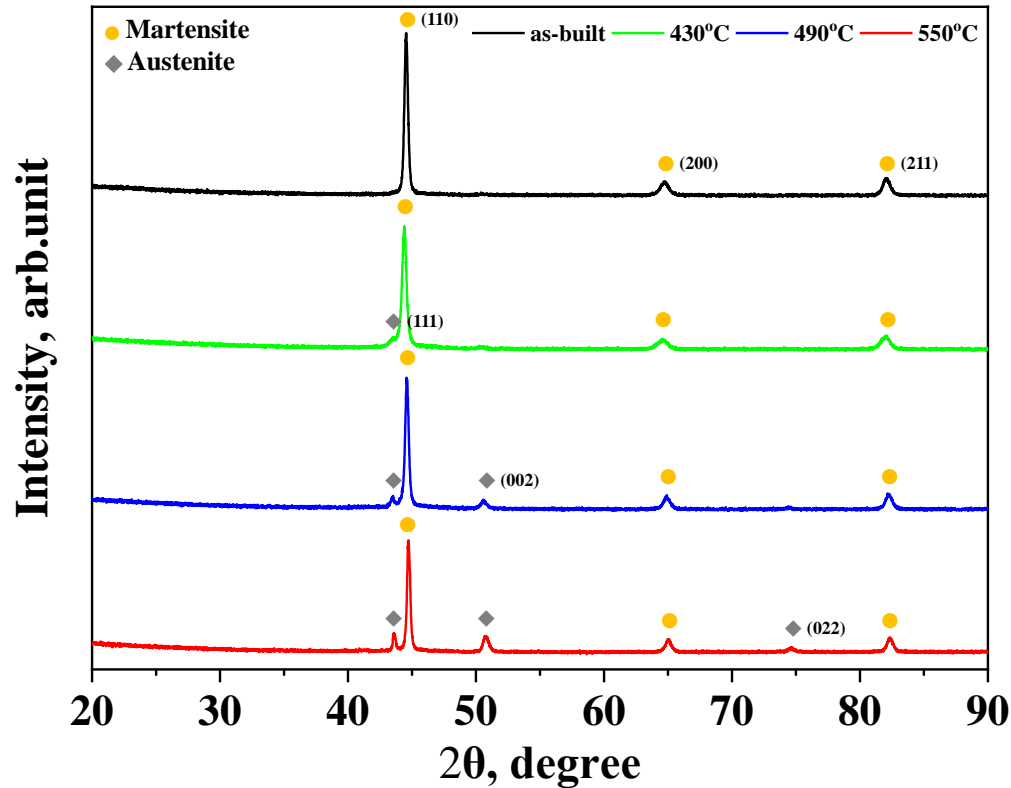
100°C



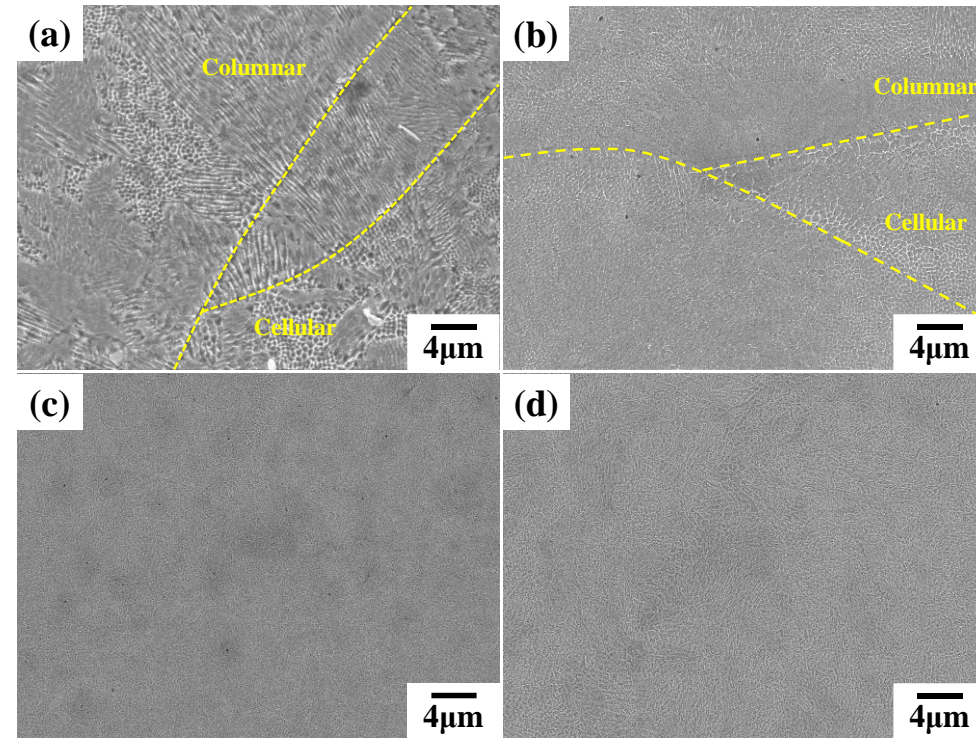
# **Additive manufacturing**



# 18Ni-300 