SEOUL NATIONAL UNIVERSITY

Status of Magnesium Research & Development in Korea

Kwang Seon Shin

Professor and Director

Magnesium Technology Innovation Center

School of Materials Science and Engineering

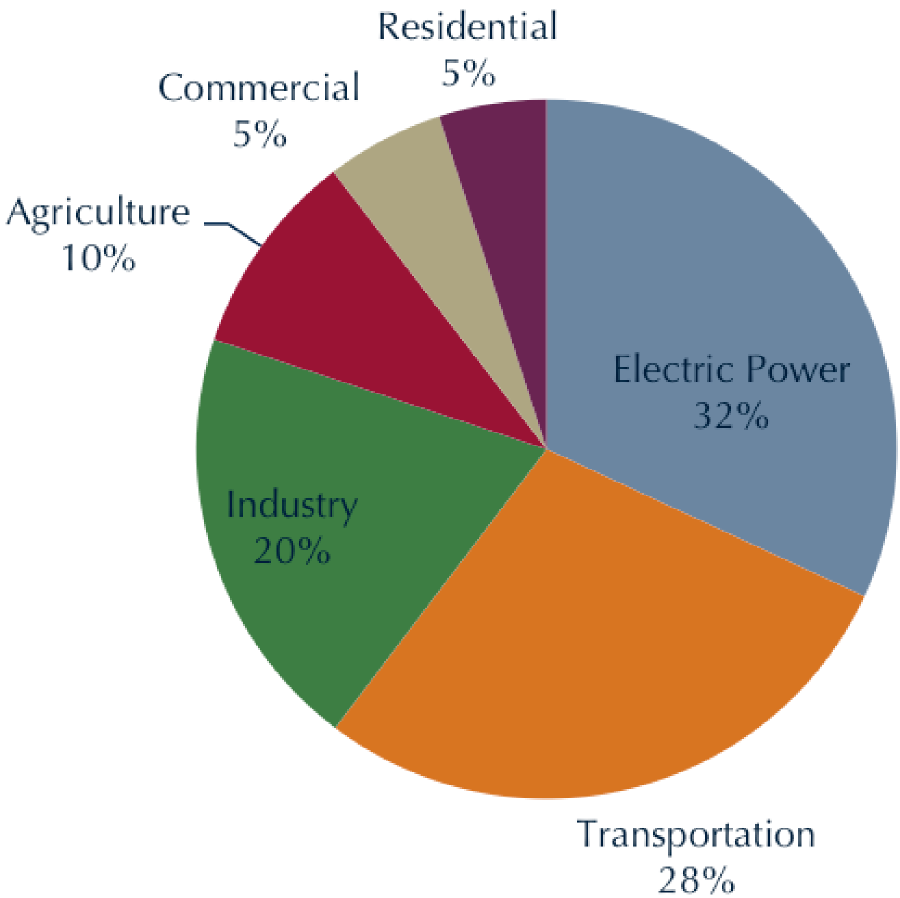
Seoul National University, Seoul 08826, Korea

Outline

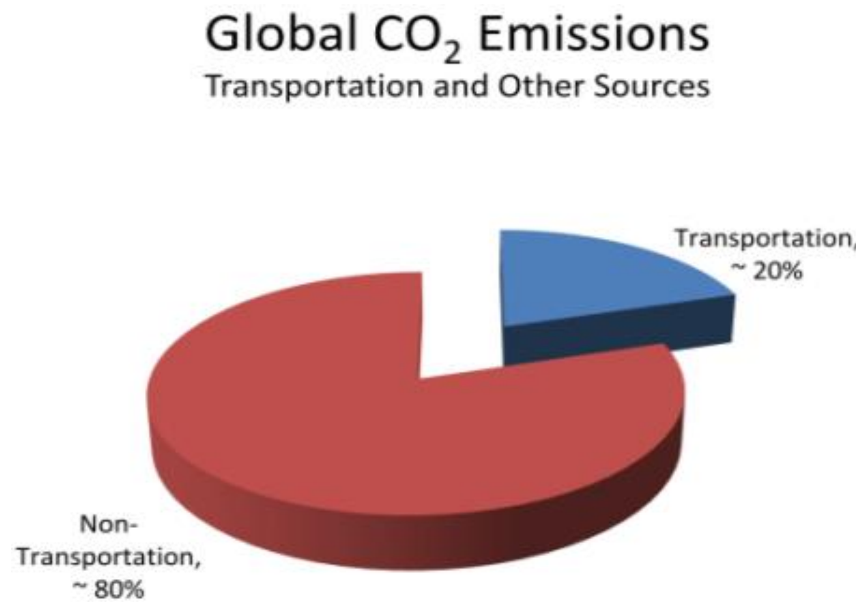
- **Background**
- **World Premier Materials (WPM) Project on Mg Alloys**
- **Korea Institute of Materials Science (KIMS)**
- **Magnesium Technology Innovation Center**
  Seoul National University
- **Additive Manufacturing of Mg Alloys (Daegun & KMTRA)**

CO_2 Emissions

- **CO_2 Emissions: Transportation > 20%**



CO_2 Emission in US by Economic Sector (2012)



Total of 35.3 Billion Tons CO_2 Produced in 2013

http://www.epa.gov/climatechange/ghgemissions/sources/transportation.html

Magnesium Alloys

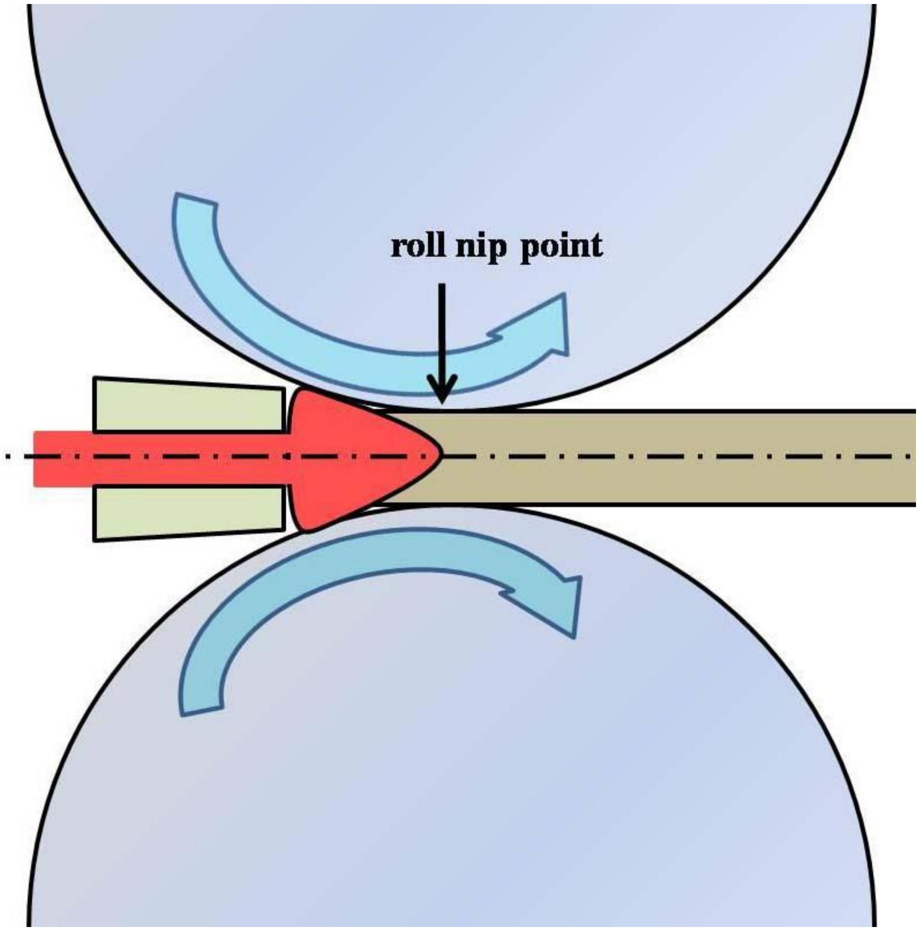
Advantages of Magnesium Alloys

- The Lightest among All Structural Metals
- ……….

Disadvantages

- Cost
- Formability
- Strength
- Corrosion Resistance
- Anisotropy
- ……….

Twin Roll Casting Process



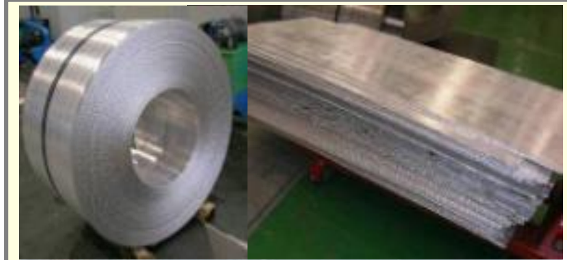
Schematic Diagram of Twin Roll Casting

- Advantages
  - Low Production Cost
  - Fine Microstructure
  - …..

M. Ferry, Direct Strip Casting of Metals and Alloys, Cambridge, UK, 2006

Status of POSCO Mg Sheet Project

- **2002.08 : Proposal for Mg Project to POSCO by SNU**
- **2003.11 : Mg Sheet Project Team Established at POSCO/RIST**
- **2004.01 : Consultant for Mg Project for POSCO/RIST**
- **2004.01 : Construction of Pilot Plant for Mg Sheet**
- **2004.11 : Completed Mg Sheet Pilot Plant**
- **2005.03 : Production of Mg Sheet (Width 600mm)**
- **2006.08 : Start Construction of Mg Sheet Plant ($60 Million)**
- **2007.07 : Commercial Production of Mg Sheet (3,000 ton/year)**
- **2010.04 : Initiation of Mg Smelting Business**
- **2013.04 : Production of 2,000mm Wide Cast Strip**
- **2016.10 : Investment of >$100M for Wide Strip Rolling Facility**
- **2019.03 : Completion of Rolling Facility for Wide Mg Strip**



Strip Caster

Reversible Warm Mill

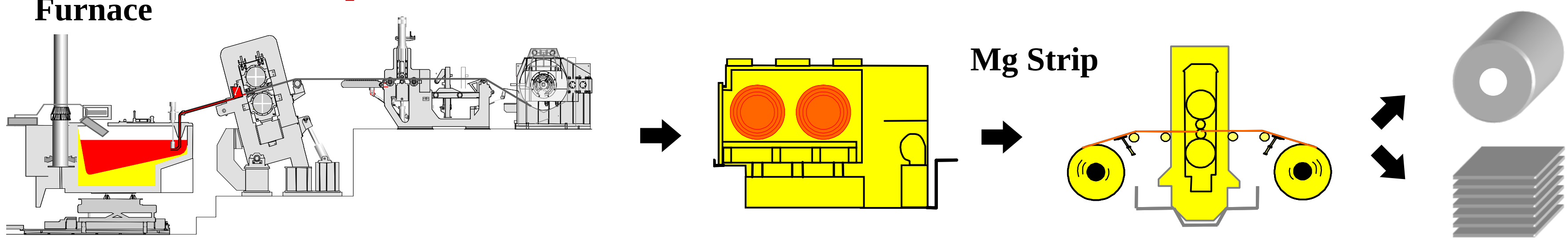
Cleaning Line

Sheet Slitting Line

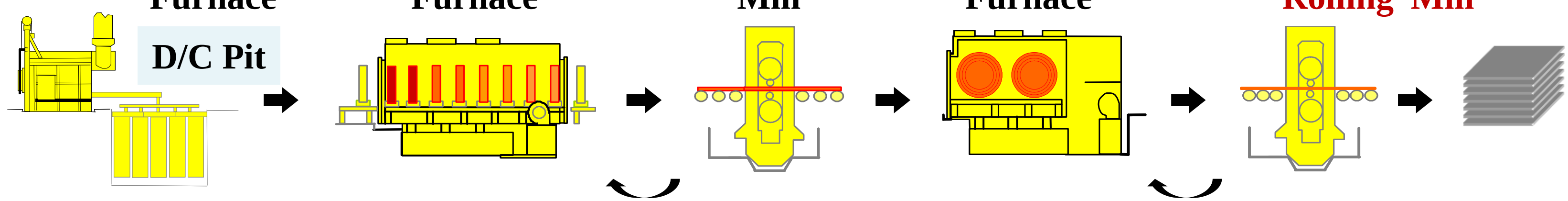
Comparison between TRC Process and Conventional Process

■ Twin Roll Casting & Continuous Rolling

POSCO WPM



■ Conventional Process: DC Casting + Tandem Rolling



※ Benefit of Strip Casting

- ✓ Continuous Process ⇒ Better Productivity & Lower Cost
- ✓ Reversible Warm Mill ⇒ Finer Microstructure

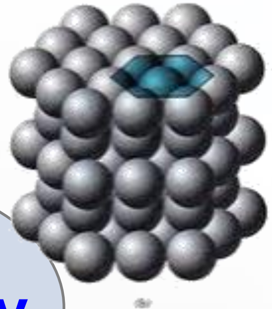
<Wide Strip Caster>

<Warm Rolling Mill>

World Premier Materials (WPM) Project on Mg Alloys

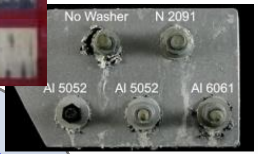
Project Title	Light Magnesium Materials for Transportation Industry
Project Leader	POSCO
Participating Organization	Renault Samsung, Ssangyong Motors, Volkswagen, Hyundai Motors, KMI, Solution Lab, Sungwoo Hitech, Shinyoung, MS Auto Tech, KSM Hyundai Sungwoo Metal, Dongnam Precision Co., Nohroo Coil Coating, KC Chemical, GlowOne, MAGNA, KIMS, RIST ※ 16 Companies, 2 Research Institutes
Project Period	2010. 9 ~ 2019. 3

Research Objectives



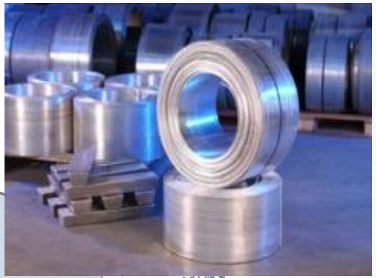
Formability

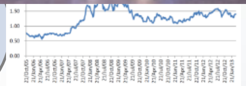
New Alloy Development



Corrosion Resistance

Mg Surface Treatment Technology





Cost

Cost Reduction

POSCO Twin Roll Cast 2,000mm Magnesium Sheet

Luggage Retainer : Renault-Samsung SM7 Nova

- Component : Between the back of the rear seat and the trunk
- Using AZ31B 1.4t sheet (POSCO)
- Weight Saving : 2.2kg

  Steel (3.6kg) → Mg (1.4kg)

Roof Panel : Porche 911 GT3 Rs

POSCO Mg Sheet

Width : 1,000mm
Weight : 3.65Kg *(Al sheet : 4.72kg)*

LG Gram Notebook 15Z970-GPB5ML

Application of Wrought Mg Alloys

Ultra Light Laptop by Magnesium Sheet

Model	 NEC Z LZ550 2013 (Japan)	 LG gram14 2015 (Korea)	✓  LG gram 15Z 960 2015 (Korea)	✓  LG All Day gram 15ZD970 2017 (Korea)	✓  Samsung Always NT900X5N-X58 2017 (Korea)
Screen Size	13.3 inch	14.2 inch	15.6 inch	15.6 inch	15 inch
Weight	875g	980g	980g	1,090g	1,250g
Magnesium Application	Mg-Li a\Alloy (D Cover)	Carbon-Magnesium and Mg-Li Alloy	Magnesium Sheet (D Cover)	Magnesium Sheet (D Dover)	Magnesium Sheet (C, D Cover)

✓ E-form (High Formable POSCO Magnesium Sheet)

KMTRA

Korea Institute of Materials Science (KIMS)

Research Activities of Magnesium Department

Alloy Development

- High-performance non-flammable alloys
- High-strength cast/wrought alloys
- High-formability wrought alloys
- Corrosion-resistant alloys
- Alloys for high-temperature applications

Processing Technology

- Grain refining technology via carbon inoculation method
- Eco-friendly recycling technology of Mg scrap
- Rolling process for high-formability sheets
- Horizontal continuous casting
- High-speed extrusion of high-strength alloys

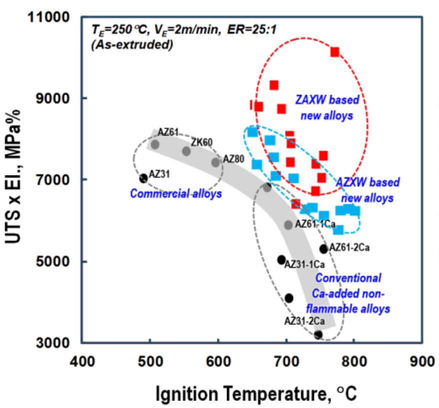
Practical Application

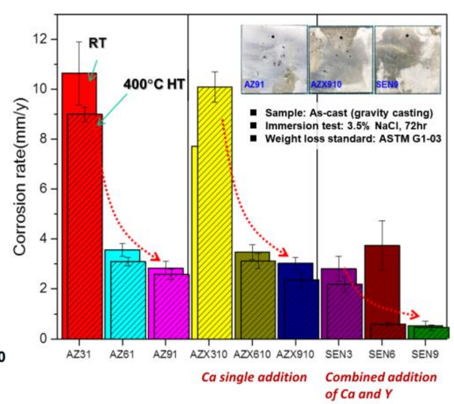
- High-strength road wheel (LPDC)
- Seat frame for airplane/train (extrusion)
- Biodegradable implant (extrusion)
- Case for electronic product (HPDC)
- In- and exterior parts for railway vehicle (extrusion)

