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Revolutionizing molding precision for aviation and urban air mobility: The power of low thermal expansion tooling in CFRTP compression forming

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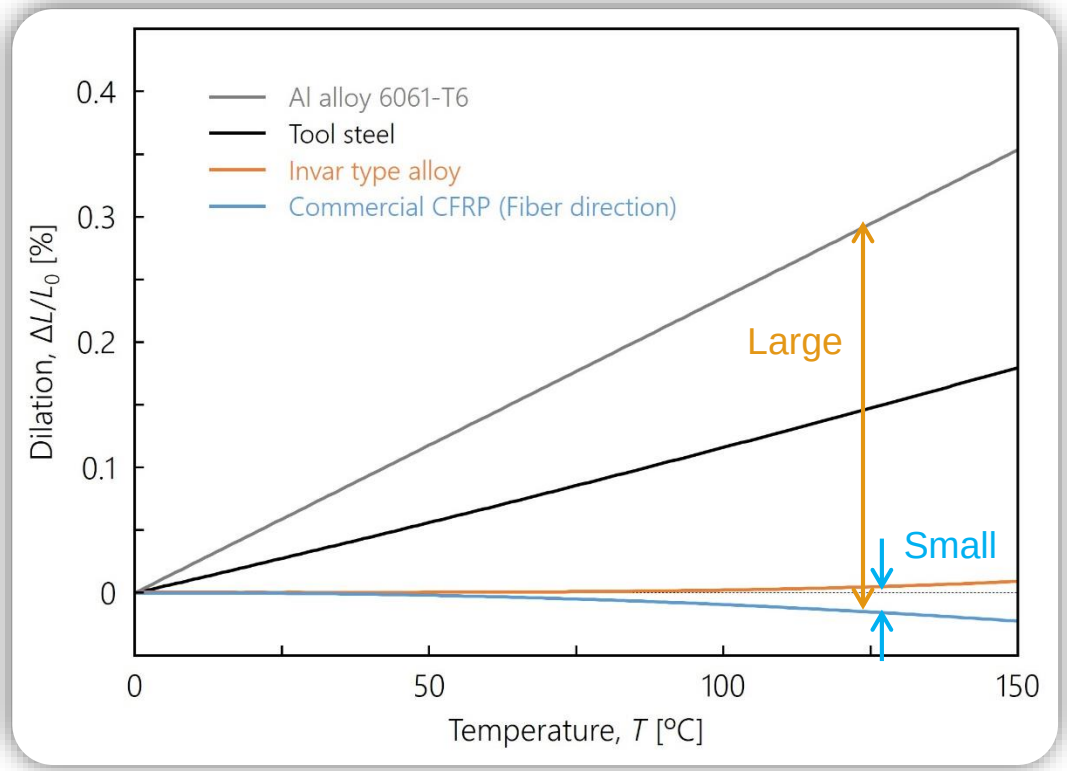
Synopsis

- **Background and motivation**
  - ✓ Introduction of low thermal expansion tooling
  - ✓ Purpose and research issues
- **Precision enhancement through low thermal expansion tooling**
  - ✓ Achieving superior molding accuracy
  - ✓ Mechanical properties of compression-formed CFRTP components
  - ✓ Enhancement of carbon fiber distribution
- **Optimizing tooling characterization for mass production of CFRTP components**
  - ✓ Improvement of yield strength of tooling
  - ✓ Overcoming machinability challenges in low thermal expansion tooling
- **Summary**

Invar tooling advantages in CFRP manufacturing



Thermal expansion curves obtained from Al alloy 6061, tool steel, Invar type alloy and commercial CFRP. The curve of CFRP was measured along its fiber direction.

