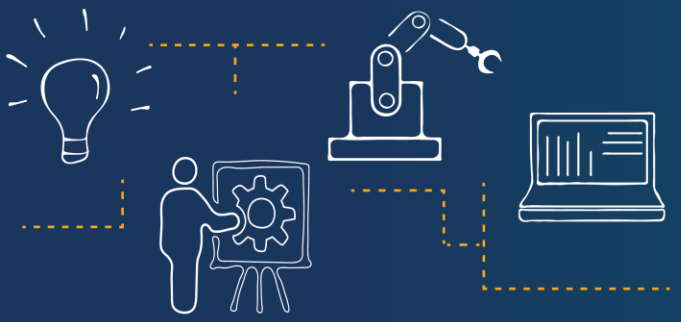
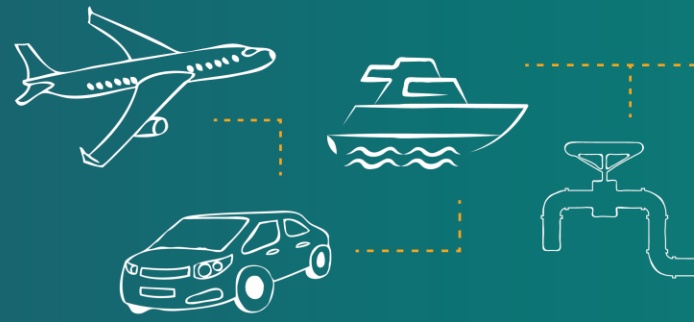


# A NEW CAMX FOR A NEW TIME



COMBINED STRENGTH. UNSURPASSED INNOVATION

CAMX
THE COMPOSITES AND ADVANCED MATERIALS EXPO

**SEPTEMBER 21-24**

A VIRTUAL EXPERIENCE

**2020**

# Development of novel tooling materials for next generation air mobility components with intricate structure


Hiromichi T. Fujii*, Naoki Sakaguchi, Haruyasu Ohno, Kotaro Ona

* fujii@shst.co.jp

Principal researcher

SHINHOKOKU STEEL CORP.



CAMX

THE COMPOSITES AND ADVANCED MATERIALS EXPO

September 21-24, 2020 / www.theCAMX.org

# Invar alloy used as a tooling material of CFRP molding

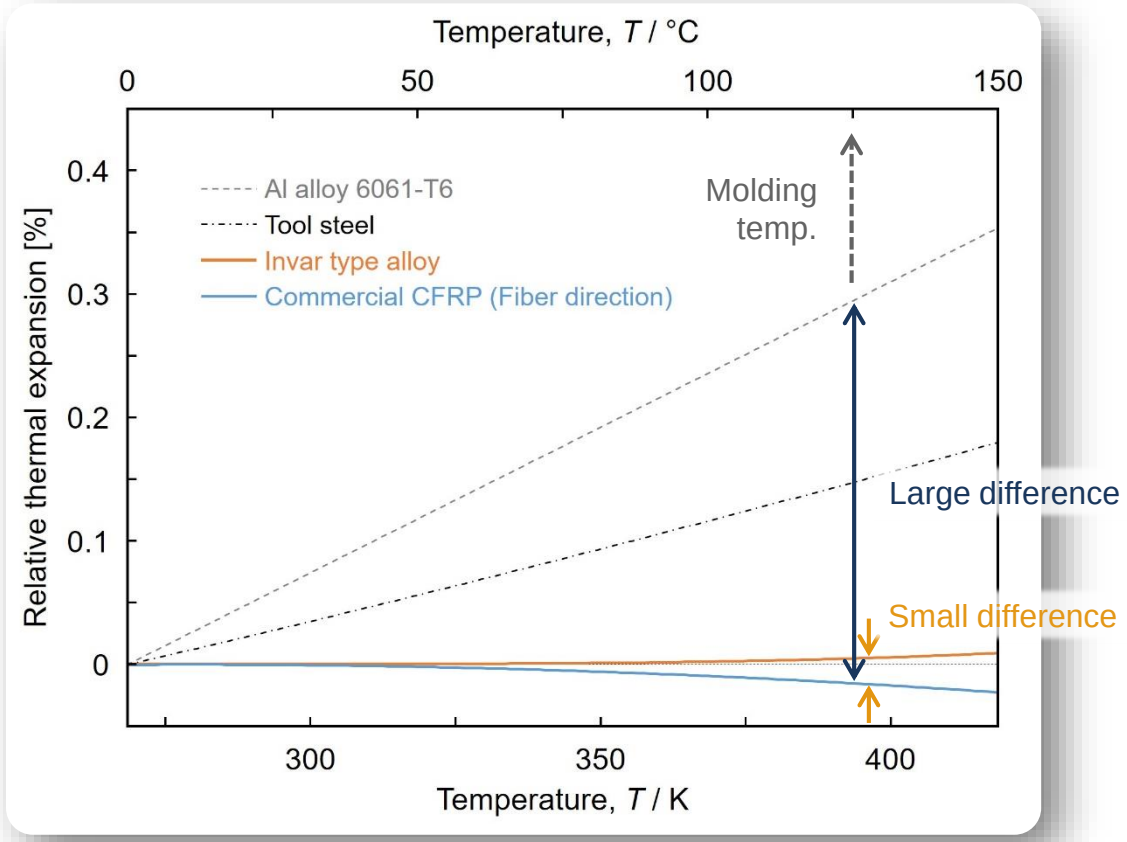
## Invar alloy

- ✓ Fe-36mass%Ni alloy
- ✓ Low thermal expansion (R.T. ~ 200ºC)
- ✓ Tooling material for CFRP components in aerospace industry

## Requirements for tooling material

- ✓ Close dimensional change to CFRP between room and molding temps.
  (Match the CTE* values of production and tooling materials)
- ✓ High durability
- ✓ Thermal stability

* Coefficient of thermal expansion




Comparison of relative thermal expansion curves to a dimension at room temperature between tooling materials.




