2017년도 1학기 심화수업

Electroplasticity in metal alloys
- AZ91 magnesium alloy, AHSS-

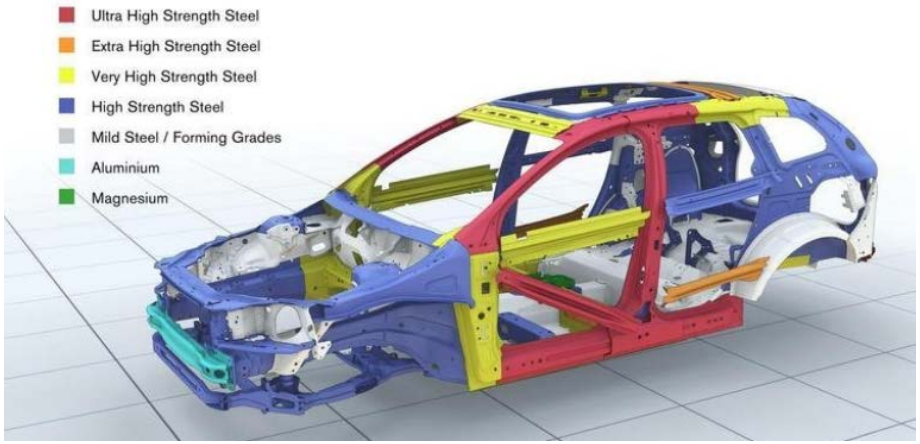
2017.03.20

Jeong Hye-Jin

CONTENTS

High strength & Lightweight automobiles

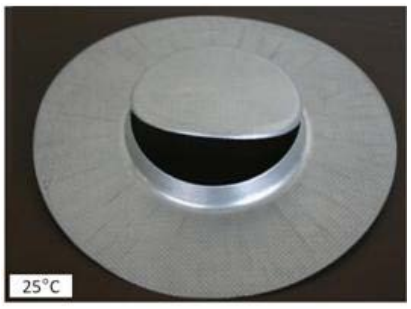
- **Body parts components**

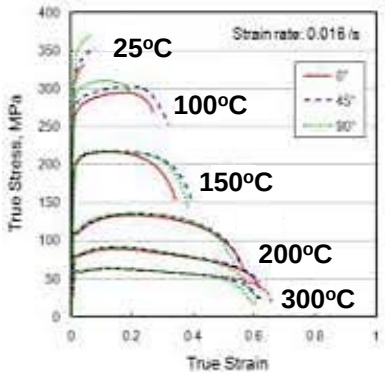


http://www.topspeed.com/cars/volvo/2009-volvo-xc60-ar52734/picture304392.html

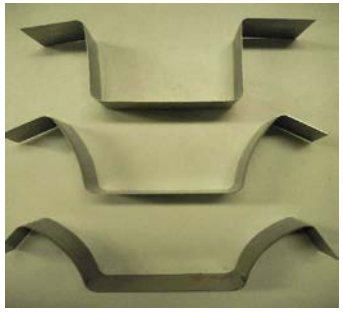
Body parts mostly consists of
high strength steel
&
lightweight metals
(Magnesium/Aluminum alloy)

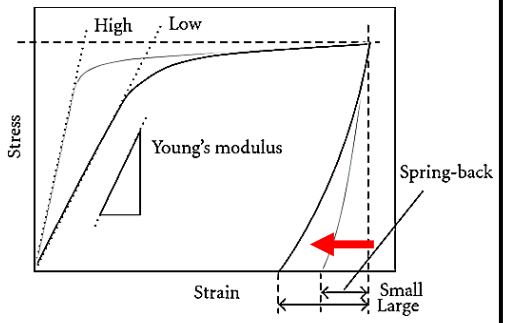
- **Limit properties of high strength & lightweight metals**





Low cold formability





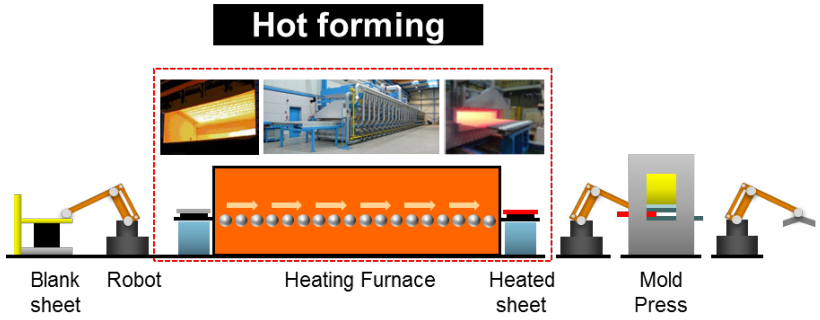
High spring back

https://www.esi-group.com/sites/default/files/software-services/1557/springback
http://openi.nlm.nih.gov/legacy/detailedresult.php?img=3132537

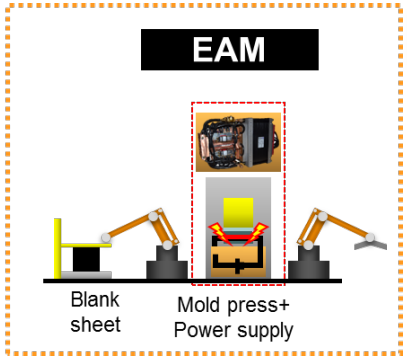
Electrically-assisted Manufacturing (EAM)

Electrically-Assisted Manufacturing (EAM)

: Metal forming by applying electric current during deformation



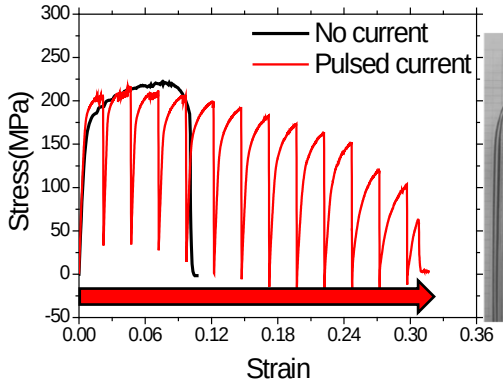
VS

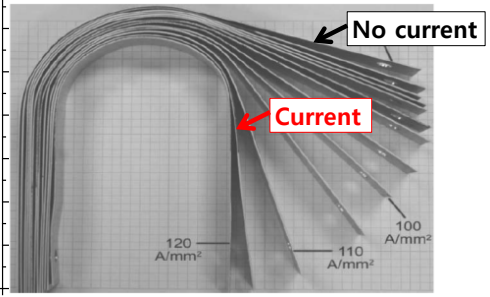


Advantages of EAM

- Space saving
- Rapid heating
- High energy efficiency
- No cost to maintain temperature of furnace/mold

▪ Enhancement of Formability



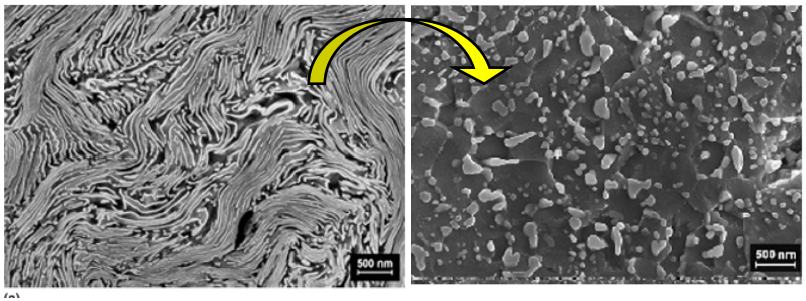


Increase of Elongation ***Decrease of Spring back***

Penn State Univ. (2009)

▪ Microstructure control

[deformed pearlitic steel] **After pulsing**

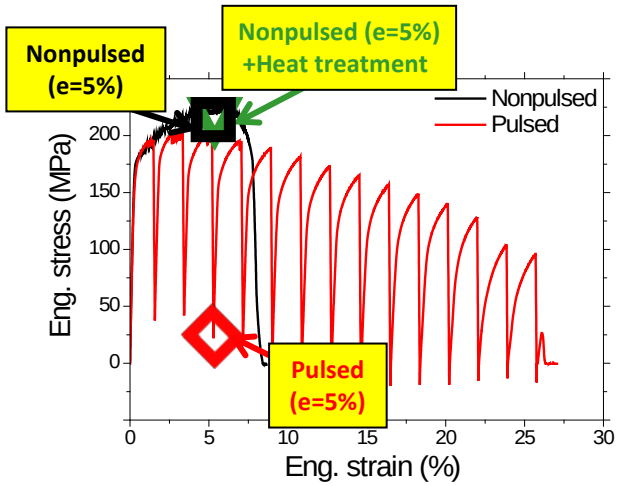


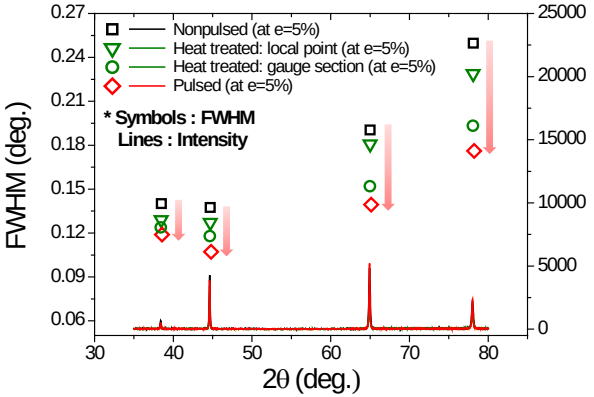
Acceleration of Spheroidization

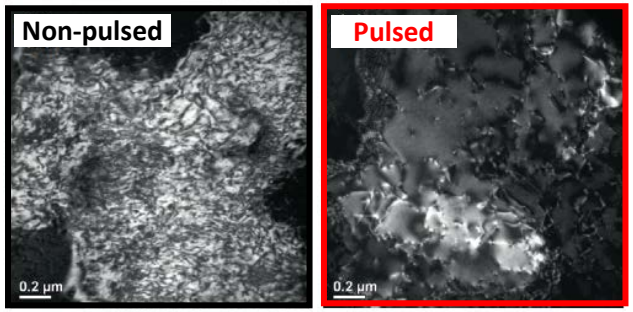
Edwin I et al., J. Mater. Res. (2010)