	Invar	CFRP
Molding cycle	2000	200
Max temp. [°C]	230	190
Max load [MPa]	none	0.69
Weight	Heavy	Light
Intricate structure	Easy	Difficult
Cost	Expensive	Affordable
Master mold	Unnecessary	Graphite, Invar, …

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Technical challenges in next-gen CFRTP tooling

Conventional aviation	Urban air mobility
✓ Large parts (Small curvature) ✓ Small batch production	✓ Small parts (Complex structure) ✓ Mass production

Next-gen CFRTP tooling

Dimensional stability	Accurate molding
Near-net-shape	Complex structure
High strength	Long tool life

Examples of small CFRP parts with complex structure

Critical needs in urban air mobility

Market explosion	$6.2 billion in 2030 (Required units number: 150 thousands)
Implementation goals	More than 12 cities in 2030 Air taxi for tens of thousands people per day
Required parts number	Tens of thousands per year (Equivalent to automotive industry)
Social acceptance	High-level manufacturing technology that meets the design requirements is essential
Start-ups	Joby Aviation, Volocopter, SkyDrive, Ehang Vertical Aerospace, …

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Research objectives

To develop mass production tooling for high-quality and high-reliability small and complex-shaped CFRTP components, towards the societal implementation of urban air mobility.

Molding accuracy

Development of new low-thermal-expansion alloys

Complex shape

Casting and 3D printing technologies

Mass production

Improvement of mechanical properties

Precision enhancement through low thermal expansion tooling

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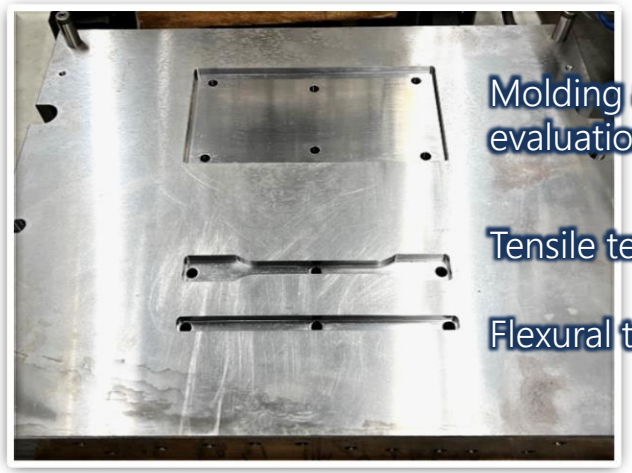
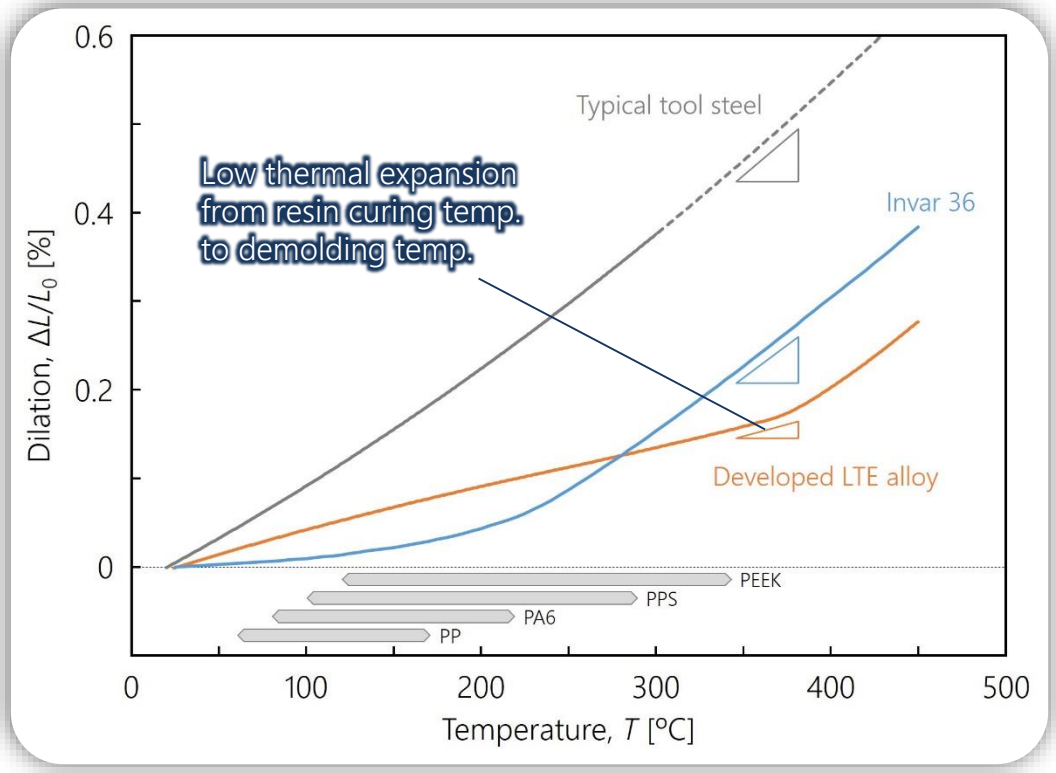
Characteristics of low thermal expansion tooling