H.T. Fujii SHINHOKOKU STEEL CORP. fujii@shst.co.jp





CAMX
September 21-24, 2020 / www.theCAMX.org

# Background and research motivation

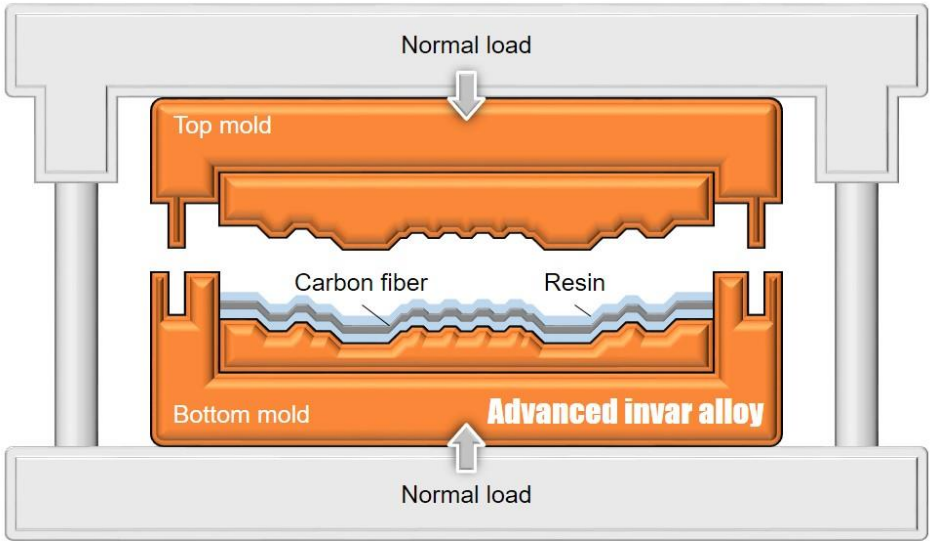
- Conventional airplane
  - ✓ Large components (Small curvature)
  - ✓ Low-volume production
- Next-gen. air mobility
  - ✓ Small components
    (Large curvature, intricate structure)
  - ✓ Mass production
- Expected issues
  - ✓ Social acceptance
  - ✓ Mass production of small components

Air bike “XTURISMO®”
(A.L.I. Technologies webpage: http://ali.jp/)

Flying car “SkyDrive”
(CARTIVATOR webpage: http://cartivator.com/)

# Press molding with advanced invar alloy molds

- Next-gen. CFRP tooling
  - ✓ Tooling formed in near-net shape
    (As-cast structure)
  - ✓ High durability
    (Decrease in aged deterioration)
  - ✓ Thermal stability
    (Precise molding of intricate structure)
  - ✓ Maintenance free
    (Automation of factory, mass production)



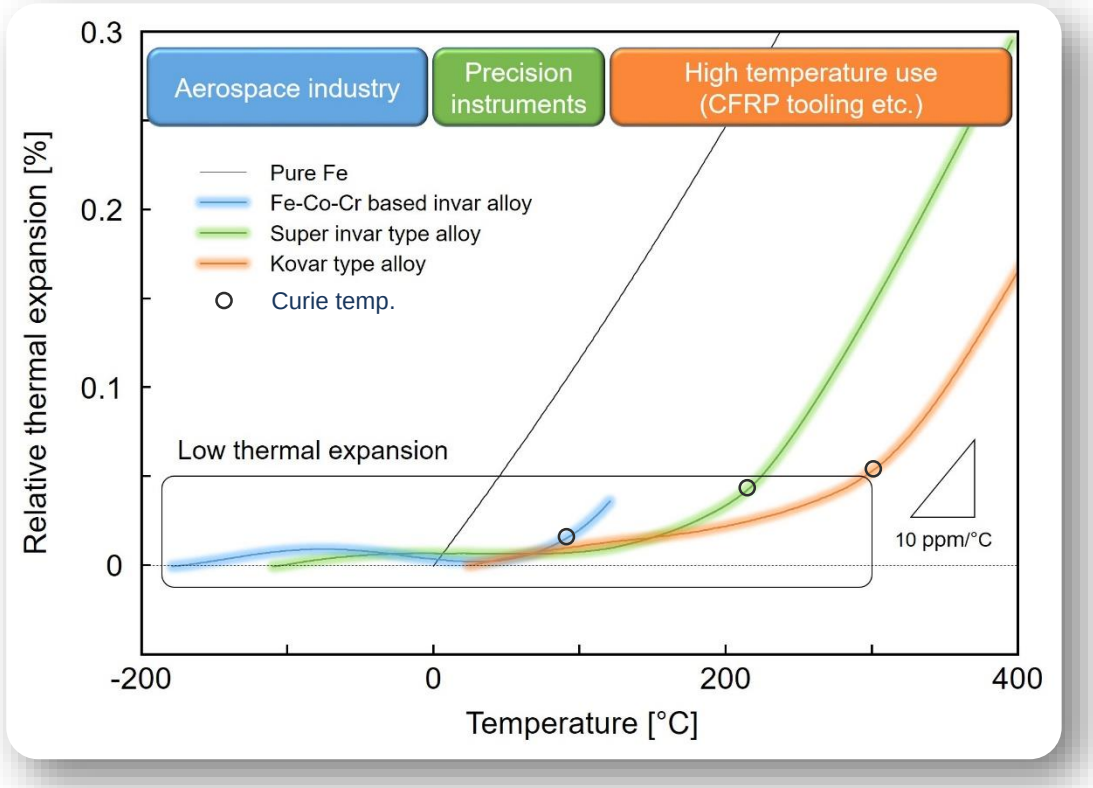

Press molding with the advanced invar alloy molds that allow mass production of the small CFRP components with intricate structure.

Cast invar alloys with supreme durability can be a powerful tool for next gen. air mobility components




H.T. Fujii SHINHOKOKU STEEL CORP. fujii@shst.co.jp

# Control of thermal expansion characteristics




Thermal expansion curves of various low thermal expansion alloys. Low thermal expansion characteristics can be obtained below Curie point.

- Thermal expansion characteristics depend on …
  - ✓ Chemical composition
  - ✓ Thermal treatment
  - ✓ Curie temperature
- Controllable thermal expansion
  - ✓ Enable to match the CTE between CFRP and invar type alloys in the desired temperature range
- Current issues
  - ✓ Low yield strength in cast alloys caused by coarse columnar grains structure

# Mechanical properties of cast invar type alloys

(a) As-cast


(b) Forged


Optical microscope images of grain microstructures in (a) as-cast and (b) forged $Fe_{63}Ni_{32}Co_5$ (super invar alloys).