maraging steel

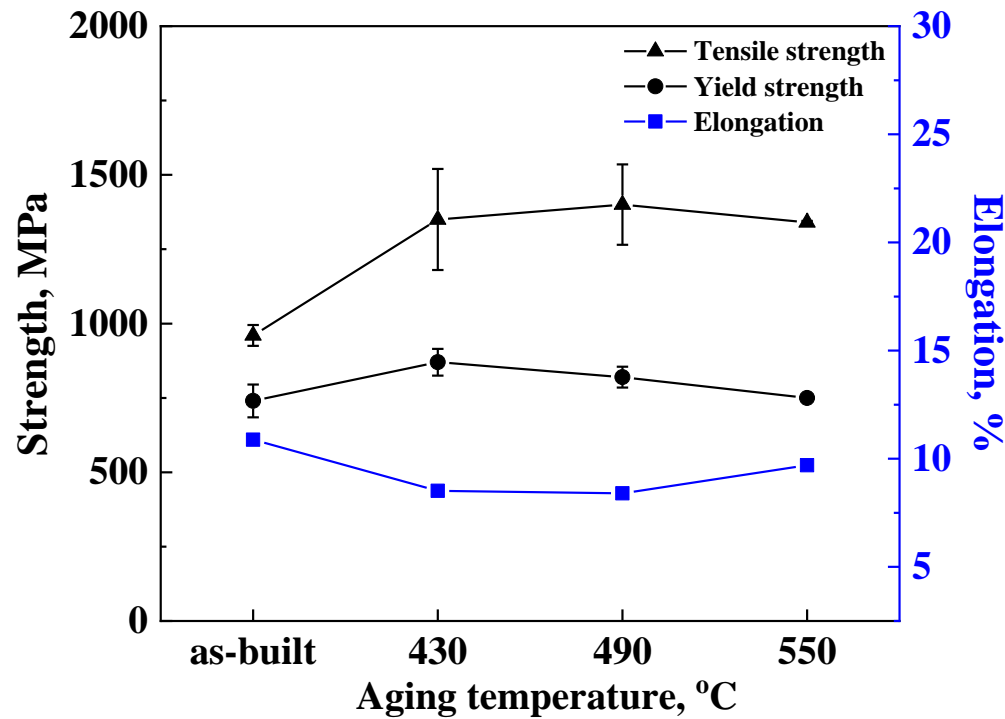


XRD pattern of PBFe 18Ni-300 maraging steel with varying aging heat treatments.