Application of EAM

- **AA5052 Al alloy**







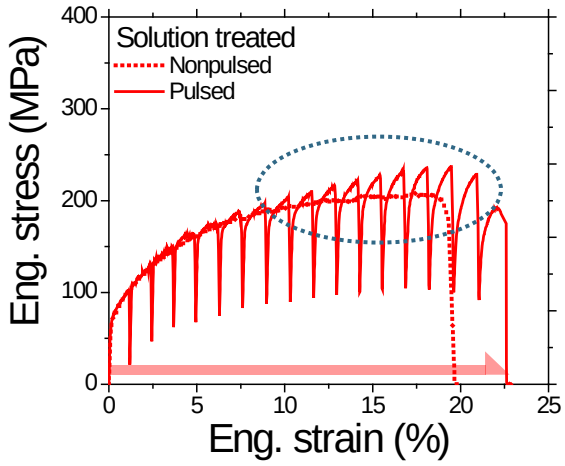
➔ ***Electrically assisted annealing***

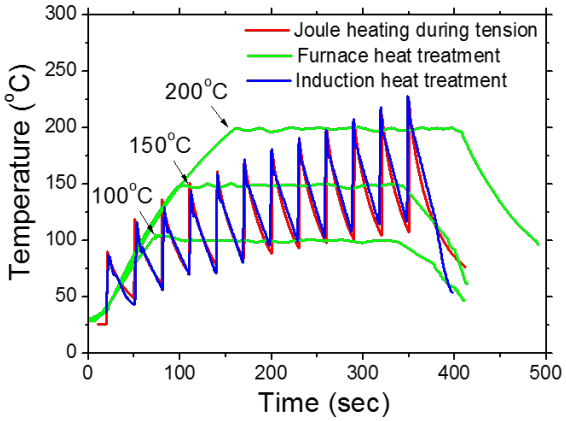
Scripta Mater. 75, 2014

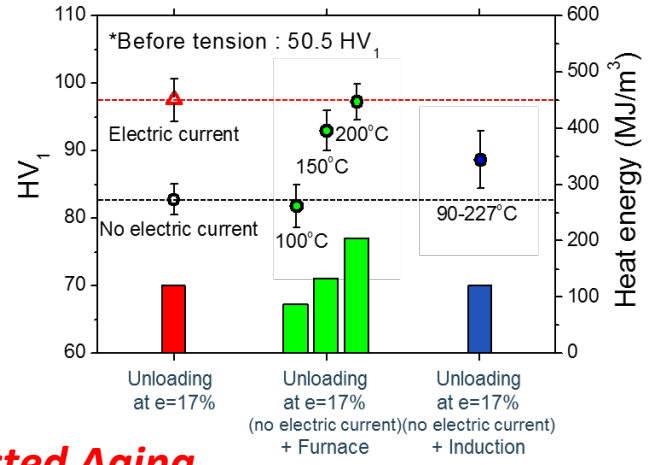
- **AA6061 alloy**

Specific heat (J/kg-°C)	910
Density (kg/m³)	2,712

$$Heat\ energy(\mathrm{J}/m^3) = m_{mass} C_{specific\ heat} \Delta Temp./\mathrm{V}_{volume}$$





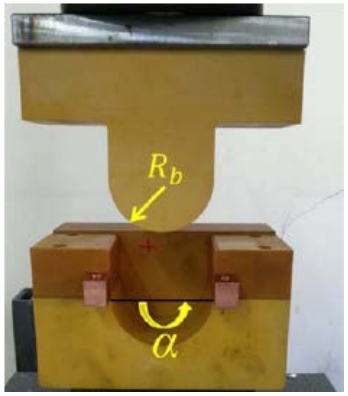


➔ ***Electrically assisted Aging***

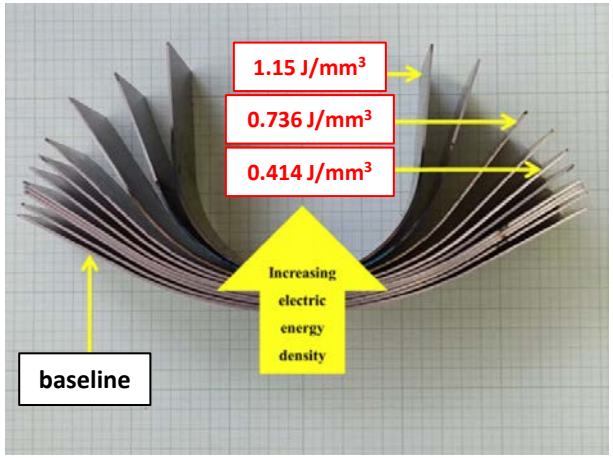
Int. J. Plast., (in Press), 2016

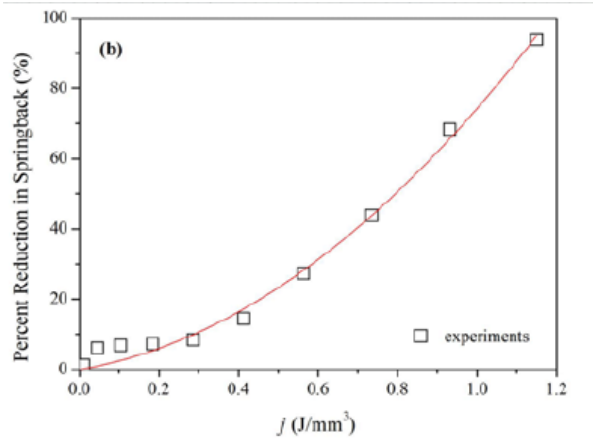
Application of EAM

- **AHSS (980 DP Steel)**



The U-bending fixture

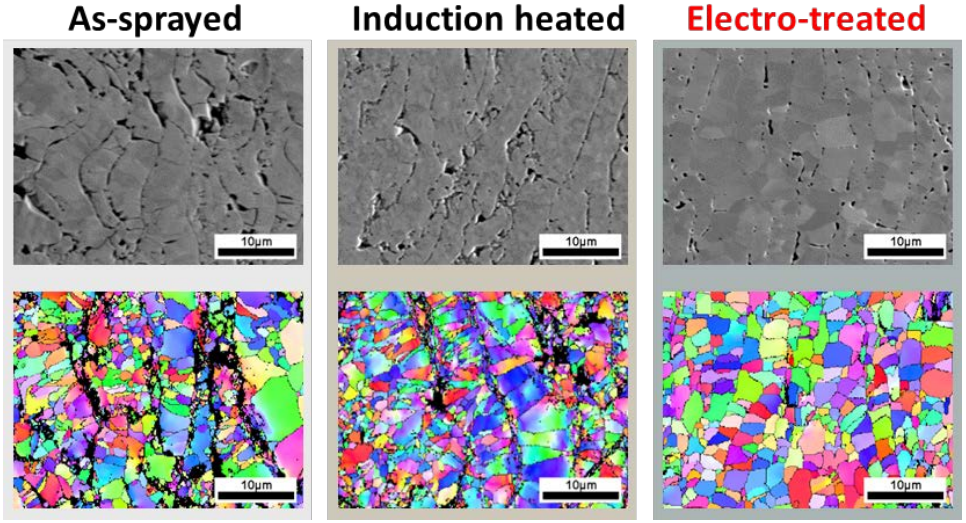


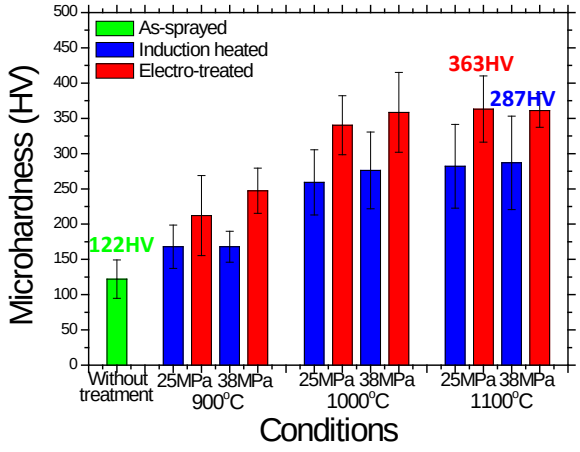


Int. J. Precis. Eng. Manuf. 15 (2014)

➔ ***Springback decreased by applying electric current***

- **Tungsten film**





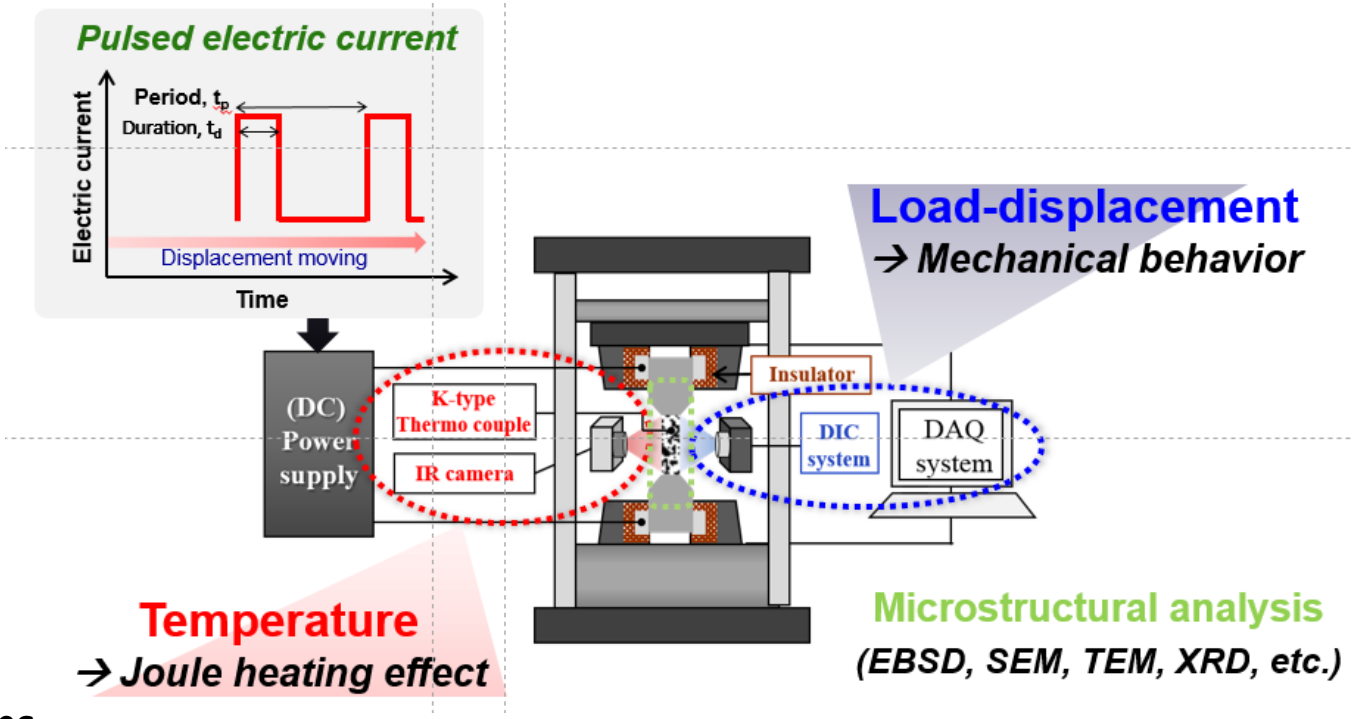
Significantly improved hardness!