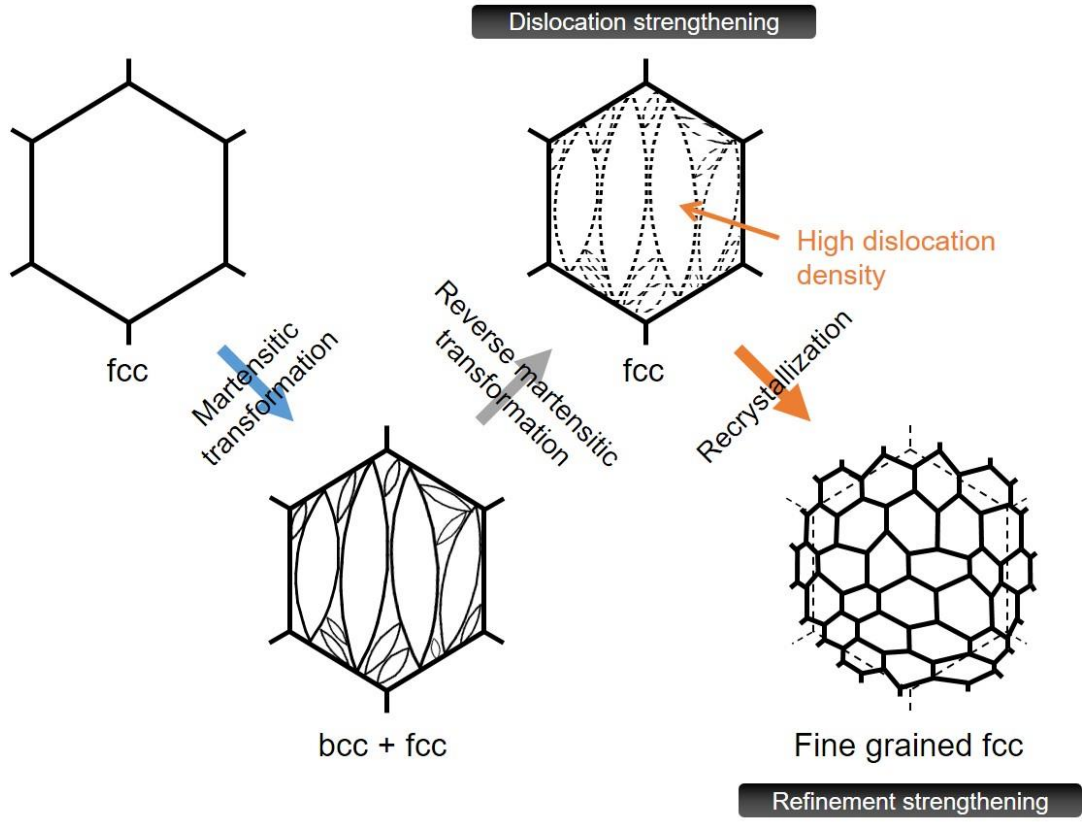
- As-cast Fe-based alloys
  - ✓ Coarse columnar grains structure formed during solidification process
  - ✓ Deterioration of mechanical properties
- Plastic working
  - ✓ Typical strengthening technique
  - ✓ Fine and equiaxed grains structure
  - ✓ Difficult to obtain intricate structure

# Strengthening technique without plastic working

- Reverse martensitic transformation
  - ✓ A metallurgical phenomenon that occurs in Fe-Ni alloys
  - ✓ High dislocation density region
- Hall-Petch relationship*
  - ✓ An inverse relationship between grain size and yield strength
- Bailey-Hirsch relationship**
  - ✓ An inverse relationship between dislocation density and yield strength

* E.O. Hall: *Proc. Phys. Soc. Lond.*, **64** (1951), 747.
** J.E. Bailey and P.B. Hirsch: *Philos. Mag.*, **5** (1960), 485.

Bailey-Hirsch relationship




Hall-Petch relationship

# Thermal treatment developed for strength improvement

## Developed cast invar alloy

Casting → **Developed thermal treatment** → Finish processing

Near-net shape — **High rigidity, Low CTE**

**Fine grains**

10mm

## Conventional cast invar alloy

Casting → Thermal treatment → Finish processing

Near-net shape — Low CTE

Coarse grains

10mm

## Forged invar alloy

Casting → Forging → Precision machining → Thermal treatment → Finish processing

Ingot — High rigidity — Low CTE

Fine grains

10mm

# Objective

To reveal the effects of reverse martensitic transformation and annealing on the mechanical properties in the low thermal expansion cast alloys for the development of novel tooling materials.

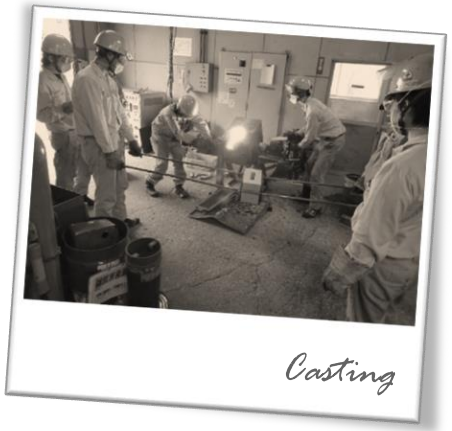


H.T. Fujii SHINHOKOKU STEEL CORP. fujii@shst.co.jp

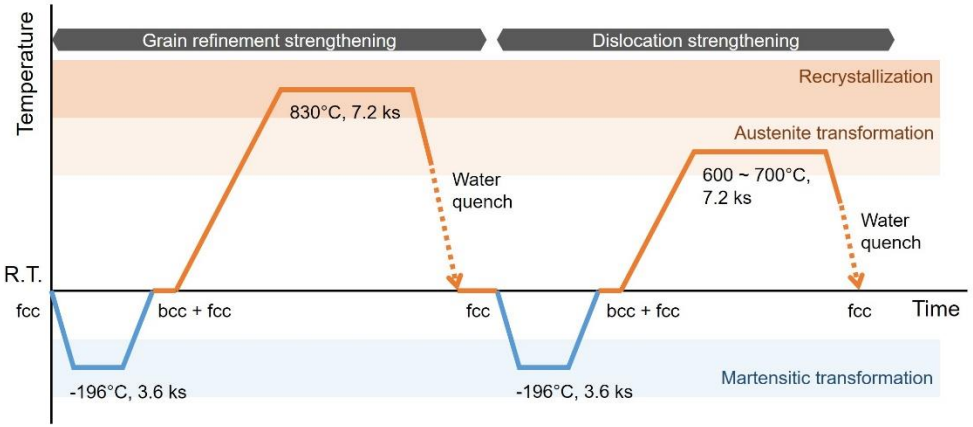
# Sample preparation

## Chemical composition

| Symbol | Chemical composition | Type of alloys | Target molding temperature [ºC] | Average CTE in conventional alloys [$10^{-6}$ / ºC] |
|---|---|---|---|---|
| I-200 | $Fe_{65.1+x}Ni_{34.9-x}$ | Invar | 200 | 2.3 (R.T. ~ 200 ºC) |
| SI-300 | $Fe_{64.2+x+y}Ni_{31.0-x}Co_{4.8-y}$ | Super invar | 300 | 4.1 (R.T. ~ 300 ºC) |
| K-400 | $Fe_{55.3+x+y}Ni_{28.2-x}Co_{16.5-y}$ | Kovar | 400 | 5.0 (R.T. ~ 400 ºC) |



