구조재료 심화연구

Effects of electric current on IF steel

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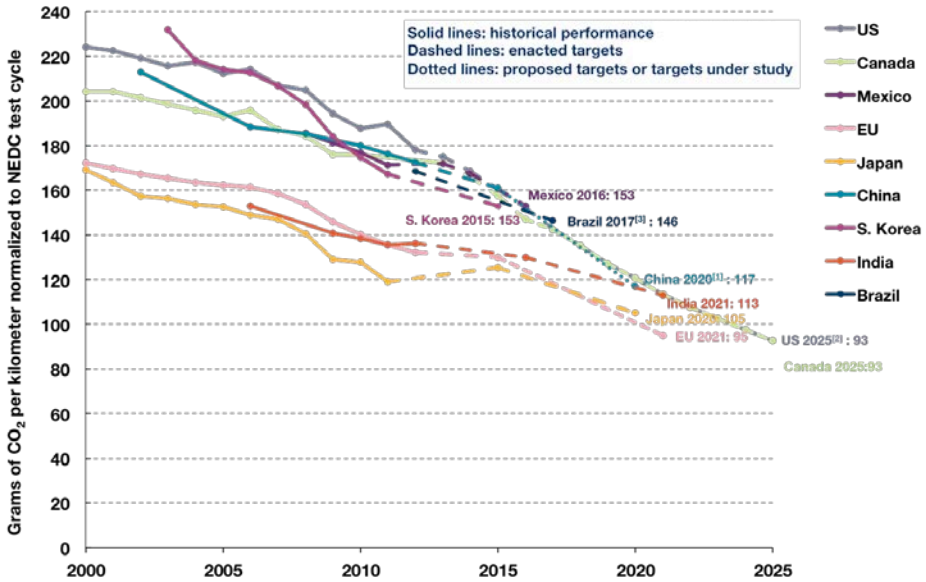
2016. 03. 21 (Mon)

Fuel economy

- **Global comparison of passenger vehicle GHG emission standards**

*GHG : greenhouse gas



[1] China's target reflects gasoline vehicles only. The target may be higher after new energy vehicles are considered.
[2] US standards GHG standards set by EPA, which is slightly different from fuel economy stadards due to low-GWP refrigerant credits.
[3] Gasoline in Brazil contains 22% of ethanol (E22), all data in the chart have been converted to gasoline (E00) equivalent
[4] Supporting data can be found at: http://www.theicct.org/info-tools/global-passenger-vehicle-standards.

Energy efficiency
&
Environmental protection policy

Automobile fuel economy regulations

(USA) behind 23.1km/l,

Imposed 137.5 penalty per 1km/l

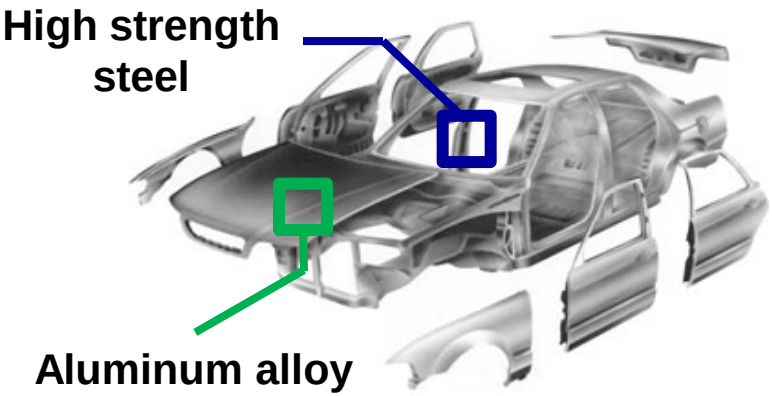
Critical importance of need for
energy reduction

Fuel efficiency

http://www.transportpolicy.net/index.php?title=Global_Comparison:_Light-duty_Fuel_Economy_and_GHG

High strength & Lightweight Vehicle

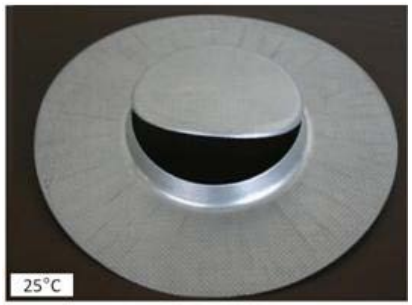
- **Body parts components**

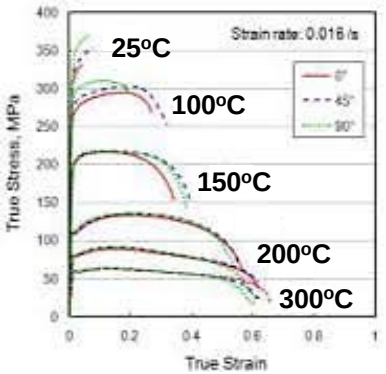


Body parts mostly consists of
high strength steel & lightweight metals

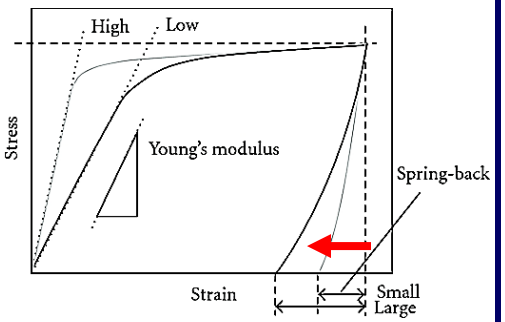
Drawback!!

Limit properties of high strength & lightweight metals





Low cold formability



High spring back

www.formingandimpact.uwaterloo.ca/Research/metal
Ken-ichi Manabe, Osamu Shimomura, Tokyo Metropolitan Univ.

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

Development of forming method

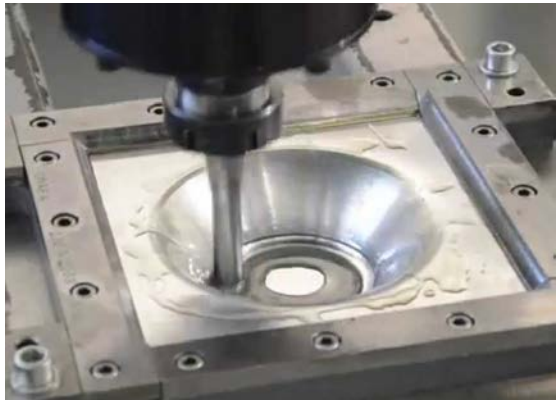
- **Hot manufacturing process**

http://thumbs.dreamstime.com/z/automatic-hot-stamping-process

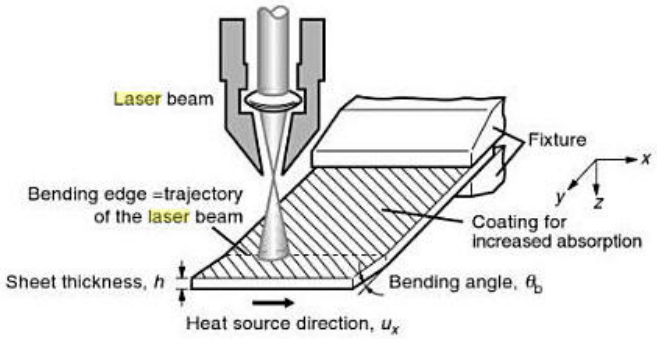
http://www.fastenerdata.co.uk/ie6-redirect/

Disadvantage → High cost, Thermal gradient, Die adhesion, Surface oxidation

- **Incremental forming**



- **Laser beam forming**



Disadvantage → Local areas deformation, High cost

single point incremental forming at university of Aveiro –SPIF-A project

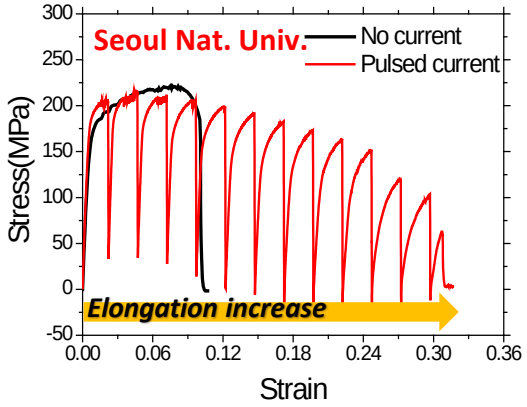
Theories, Methods and Numerical Technology of Sheet Metal Cold and Hot Forming Springer Series in Advanced Manufacturing (2013) 35-45.