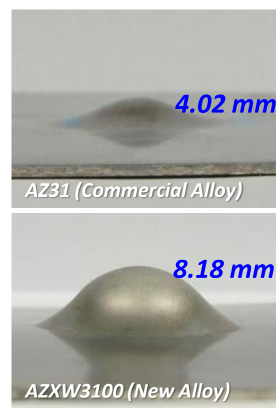
Korea Institute of Materials Science (KIMS)

Non-flammable Stainless Mg Alloy

- **Main Contents**
  - Development of Non-flammable Stainless Magnesium Alloys for Automobiles, High-speed Trains, and Aircrafts
- **Major Achievements**
  - Environmentally friendly (SF_6-free) alloys and processes (refining, melting, casting)
  - World best corrosion resistant Mg alloy (0.13 mm/y in 3.5% NaCl solution for 240 hr)
  - Development of NF-stainless Mg alloy sheet with excellent RT-formability (LDH: 8.2 mm)
  - Commercialization (IT, seat frame, etc.) & technology transfer



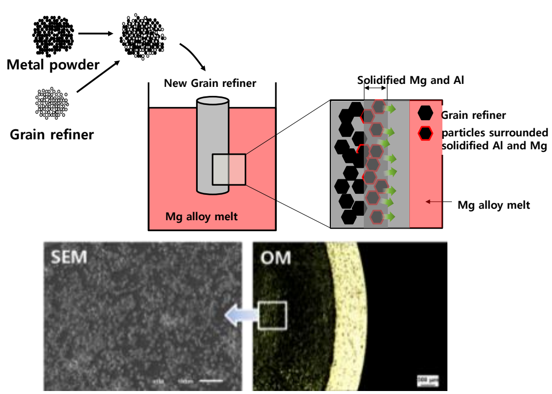


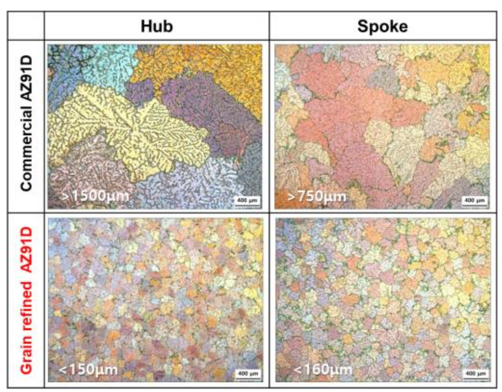


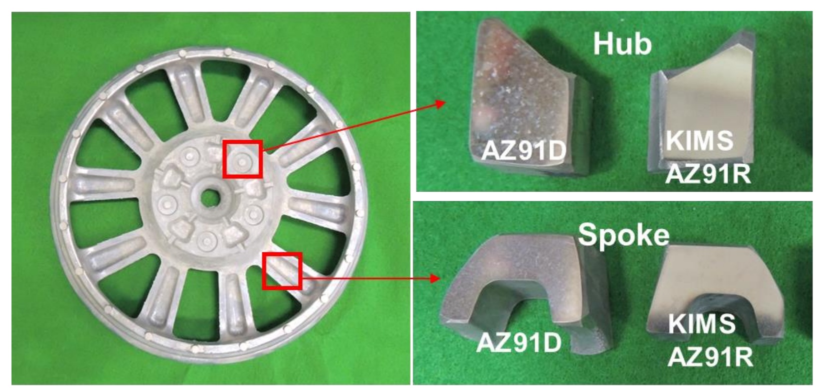
Korea Institute of Materials Science (KIMS)

Grain Refining Technology

- **Main Contents**
  - Development of grain refiner applicable to commercial AZ-series components
  - Development of high-efficiency grain refiner applicable to large-scale mass production
  - Development of high-strength Mg cast parts with grain refinement technology
- **Major Achievements**
  - Grain refinement to 1/10 of commercial alloys in low-pressure casting process of pilot scale
  - Development of grain refiner capable of continuous injection into mass-production process
  - Development of AZ91 road wheel with superior mechanical strength & elongation







Korea Institute of Materials Science (KIMS)

Eco-friendly Recycling Technology

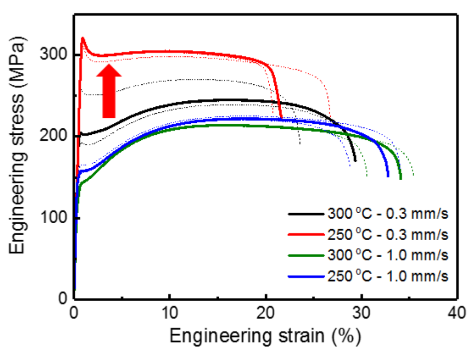
- **Main Contents**
  - Establishment of processing technology for pilot-scale (150 tpy) plant of Mg-based end-of-life scraps
  - Development of high value-added alloying technology utilizing Ca and Y additions
- **Major Achievements**
  - Reduction of Global Climate Impact (GCI) by 92% compared to traditional process ($7.2\ kg_{CO2}/kg_{Mg} \rightarrow 0.6\ kg_{CO2}/kg_{Mg}$)
  - Achievement of recycling rate of 89.6% and non-metallic inclusion level of 18.2 ppm

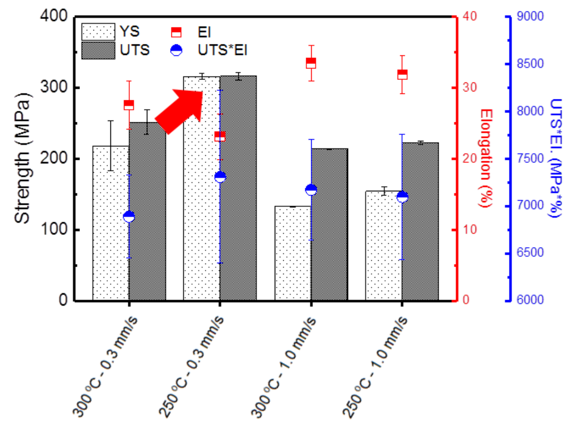
Korea Institute of Materials Science (KIMS)

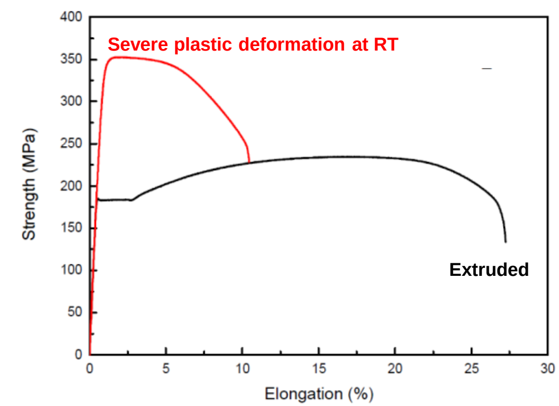
High-strength Biodegradable Mg Alloy

- **Main Contents**
  - Increase in reliability by upgrading production technology of biodegradable Mg implant
  - Development of thermo-mechanical treatment for enhancement of mechanical properties of biodegradable Mg alloy
- **Major Achievements**
  - Development of high-strength biodegradable Mg alloy (UTS x El. > 7,000 MPa·%)

    (Commercial biodegradable Mg alloy: 2,500 MPa·%)
  - Enhancement of mechanical properties through severe plastic deformation at room temperature



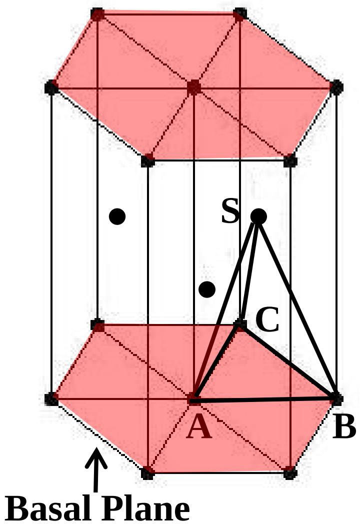


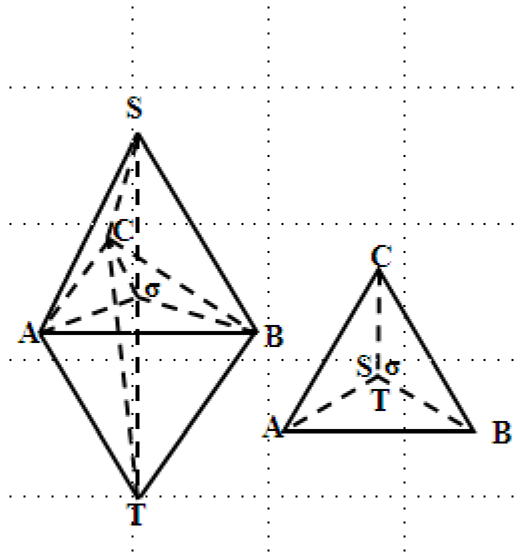


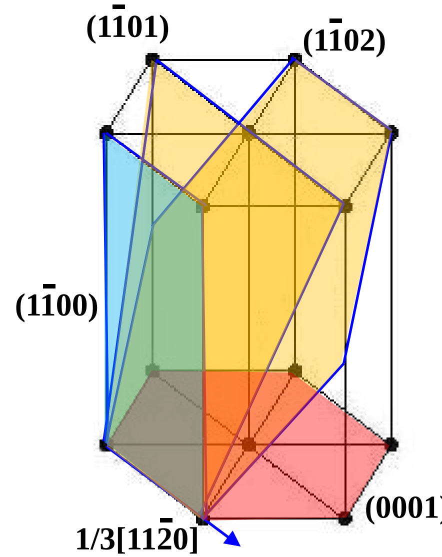
High Performance Magnesium Alloys

- **Low Cost**
- **High Formability**
- **High Strength**
- **High Corrosion Resistance**
- **Nonflammability**
- **Isotropic Mechanical Properties**
- **High Modulus**
- **Low Density**
- **……….**

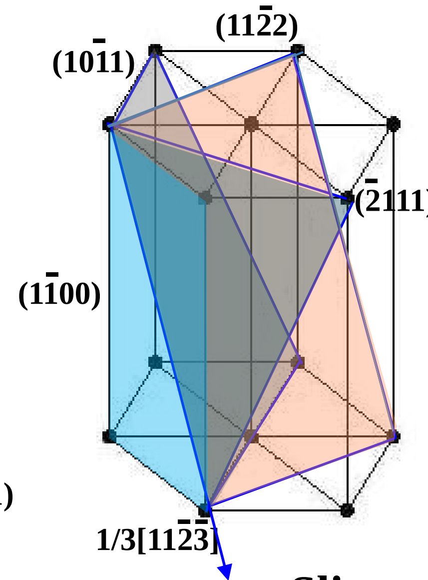
Slip Modes in Magnesium







<a> Slip



<c+a> Slip

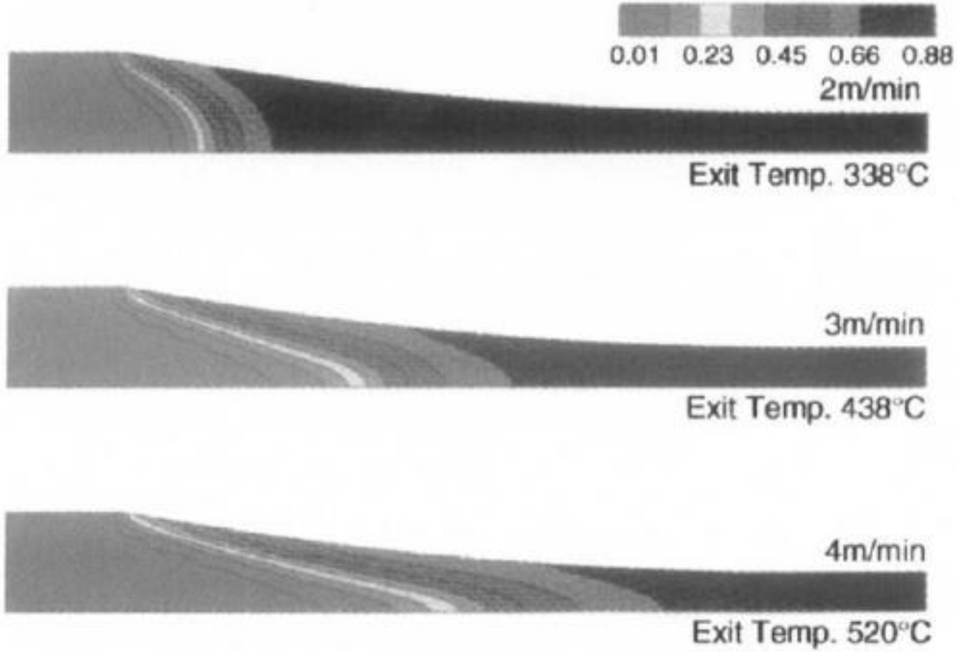
Type of Dislocation	Number of Systems (Independent)	Burgers Vector	Magnitude of Burgers Vector	Slip System	
a (AB)	3 (2)	1/3<11$\bar{2}$0>	|a|=3.209	Basal	{0001} <11$\bar{2}$0>
	3 (2)			Prism-I	{10$\bar{1}$0} <11$\bar{2}$0>
	6 (4)			Pyramidal-I	{10$\bar{1}$1} <11$\bar{2}$0>
c (ST)	3 (2)	<0001>	|c|=5.211	Prism-I	{10$\bar{1}$0} <0001>
	3 (2)			Prism-II	{11$\bar{2}$0} <0001>
c+a (ST+AB)	6 (5)	1/3<11$\bar{2}$3>	$\{\|a\|^2+\|c\|^2\}^{1/2}=6.120$	Pyramidal-II	{11$\bar{2}$2} <11$\bar{2}$3>

Research Programs at Magnesium Technology Innovation Center

- **Development of Advanced Mg Alloys**
  - Computer Simulation for Phase Formation by Thermodynamic Calculations and Flow/Solidification Behavior
  - High Strength/High Formability Alloys
  - High Temperature Alloys
  - Corrosion Resistant Alloys and Biodegradable Materials
- **Characterization of Microstructure/Texture and Mechanical Properties**
  - Prediction of Deformation Behavior by Crystal Plasticity Simulation
  - Manufacturing and Characterization of Mg Single Crystals
  - Analyses of Microstructure/Texture, Dislocation, Twin
  - Mechanical Properties and Corrosion Behavior
  - Creep and Fatigue Properties
- **Development of Twin Roll Casting/Extrusion/Rolling Processes**
- **Semi-Solid Processing of Mg Alloys**
- **Surface Treatment: Plasma Electrolytic Oxidation Coating**
- **Development of Mg Die Casting Components for Automobile and Electronic Industries**

Development of Twin Roll Cast Mg Alloys with High Strength and High Formability

Solidification Behavior & Segregation



Increasing Roll Speed: Increasing Exit Temp.