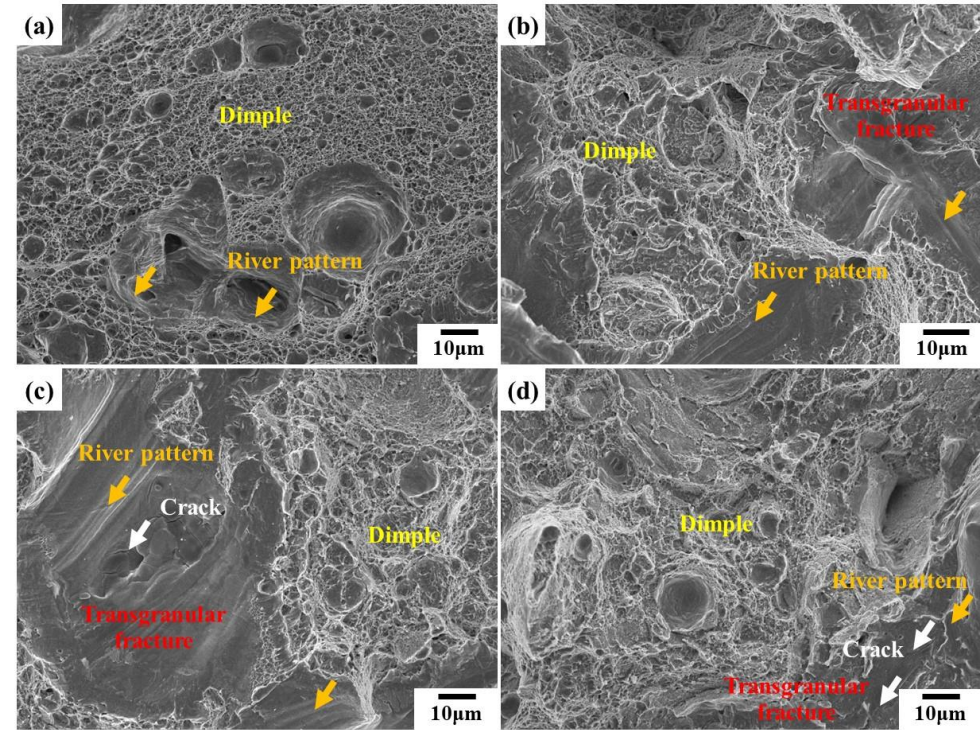


Microstructure of 18Ni-300 maraging steel with different annealing heat treatment temperature of (a) as-built, (b) 430 °C, (c) 490 °C, and (d) 550 °C.