Electrically-assisted forming (EAF)

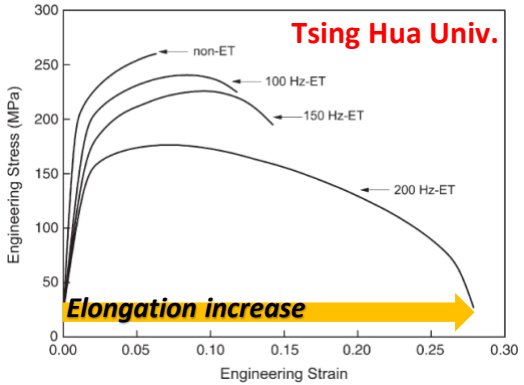
Electrically-assisted forming

➢ Technics for improving formability by applying high current density during deformation

Characteristic change through electric current

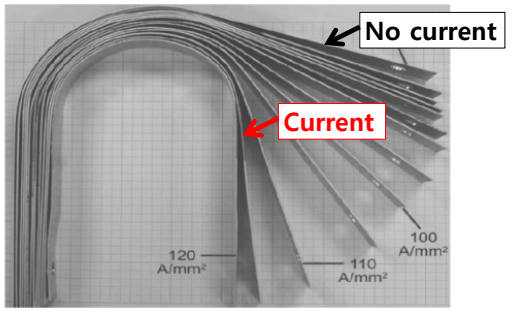


Al alloy (2014)



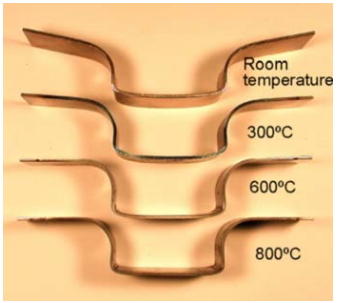
Mg alloy (2010)

Reduction of Spring back



Penn State Univ. (2009)

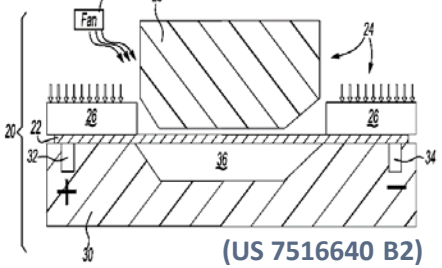
Rapid heating



Toyohashi Univ. (2005)

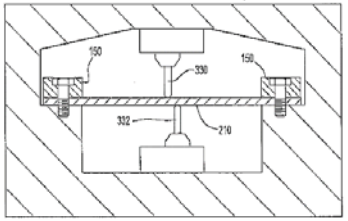
Applicability of Real process (patent)

Die Punching



(US 7516640 B2)

Double side incremental forming

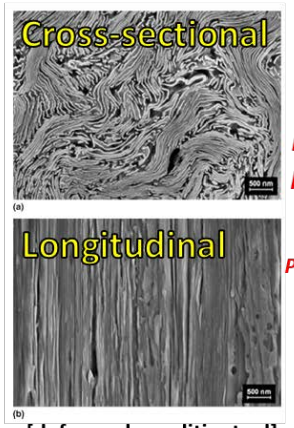


(US 20120055217 A1)

Electro-treatment

Microstructure control by electric current

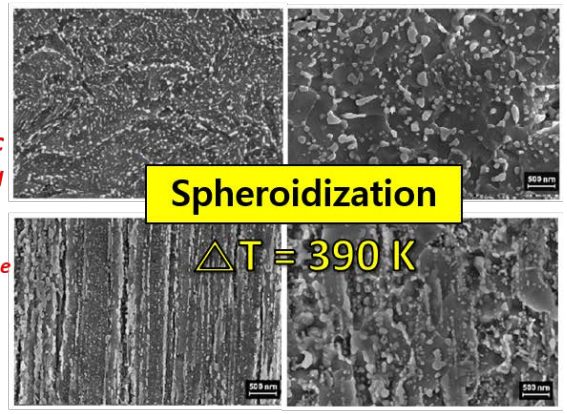
Accelerated spheroidization induced by high intensity electric pulse



[deformed pearlitic steel]
(true strain=3.00)

Electric pulsing

Peak pulse width =150μs



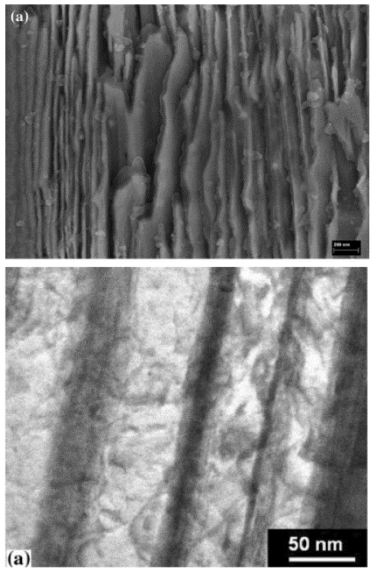
[9.82x10³ A/mm²] [10.7x10³ A/mm²]

For 100% spheroidization : 700°C, 500hr

Ref) Edwin I, Samuel, Arghya Bhowmik, J. Mater. Res. (2010)

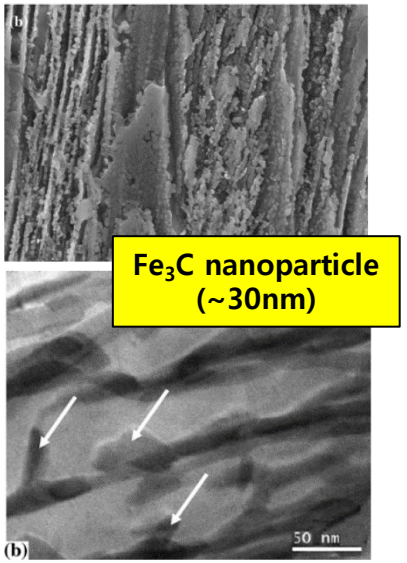
Electro pulse-induced cementite nanoparticle formation