- **Factors Affecting Solidification Behavior**
  - **Thermal Properties of Alloys**
  - **Freezing Range of Alloys**
  - **Melt Temperature**
  - **Setback Distance**
  - **Roll Speed**
  - **Roll Separating Force**

- **Development of New Mg Alloys for TRC Process**
- **Optimization of Processing Parameters**

P. Thomas, Continuous Casting of Aluminium Alloys, Institute of Physics, 2003, UK, 26-47

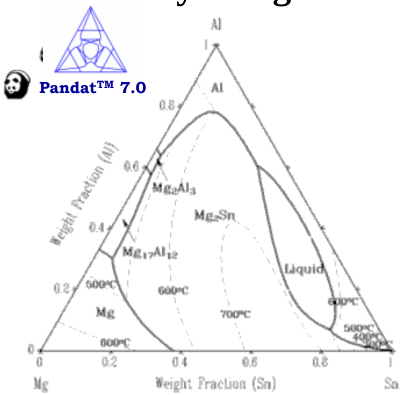
ICME for Alloy Design and Materials Processing

Pandat™

Thermodynamic Calculations

Prediction of Stable Phases

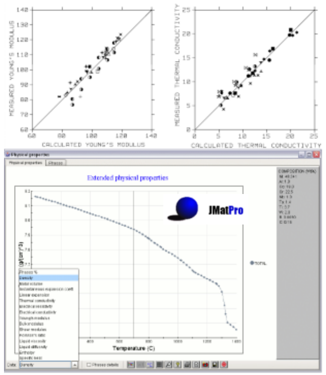
Alloy Design



JMatPro™

Thermodynamic Calculations

Prediction of Material Properties, Alloy Design



LaboTex

Texture Analysis

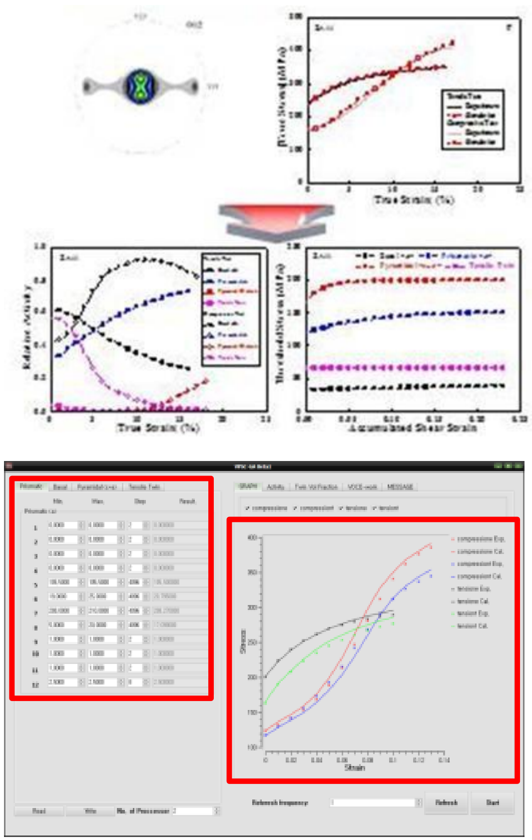
ODF Calculation

VPSC-GA

Texture Simulation Based on Visco-Plastic Self-Consistent Model and Genetic Algorism

Prediction of Texture & Stress State during Deformation

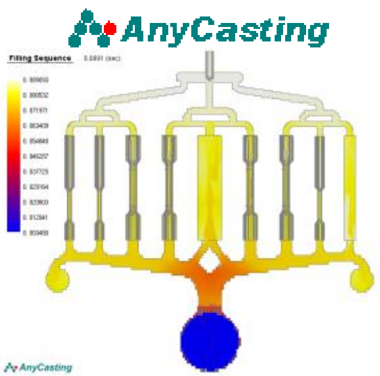
Guide for Alloy Design



AnyCasting™

Analysis of Flow and Solidification Behavior

Die Design, Defect Analysis

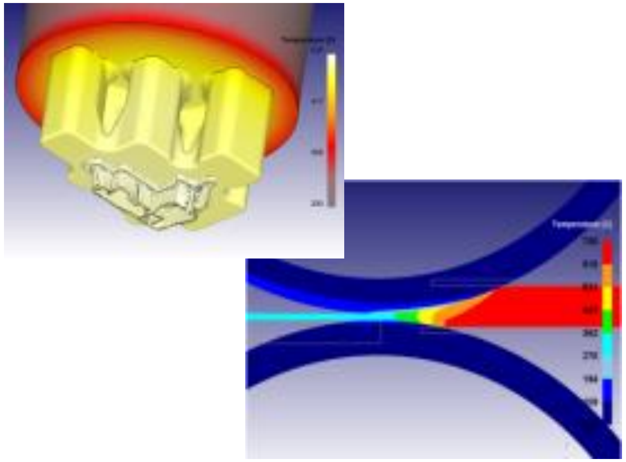


DEFORM™

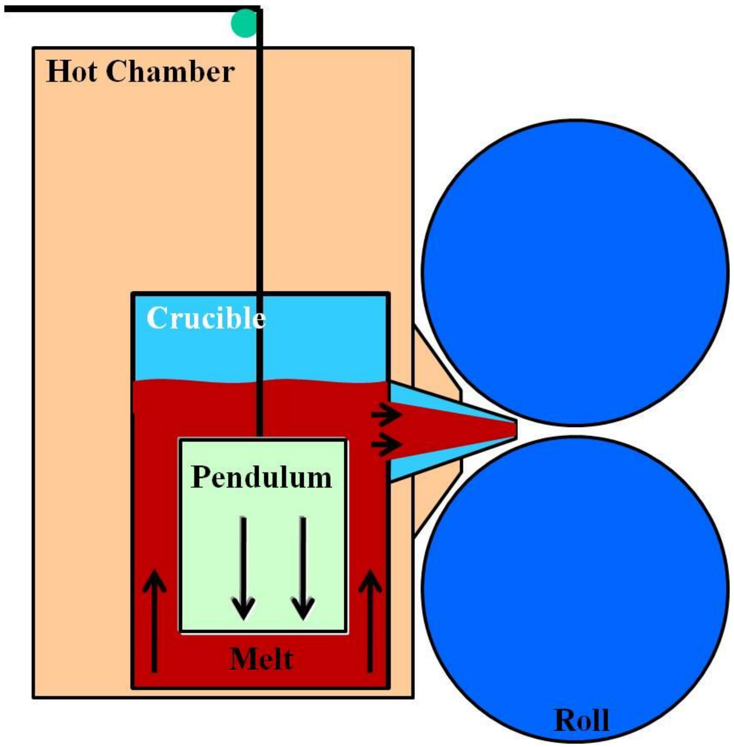
Simulation of Deformation Behavior during Material Processing by FEM

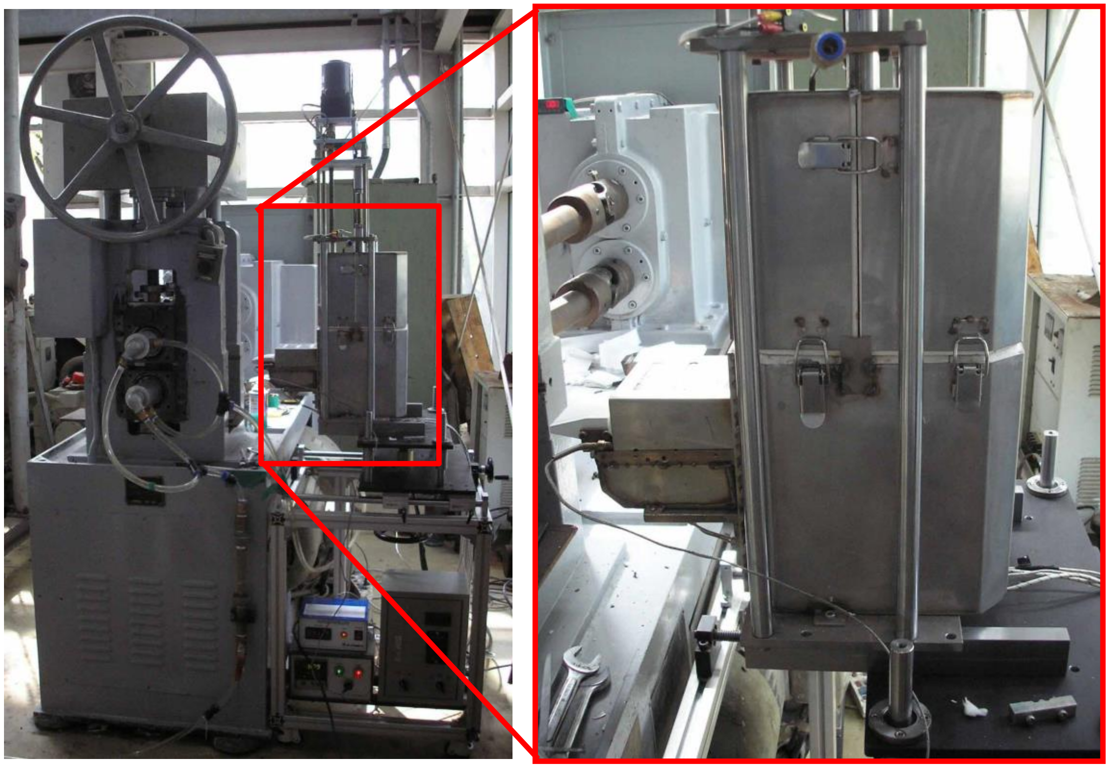
Simulation of Extrusion and Twin Roll Strip Casting Processes

Guide for Process Development



Manufacturing Process for TRC Plates

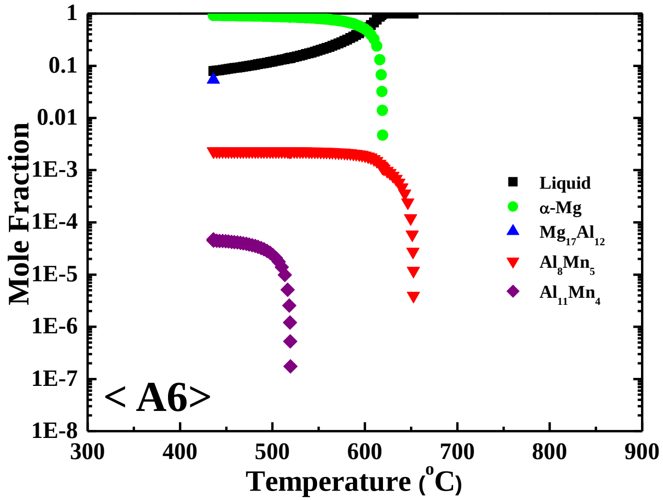


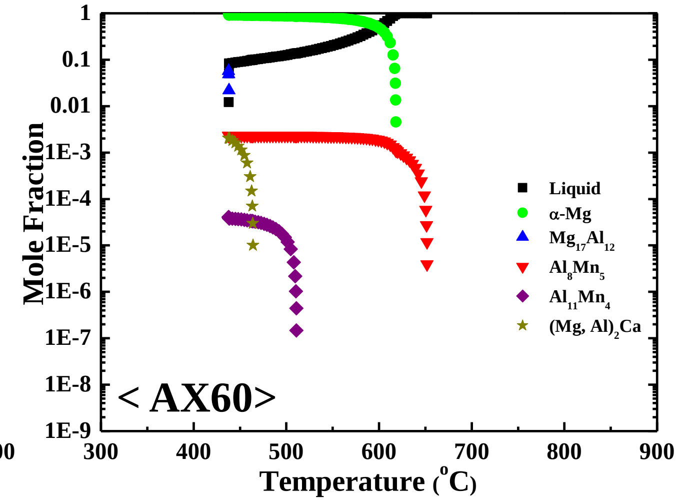


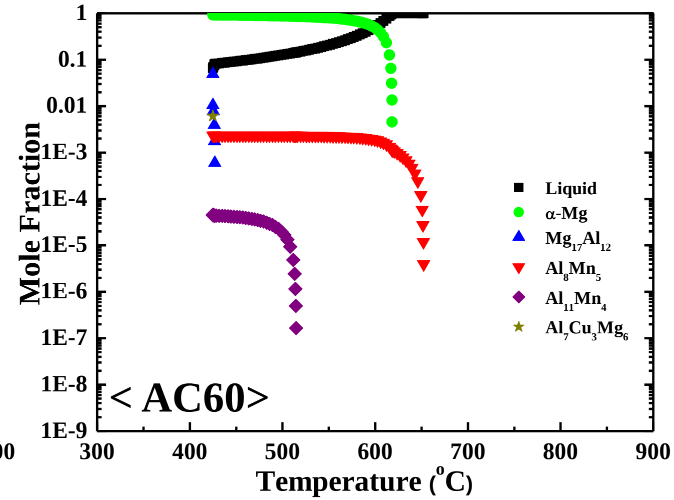
- **Fabrication of TRC Mg Alloy Plates**
  - ➤ Thickness: 3.0~3.3mm
  - ➤ Width: 50~65mm
  - ➤ Length: 2,500~3,500mm

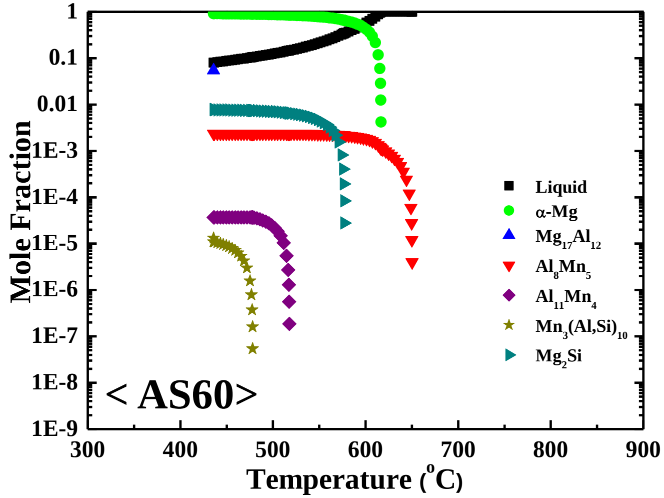
- **Development of New TRC Mg Alloys with Low Segregation & Improved Formability**

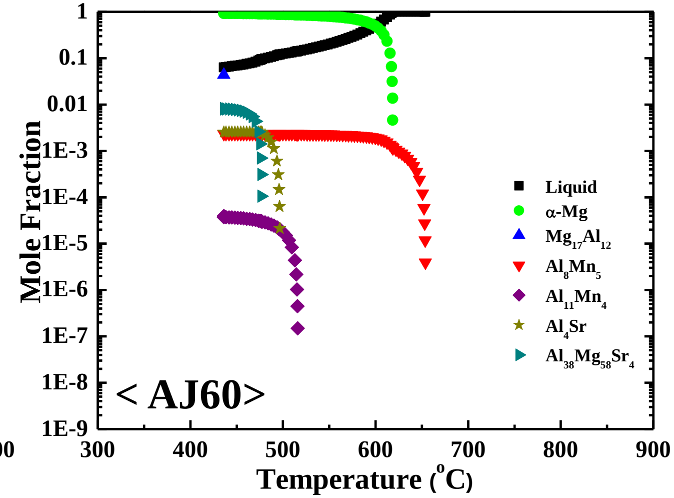
Solidification Behavior of Mg-6Al-X (Scheil Condition)

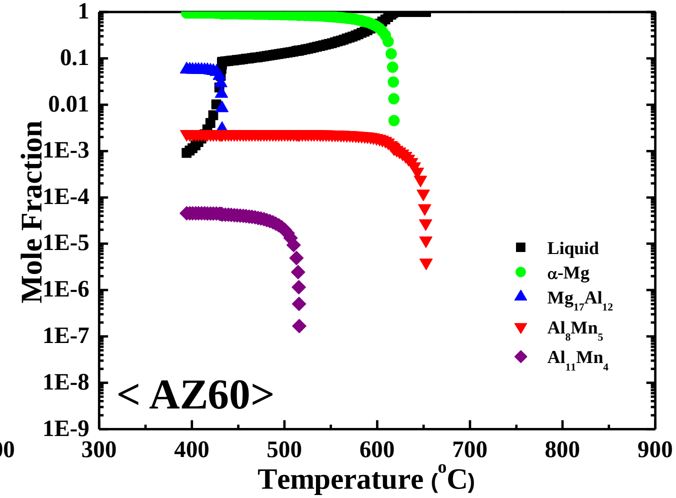




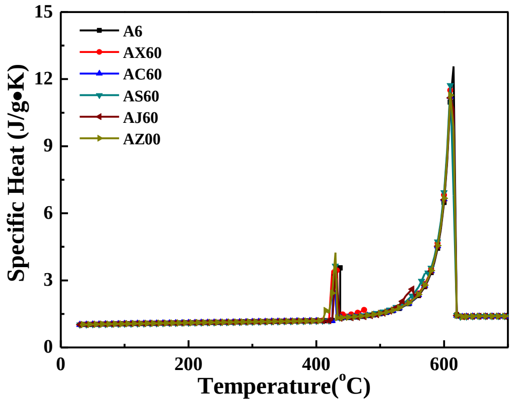




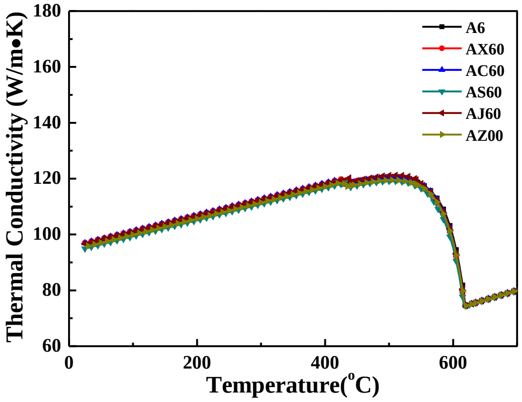




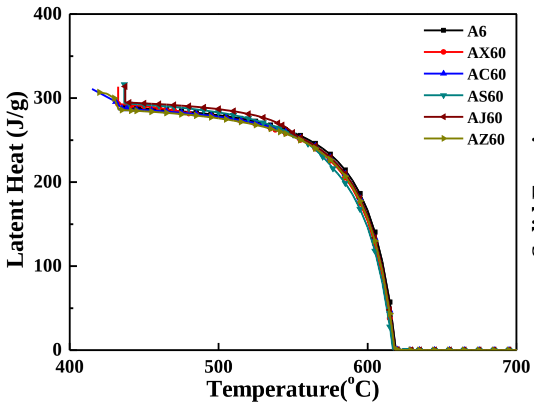
Thermal Properties of Mg-6Al-X Alloys for TRC Simulation