- **Tooling for compression forming tests**
  - ✓ Low thermal expansion (LTE) tooling
  - ✓ Tool steel tooling (for comparison)

- **Specimen shape**

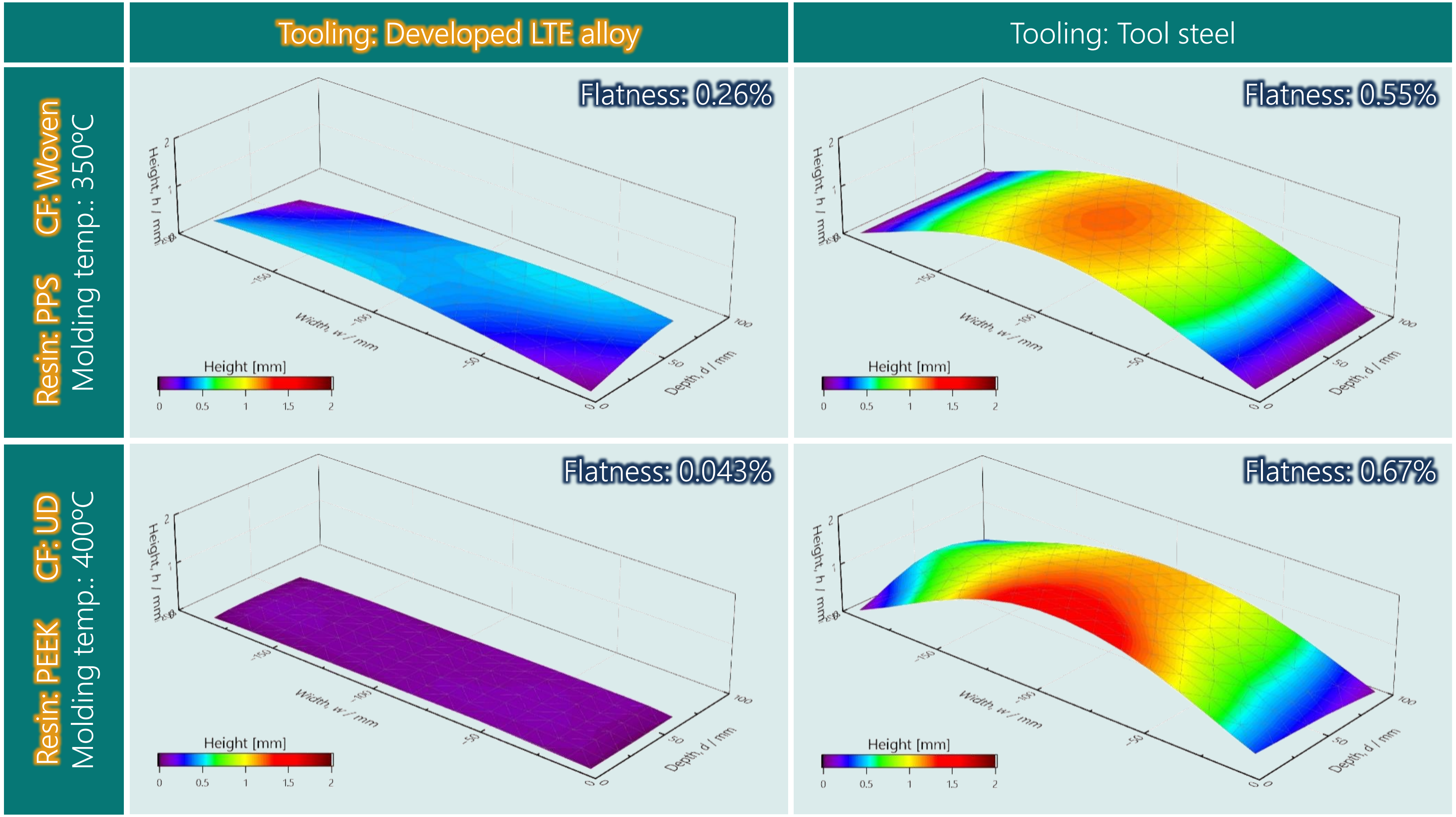


Overview of tooling used for compression forming tests of CFRTP.