➔ ***Electrically assisted Densification***

International Journal of Refractory Metals and Hard Materials (2016)

Experimental Procedure

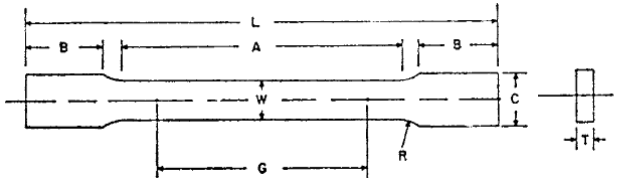
- **Instrumental set-up**



- **Specimens**

	Composition	Characteristic
AZ91 Mg alloy	9Al-1Zn	YS 290MPa, El 7%
Complex Phase steel (DP 980 소둔)	0.07C-2.5Mn-0.96Cr-0.05Nb	YS 849MPa, TS 1030MPa, El 9.3%

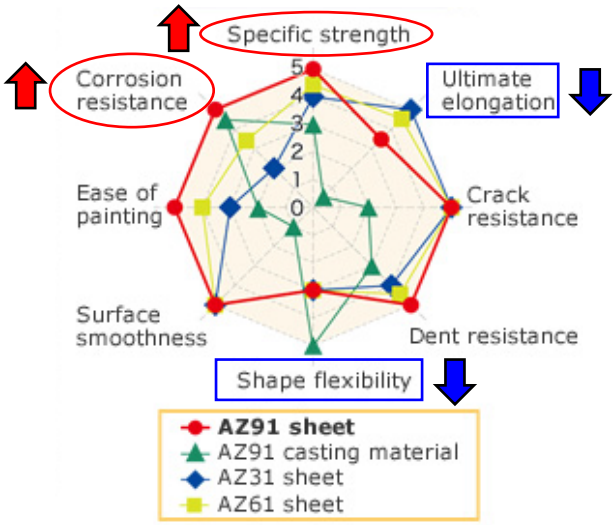
[Tensile specimen (ASTM E8)]



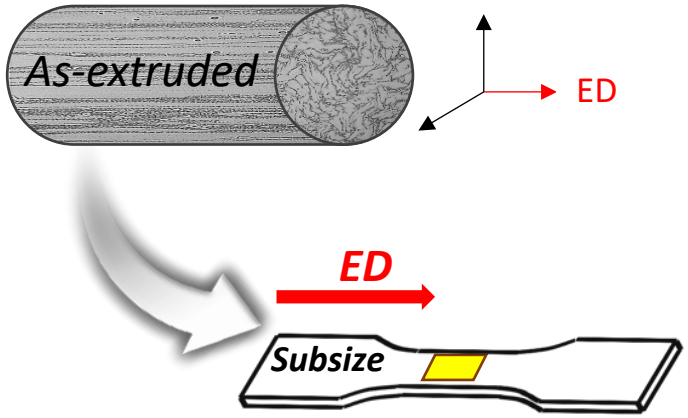
	Sub size	Standard size
G	25	50
W	6.25	12.5
L	100	200

Experimental Procedure

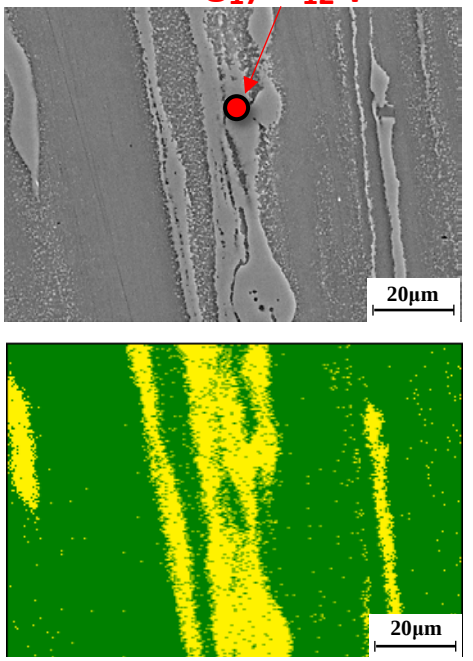
Property of AZ91



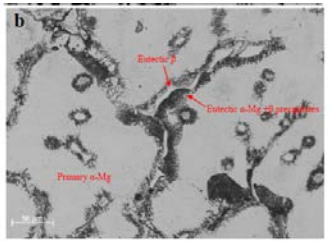
As-received specimen



EDS & SEM Analysis



Draw backs

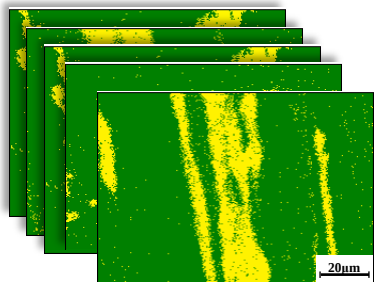


β phase ($Mg_{17}Al_{12}$)

- **β ($Mg_{17}Al_{12}$) phase**
- Intermetallic phase
- exist at α-Mg grain boundary
- brittle β phase
- Melting point : 330 – 350 °C

➔ ***Low formability***

Additional Heat treatment *or* ***grain refinement*** *process is required*

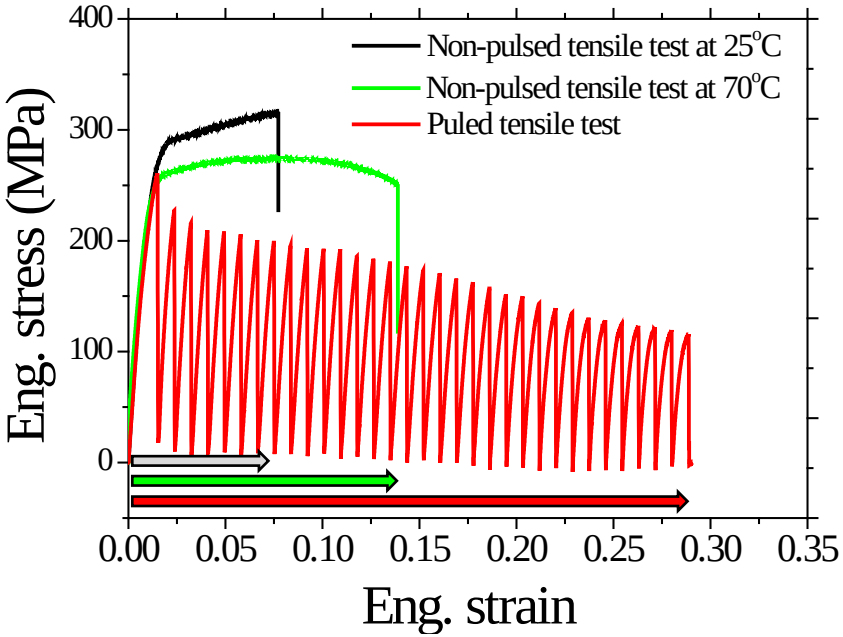


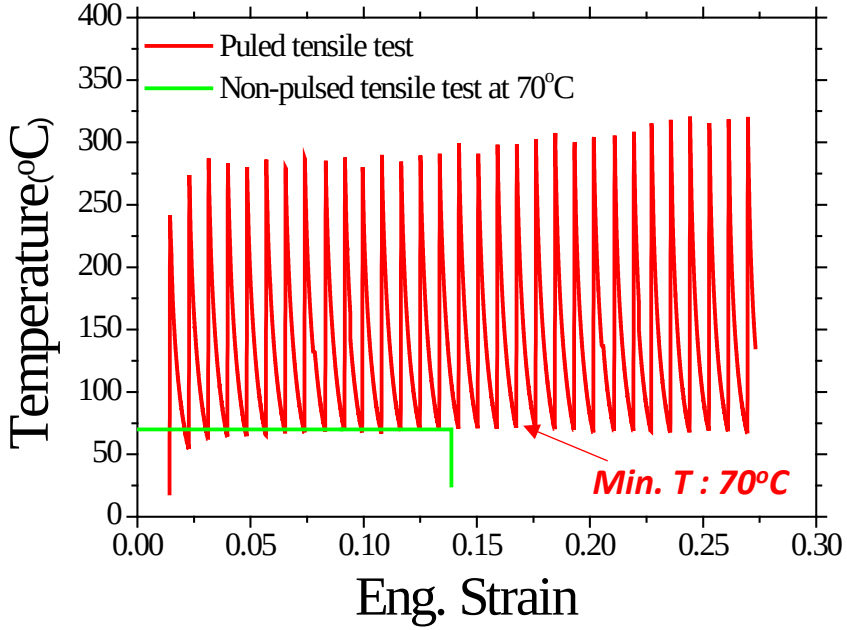
More than 5 images in each specimen

Phase	Fraction (%)
$Mg_{17}Al_{12}$	21.1 ± 3.4

Magnesium alloy (AZ91)

- **Pulsed tensile test**
  - Current density (ρ_i): 80A/mm^2, duration=0.5s. period=20s
  - Cross head speed : 1.0 mm/min



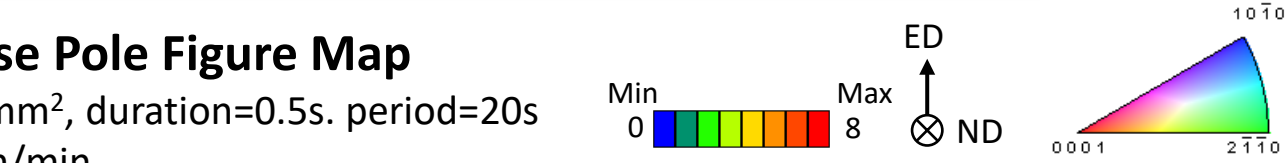


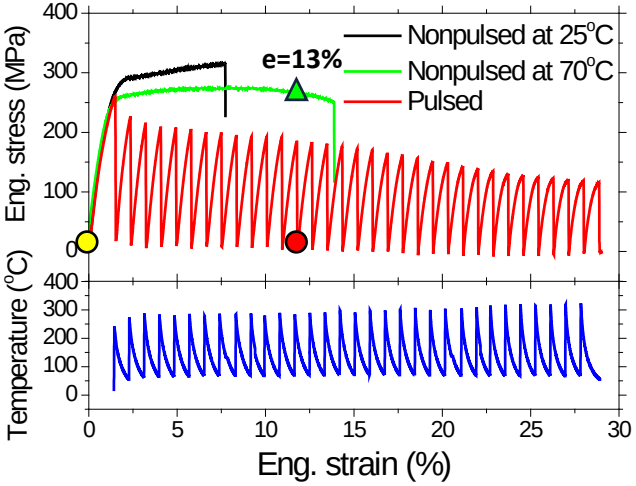
Property	Non-pulsed at 25°C	Non-pulsed at 70°C	Pulsed
Yield stress	290 *MPa*	250 *MPa*	-
Fracture elongation	7%	13.9%	**28.9%**

Why?