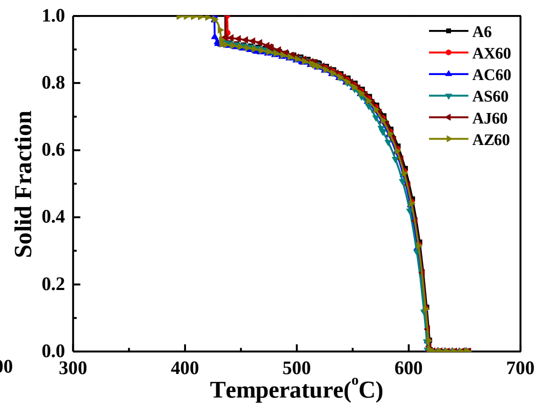
<Specific Heat>



<Thermal Conductivity>



<Latent Heat>

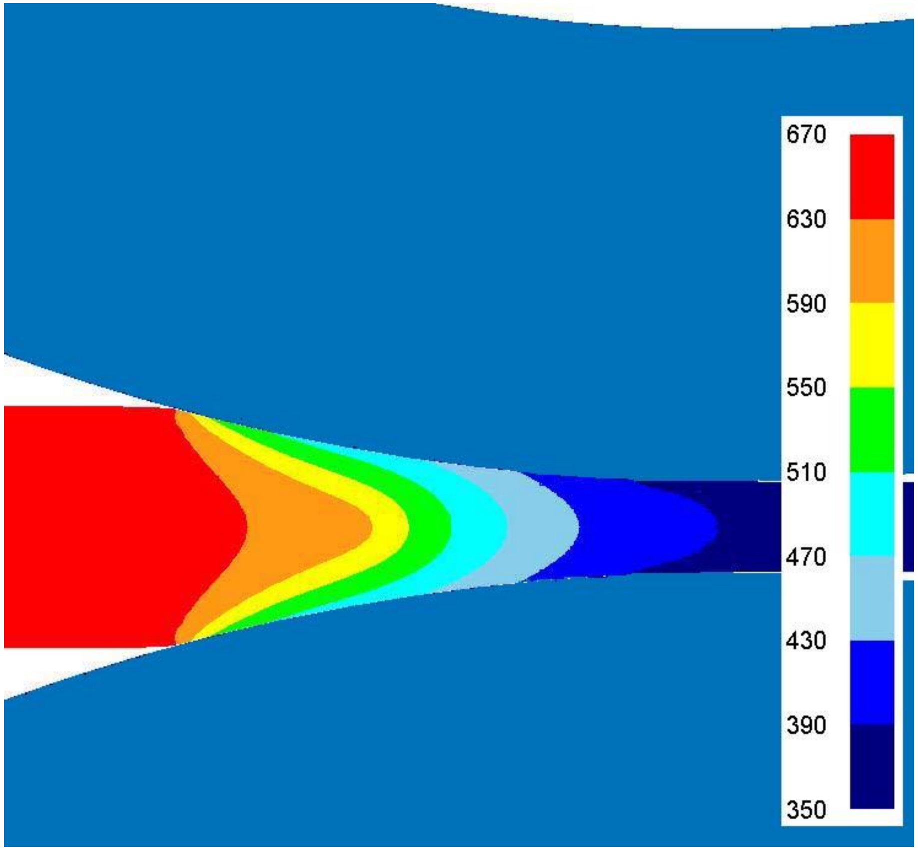


<Solid Fraction>

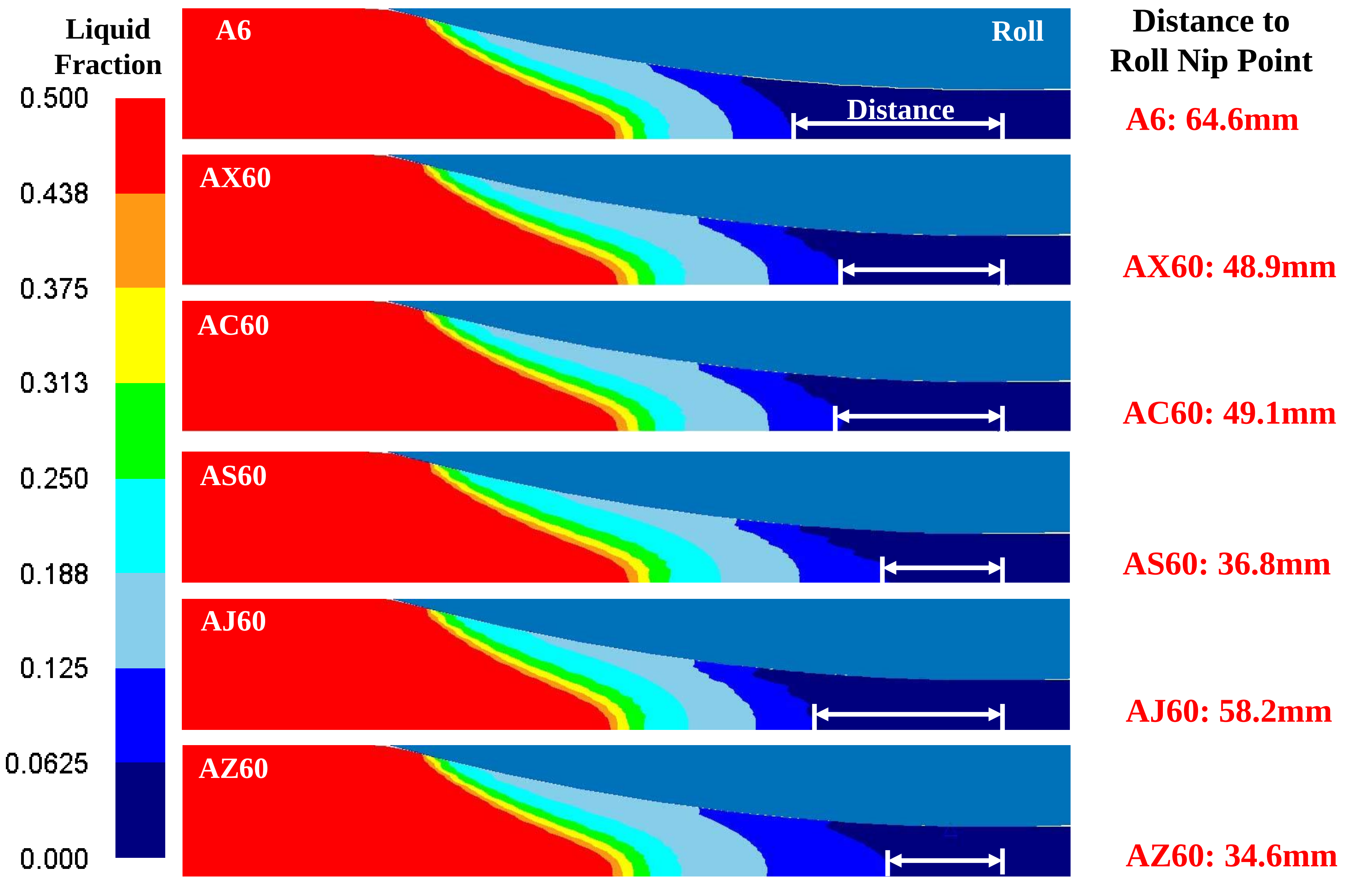
■ **Simulation Conditions**

➤ **Melt Temp.: 670°C**

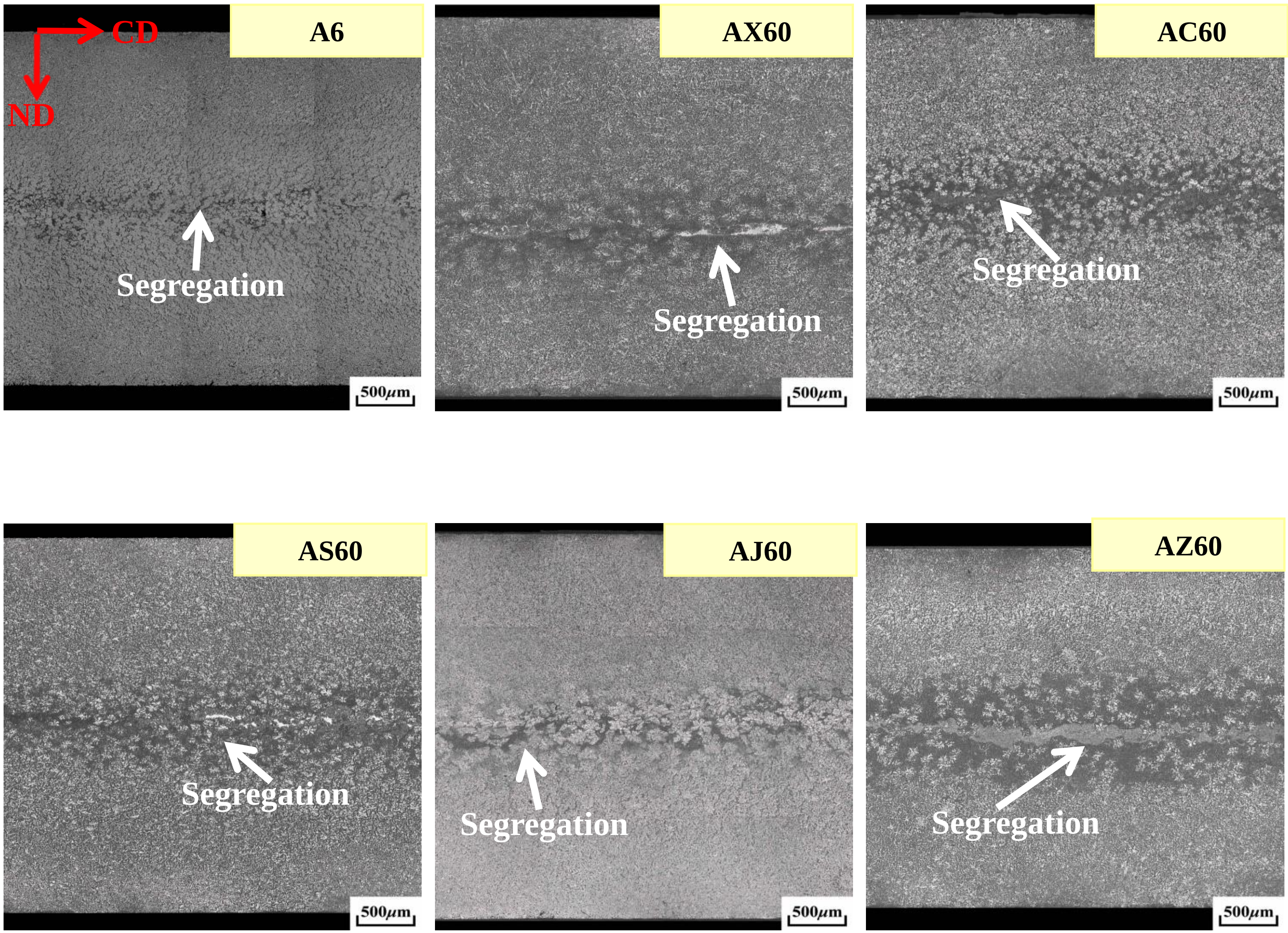
➤ **Roll Speed: 3mpm**



Simulation of Liquid Fraction During TRC Process



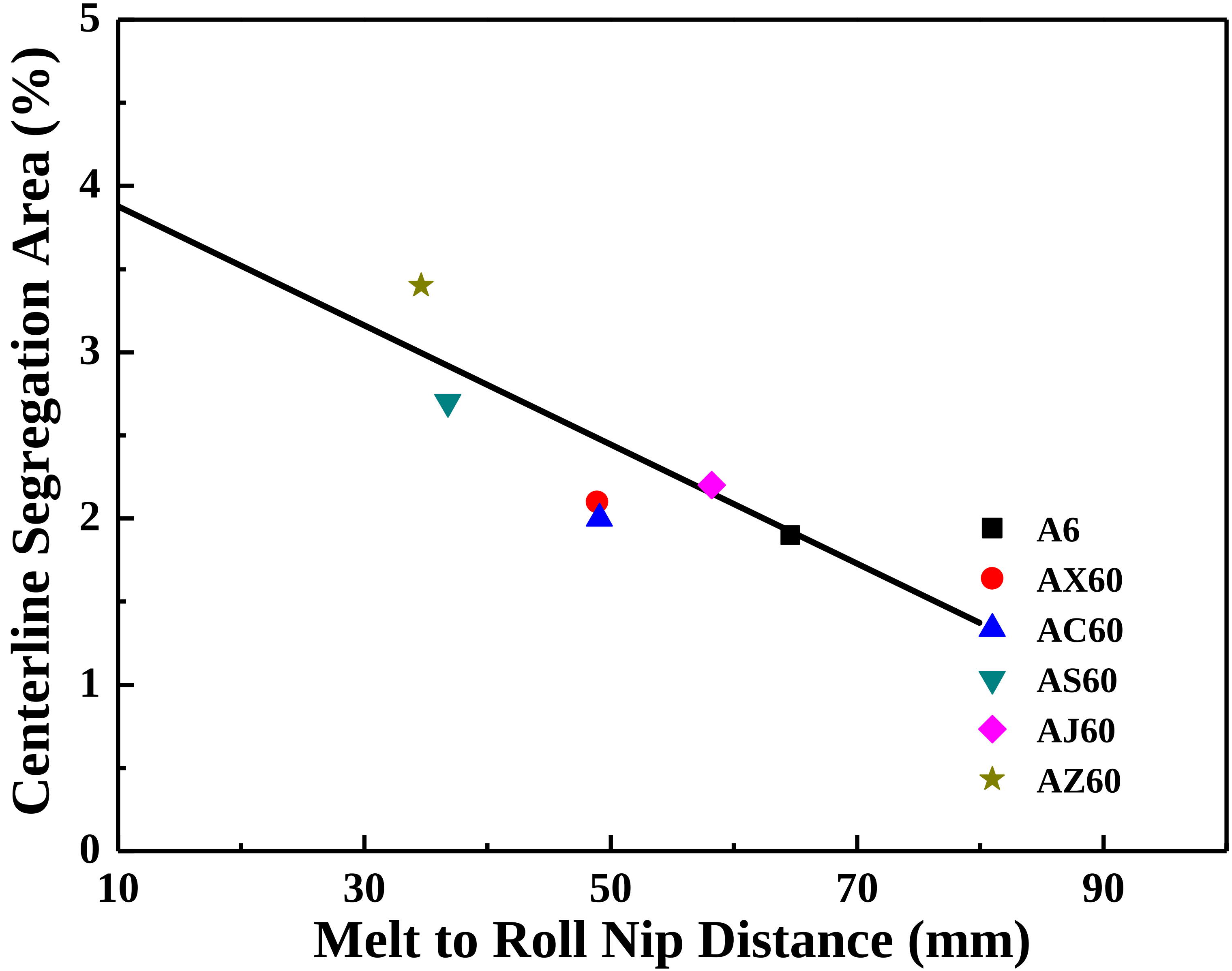
Microstructure of TRC Mg-6Al-X Alloys



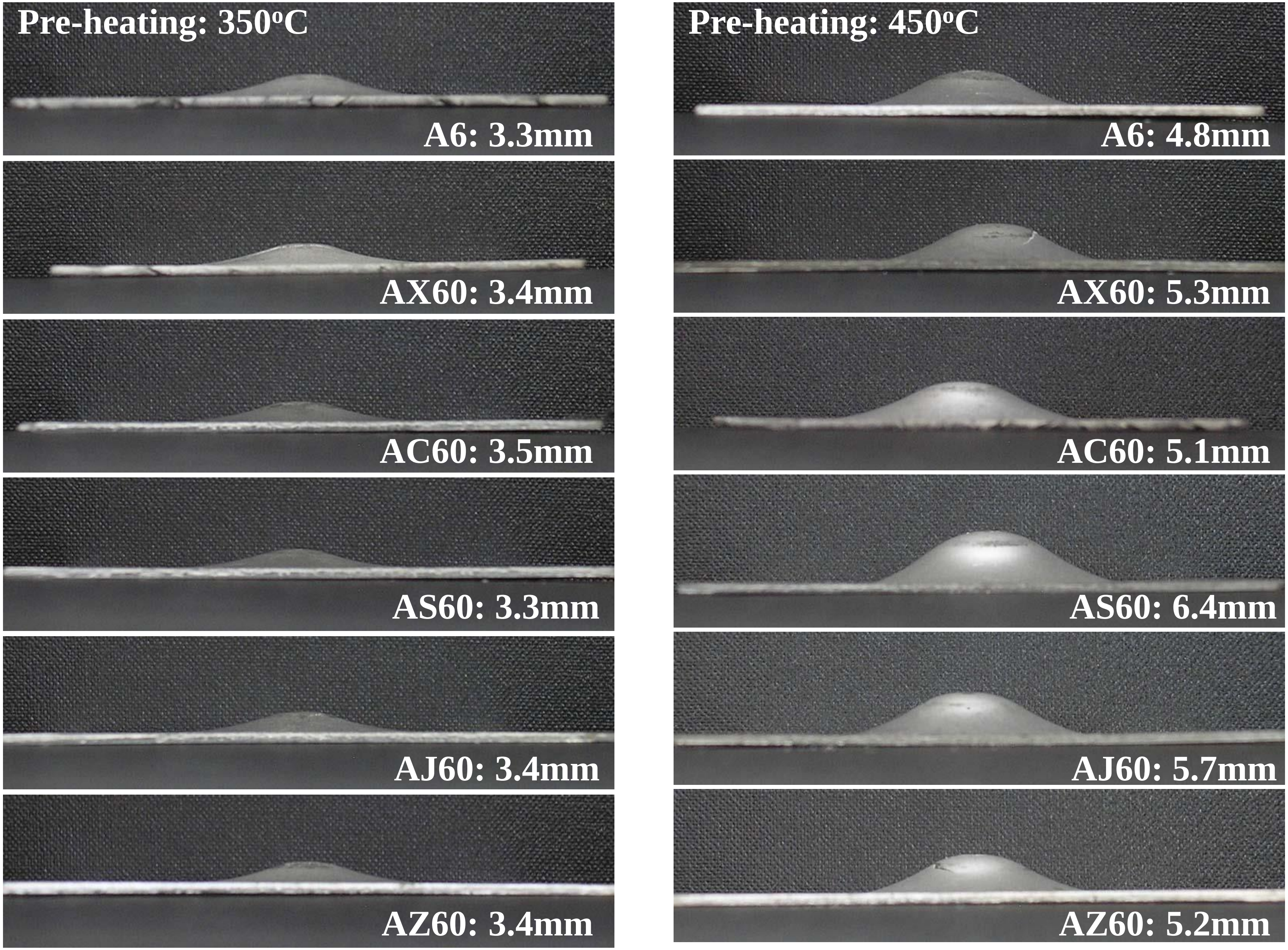
- **Segregation Factors**
  - **Freezing Range**
  - **Second Phase**
  - **Solidification Behavior**
  - **Partition Coefficient**