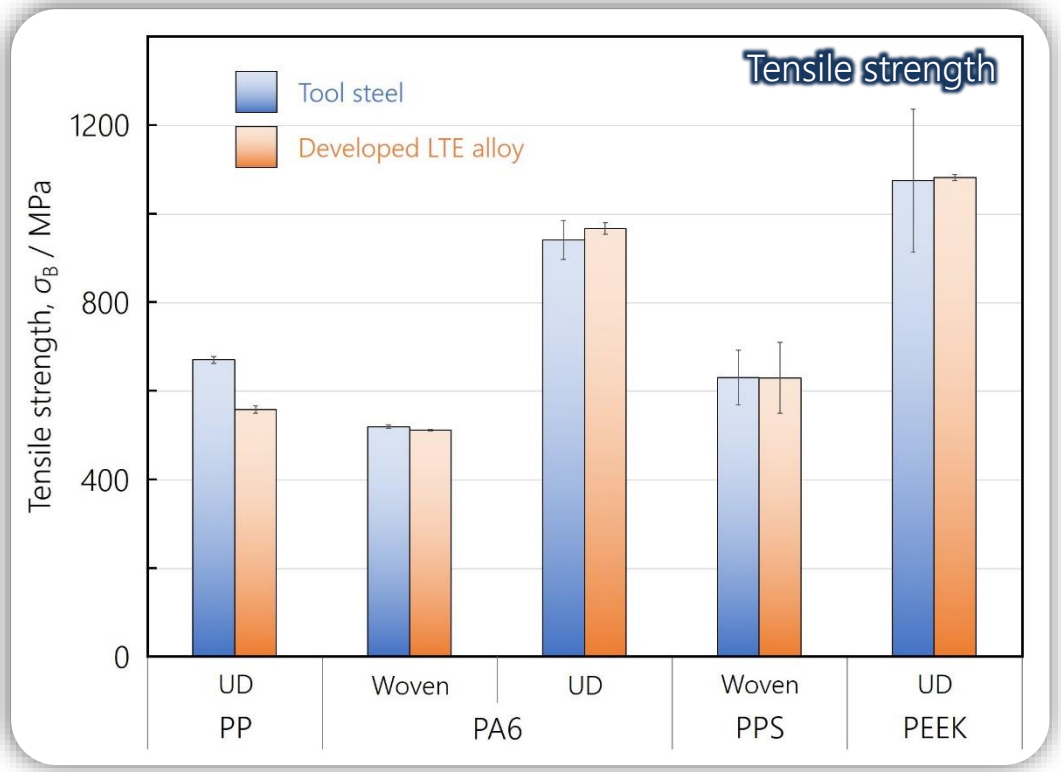


Thermal expansion curves obtained from tooling materials used for compression forming tests of CFRTP. For comparison, a curve of Invar 36 is also shown by blue line.