in deformed pearlitic steels



Electric pulsing

Peak pulse width =150μs



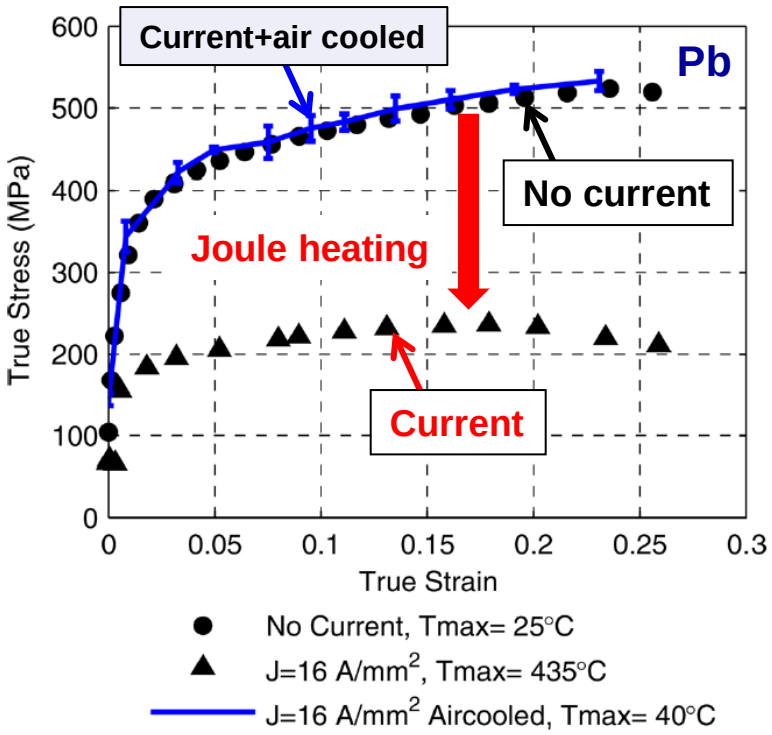
[9.61x10³ A/mm²]

Ref) R. S. Qin, E. I. Samuel, A. Bhowmik, J. Mater. Sci. (2011)

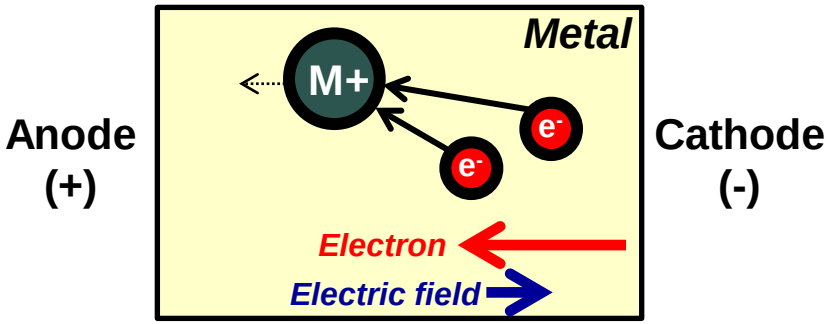
Underlying mechanism

- **Joule heating vs Electron wind vs other..?!**

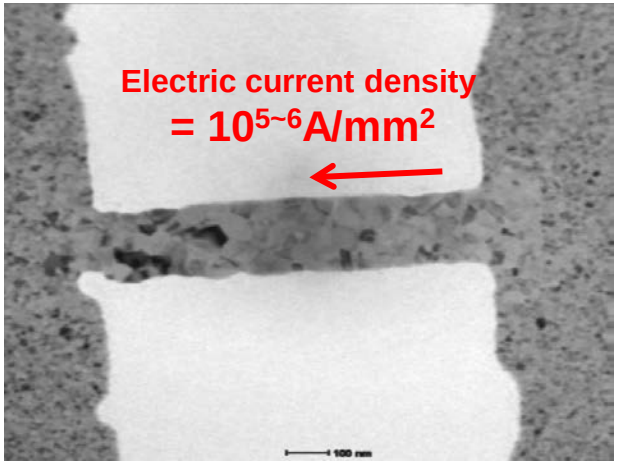
- **Joule heating effect**
  - Goldman et al (1981), Kilmov et al (1984), Cao et al (2013)



- **Electromigration (Electron wind effect)**
  - Troitskii et al(1969), Conrad/Xu et al(1988)



$F_{total} = F_{electron\ wind} + F_{direct\ action\ of\ electric\ field}$



S. Mahabunphachai et al, J. Eng. Mater. Technol. 135 041003 (2013) ,T. Kozlova et al, Nanotechnology, 24 505708 (2013)

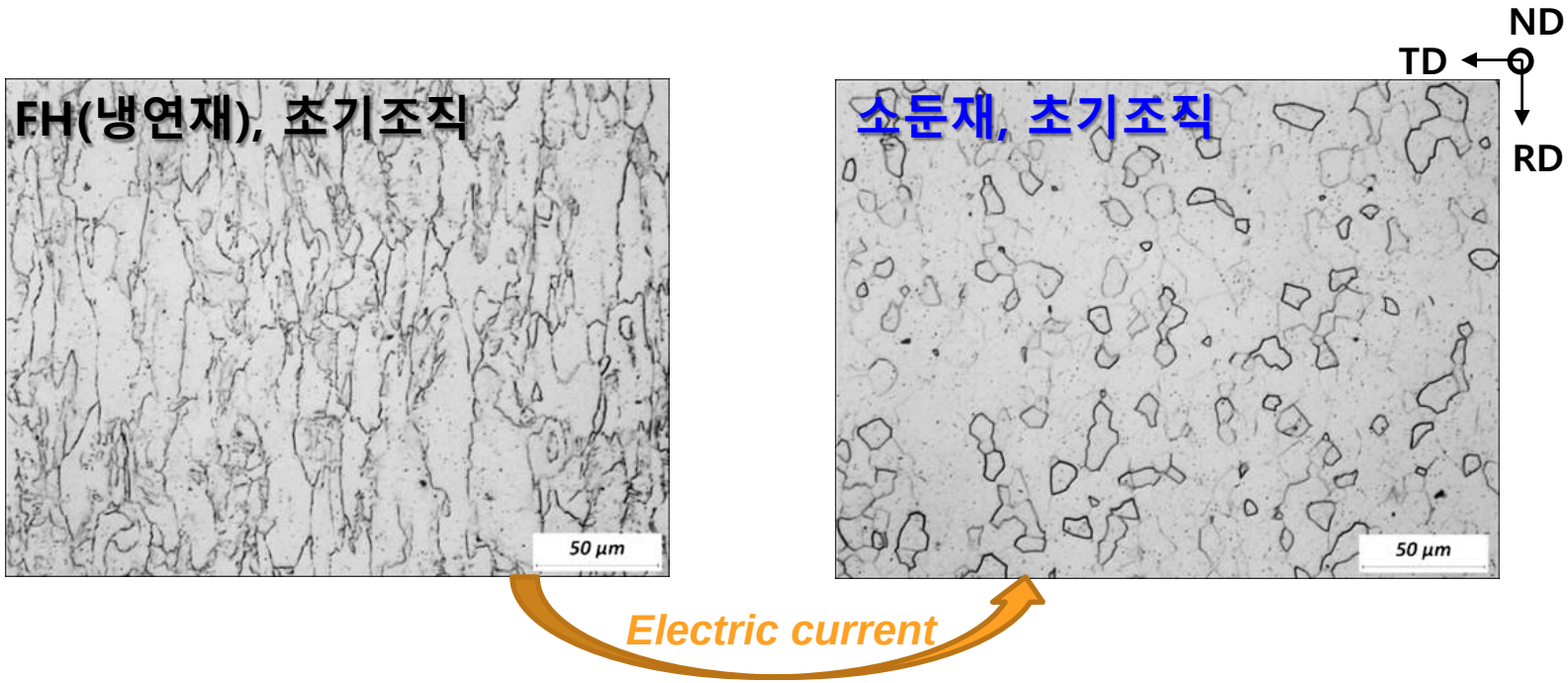
P.D. Goldman et al, Scripta Matall. 15 353-356 (1981), D.G.Pierce, P.G.Brusius, Microelectronics Reliability (1997)