Mg Alloys	Centerline Segregation %
A6	1.9
AX60	2.1
AC60	2.0
AS60	2.7
AJ60	2.2
AZ60	3.4

Centerline Segregation Area and Melt to Roll Nip Distance



Photographs of Mg-6Al-X Alloys after Erichsen Tests



Mg-Zn-X-Ca TRC Plates

Z4

ZX40

ZAX400

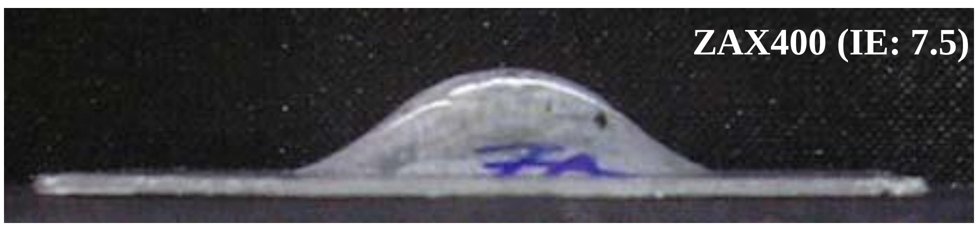
ZWX400

ZCX400

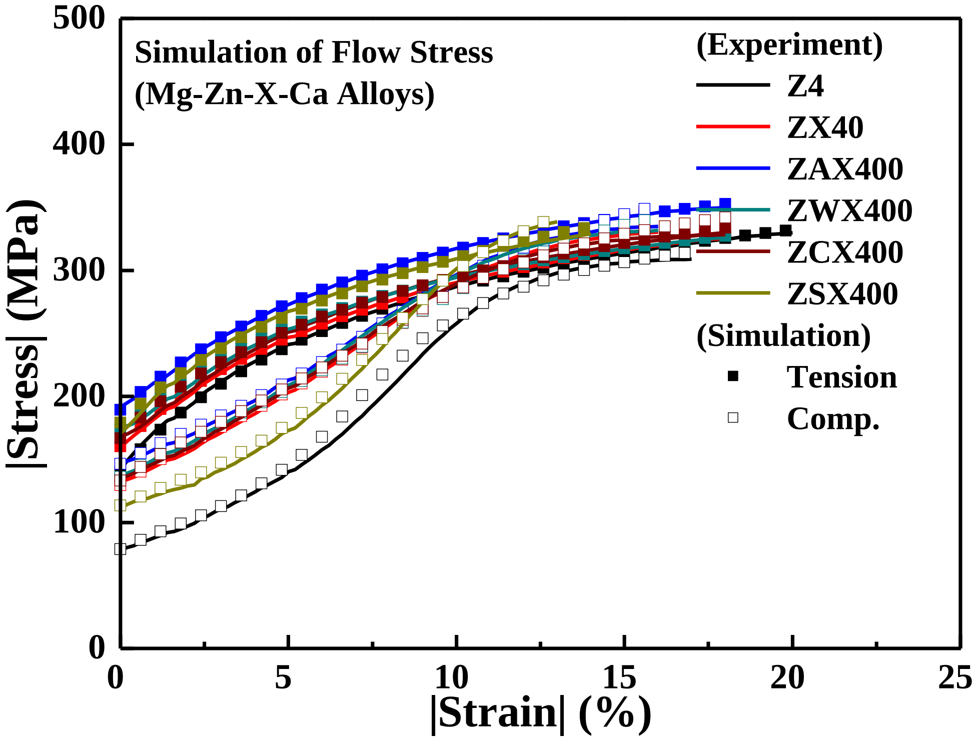
ZSX400

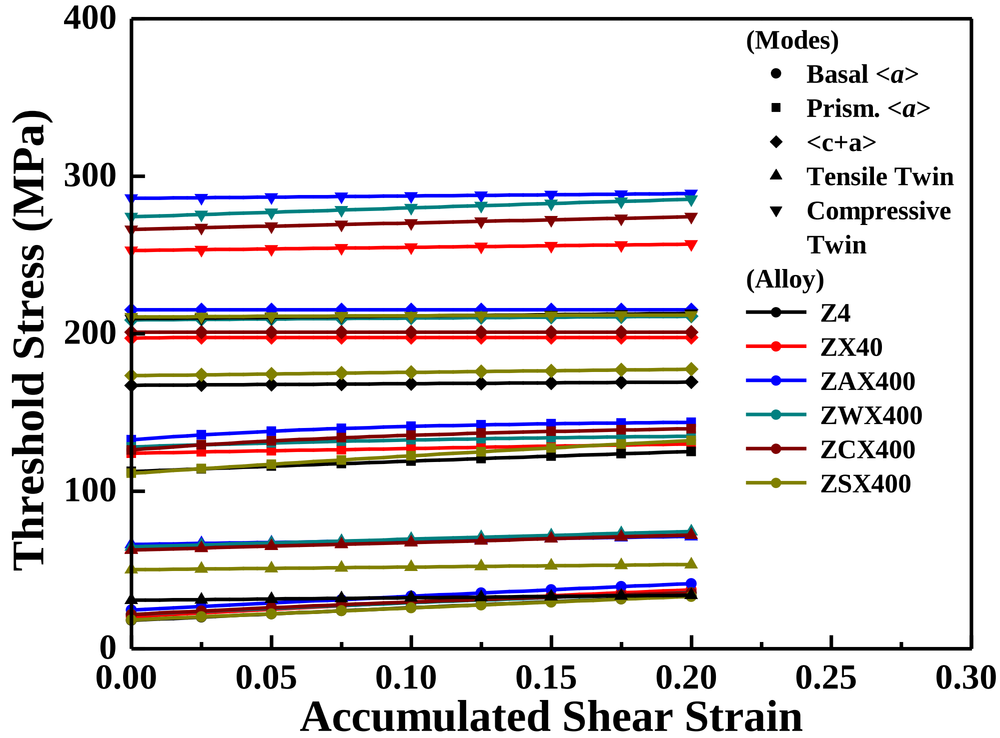
Photographs of Mg-Zn-X-Ca Alloys after Erichsen Tests

- **Erichsen Tests**
  - ➤ Punch Diameter: 20mm
  - ➤ Punch Speed: 5mm/min.

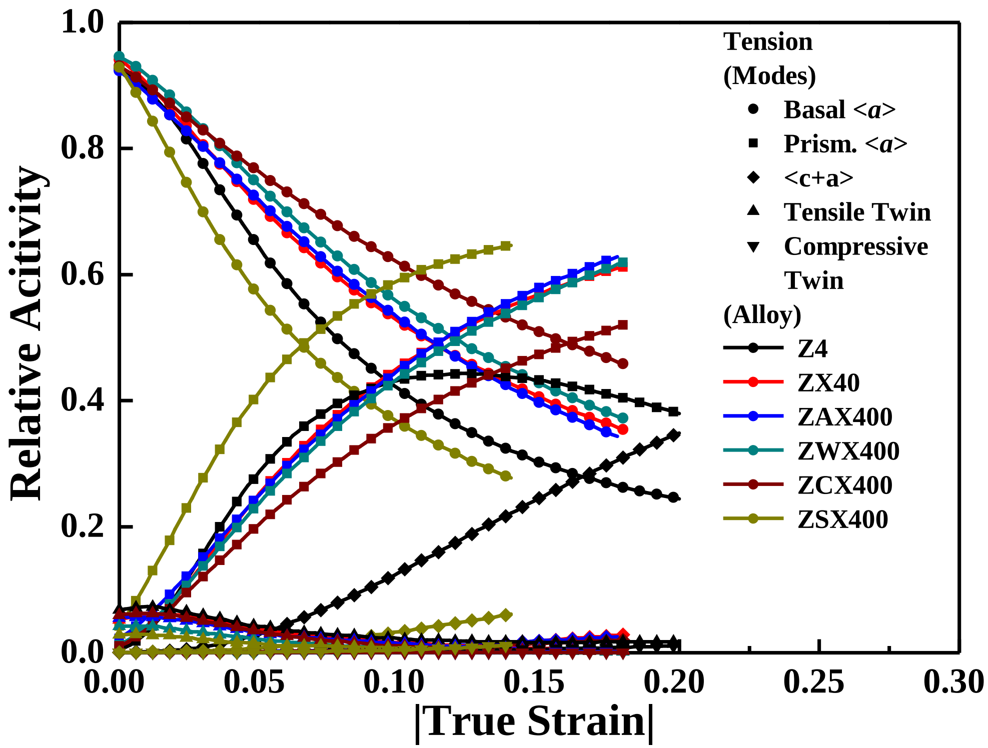


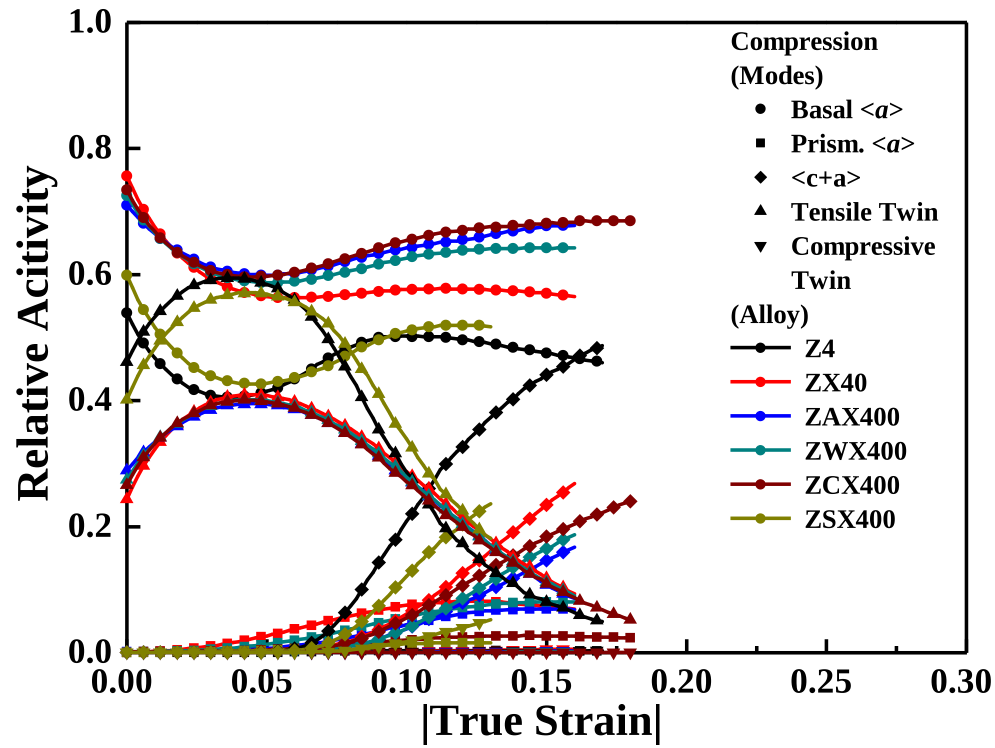
VPSC Simulation Results of Mg-Zn-X-Ca Alloys





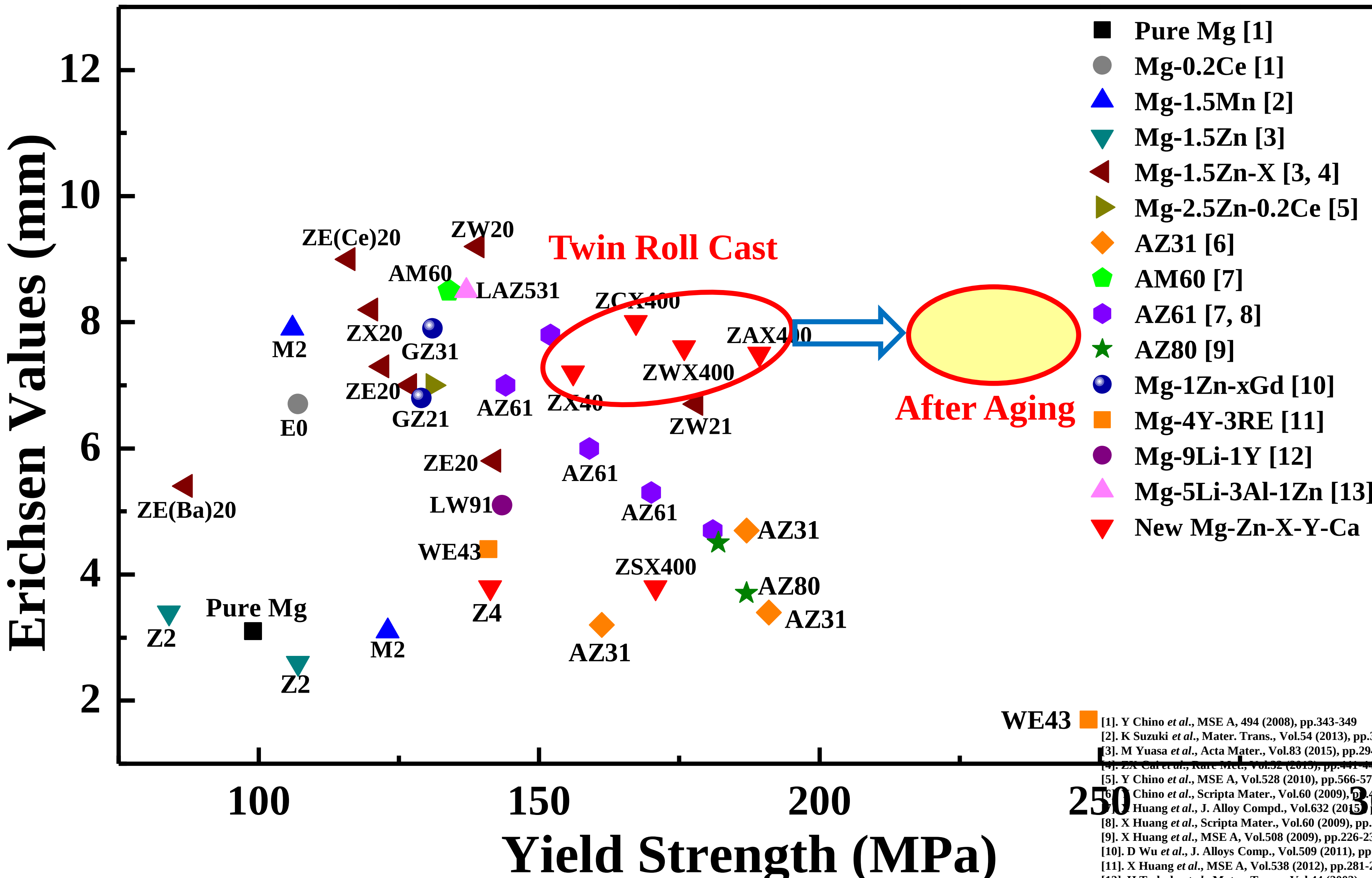
Activities of Deformation Mode of Mg-Zn-X-Ca Alloys





- **Deformation Modes**
  - **Tension: Initially Basal <*a*> Slip & Later Prismatic <*a*> Slip Activated**
  - **Compression: More Basal <*a*> Slip Activated for High Formability**