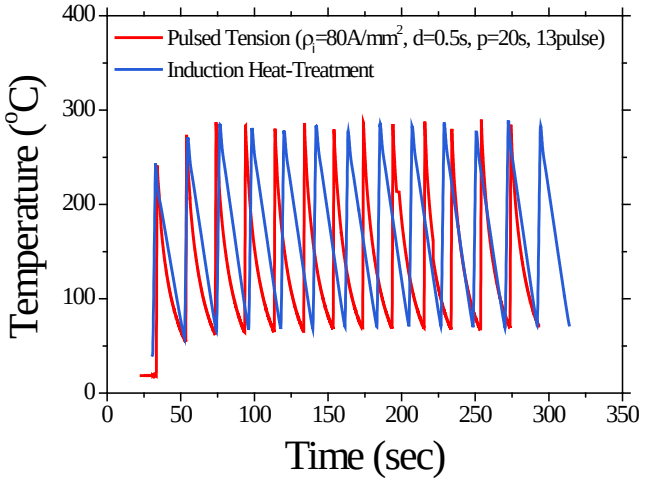
Magnesium alloy (AZ91)

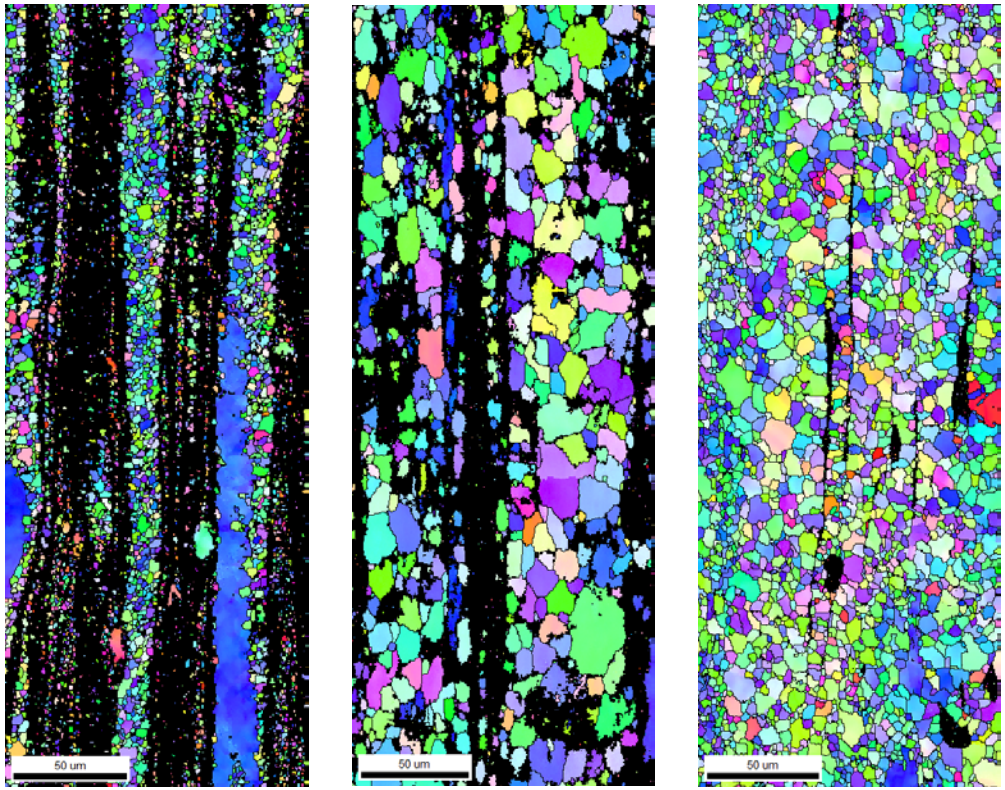
- **EBSD Analysis : Inverse Pole Figure Map**
  - Current density (ρ_i): 80A/mm^2, duration=0.5s. period=20s
  - Cross head speed : 1.0 mm/min





- **△ Non-pulsed tension at 70°C + Induction H-T**





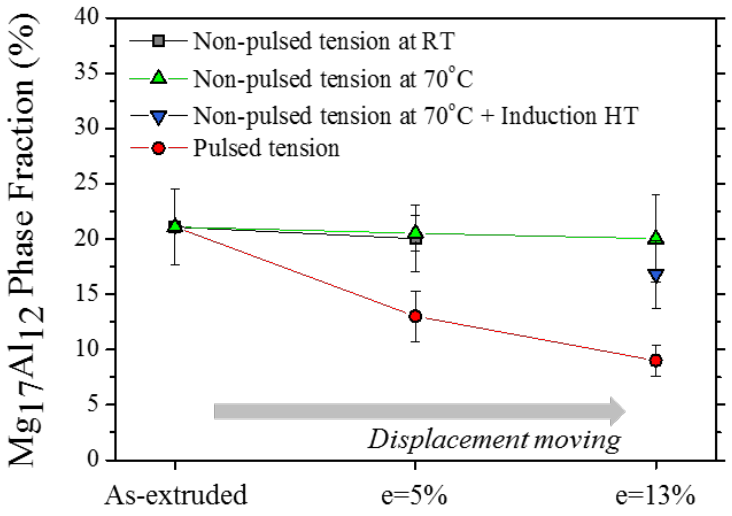
As-received

Eng. Strain : 13%
Non-pulsed tension at 70°C
+ Induction H-T

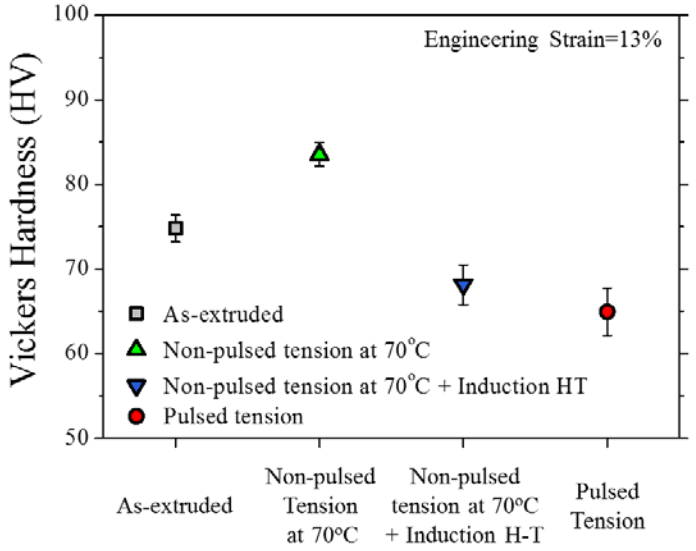
Pulsed tension

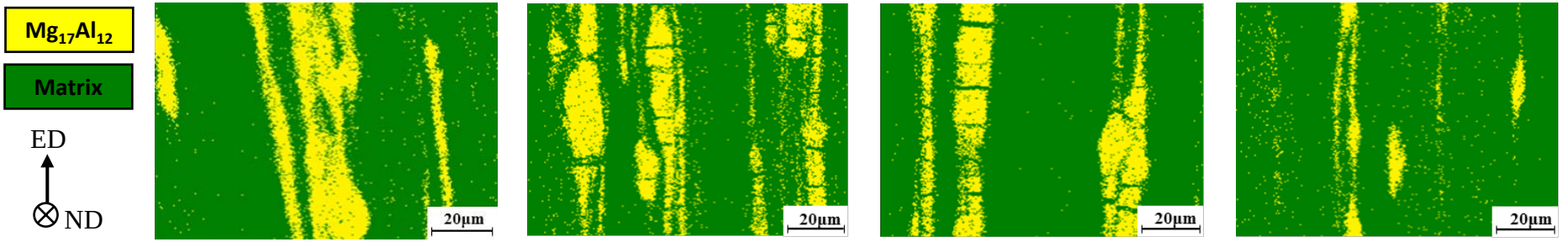
Magnesium alloy (AZ91)

- **$Mg_{17}Al_{12}$ Phase Fraction**



- **Vickers Hardness Measurement**





Eng. Strain : 0%
As-received

Eng. Strain : 13%
Non-pulsed tension at 70°C

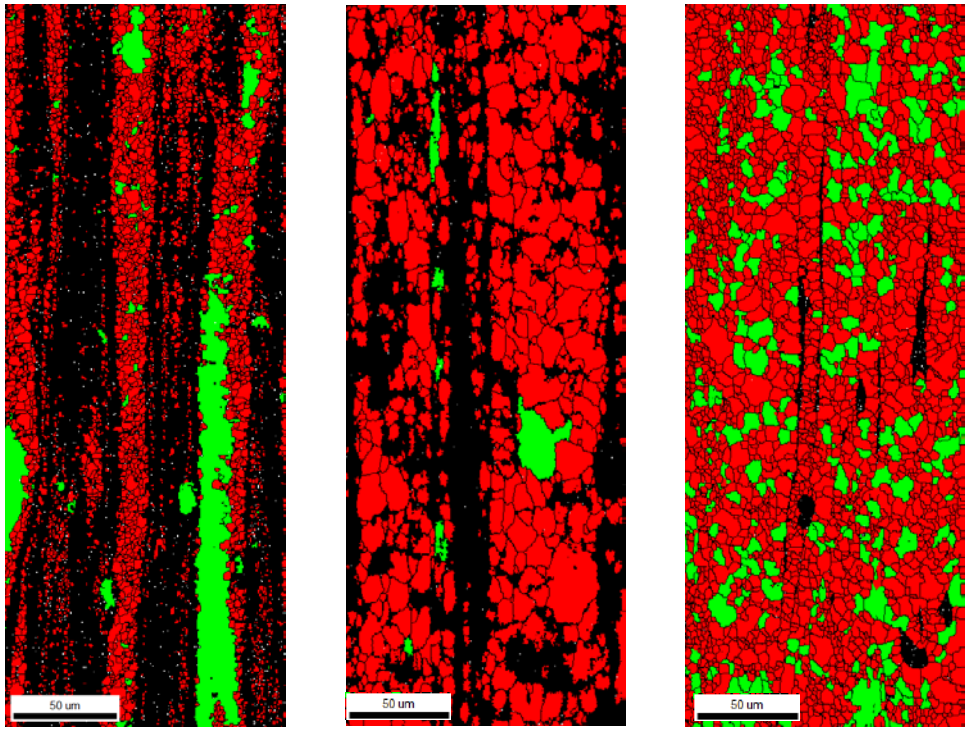
Eng. Strain : 13%
Non-pulsed tension at 70°C
+ Induction heat treatment