Specimen Information

- **Specimen procedure**

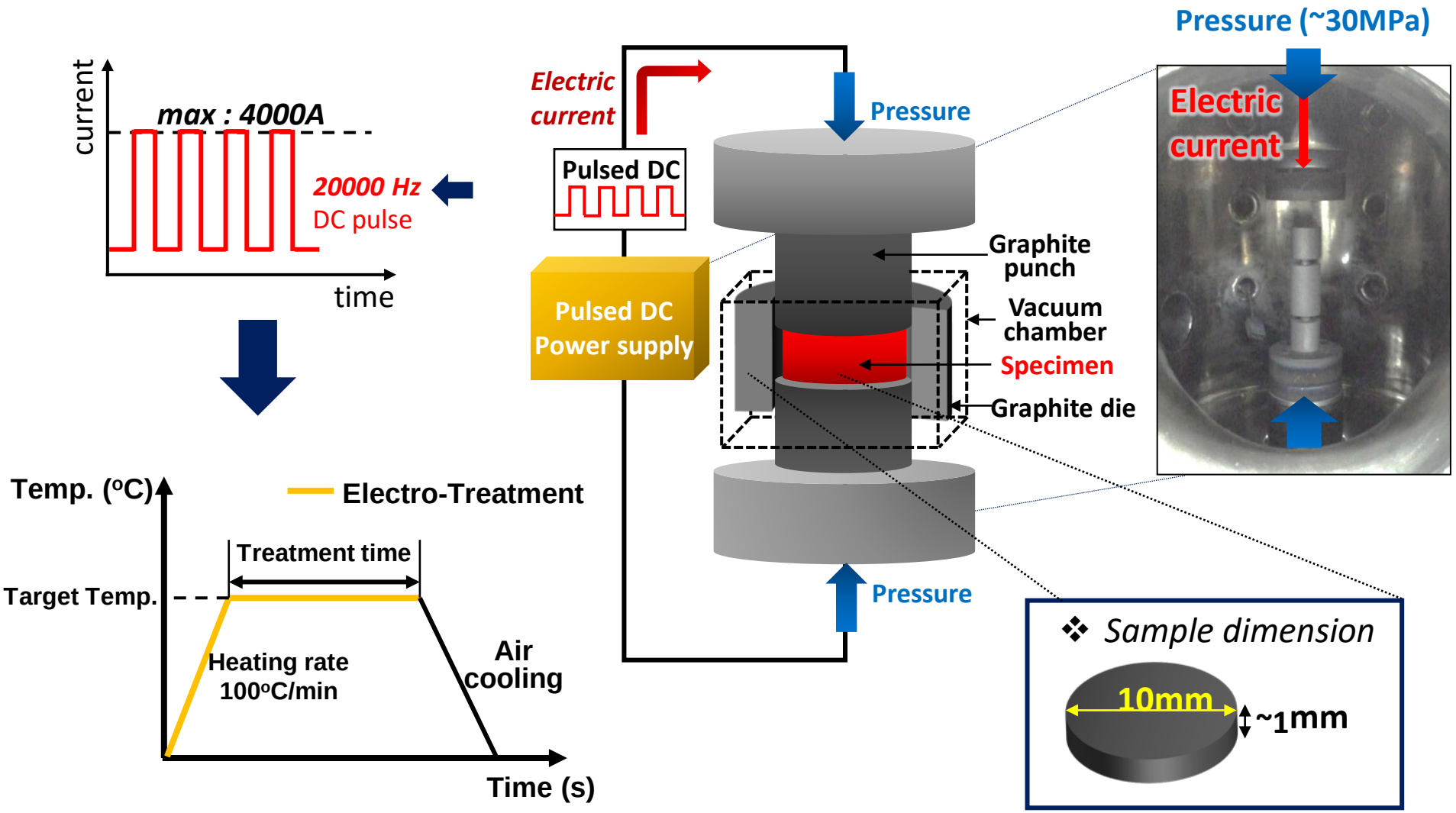
- **Composition** (wt.%)

C	Mn	P	Al	Nb	B
0.001	0.2	0.045	0.04	0.02	0.0005



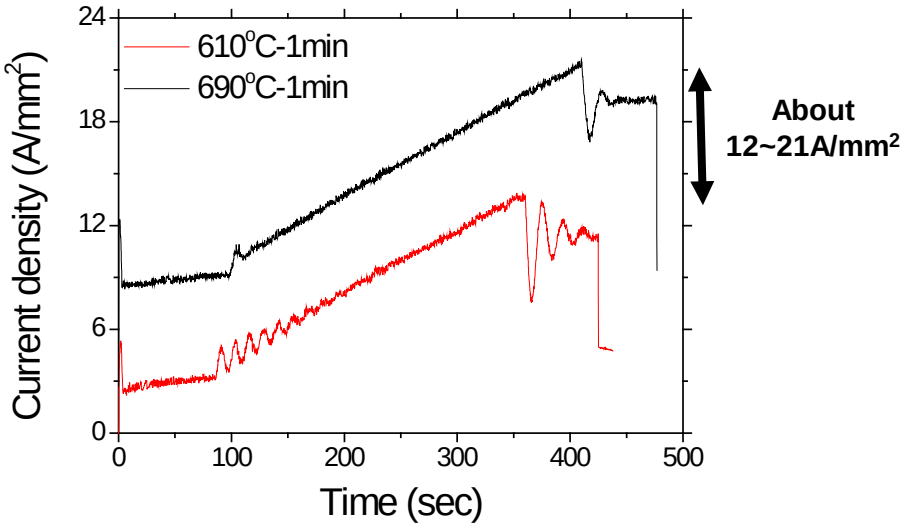
The effects of electric current on recrystallization of IF steel