# 18Ni-300 maraging steel



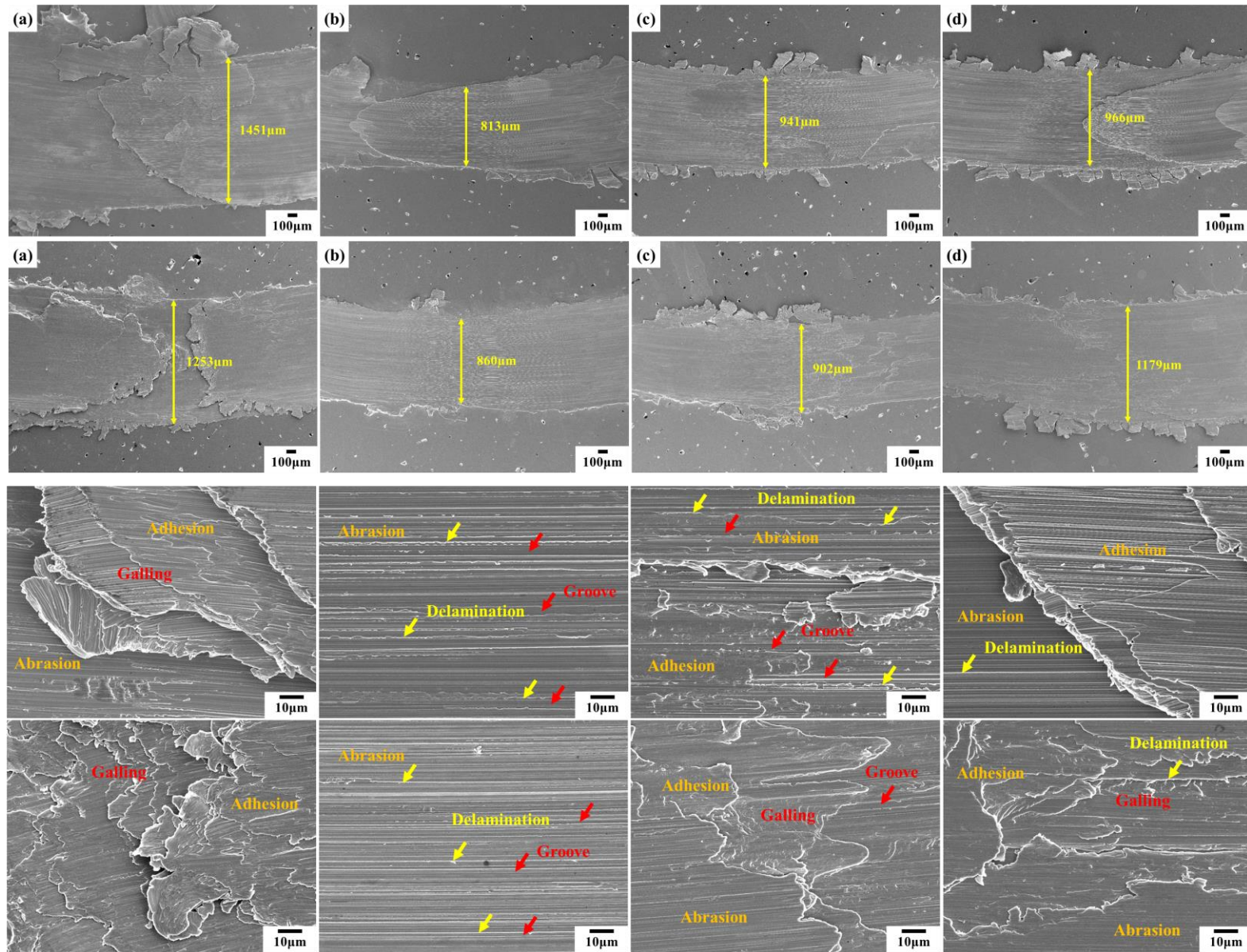
Tensile strength, yield strength, and elongation with variations at different aging temperatures.