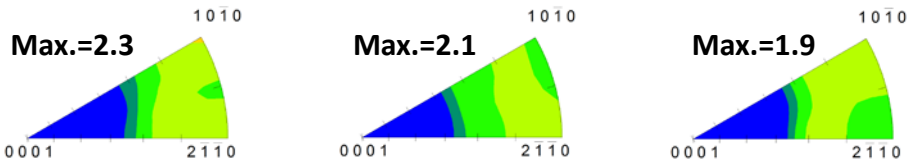
Eng. Strain : 13%
Pulsed tension

➔ ***Electric current induced Dissolution of $Mg_{17}Al_{12}$***

Magnesium alloy (AZ91)

- **EBSD Analysis : Grain Orientation Spread Map**
  - Current density (ρ_i): 80A/mm^2, duration=0.5s. period=20s
  - Cross head speed : 1.0 mm/min

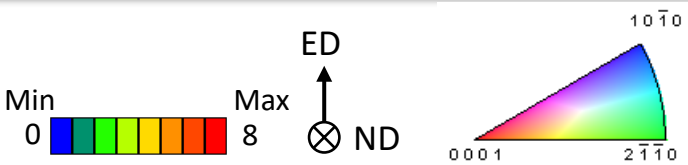




As-received

Eng. Strain : 13%
Non-pulsed tension at 70°C
+ Induction H-T

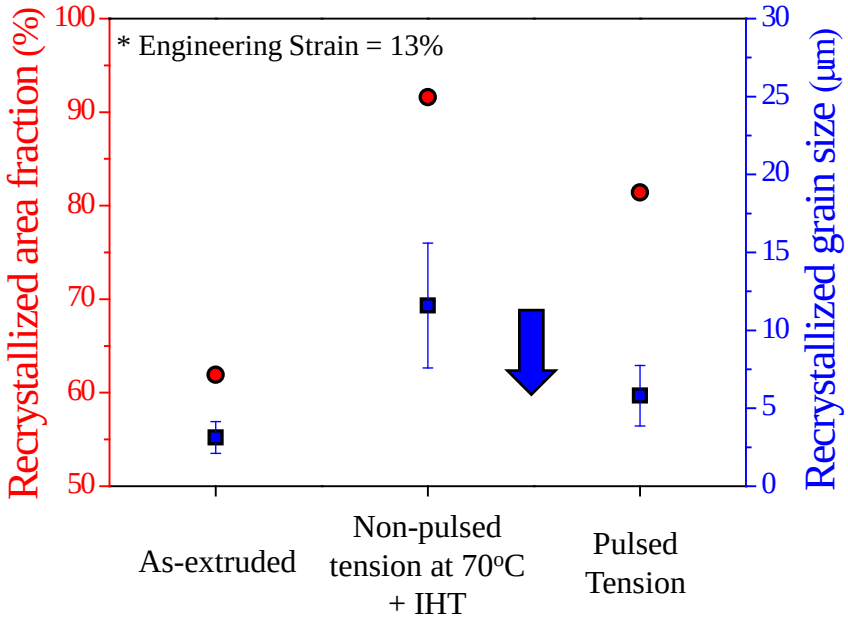
Pulsed tension



Recrystallized grain

Un-recrystallized grain

Recrystallized grain : 0<GOS<2°

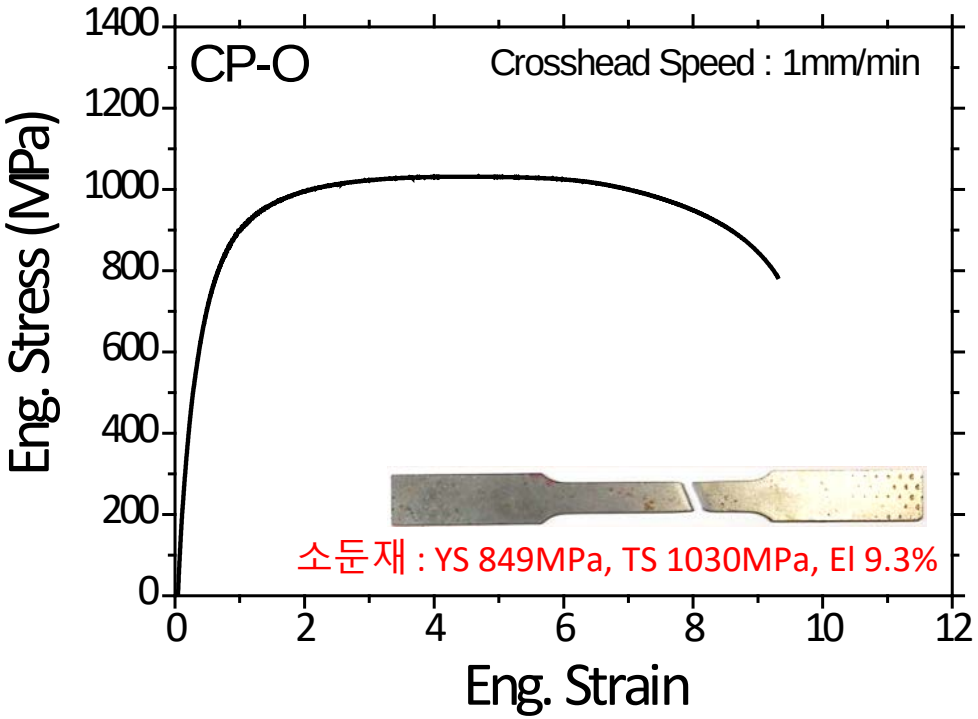


980MPa grade steel

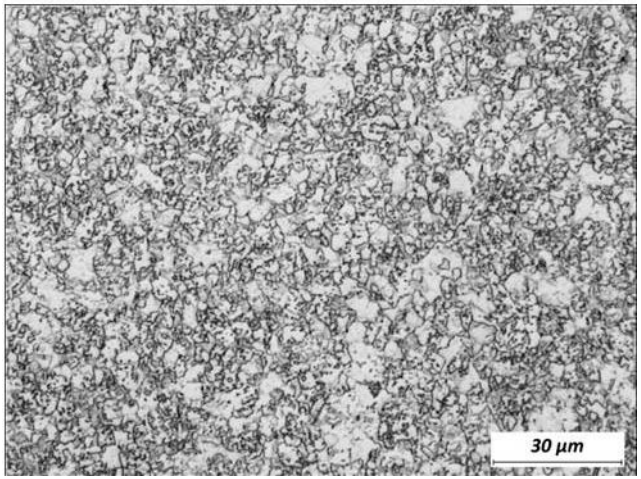
- **Composition** (wt.%)

C	Mn	Cr	Nb
0.07	2.5	0.96	0.05

- **CP강 : 소둔재**

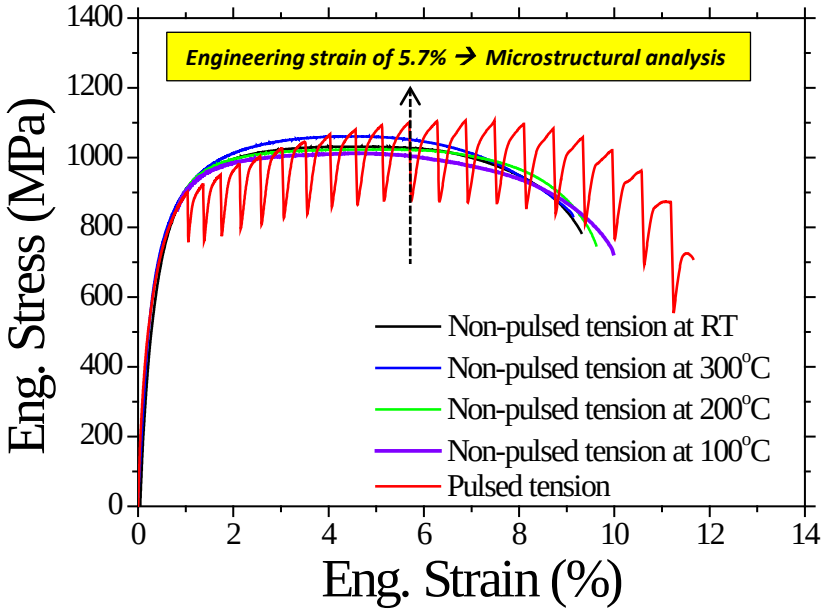


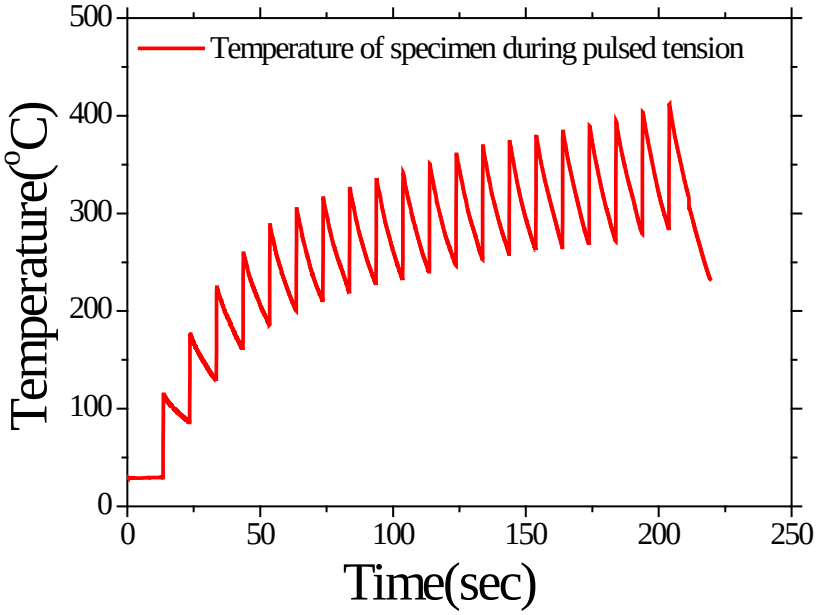
- **Optical image**



980MPa grade steel

- **Pulsed tensile test**
  - Current density (ρ_o): 95A/mm^2, duration=0.1s. period=10s
  - Cross head speed : 1.0 mm/min
  - ***ρ_o=current density based on initial cross-sectional area***