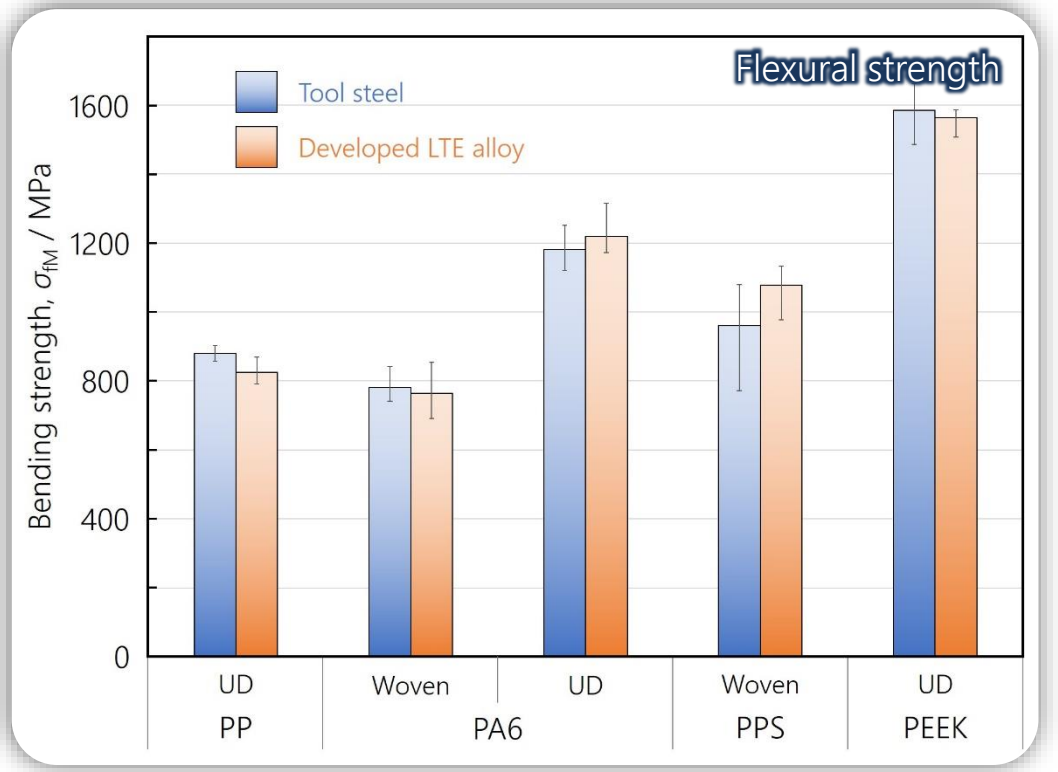
Achieving superior molding accuracy with LTE tooling



Mechanical properties of CFRTP components



Comparison of tensile strength of CFRTP specimens using different resins and carbon fibers: Conventional tool steel and low thermal expansion tooling.

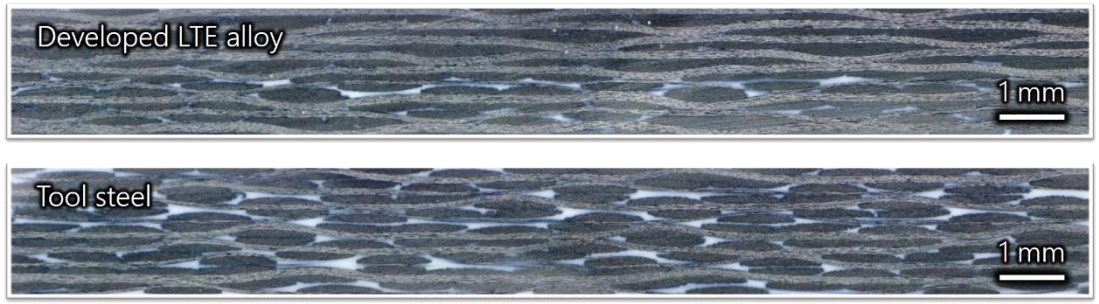


Comparison of flexural strength of CFRTP specimens using different resins and carbon fibers: Conventional tool steel and low thermal expansion tooling.