Instrumental Set-up



Experimental condition

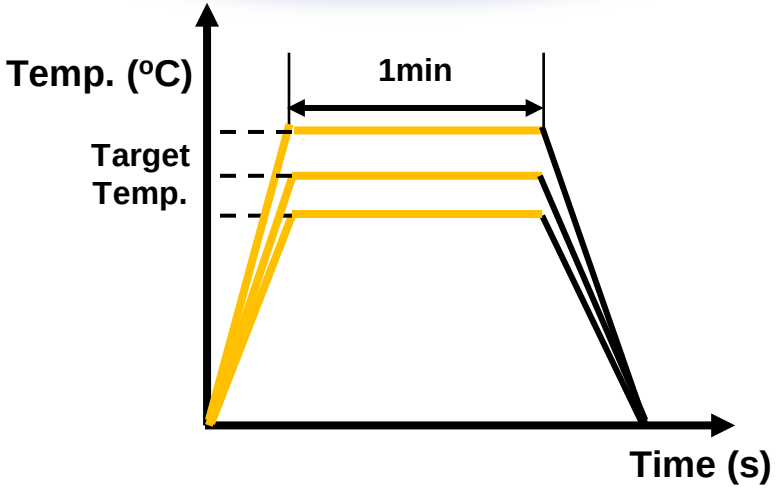
- **Current condition**



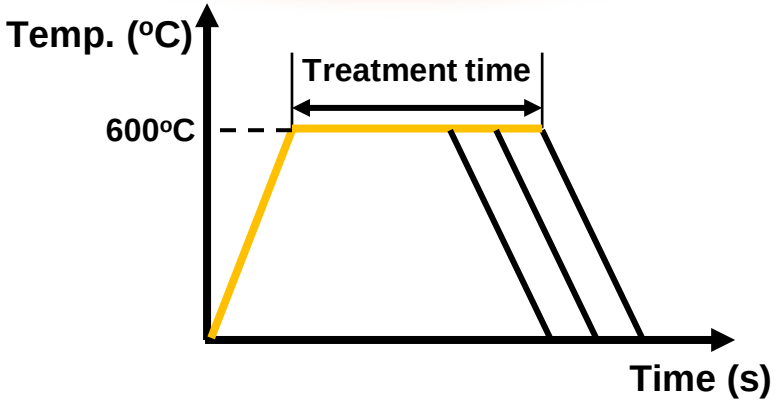
DC current was induced during test

- **Case study**

About temperature



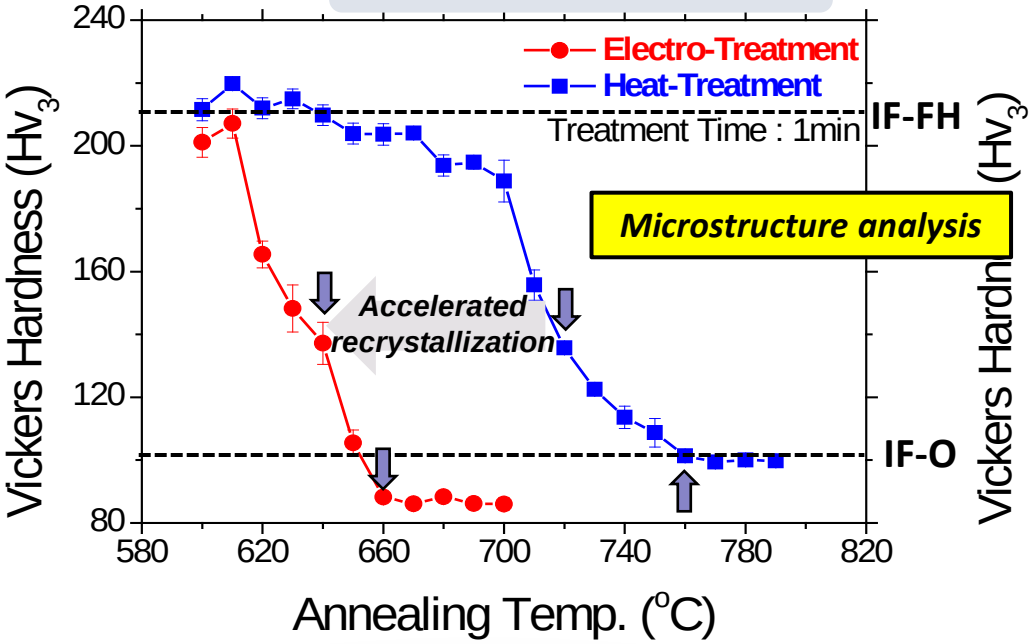
About time



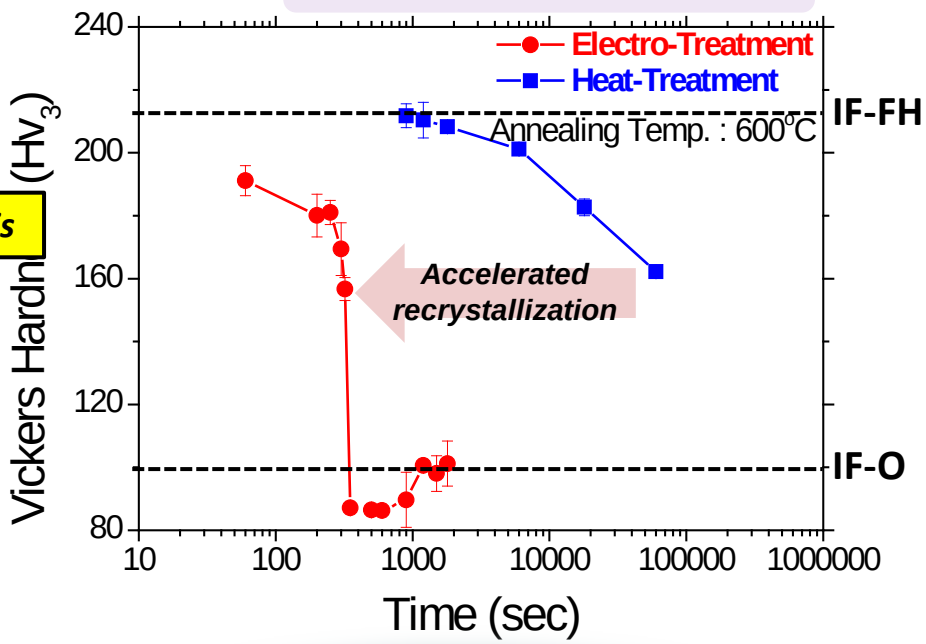
Improvement of Recrystallization kinetics

- **Vickers hardness analysis**

※ At fixed time : 1min



※ At fixed temp. : 600°C



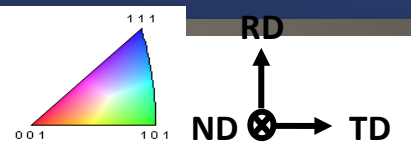
Temp. for full recrystallization
E.T. → 660°C
H.T. → 760°C

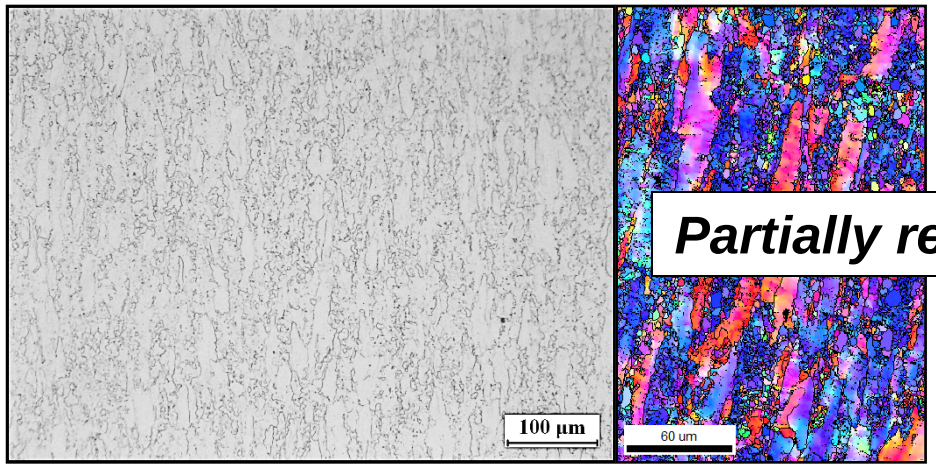
Time for full recrystallization
E.T. → ~10 min
H.T. → Not fully recrystallized after 1000min