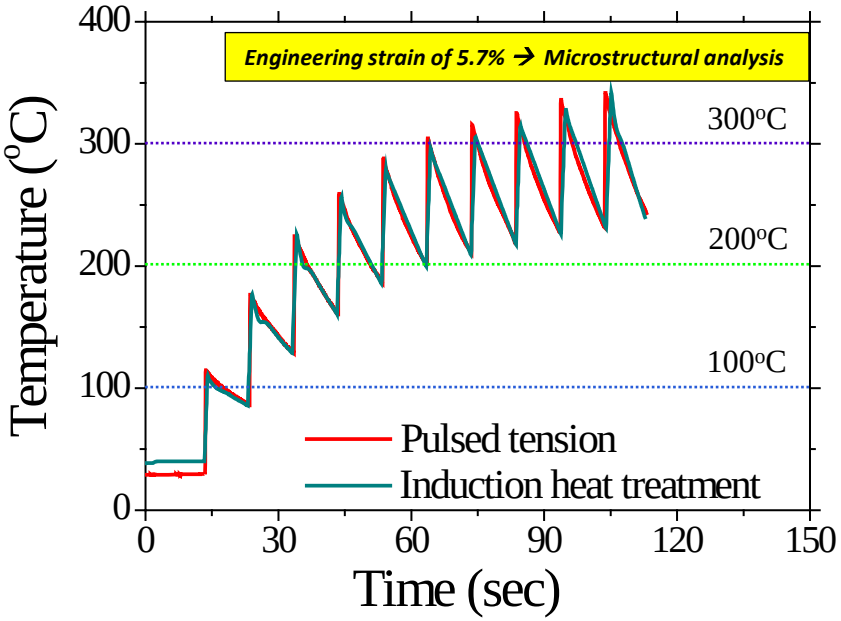


Property	Non-pulsed	Pulsed	100°C	200°C	300°C
UTS	1030 *MPa*	1107*MPa*	*1012MPa*	*1023MPa*	*1060MPa*
Fracture elongation	9.3%	**12.1%**	**10%**	**9.6%**	**9.1%**

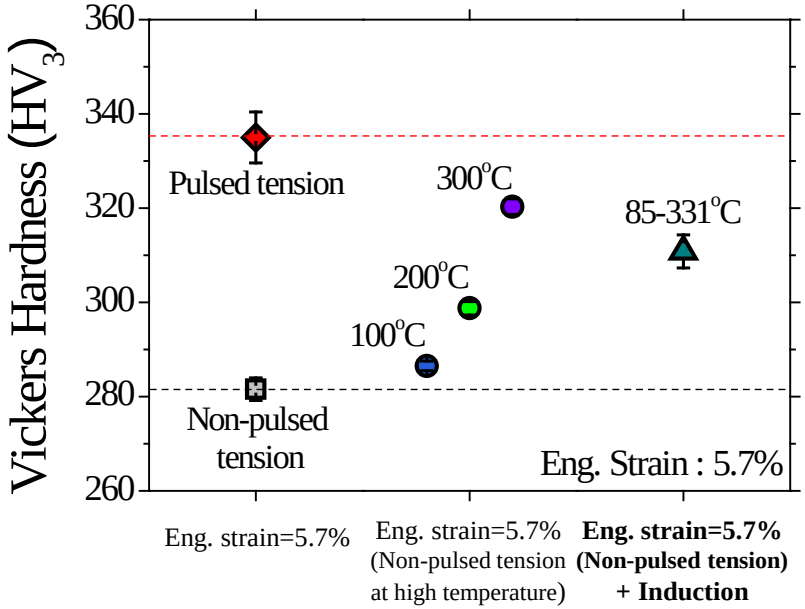
980MPa grade steel

- **Pulsed tensile test**
  - Current density (ρ_o): 95A/mm^2, duration=0.1s. period=10s
  - Cross head speed : 1.0 mm/min
  - ***ρ_o=current density based on initial cross-sectional area***

- **Temperature history**



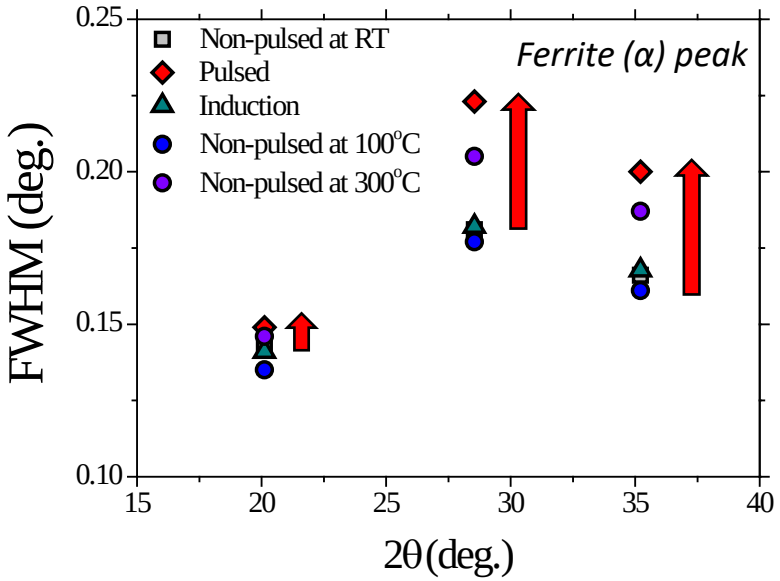
- **Vickers Hardness Measurement**



➔ *From the Vickers hardness measurement, it can be observed that **applying electric current** can accelerate "**aging effect**" with a distinct effect from Joule heating*

980MPa grade steel

- **XRD Analysis : FWHM Value**



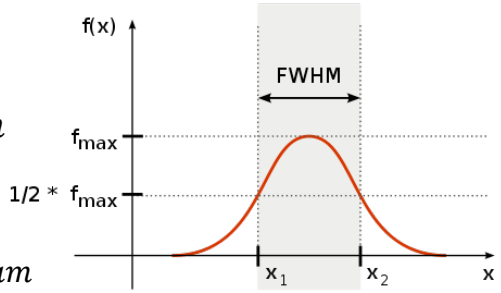
❖ ***Williamson-Hall (WH) approach***

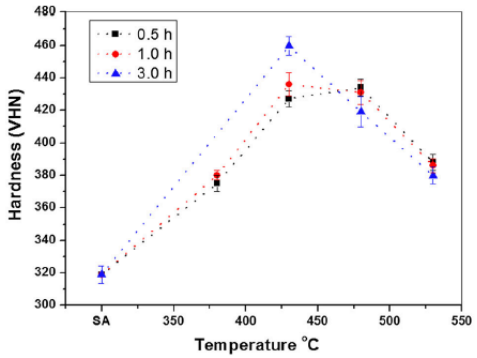
$$\beta^* = \frac{1}{D} + 2\varepsilon K$$

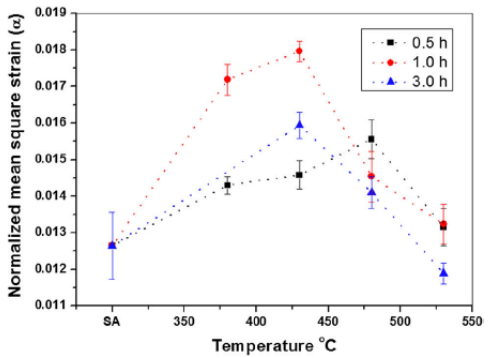
β : *Full Width at Half Maximum*

$\beta^* = \frac{\beta \cos\theta}{\lambda}$, D : *average grain size*

$K = \frac{2\sin\theta}{\lambda}$, λ: *wavelength of Xray beam*







- ***Annihilation of dislocations*** *and* ***fine precipitation*** *occur simultaneously on aging*
- *The hardness and micro strain are increased by* ***formation of precipitates*** *which are coherent with matrix*
- *The coarsening of the precipitation leading to loss of coherency with the matrix*
  ➔ *decrease of micro strain with increasing temperature*

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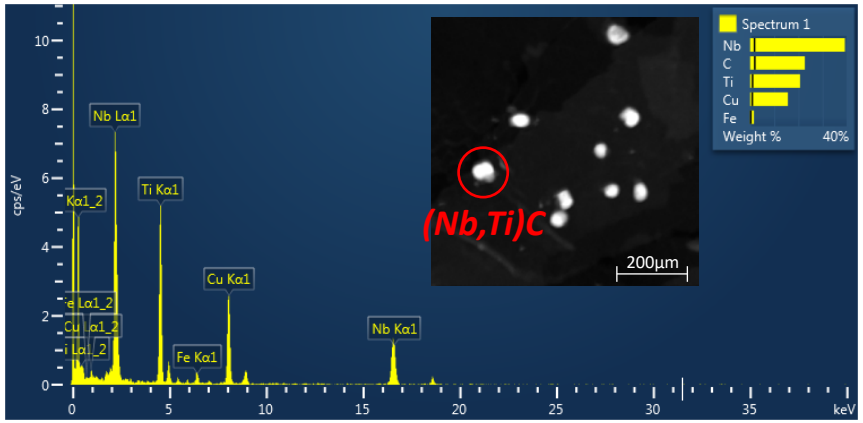
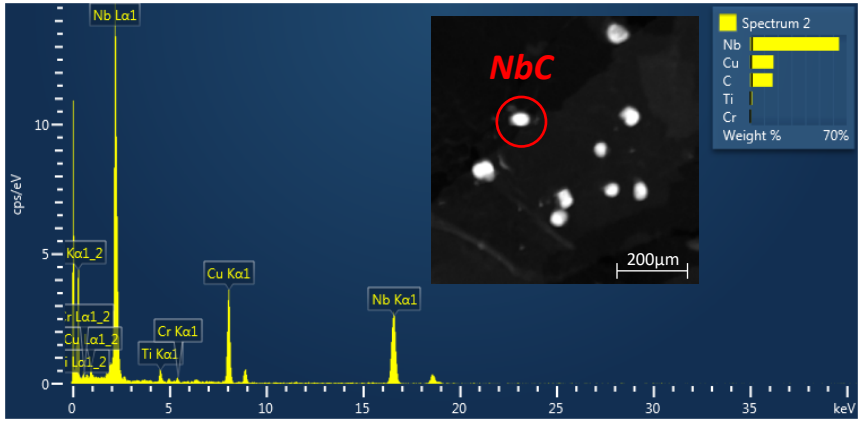
980MPa grade steel

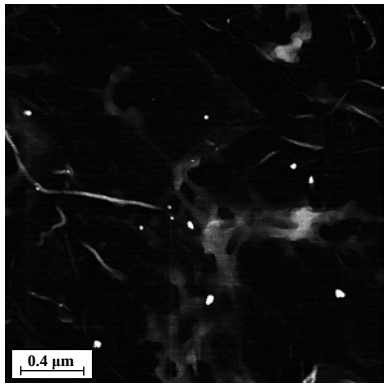
- **TEM Analysis** *at engineering strain of 5.7%*