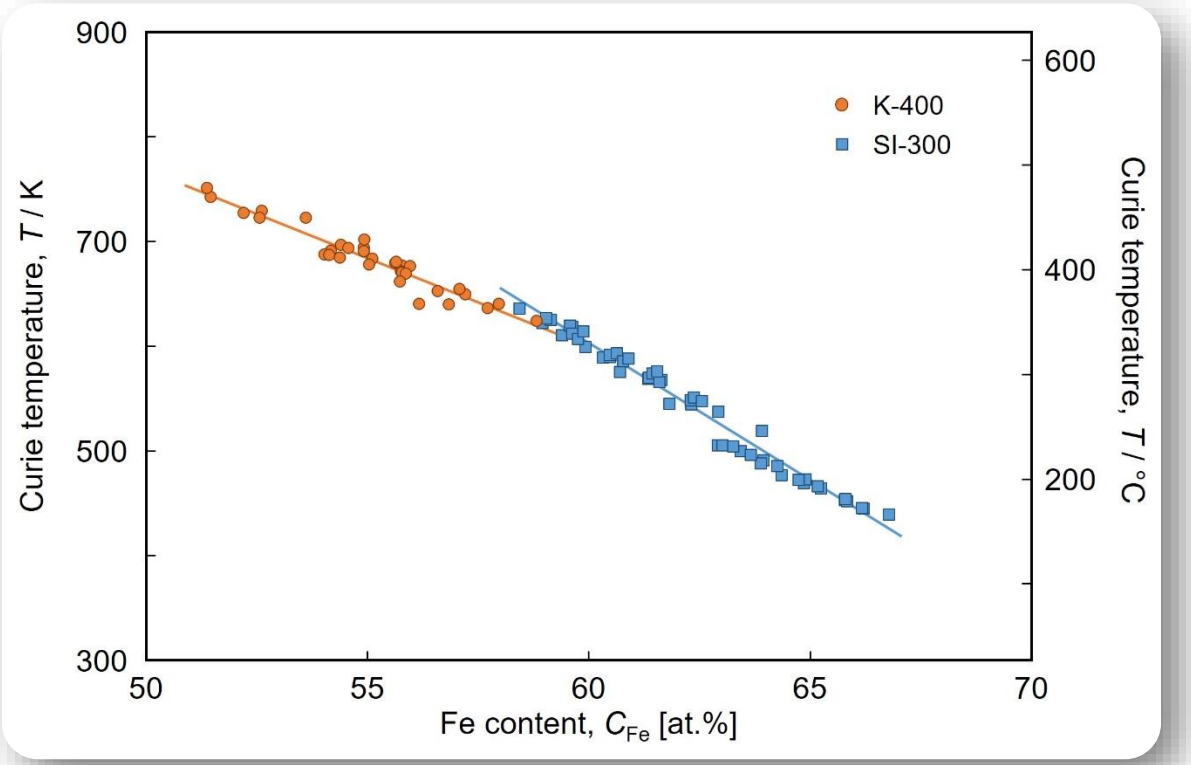

## Thermal treatment




# Results and discussion

# Control of Curie temperature

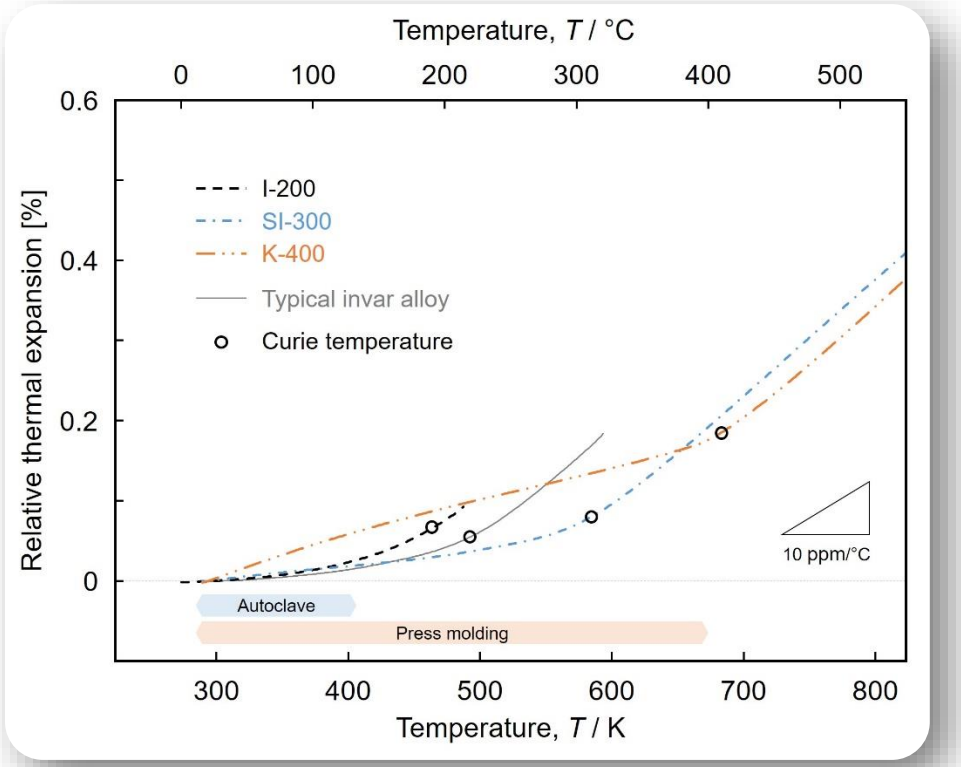
- Curie temperatures in low thermal expansion alloys
  - ✓ Linearly decrease with increasing Fe content both in SI-300 and K-400
  - ✓ Change from 180ºC to 360ºC and from 350ºC to 450ºC in SI-300 and K-400, respectively
- Low thermal expansion characteristics
  - ✓ Enable to be maintained up to 360ºC and 450ºC in SI-300 and K-400, respectively




Relationship between Curie temperature and Fe contents in SI-300 and K-400. Curie temperatures were estimated from the inflection points of thermal expansion curves.