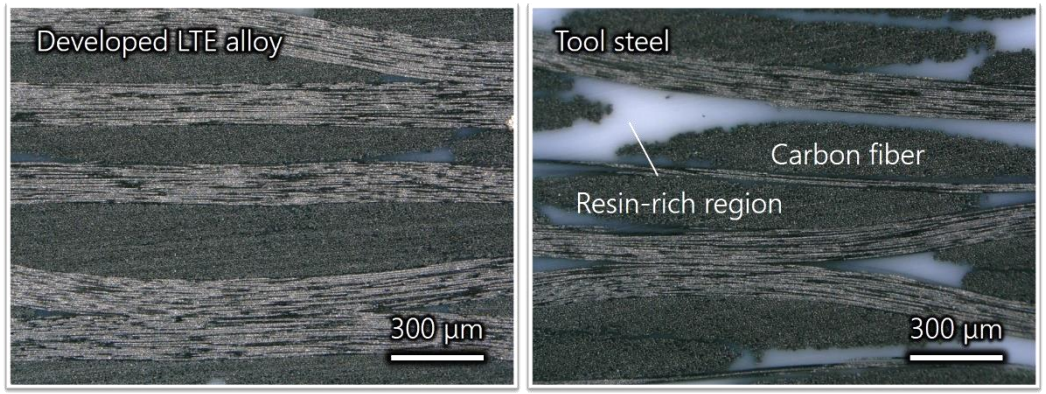
Enhancing CF distribution with LTE tooling

Improvement of CF density

- ✓ By using LTE tooling, the volume fraction (V_f) of carbon fibers has increased
- ✓ When using conventional tool steel tooling, thermal contraction occurs during the temperature decrease from curing to demolding
- ✓ The thermal contraction of the tooling may result in non-uniform stress distribution during molding, leading to the potential for non-uniform carbon fiber density



(a)



(b)

(a) Cross-sectional macro photographs of CFRTP specimens press-formed using LTE and conventional tool steel tooling, along with (b) enlarged views of the macro photographs.

Optimizing tooling characteristics for mass production of CFRTP components

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Innovative manufacturing process for LTE tooling