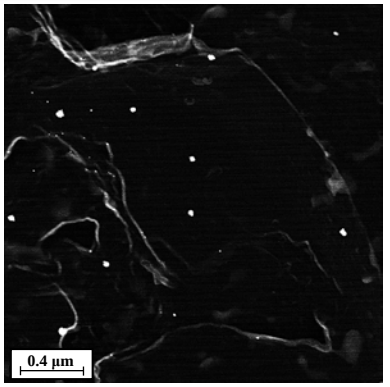
(Using Cu grid and replica film, specimens were prepared)



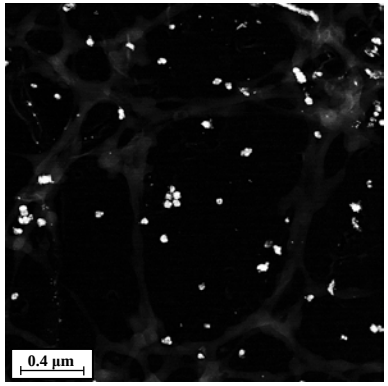


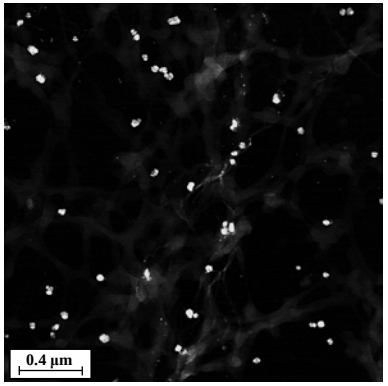
Non-pulsed Tension





Pulsed Tension

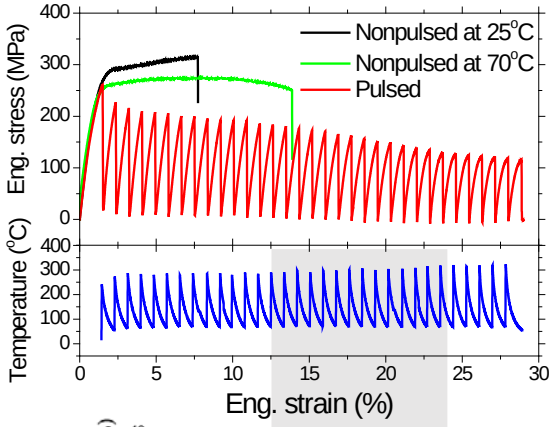


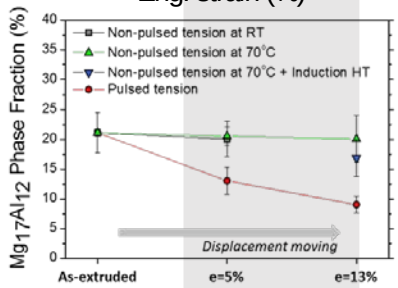


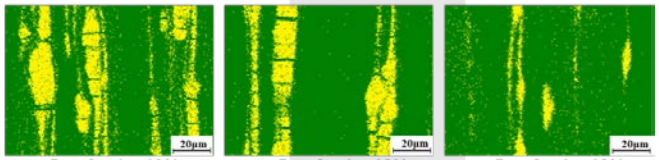
➔ *Electric current can assisted "**aging effect**" during plastic deformation due to formation of Nano-sized precipitation such as NbC*

Summary

- **AZ91 Mg alloy**

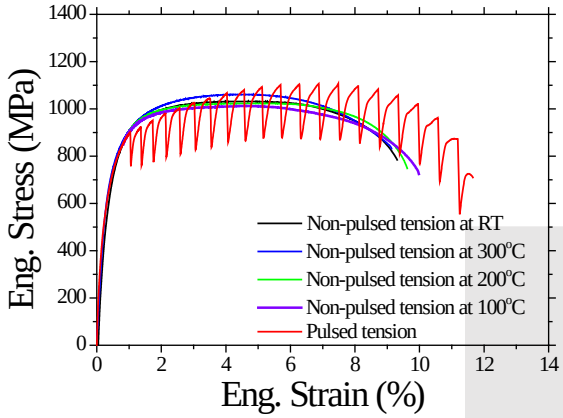


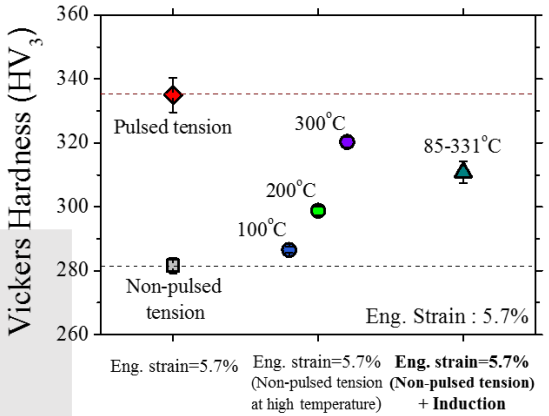


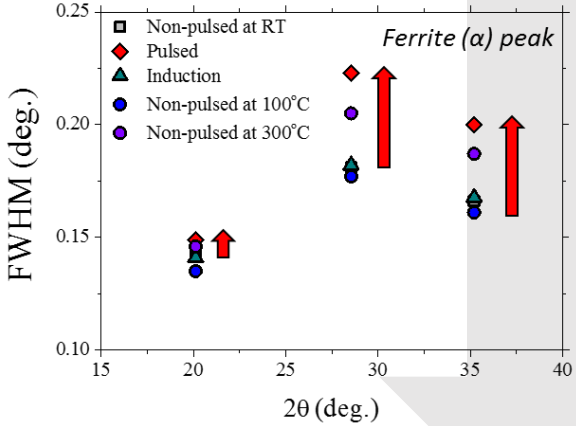


➔ ***Electric current*** *assisted "****dissolution effect****"*
during plastic deformation

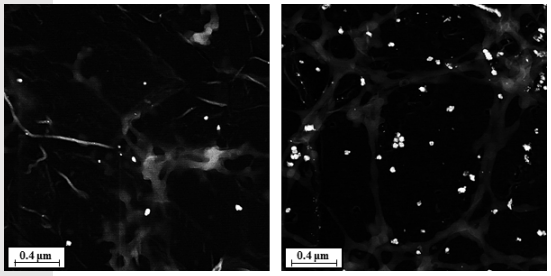
- **CP (DP980) steel**







Non-pulsed **Pulsed**



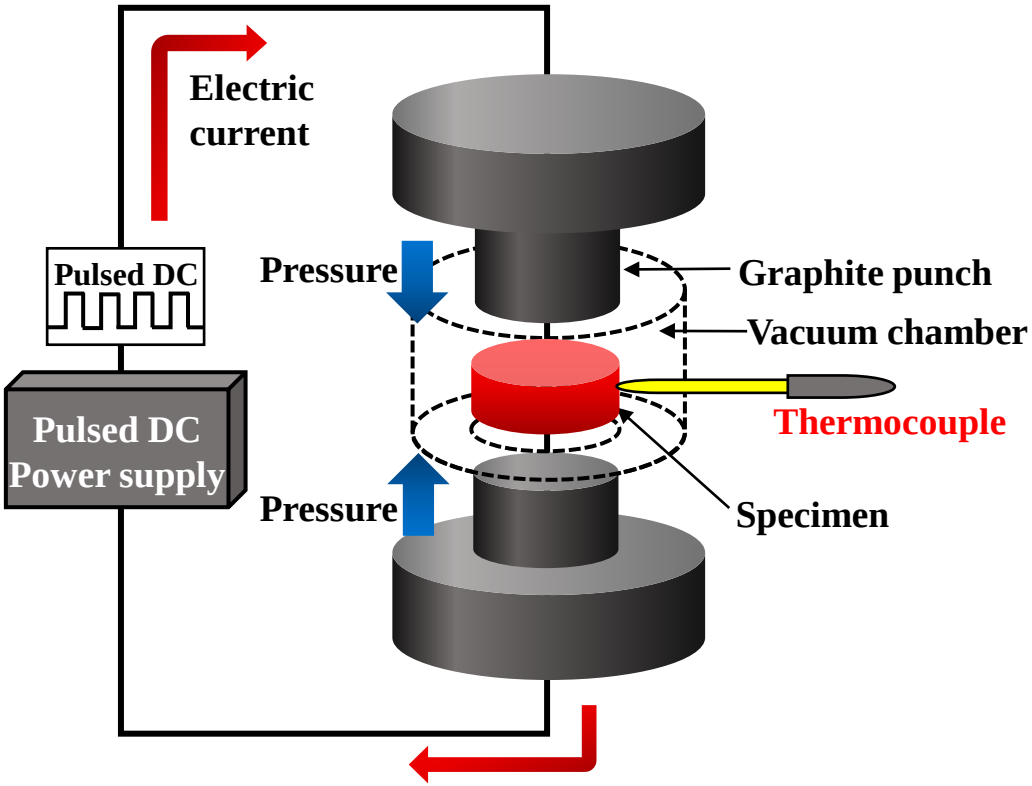
➔ *Electric current assisted "****aging effect****"*
during plastic deformation

Applicability of EAM technique to Forming process

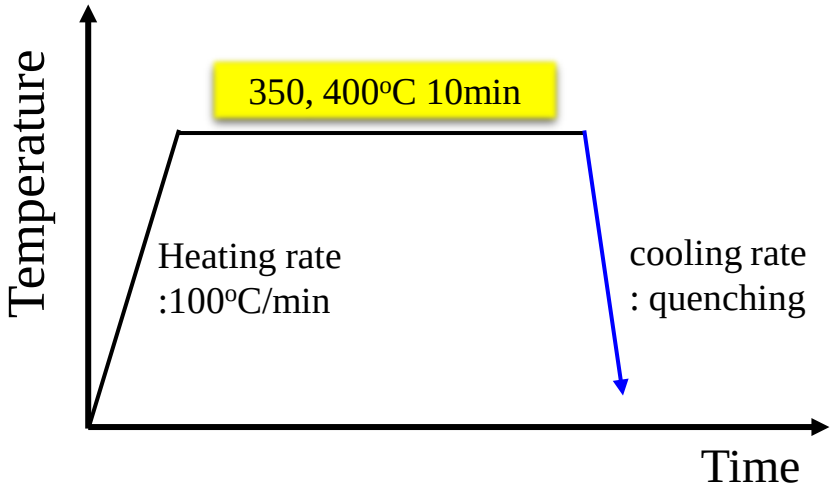
Thank you for listening

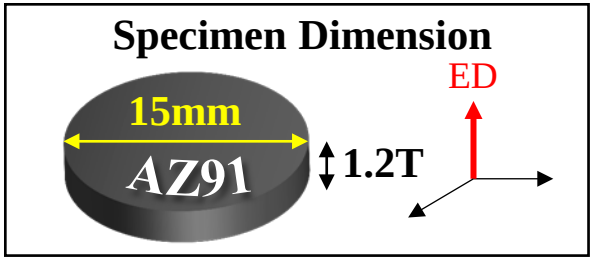
Magnesium alloy (AZ91)