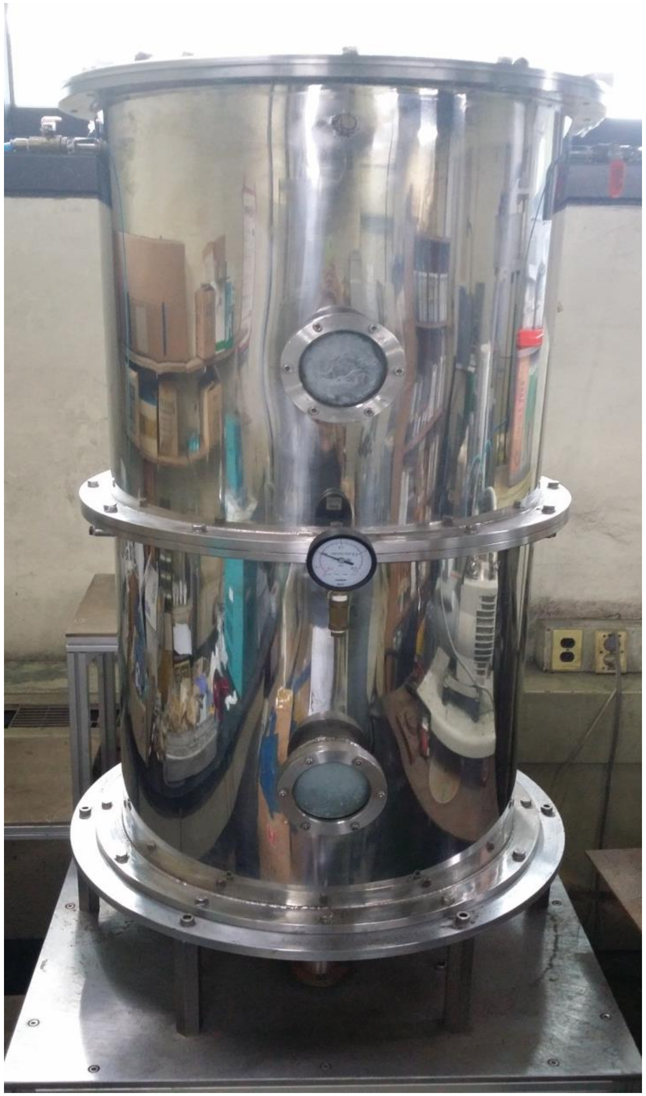
Relationship Between Erichsen Value and Yield Strength



[1]. Y Chino *et al.*, MSE A, 494 (2008), pp.343-349
[2]. K Suzuki *et al.*, Mater. Trans., Vol.54 (2013), pp.392-398
[3]. M Yuasa *et al.*, Acta Mater., Vol.83 (2015), pp.294-303
[4]. ZX Cai *et al.*, Rare Met., Vol.32 (2013), pp.441-447
[5]. Y Chino *et al.*, MSE A, Vol.528 (2010), pp.566-572
[6]. Y Chino *et al.*, Scripta Mater., Vol.60 (2009), pp.447-[illegible]
[7]. X Huang *et al.*, J. Alloy Compd., Vol.632 (2015), pp.94-[illegible]
[8]. X Huang *et al.*, Scripta Mater., Vol.60 (2009), pp.651-654
[9]. X Huang *et al.*, MSE A, Vol.508 (2009), pp.226-233
[10]. D Wu *et al.*, J. Alloys Comp., Vol.509 (2011), pp.2856-2863
[11]. X Huang *et al.*, MSE A, Vol.538 (2012), pp.281-287
[12]. H Taduda *et al.*, Mater. Trans., Vol.44 (2003), pp.2266-2270
[13]. Q Yang *et al.*, Int. J. Mater. Forum, (2014)

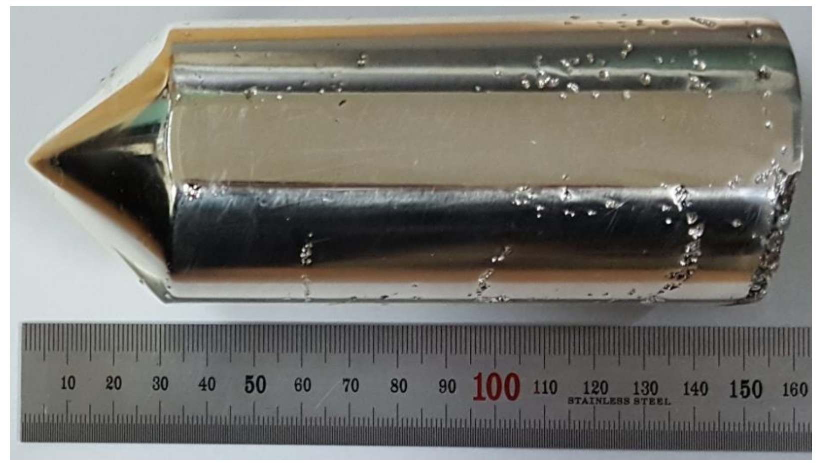
Fundamental Study on Deformation Behavior of Mg Single Crystals

The Largest Magnesium Single Crystal!



Mg Single Crystal

150mm(L) × 58mm(Dia.)

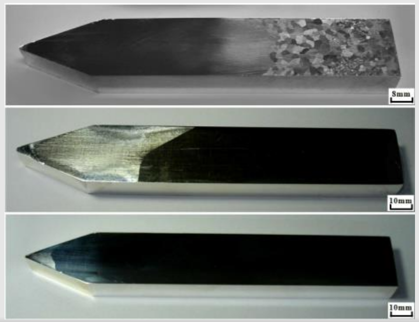


Experimental Procedures

Single Crystal Growing

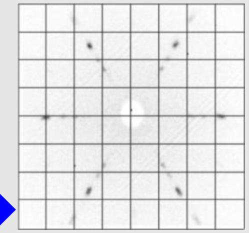

Bridgman Method

Experimental Condition:
Furnace : 750°C
Ar, Water Supply
Speed : 5 mm/hr (RPM = 70)

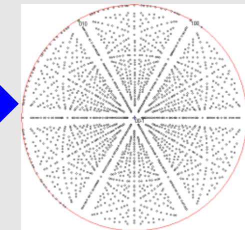


Pattern Acquisition & Indexing


X-ray Laue Machine



Stereographic Projection



Mechanical Test


R & B UNITECH

Microstructure Characterization & Texture Measurement

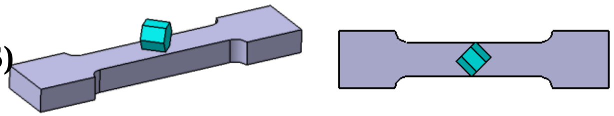

F20


X'Pert PRO MRD


SU70+TSL6.1(EBSD)

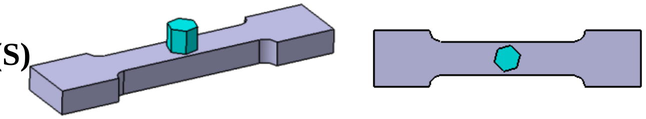
Various Sample Orientations Used for Mechanical Testing

Orientation A (S)



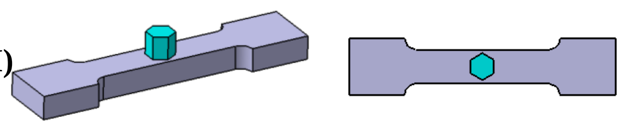
LD	Slip System	Schmid Factor
[$\bar{40}$ 20 20 37]	Basal	0.50
	Prismatic	0.22
	c+a	0.28
	Tensile Twin	0.25
	Compression Twin	0.29

Orientation B (S)



LD	Slip System	Schmid Factor
[90 $\bar{123}$ 33 0]	Basal	0
	Prismatic	0.5
	c+a	0.42
	Tensile Twin	0.47
	Compression Twin	0.39

Orientation C (M)

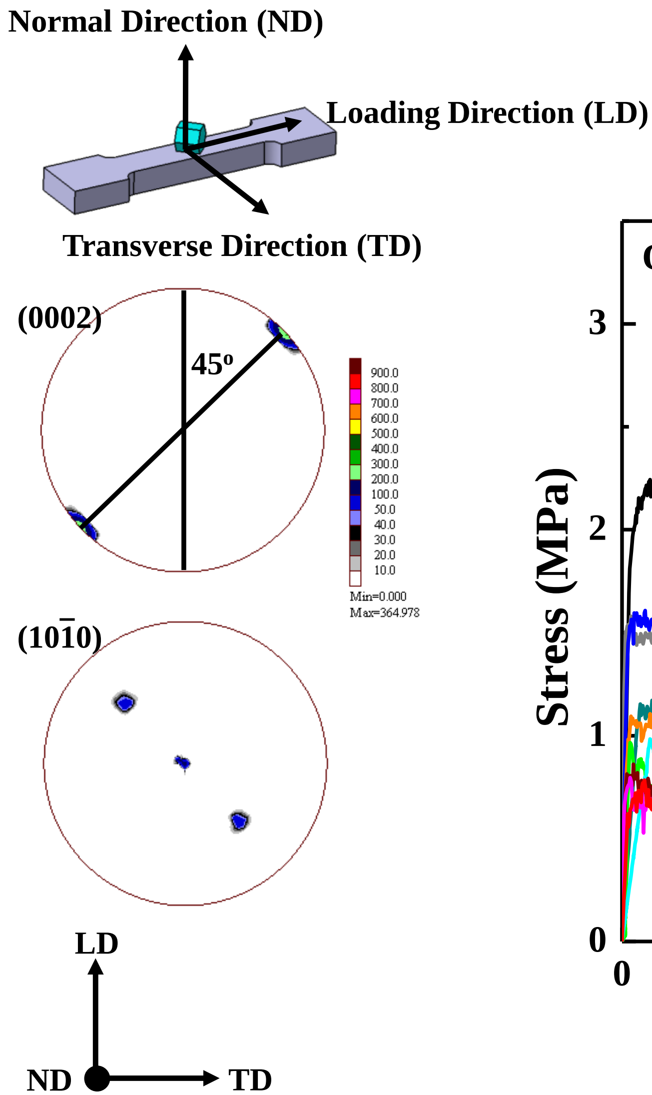


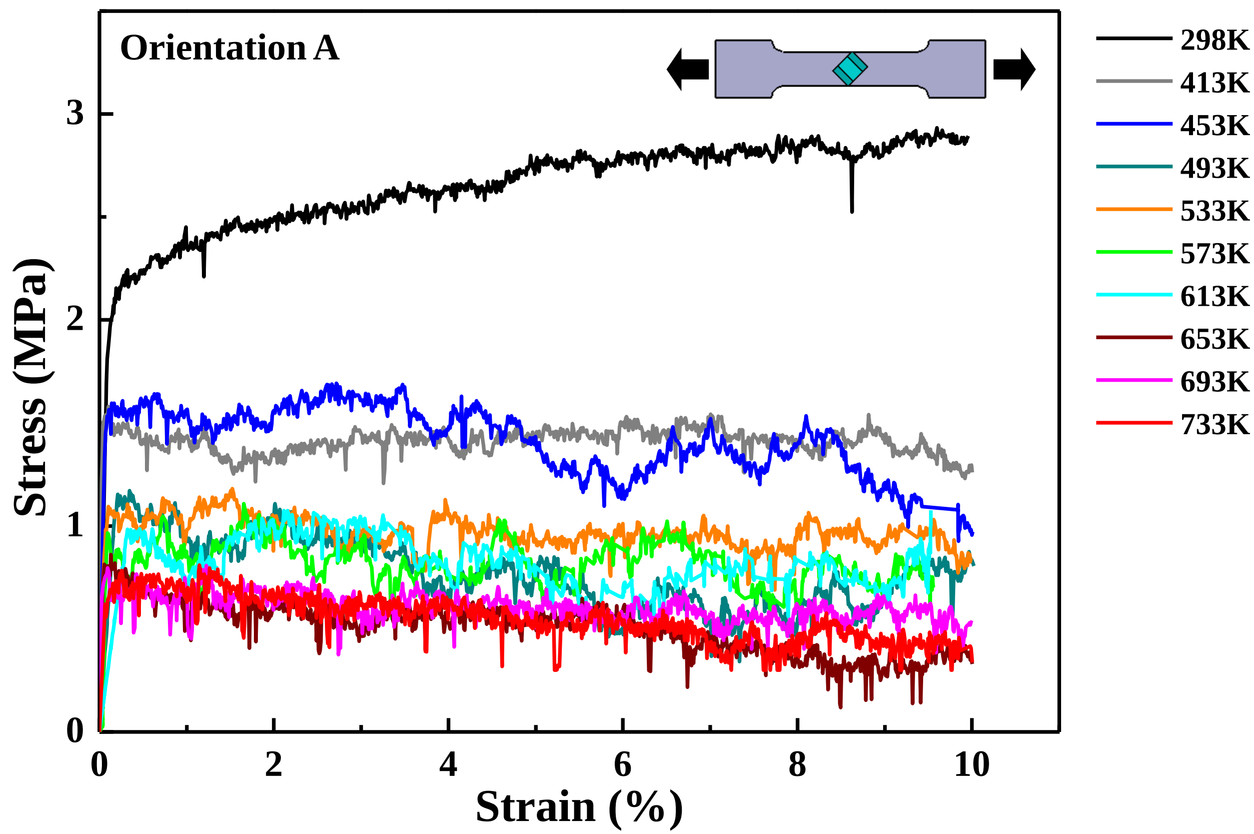
LD	Slip System	Schmid Factor
[0 $\bar{1}$ 1 0]	Basal	0
	Prismatic	0.43
	c+a	0.33
	Tensile Twin	0.50
	Compression Twin	0.42

→ **VPSC-GA Simulation**

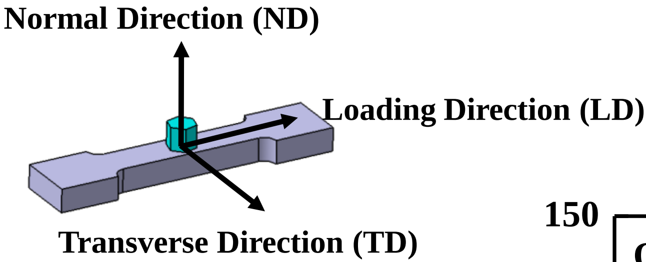
S: Single Slip, M: Multiple Slip

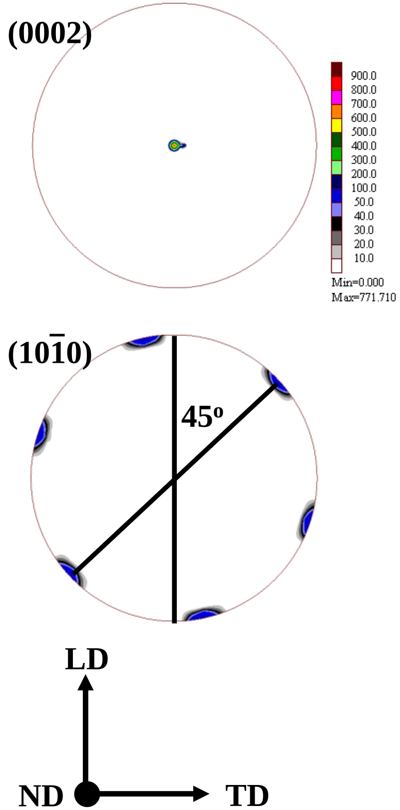
Tensile Direction // $[\overline{40}\ 20\ 20\ 37]$: Basal Slip Activation