Tensile fracture surface SEM images with different aging temperature of (a) as-built, (b) 430 °C, (c) 490 °C, and (d) 550 °C

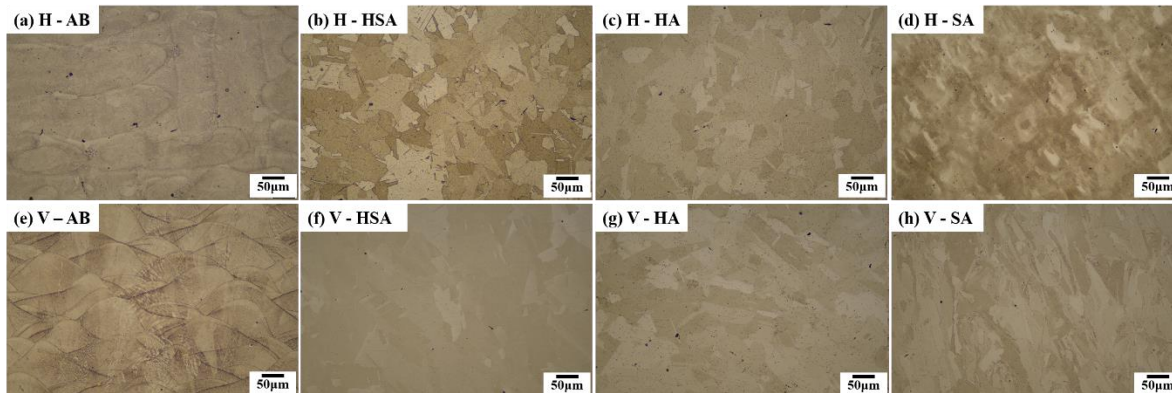
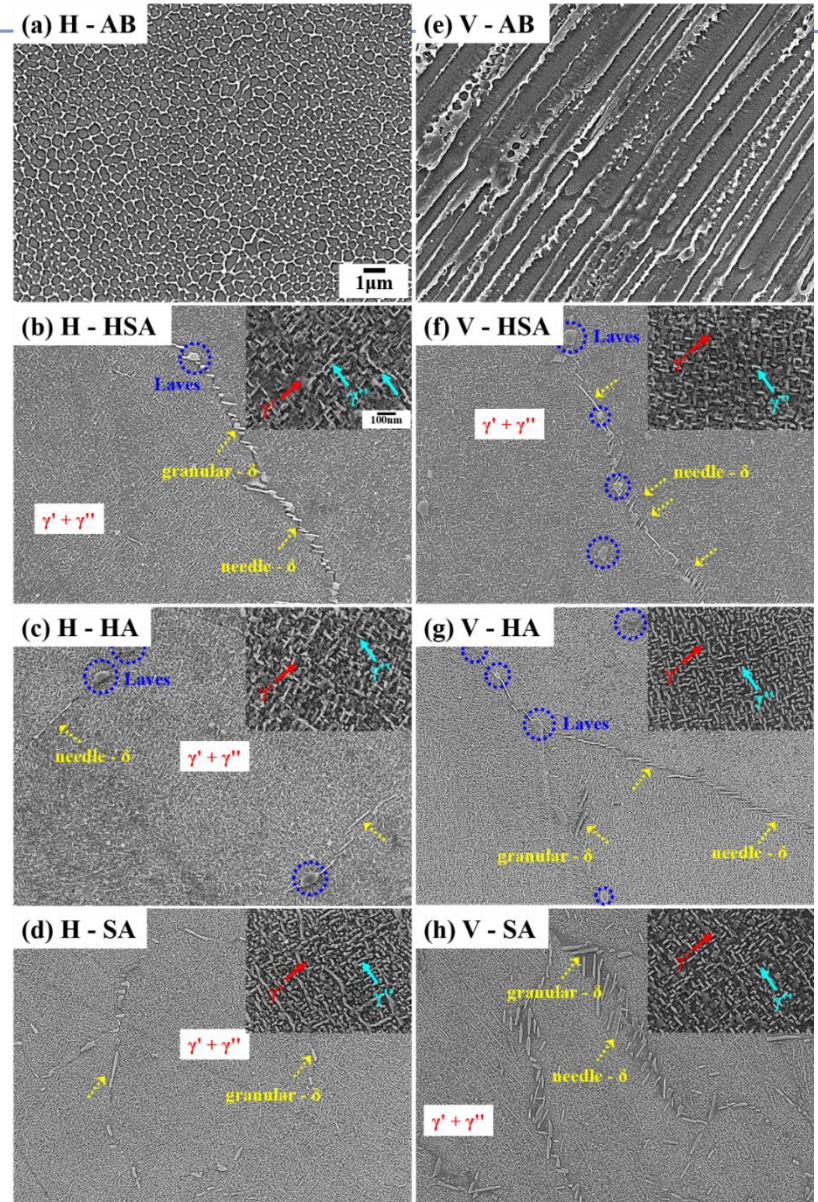
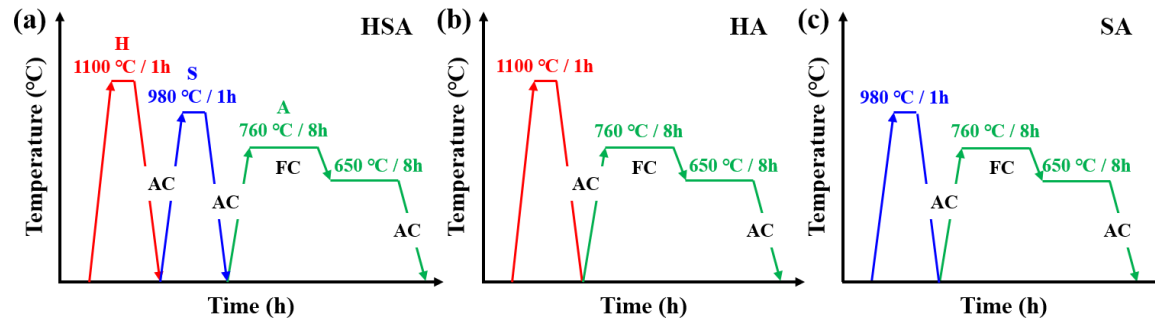