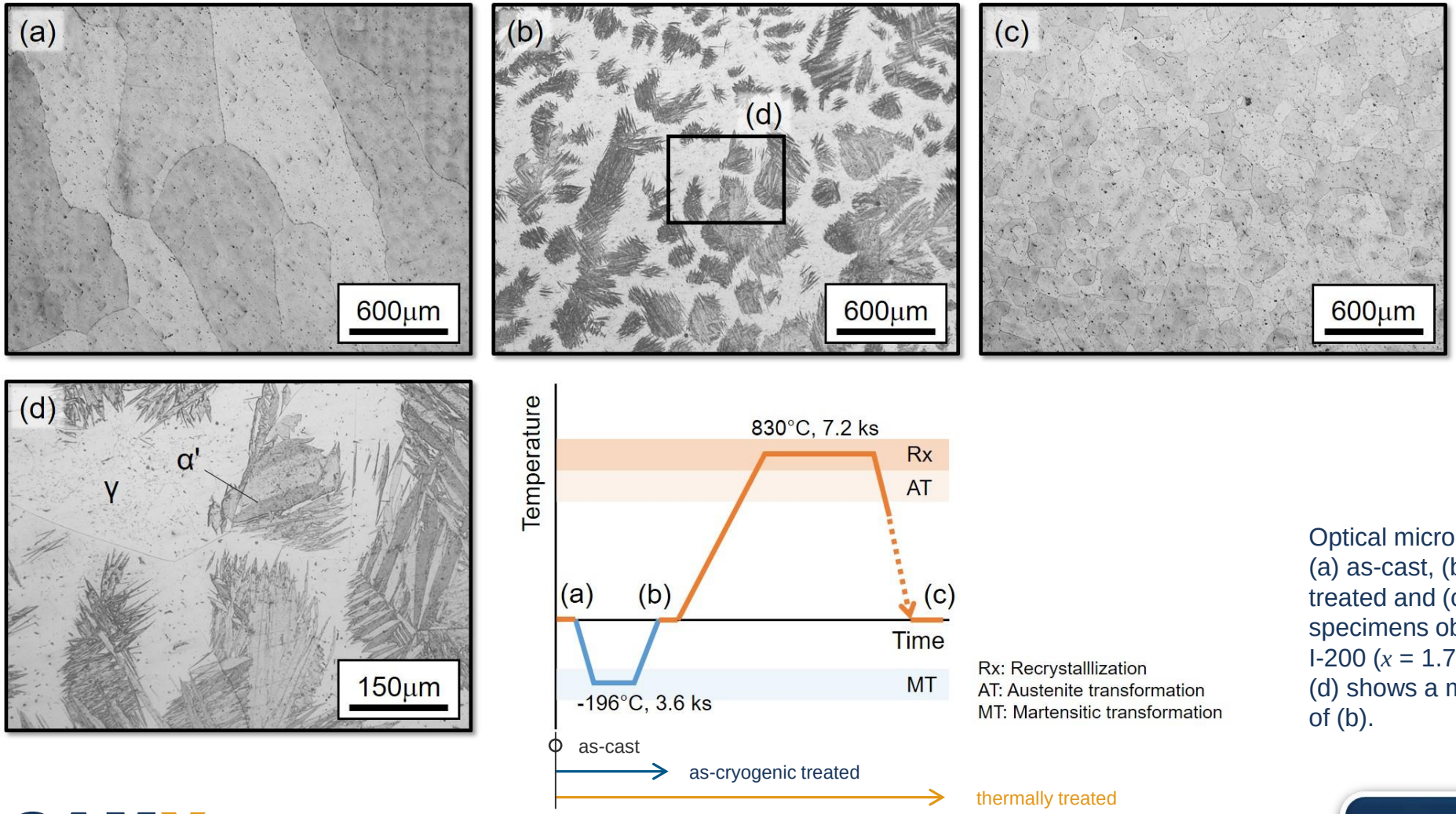
# Thermal expansion behavior of developed alloys

- Low thermal expansion characteristics
  - ✓ Maintained below Curie temperature in each alloy
  - ✓ Applicable in wide molding temperature range in press molding
- Chemical composition
  - ✓ Adjusted by 0.1% accuracy for causing martensitic transformation at liquid nitrogen temperature



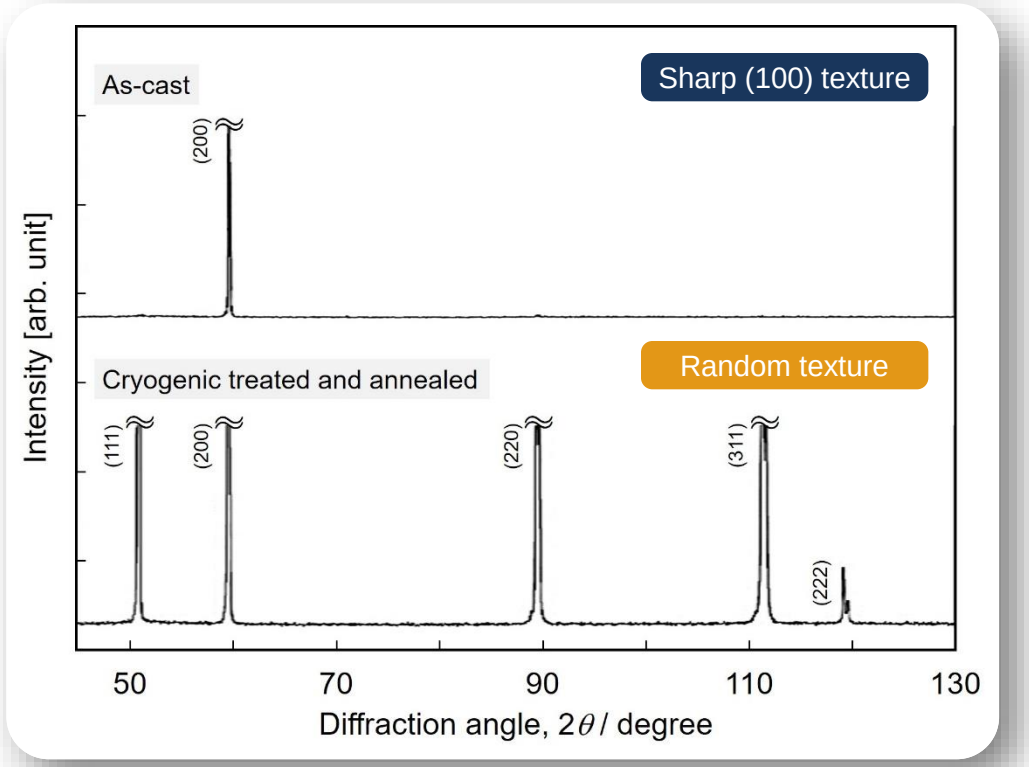

Relative thermal expansion curves to a dimension at 20 ºC (room temperature) obtained from I-200, SI-300, K-400 and a typical invar alloy $Fe_{65}Ni_{35}$.