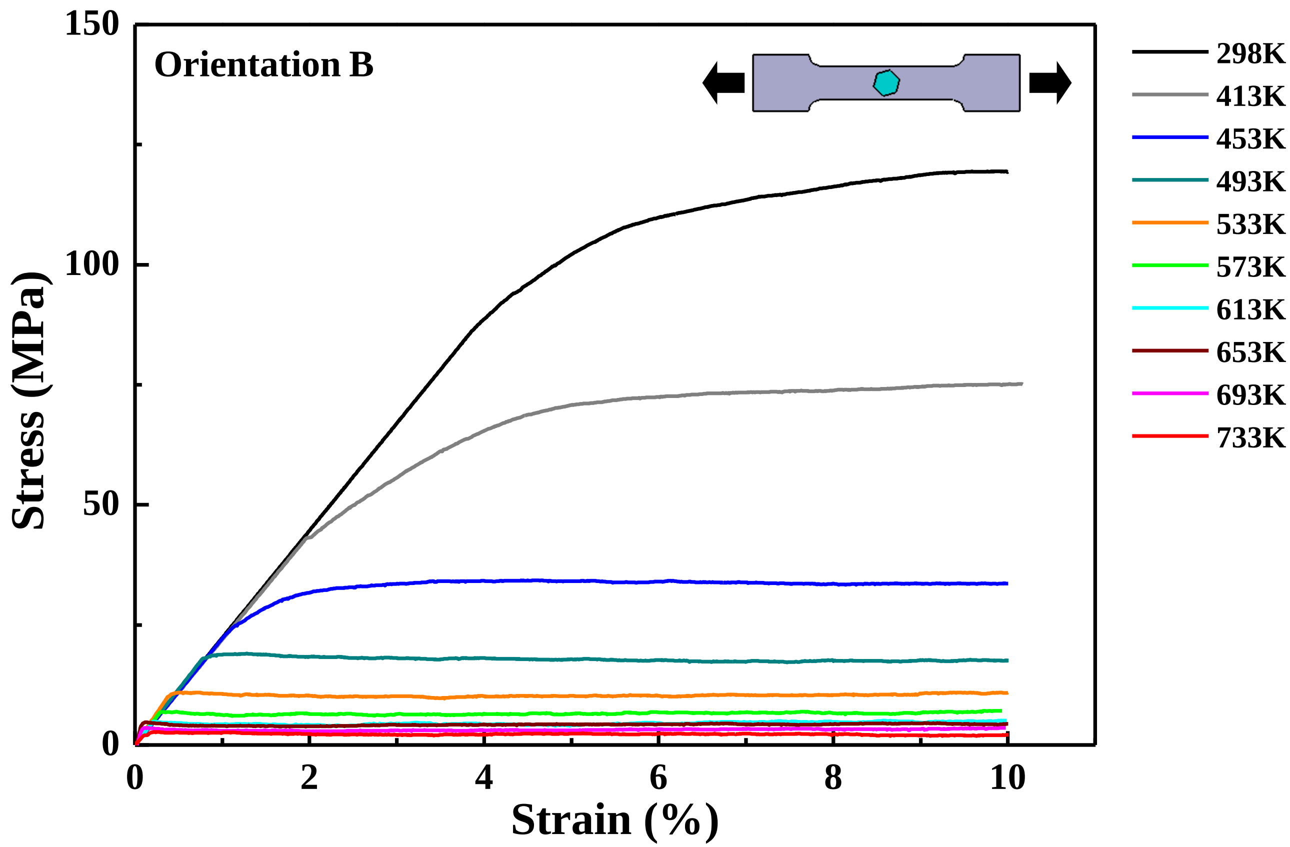




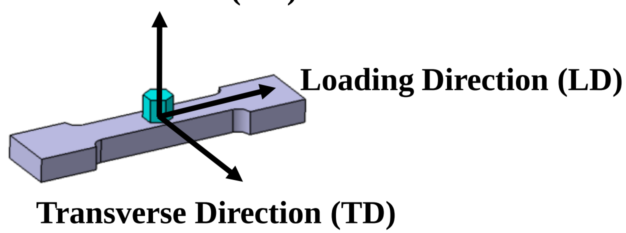
Tensile Direction // $[90\ \overline{123}\ 33\ 0]$: Prismatic Slip Activation

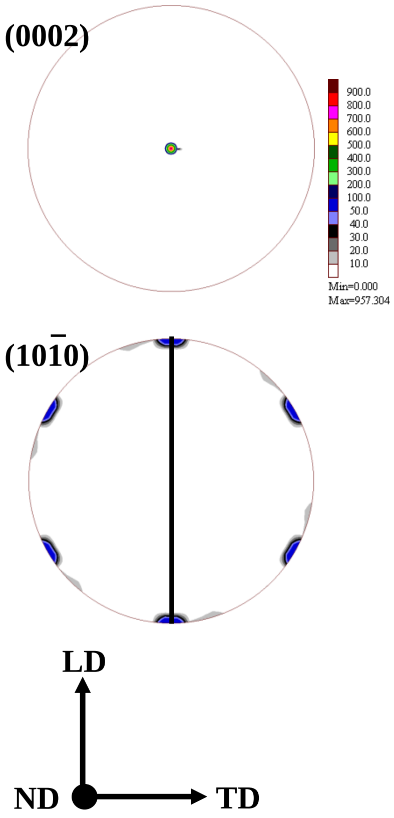




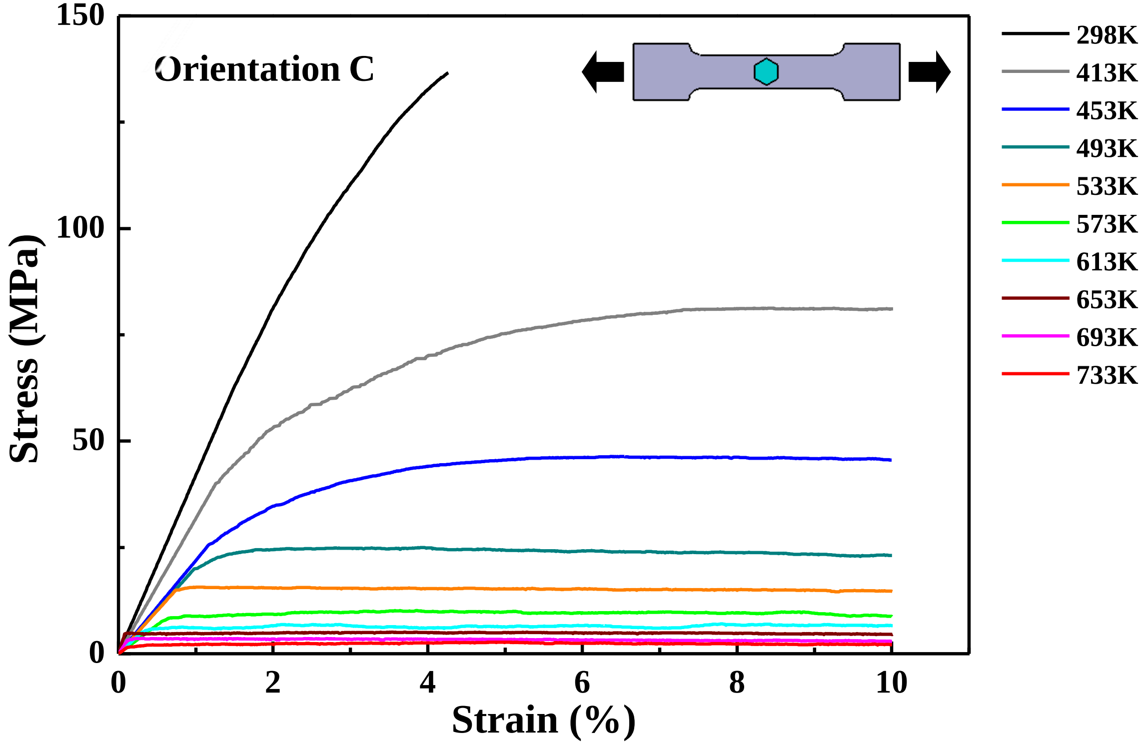


Loading Direction // [0 $\bar{1}$ 1 0]

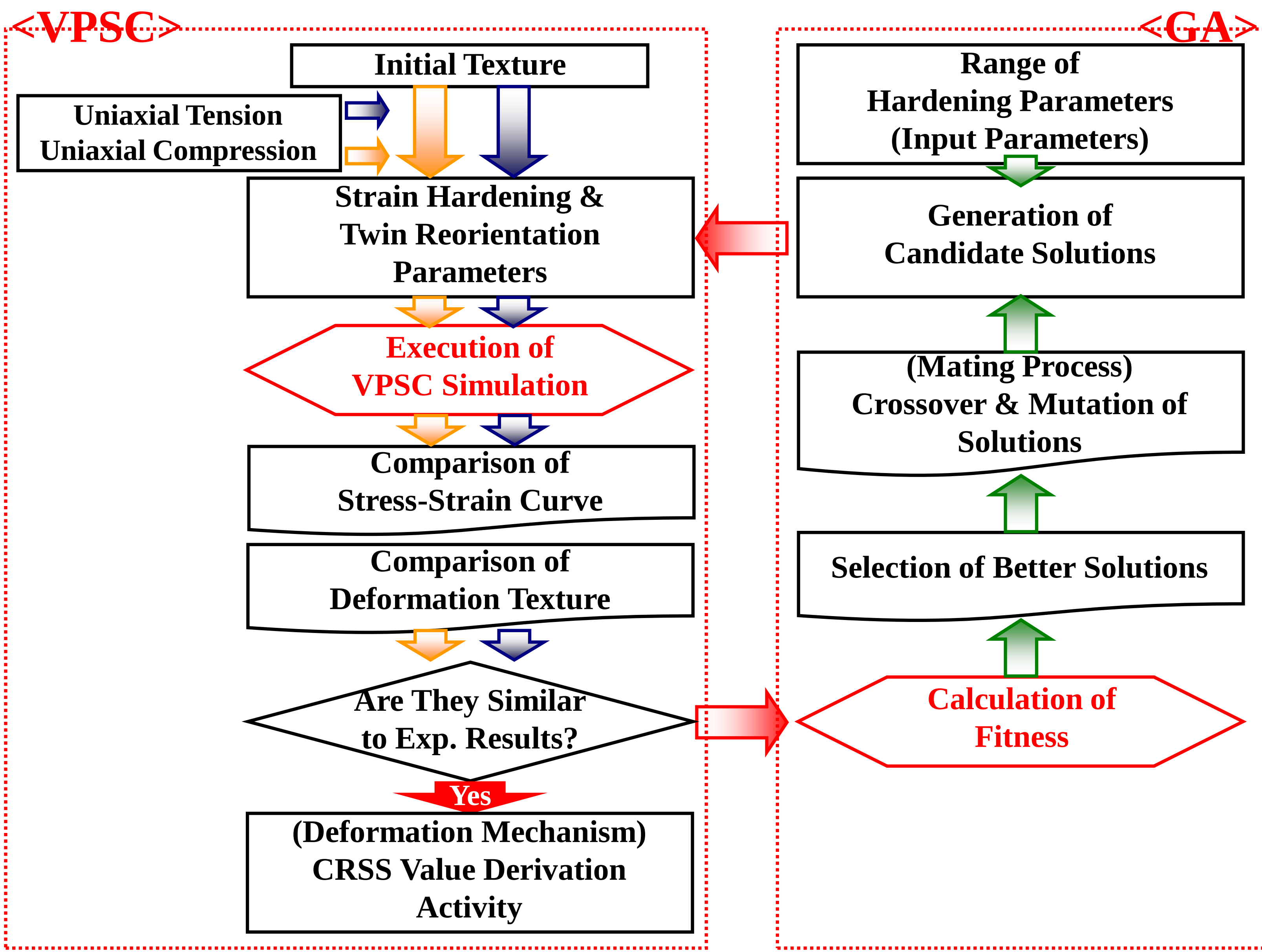




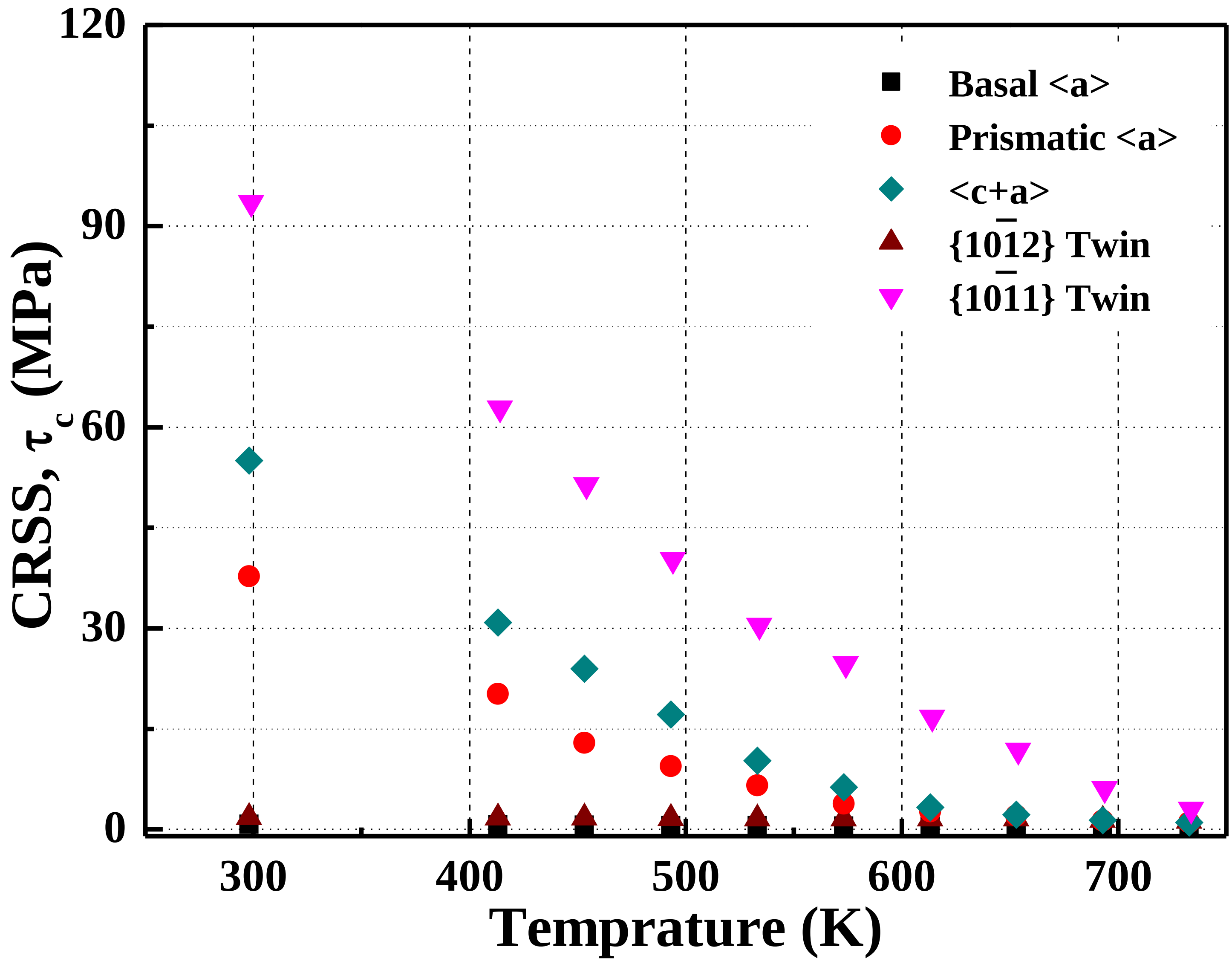
LD	Slip System	Schmid Factor
[0 $\bar{1}$ 1 0]	Basal	0
	Prismatic	0.43
	Pyramidal I	0.38
	Pyramidal II	0.30
	c+a	0.33
	Tensile Twin	0.50
	Compression Twin	0.42