# 18Ni-300 maraging steel

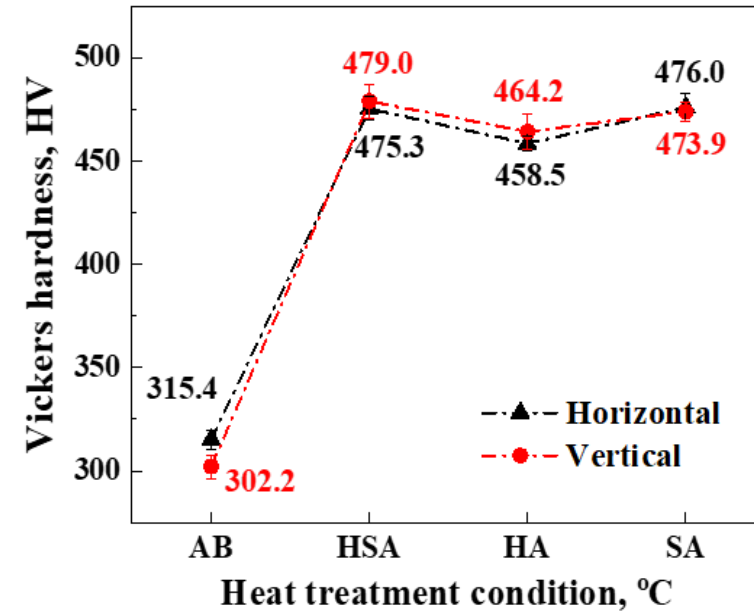
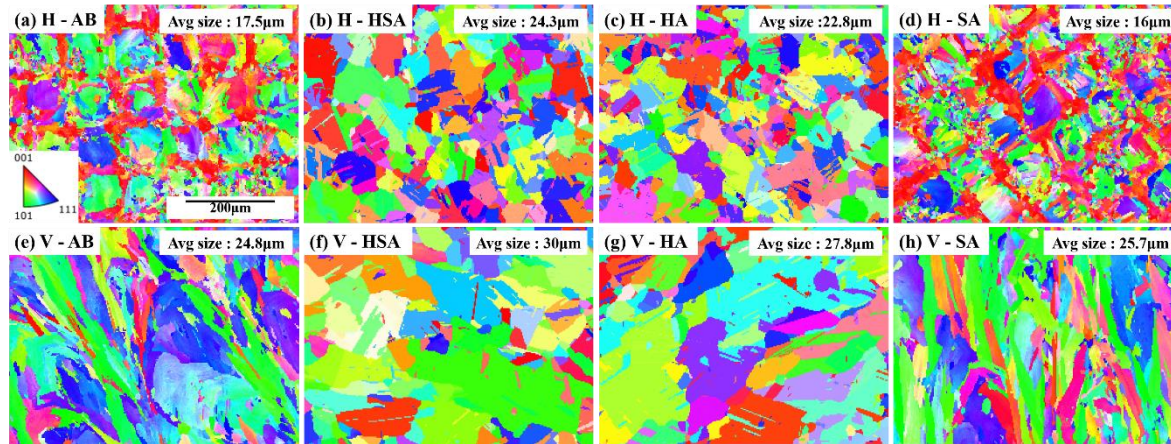