# Microstructural evolution during thermal treatment




Optical micrographs observed in (a) as-cast, (b) as-cryogenic treated and (c) thermally treated specimens obtained from the I-200 ($x$ = 1.7) cast block.
(d) shows a magnified micrograph of (b).

# Randomization of crystallographic orientations




XRD profiles obtained from the as-cast and thermally treated (cryogenic treated and annealed) SI-300 specimens.

- As-cast invar alloy
  - ✓ Coarse columnar grains structure
  - ✓ Sharp (100) texture
- Thermally treated cast invar alloy
  - ✓ Fine and equiaxed grains structure
  - ✓ Randomly distributed grains
- Controlled grains microstructure
  - ✓ Low thermal expansion cast alloy with stable and superior mechanical properties

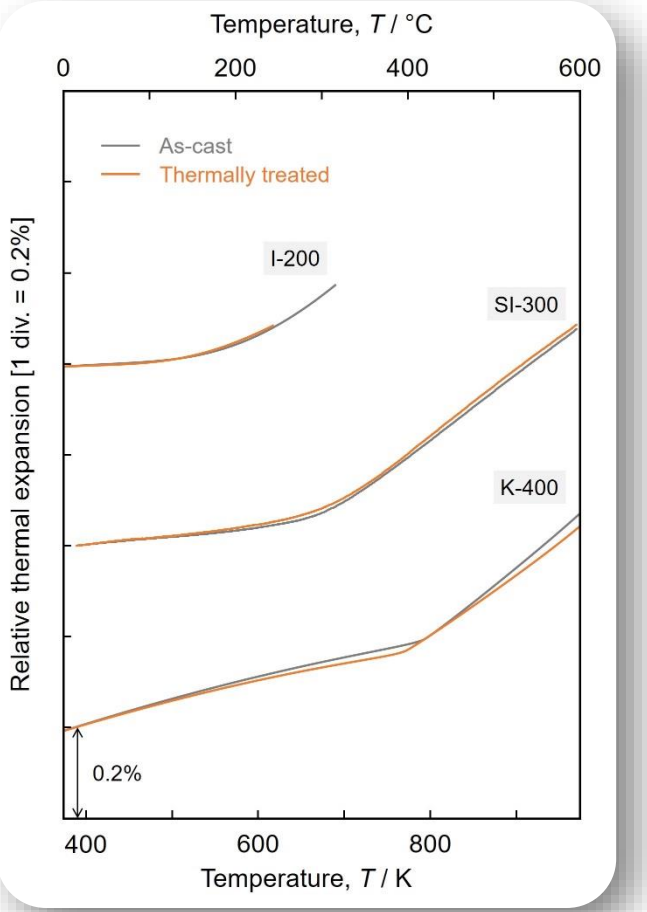


H.T. Fujii SHINHOKOKU STEEL CORP. fujii@shst.co.jp

# Maintenance of low thermal expansion characteristics

- Effect of thermal treatment on thermal expansion characteristics
  - ✓ Few effects were observed between thermal expansion curves of as-cast and thermally treated specimens

- Cryogenic treatment and annealing
  - ✓ Powerful technique to obtain low thermal expansion cast alloys with high strength

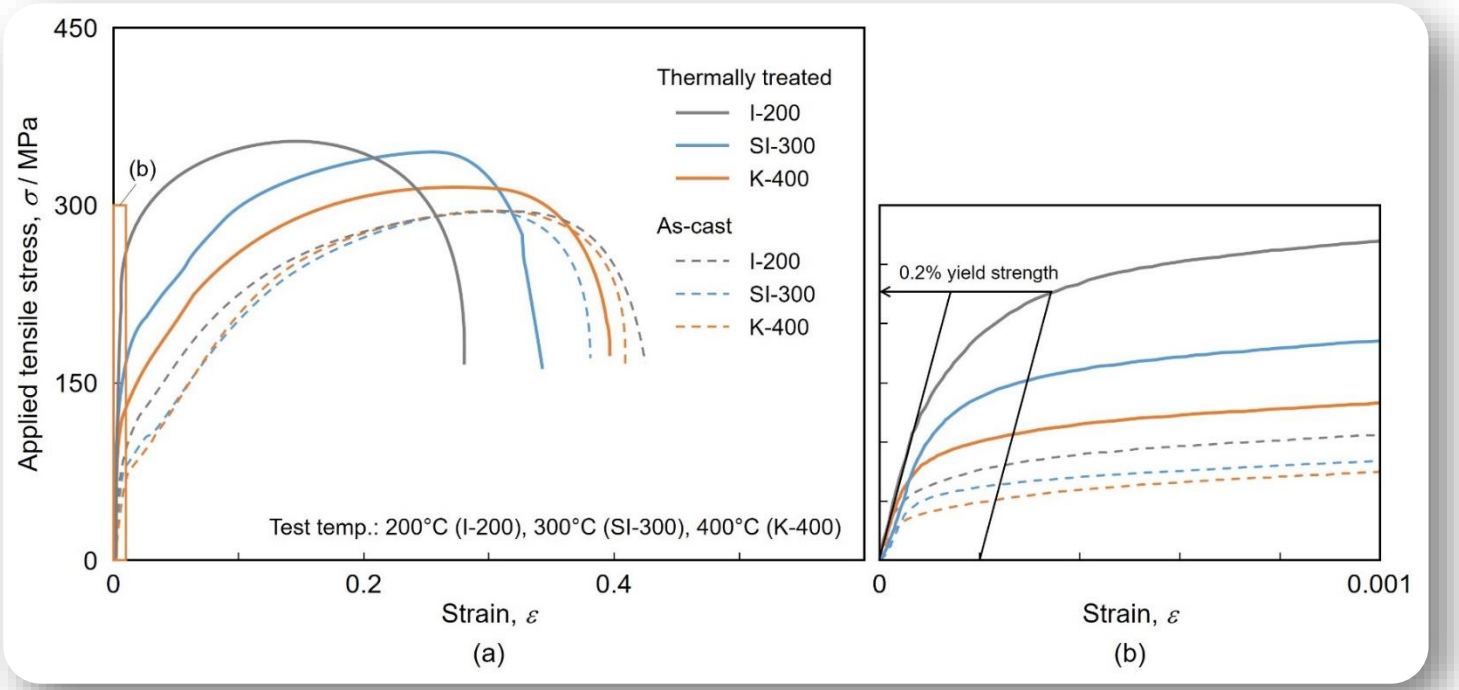



Comparison of relative thermal expansion curves to the dimensions at 20 ºC (room temperature) between the as-cast and the thermally treated I-200, SI-300 and K-400 specimens.