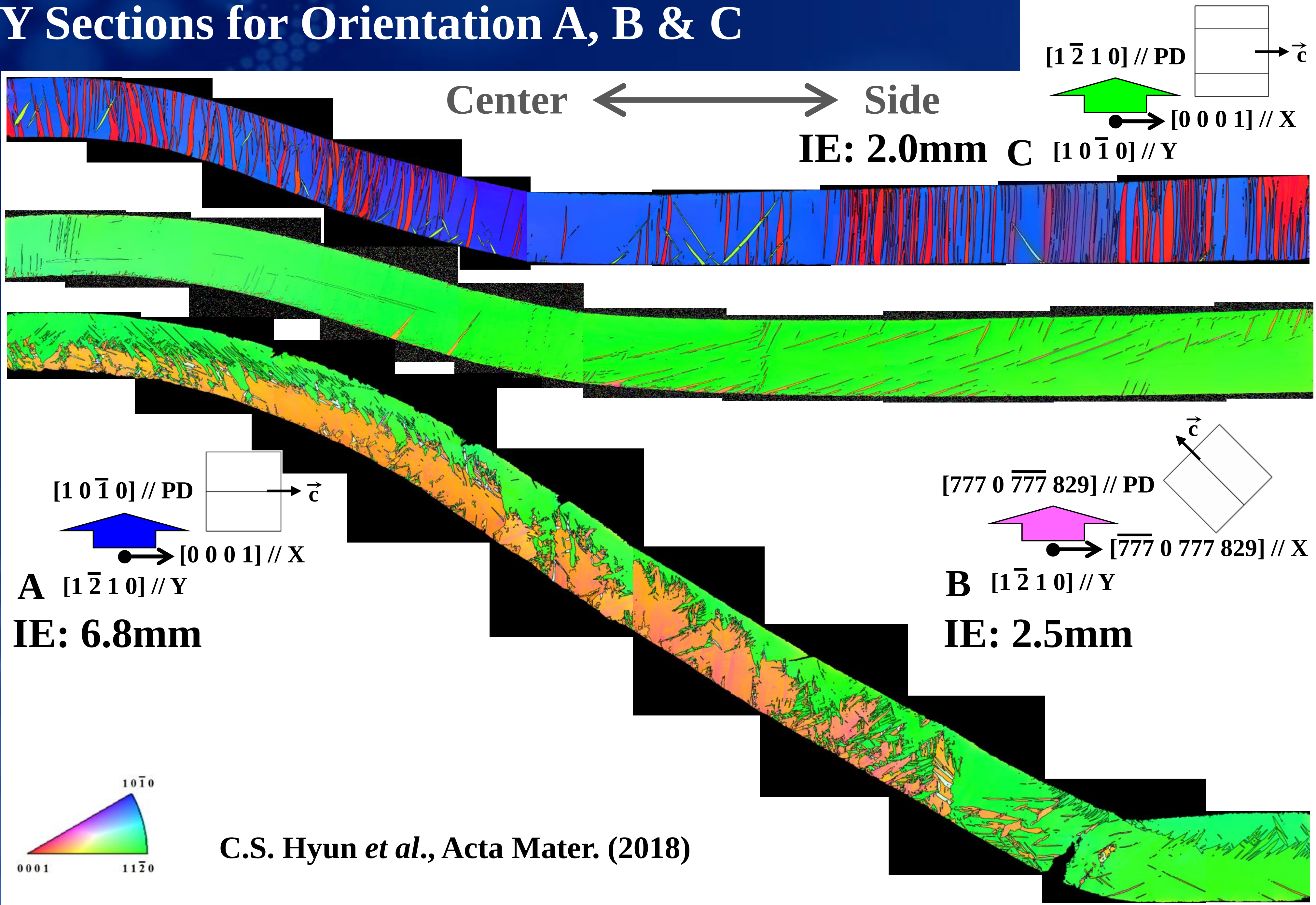
Procedure for VPSC-GA Simulation



Effects of Temperature on CRSS for Slip and Twinning Modes



Y Sections for Orientation A, B & C

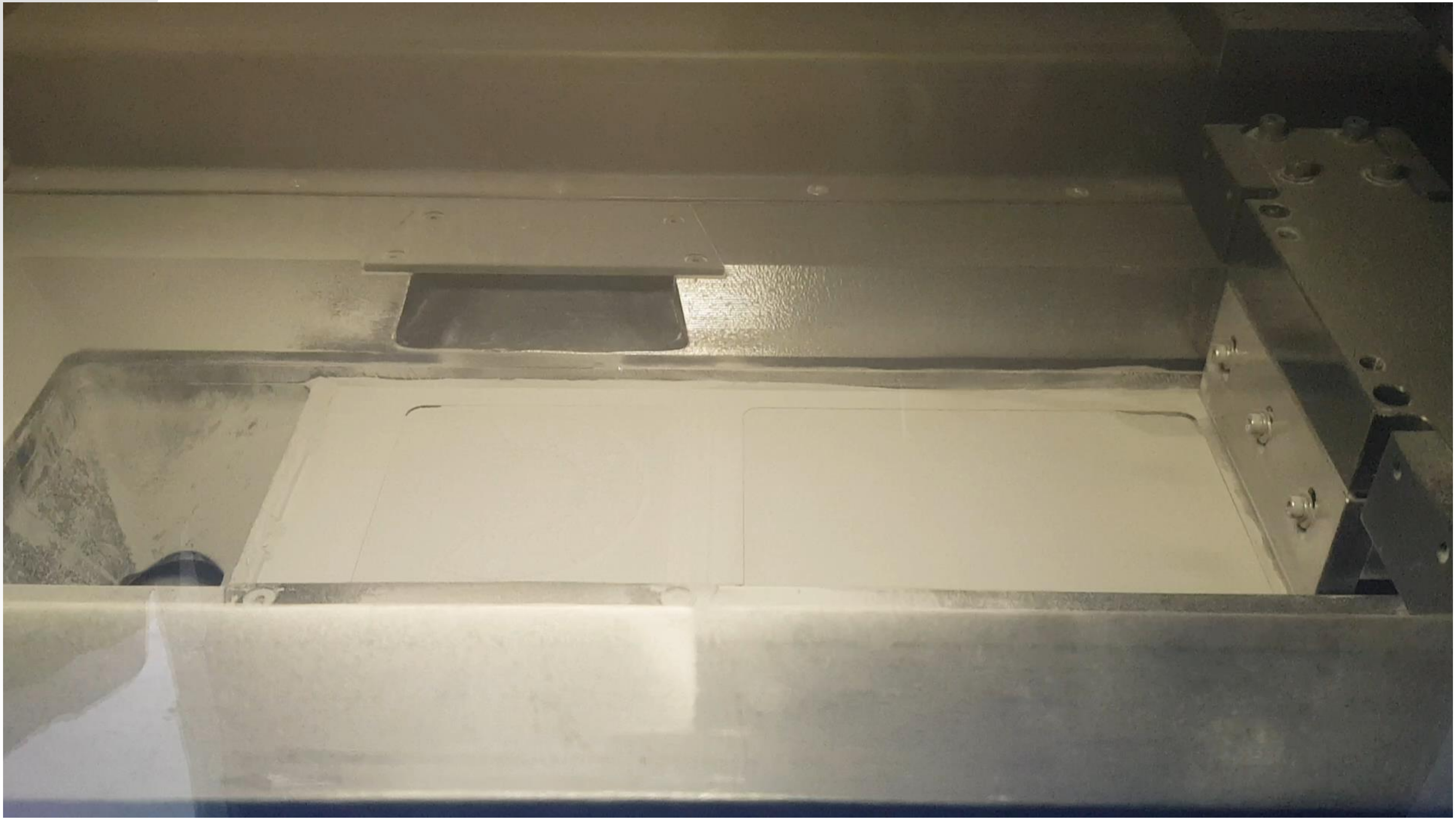


C.S. Hyun *et al*., Acta Mater. (2018)

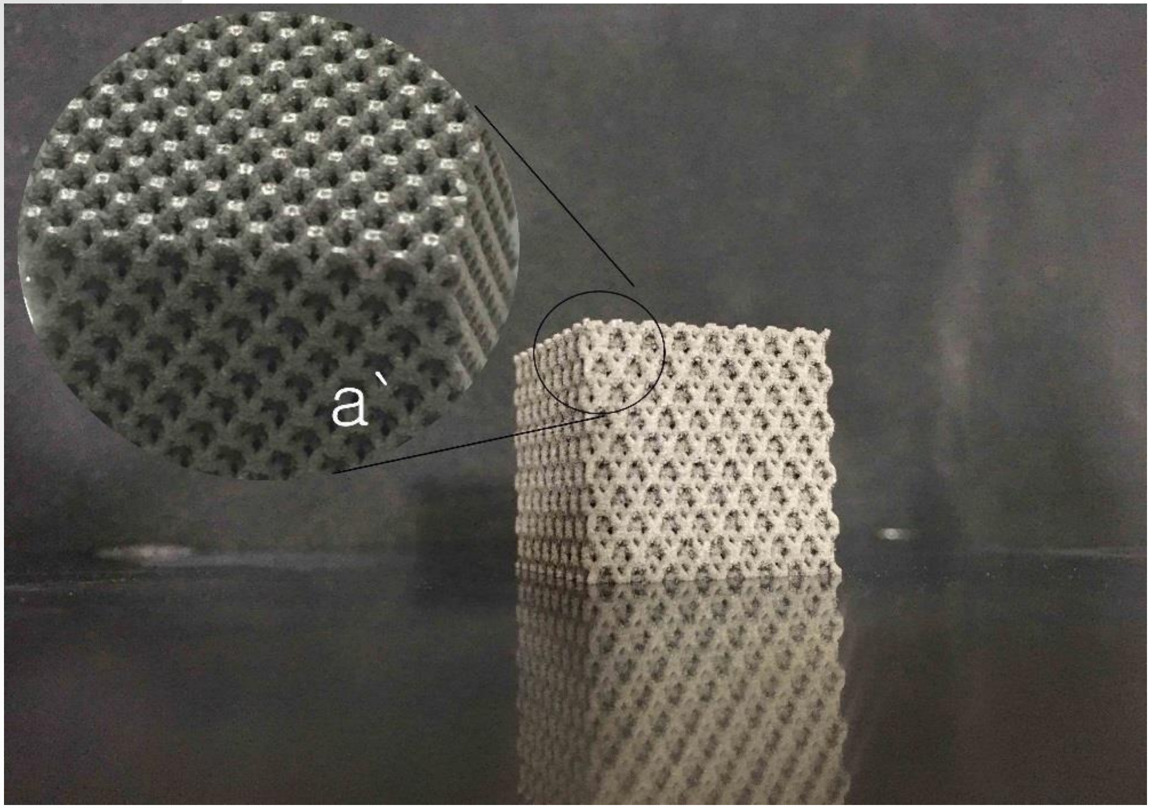
Magnesium 3D Printer (Daegun Tech & KMTRA)

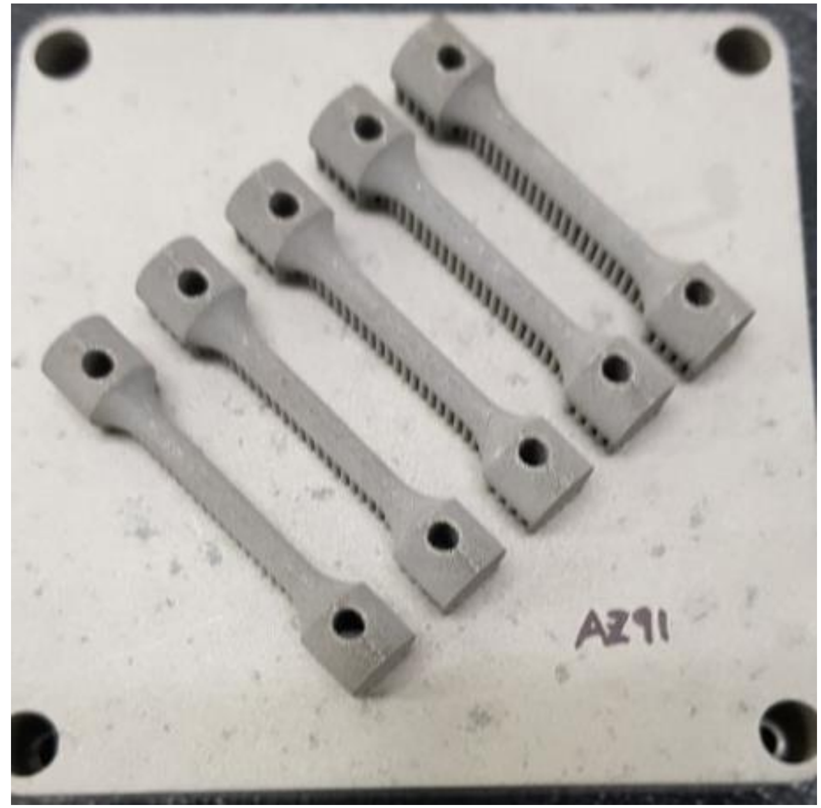
Build Volume	60x60x80
Layer Thickness	0.04mm~0.08mm
Focus Diameter	50 um
Scan Speed	Up to 7.0m/s
Laser Type	Yb-fiber Laser 200W
Dimensions (W*D*H)	1,540x1,215x2,000
Weight	1,500kg
Power	AC 220V 30A
Power Consumption	Max 2.2 kW
Gas	Argon

3D Printing of Mg Alloy

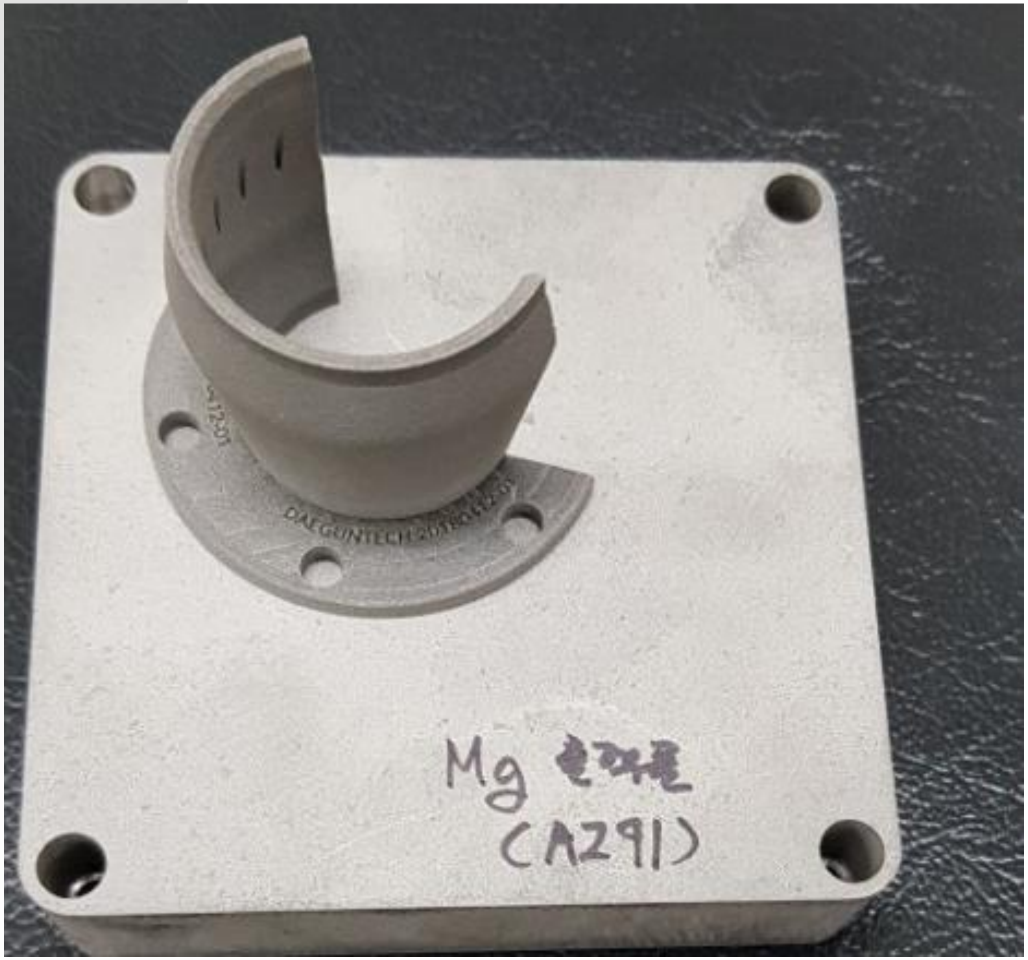


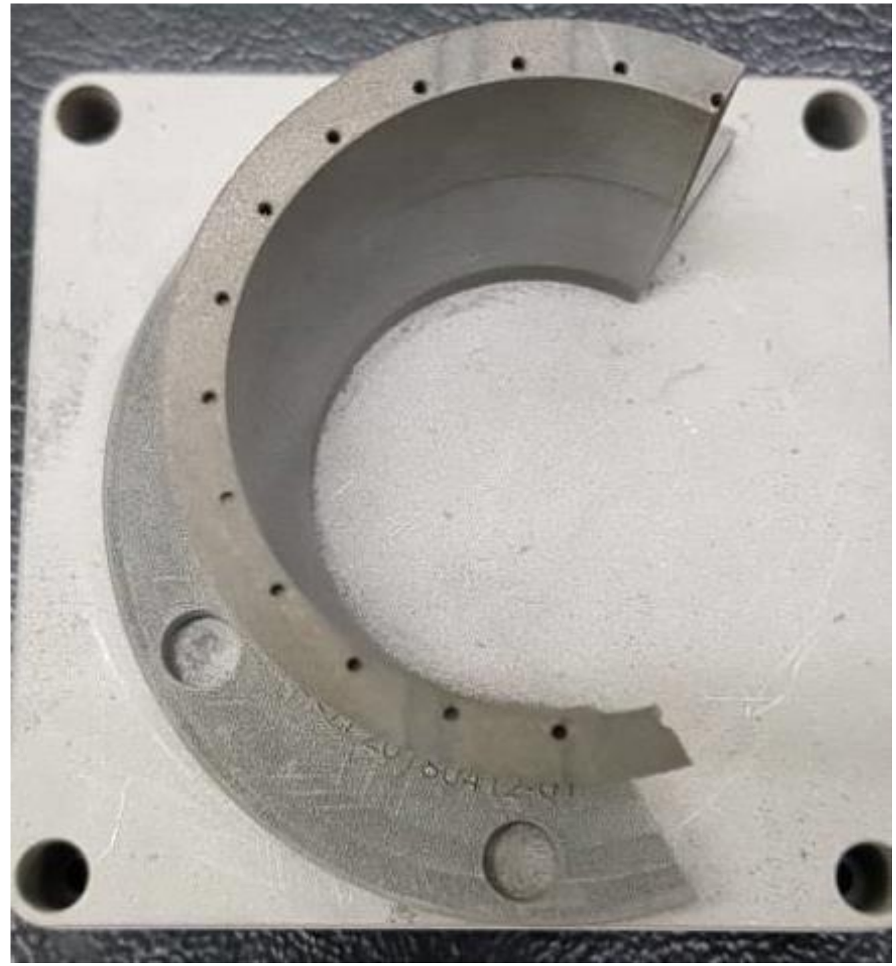
3DP of Magnesium Alloys





3DP of Magnesium Alloys





Thanks for your kind attention !

The 10th International Conference on Magnesium Alloys and their Applications
Jeju Island, Korea