Recrystallization occurs more rapidly in Electro-Treatment

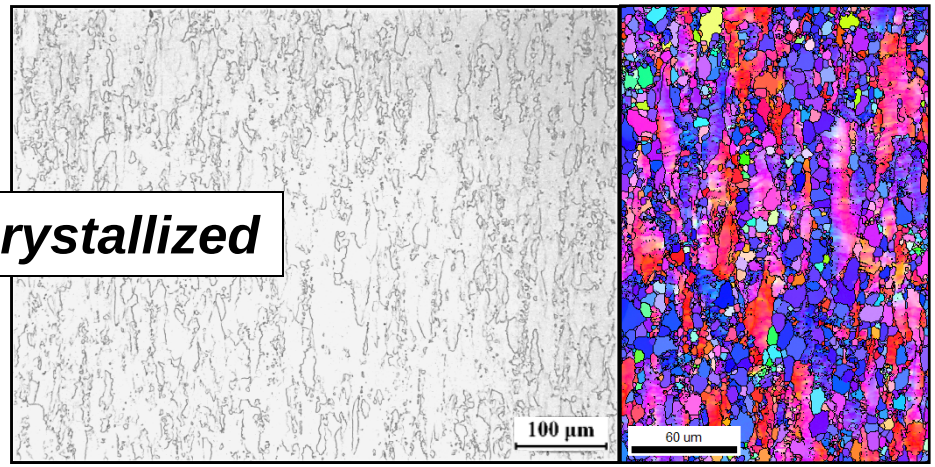
Improvement of Recrystallization kinetics

- **OM & EBSD analysis**



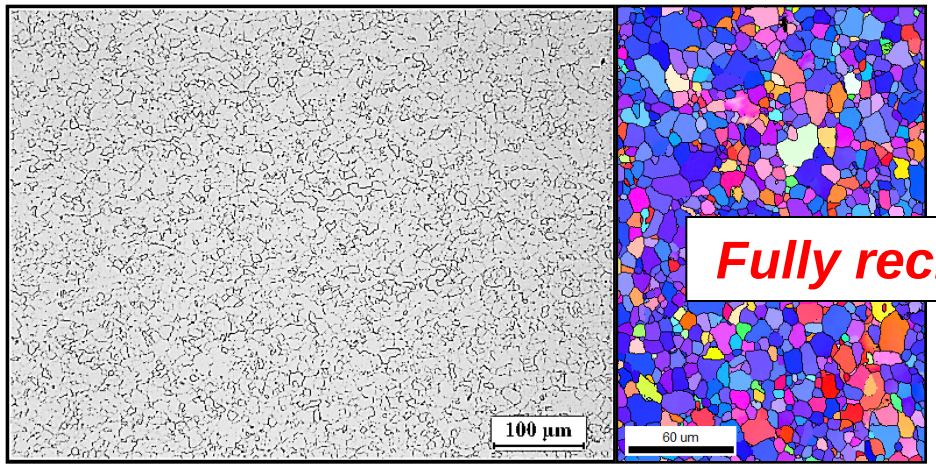


Partially recrystallized

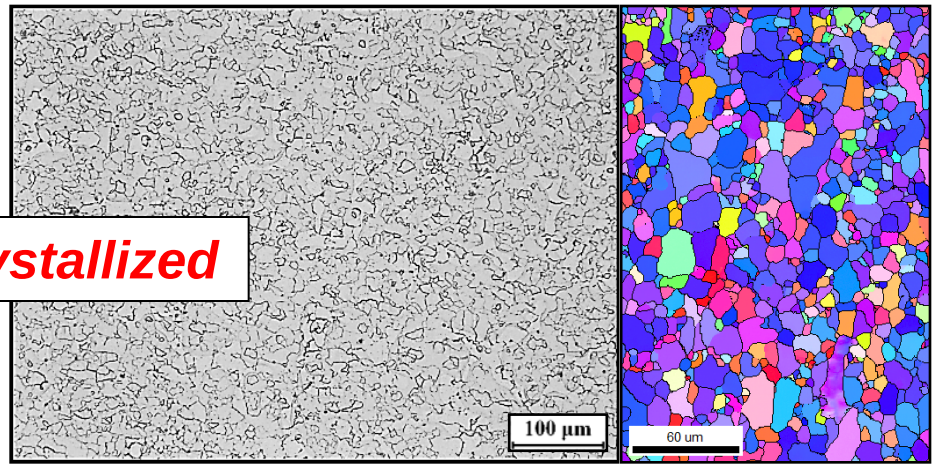


Electro-Treatment
630℃-1min

Heat-Treatment
710℃-1min



Fully recrystallized

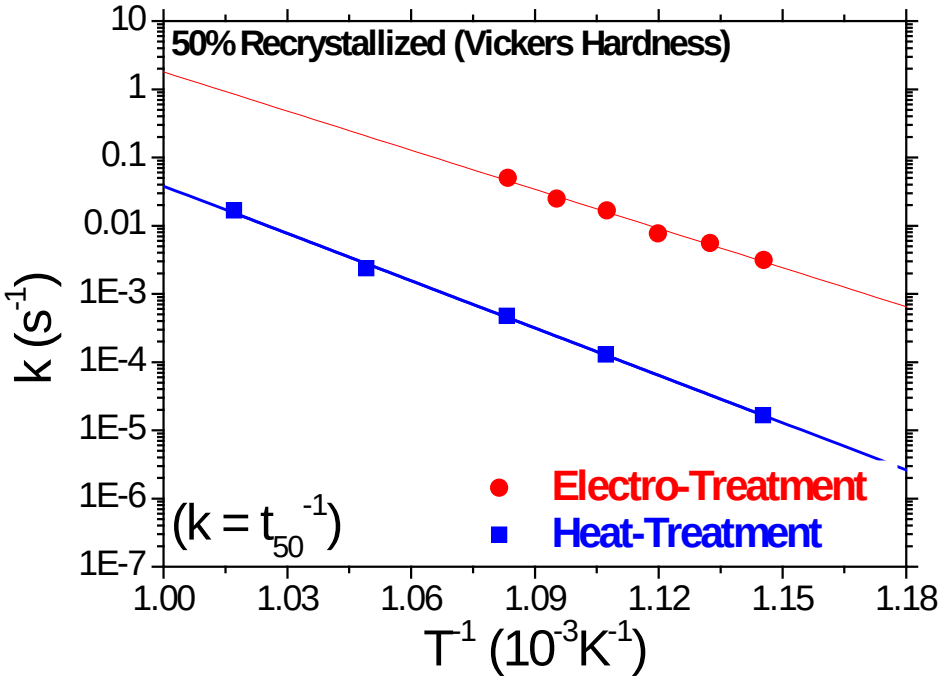


Electro-Treatment
660℃-1min

Heat-Treatment
760℃-1min

Improvement of Recrystallization kinetics

- **Derived activation energy by *Arrhenius equation***



Activation energy

$Q_{E.T.}$ = 366 ± 18.7 KJ/mol

∧

$Q_{H.T.}$ = 443 ± 9.0 KJ/mol

Activation energy : ~420 KJ/mol

Johnson Go, Univ. of British Columbia (1998)

Activation energy under Electro-Treatment Is smaller than that under Heat-Treatment