H.T. Fujii SHINHOKOKU STEEL CORP. fujii@shst.co.jp

# Effects of thermal treatment on mechanical properties




(a) Stress-strain curves obtained from the as-cast and the thermally treated I-200, SI-300 and K-400 specimens at 200 ºC, 300 ºC and 400 ºC, respectively. (b) A magnified view of the region in low strain range indicated by orange square in (a).

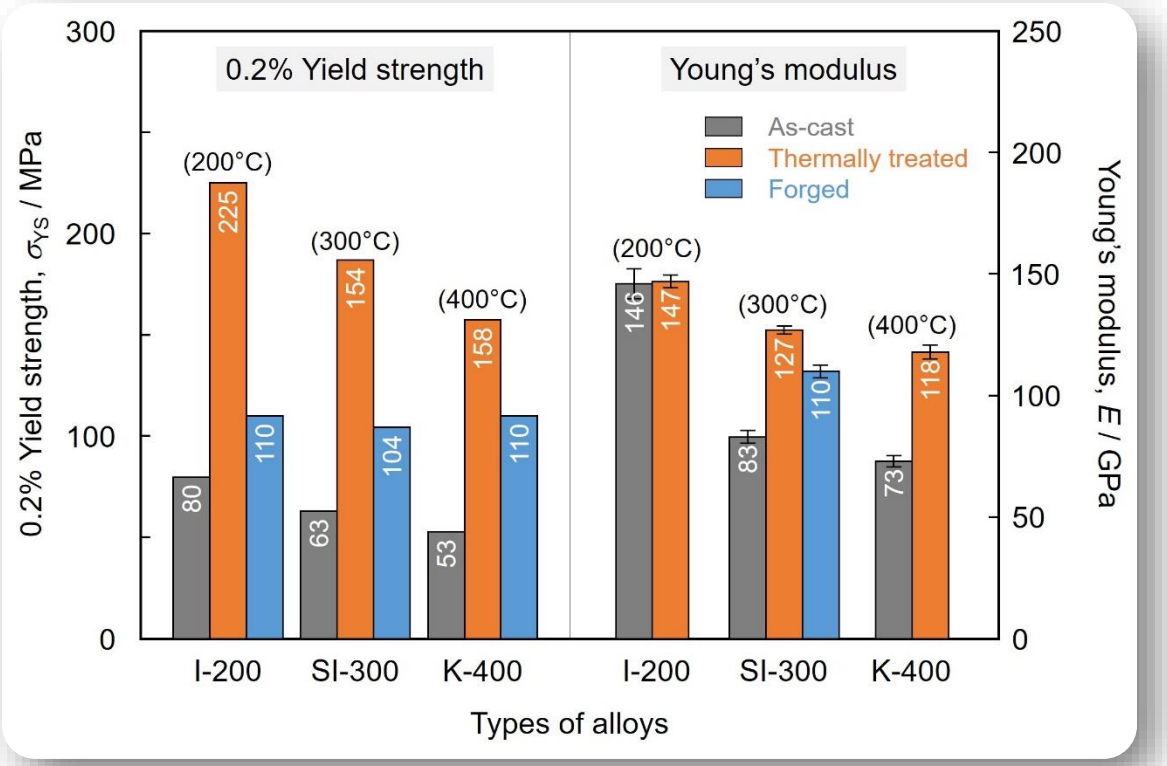
- Increase in tensile strength by thermal treatment
  - ✓ Applied stress in thermally treated specimens is higher than that in as-cast specimens
  - ✓ Increase in strength is caused by grain refinement



H.T. Fujii SHINHOKOKU STEEL CORP. fujii@shst.co.jp

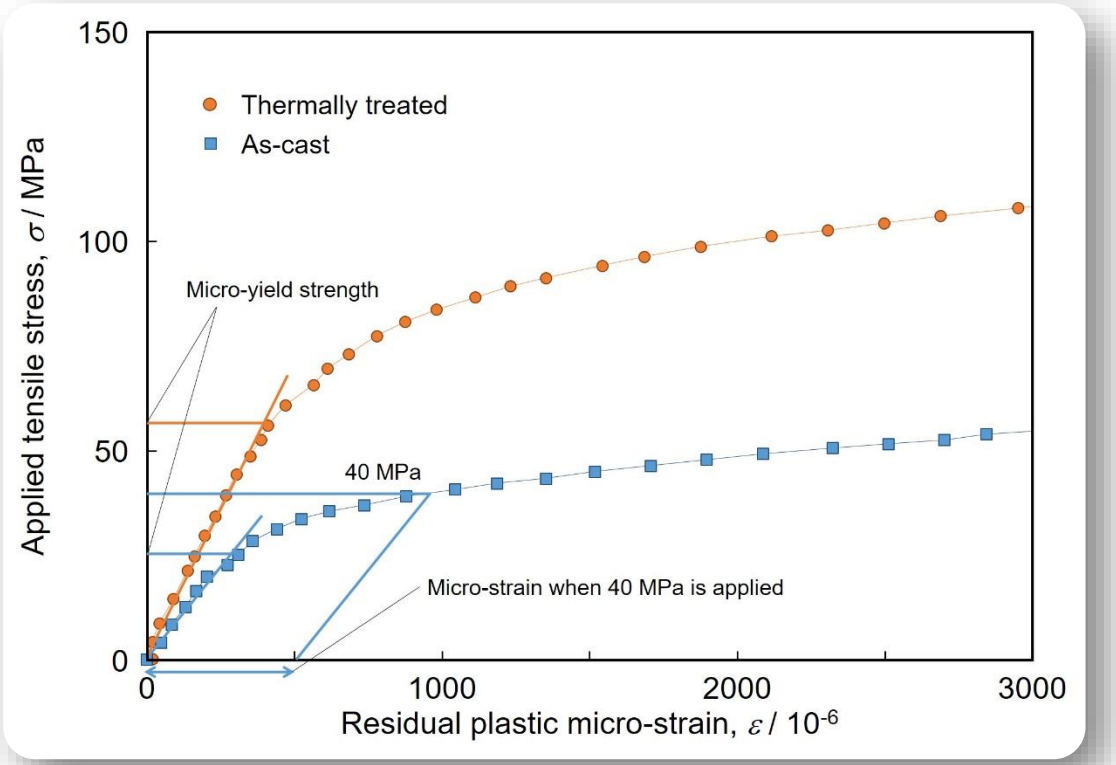
# Improvement of mechanical properties

- Drastic improvement of yield strength
  - ✓ Improved more than 2.2 times by thermal treatment
  - ✓ Higher than forged alloys with fine grains structure
- Improvement of Young's modulus
  - ✓ Improved by thermal treatment in SI-300 and K-400




0.2% yield strength and Young's modulus of the as-cast and the thermally treated I-200, SI-300 and K-400 specimens estimated from the stress-strain curves.