# Inconel 718

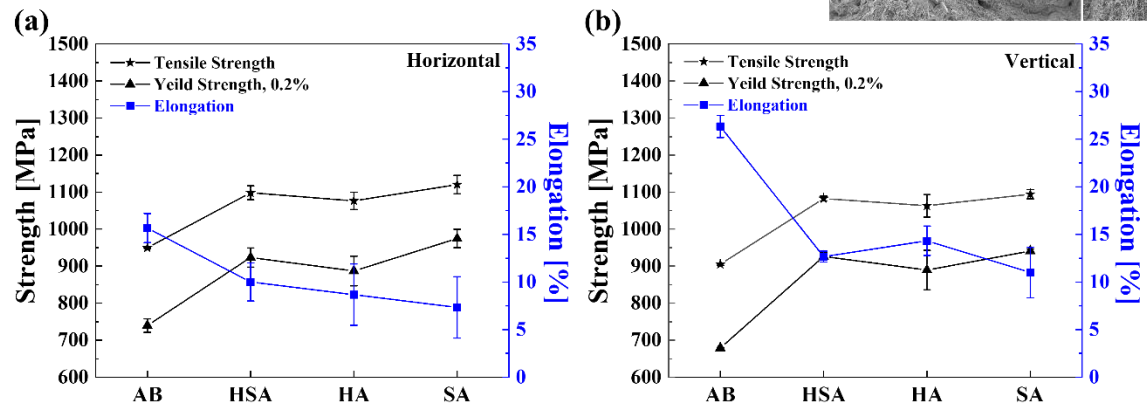
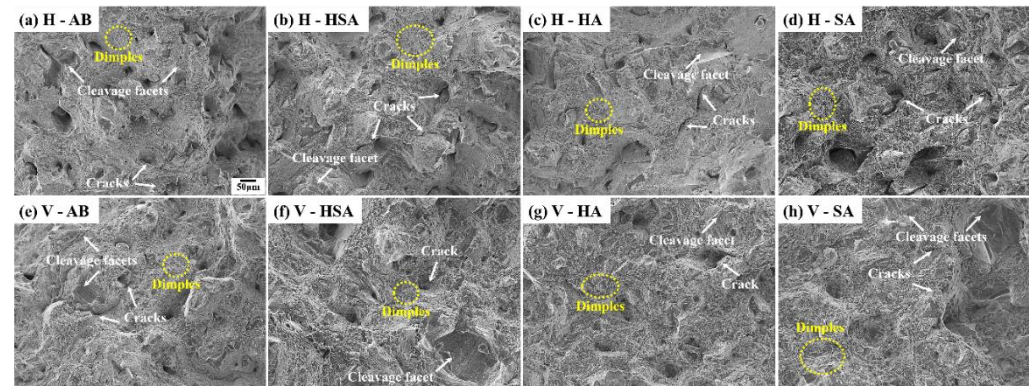
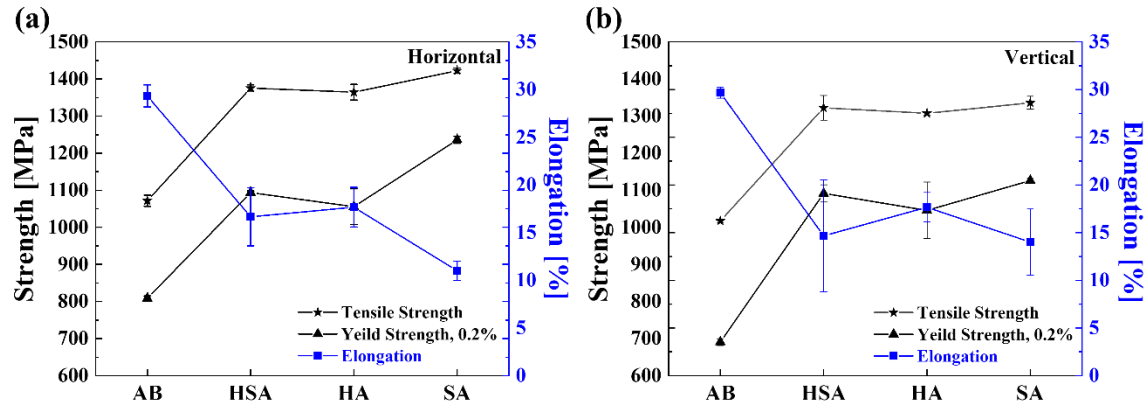