Developed cast Invar

Casting → Cryogenic and heat treatment → Finish processing

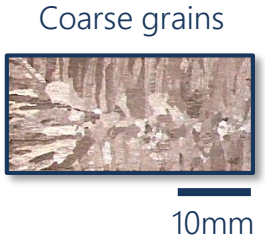
Near-net shape | High rigidity, Low CTE

→ Higher yield strength → Longer tooling life

Conventional cast Invar

Casting → Heat treatment → Finish processing

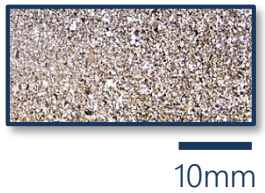
Near-net shape | Low CTE



Forged Invar

Casting → Forging → Machining → Heat treatment → Finish processing

Ingot | High rigidity | Low CTE



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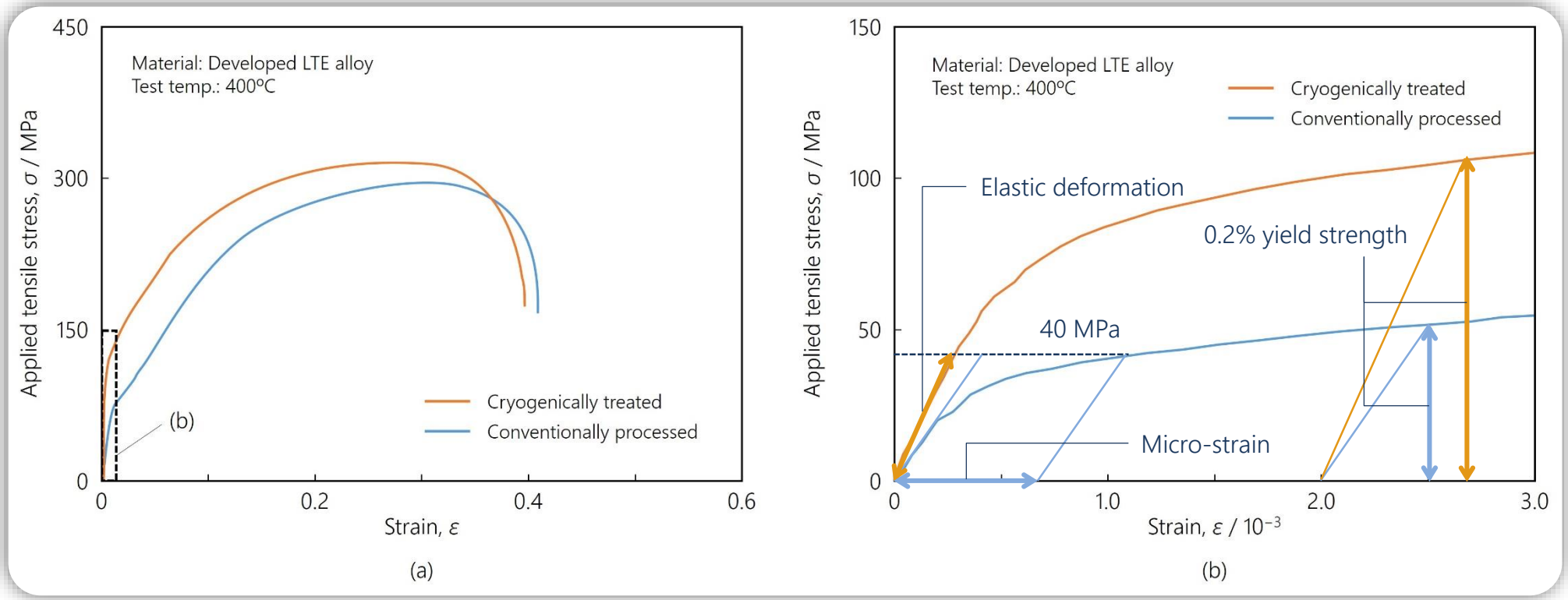
Improvement of tooling life through cryogenic treatment



(a) Comparison of stress-strain curves for low thermal expansion alloy prepared by casting with and without unique thermal treatment, and (b) enlarged view of low-strain region.

Tooling reinforcement is expected to reduce deformation, extend lifespan and enhance precision.

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Overcoming machinability challenges in LTE tooling

Drilling test

- ✓ Cutting tool: High-speed steel drill
- ✓ Workpiece: Developed LTE alloy
  Commercial LTE alloy
- ✓ Machining:

Cutting speed	45 m/min
Feed rate	0.013 mm/rev
Hole diameter	ϕ2.6 mm
Machining depth	13 mm
Machining cycles	100

(a) (b)

A comparison of tool wear after machining with a high-speed drill on (a) development low thermal expansion alloy (VIC-65) and (b) commercially available low thermal expansion alloy (Kovar)

Our innovative alloying technology has significantly improved the machinability of low thermal expansion tooling, addressing their primary weakness.

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Summary

Our low thermal expansion tooling significantly improved the molding accuracy of CFRTP compression-formed parts, and the yield strength of the cast tooling were greatly enhanced through cryogenic processing. These findings are expected to make a significant contribution to the advancement of the manufacturing processes for urban air mobility components.

Molding accuracy

Development of new low-thermal-expansion alloys

Complex shape

Casting and 3D printing technologies

Mass production

Improvement in mechanical properties

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THANK YOU FOR LISTENING

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