【 Pulsed Electro-treatment Equipment】



【 Schematic diagram of Condition】



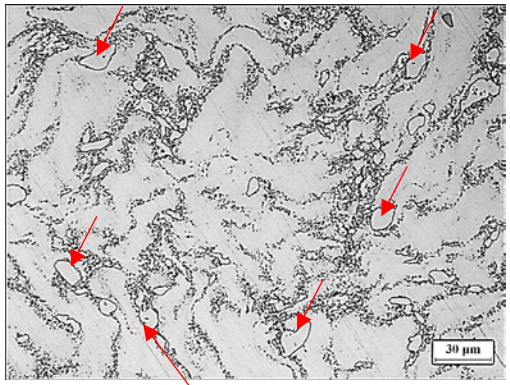


Magnesium alloy (AZ91)

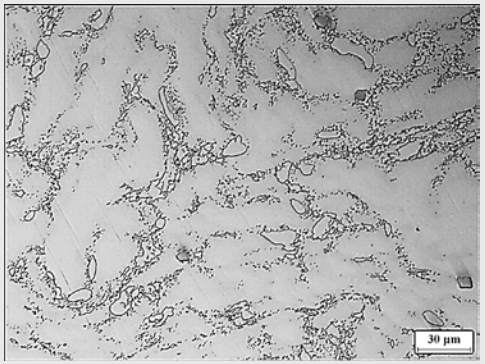
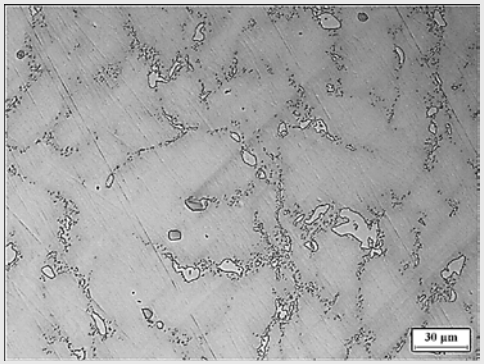
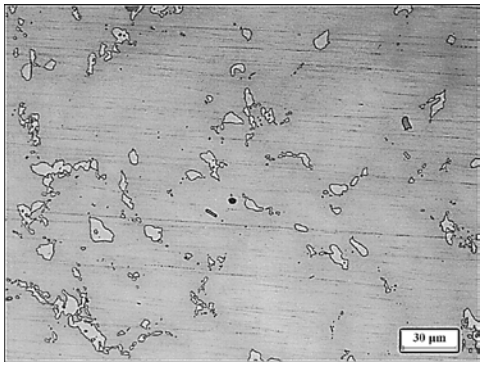
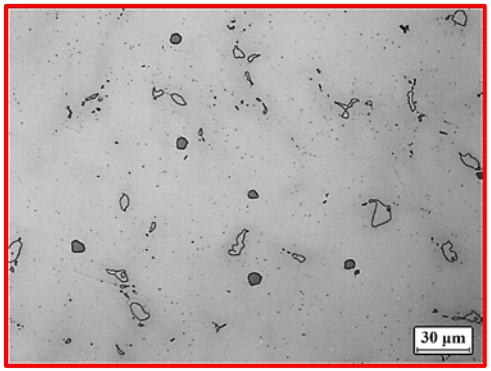
- **Microstructure analysis : OM**

❖ *Practical solution treatment condition : 380 ~ 420°C _ 30min~ 1hrs*

Initial



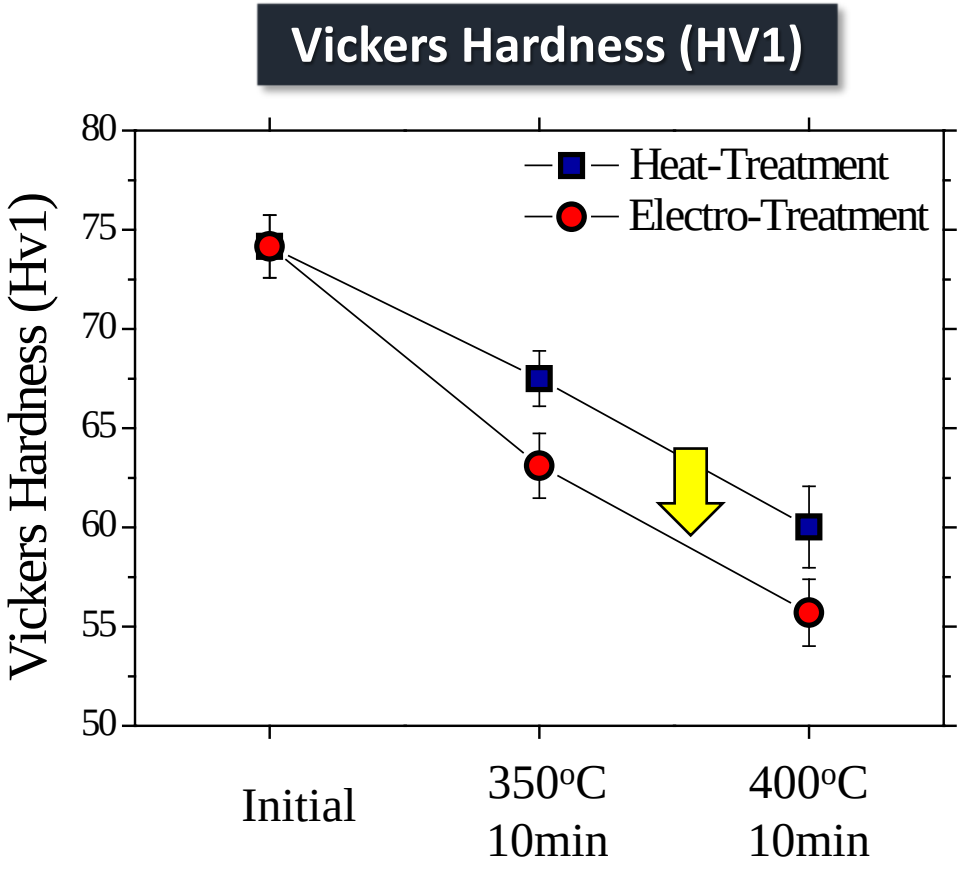
$Mg_{17}Al_{12}$

	Conventional Heat-Treatment	Electro-Treatment
350°C, 10min		
400°C, 10min		

➔ *Fraction of **$Mg_{17}Al_{12}$ phase** : Conventional heat-treatment **> Electro-Treatment***

Magnesium alloy (AZ91)

- **Microstructure analysis : Vickers Hardness Measurement**

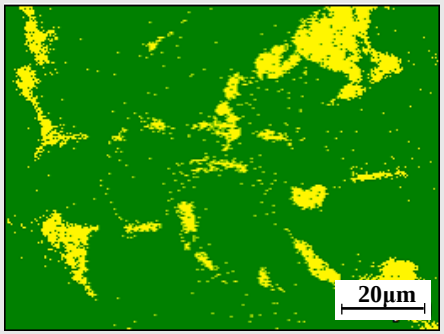
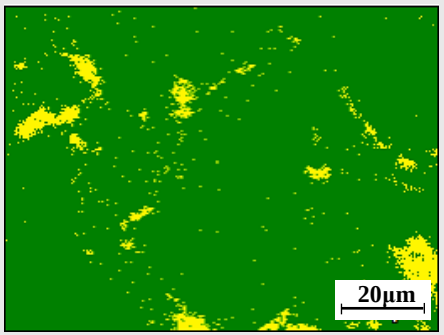
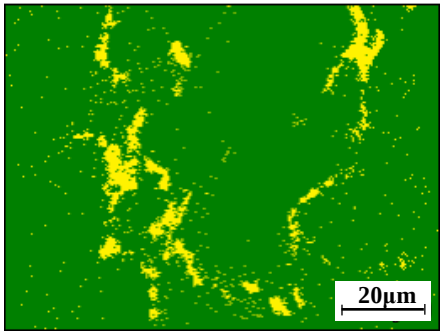
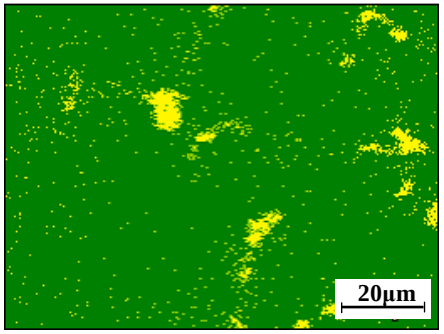


The solution heat-treatment dissolves $Mg_{17}Al_{12}$ phase to matrix

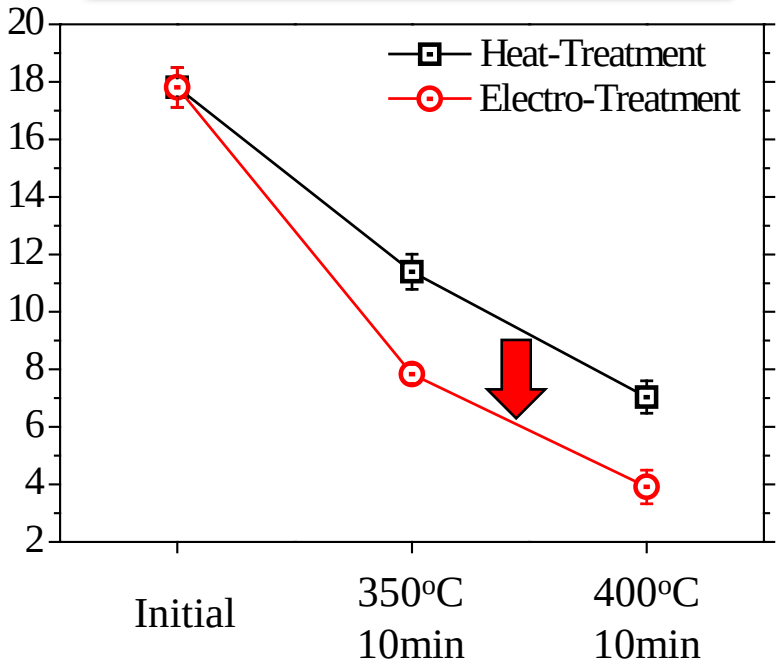
➔ *This makes* ***the hardness of specimen decreased!!***

Magnesium alloy (AZ91)

- **Microstructure analysis : EDS phase mapping**

	Conventional Heat-Treatment	*Electro-Treatment*
350°C, 10min		
400°C, 10min		

$Mg_{17}Al_{12}$ phase Fraction (%)



$Mg_{17}Al_{12}$

Matrix

➔ *it was observed that dissolution kinetic of **$Mg_{17}Al_{12}$ phase** is accelerated by **EAM***