# Inconel 718





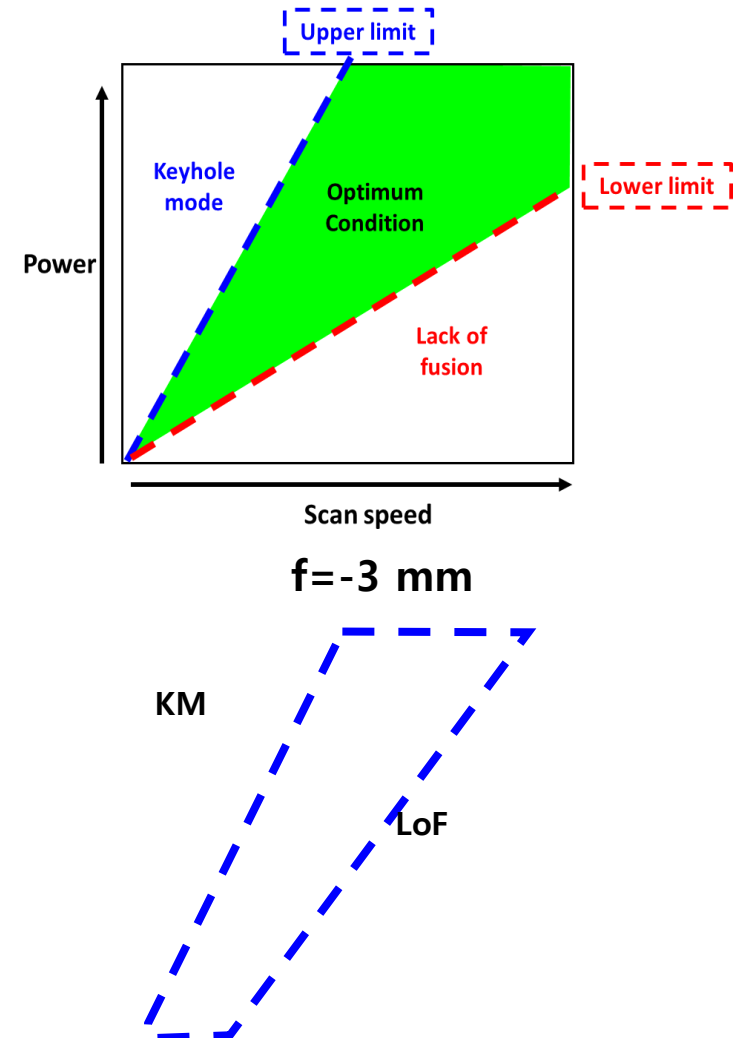
# Inconel 718



# Lab. instrument

## ☐ Metal 3D printer

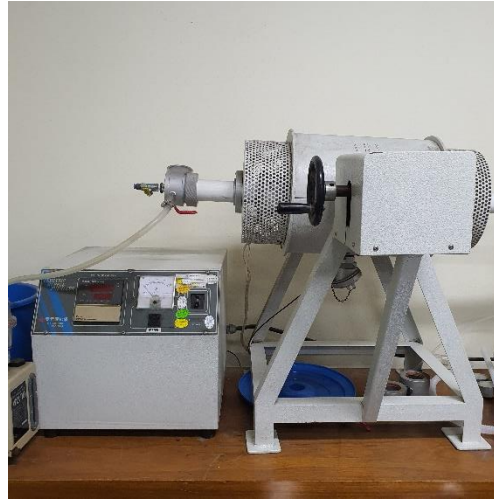
- SLM machine: GE Additive Cusing M1 (Fiber laser 400W)
- Stainless steel 316L, Inconel718
- Build plate size: 245 x 245 x 245 mm



# Lab. instrument



**Charpy impact tester**



**Tube furnace**



**Rolling machine**



**Metallography preparation**



**H.T. furnace**



**Optical microscopy**



# Lab. instrument



**Salt bath furnace**



**Oil Bath**



**Creep tester**



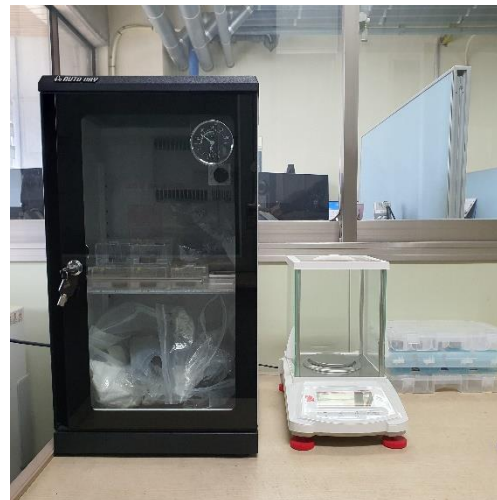
**Wear tester**



**Salt spray corrosion test**



**Fume hood**



**Desiccator & micro balance**

# Thank you!

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