Assumption Electrical energy ↔ Activation energy for recrystallization

→ Analysis of the effect of electric current on recrystallization

Improvement of Recrystallization kinetics

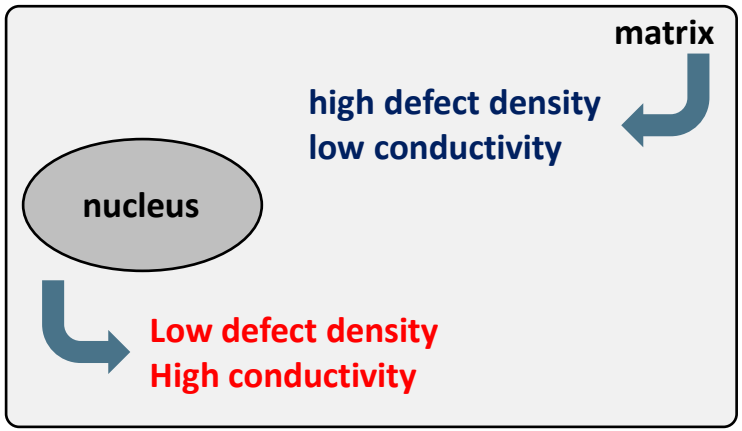
- **Electric current effect on decrease of activation energy**

$$\Delta G = \Delta G_0 + \Delta G_e$$

(ΔG_0: thermal, ΔG_e: athermal)

$$\Delta G_e = \mu_0 g \xi(\sigma_1, \sigma_2) j^2 \Delta V$$

μ_0 : magnetic susceptibility
g : positive geometric factor
J : electric current density
ΔV : volume of a nucleus
$\boldsymbol{\xi(\sigma_1, \sigma_2) = (\sigma_2 - \sigma_1)/(\sigma_1 + 2\sigma_2)}$
[σ_1, σ_2 : conductivity of nucleus, matrix]



➔ $\sigma_1 < \sigma_2$

➔ $\xi(\sigma_1, \sigma_2) < 0$

➔ $\Delta G_e < 0$

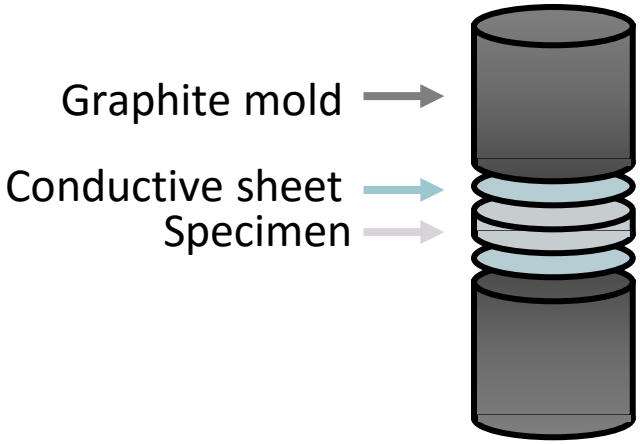
➔ *Spontaneous reaction process*

Recrystallization is accelerated by electric current

[Ref] Yizhou Zhou et al., J. Mater. Res., Vol. 17, 2002
Yanbin Jiang et al., J. Mater. Res., Vol. 24, 2009
Guoliang Hu et al., Mat. Transac., Vol. 51, 2010

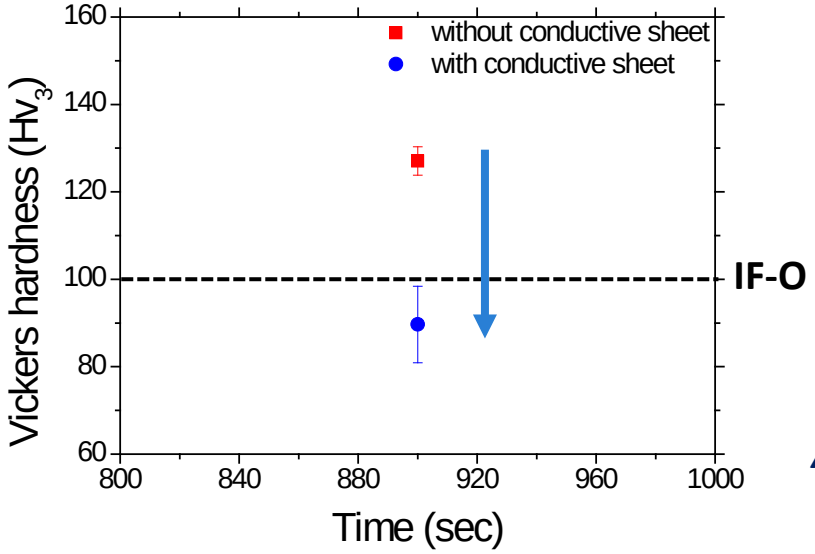
Effect of electric current on Carburization

- **Carburization by the graphite mold**



Case 1 : without conductive sheet

Case 2 : with conductive sheet

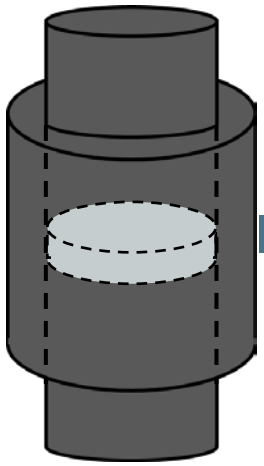


When not using conductive sheet,
Hardness increase caused by C diffusion

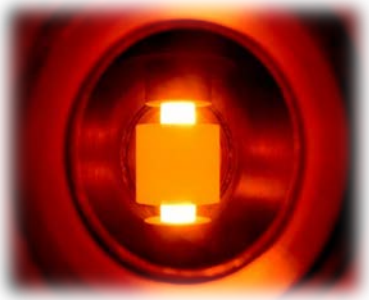
Analysis of the electric current effect on carburization

Effect of electric current on Carburization

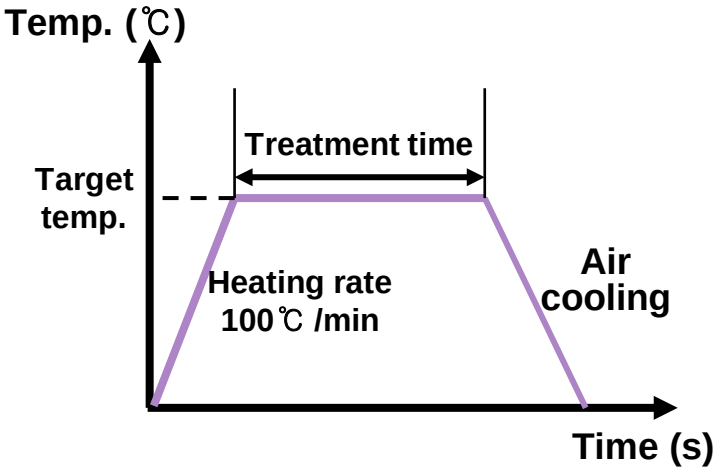
- **Experimental condition**



Electro-Treatment



Heat-Treatment



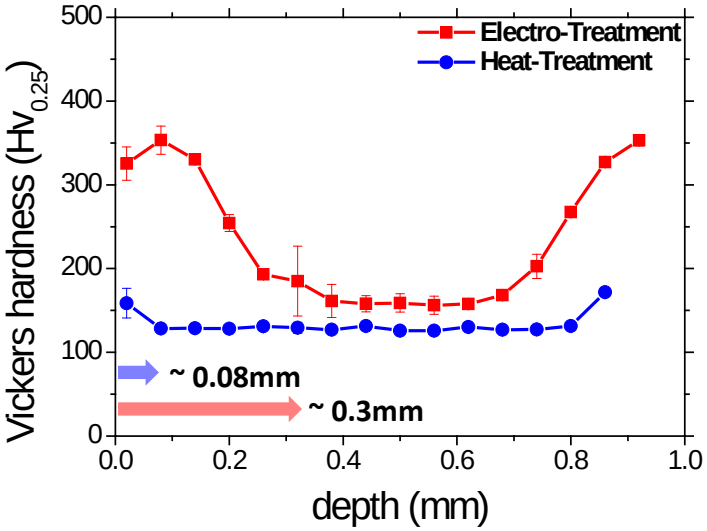
Analysis of the electric current effect on the carburization