# Improvement of lifetime




Stress-strain curves in low strain range obtained from the as-cast and the thermally treated K-400 specimens at 400 ºC.

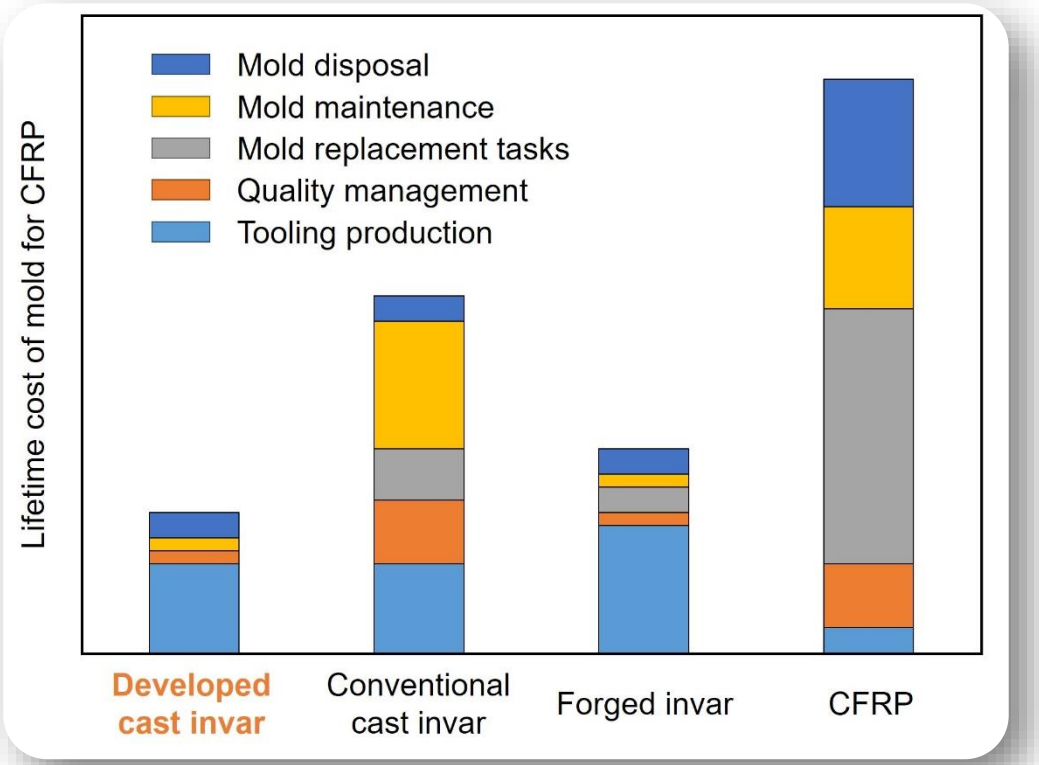
- Drastic decrease in aged deterioration
  - ✓ 40 MPa is assumed to be locally applied by stress concentration during press molding
  - ✓ Cyclic applied stress during mass production will produce aged deterioration of tooling materials
  - ✓ No micro-strains are accumulated in thermally treated cast invar alloys

- Expected technological benefits
  - ✓ Drastic improvement of tooling lifetime
  - ✓ Stable products quality
  - ✓ Automation of factory




H.T. Fujii SHINHOKOKU STEEL CORP. fujii@shst.co.jp

# Technological advantages of developed invar alloys




Summary of lifetime cost in each tooling material for small CFRP component with an intricate structure.

- Tooling lifetime cost
  - ✓ Long lifetime (Decrease in replacement cost)
  - ✓ Stable components quality (Decrease in maintenance cost)
  - ✓ High recyclability (Decrease in disposal cost)



H.T. Fujii SHINHOKOKU STEEL CORP. fujii@shst.co.jp

# Summary

- ✓ Yield strength of the low thermal expansion cast alloys at desired CFRP molding temperature can drastically increase by the application of reverse martensitic transformation.

- ✓ Low thermal expansion cast alloy with high strength can be a powerful tool in molding of small CFRP components with intricate structure for next gen. air mobility. In particular, the developed alloys will allow for precise production of components with high level of safety that enables to social acceptance.

# THANK YOU
# FOR WATCHING

CAMX
THE COMPOSITES AND ADVANCED MATERIALS EXPO

SEPTEMBER 21-24
A VIRTUAL EXPERIENCE
2020

新報国製鉄株式会社
SHINHOKOKU STEEL CORPORATION


Hiromichi T. Fujii, Ph.D.
fujii@shst.co.jp
Principal researcher
SHINHOKOKU STEEL CORP.

# CAMX 2020 発表論文

題　目：“Development of Novel Tooling Materials for Next Generation Air Mobility Components with Intricate Structure”
著　者：Hiromichi T. Fujii, Naoki Sakaguchi, Haruyasu Ohno, and Kotaro Ona
年　　：2020
頁　　：TP20-0062 (14 pages)
概　要；

Thermal expansion characteristics between room and molding temperatures were analyzed in low thermal expansion alloys developed as novel tooling materials for small CFRP components with intricate structure. Low thermal expansion characteristics of the developed alloys could be maintained up to 400 ºC. The developed alloys prepared by casting were processed by cryogenic treatment and annealing to improve the mechanical properties. The mechanical properties were examined by tensile tests of round-bar specimens. Yield stress of the processed alloys showed more than twice of as-cast alloys. The drastic improvement of the mechanical properties was found to be attributed to the grain refinement and the high density dislocations through microstructural characterization. Cryogenic treatment and annealing process was also found to possibly reduce variation of mechanical properties. These discoveries suggested that the developed alloys could improve the tooling lifetime and reduce the manufacturing cost in CFRP molding for next generation air mobility.

URL: https://www.nasampe.org/store/viewproduct.aspx?ID=17609307