Effect of electric current on Carburization

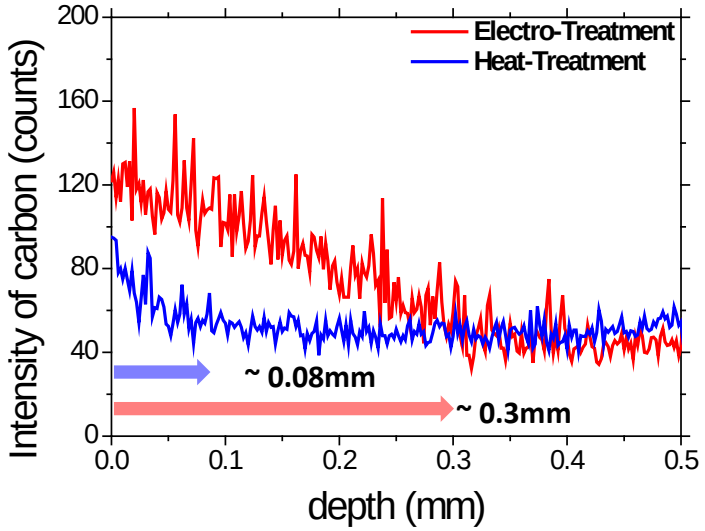
- **Hardness profile & EPMA analysis**

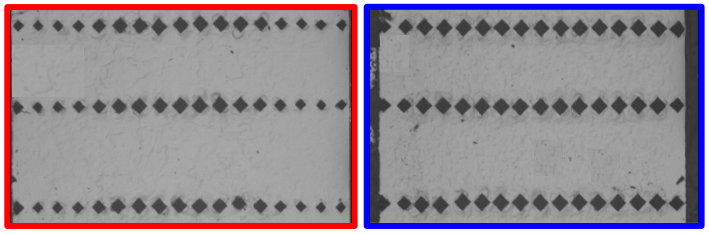
Treatment condition : 800℃-30min under 30MPa

[Hardness profile]



[EPMA analysis]





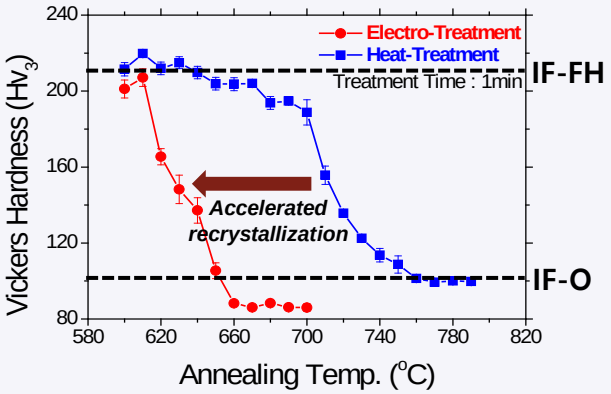
※ **Carburized depth**

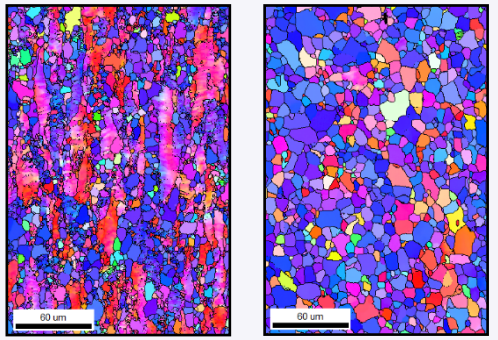
Electro-Treatment : ~ 0.3mm

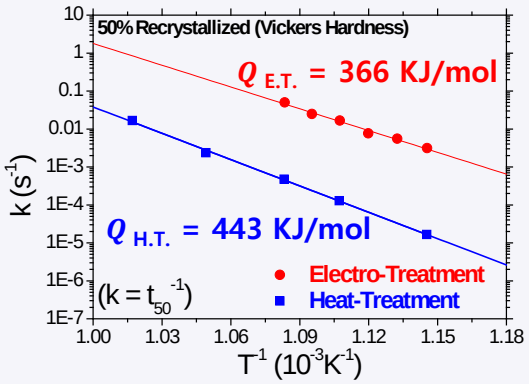
Heat-Treatment. : ~ 0.08mm

Carburization is accelerated under Electro-Treatment

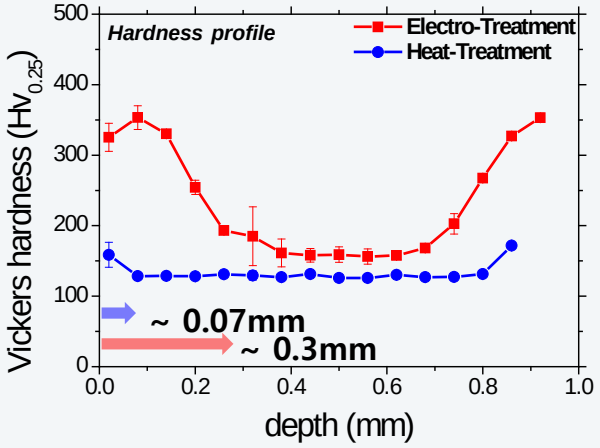
Summary

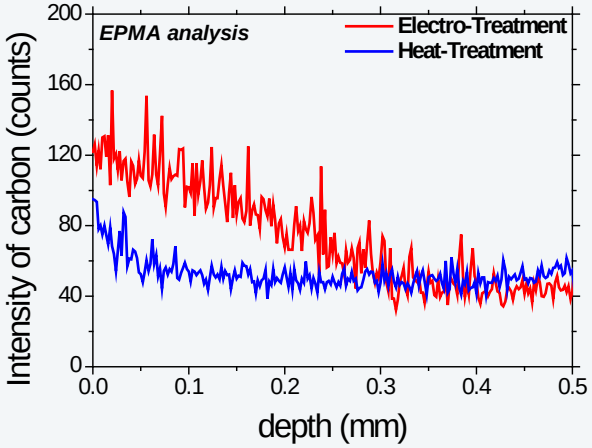






비통전 대비 통전 시 전류인가에 따른 재결정 활성화 에너지 저감





통전처리 시 열처리에 비해 고상 침탄 활성화

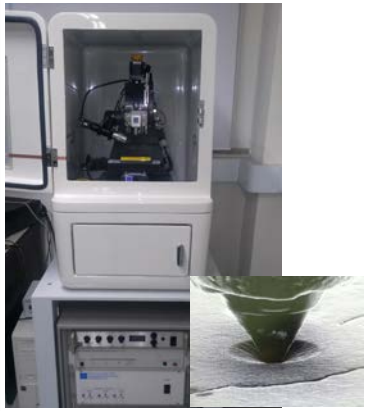
Available Equipment in MMMPDL

Cutting & Polisher system

Dilatometer

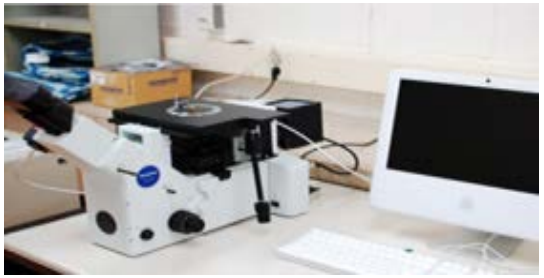
Tensile tester

Hardness tester



Nano-indenter

Vacuum system furnace



Optical microscope

Available Equipment in SNU

XRD

SEM & EBSD

Thank you !