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Unlocking the potential of non-ferromagnetic Invar-type alloys in space exploration

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

Shinhokoku Material Corp.

* fujii@shst.co.jp

新報国マテリアル株式会社
SHINHOKOKU MATERIAL CORPORATION

Outline

- Background and motivation
  - ✓ Introduction of low thermal expansion alloys
  - ✓ Non-ferromagnetic Cr-based Invar-type alloys
- Experimental procedure
- Results and discussion
  - ✓ Achieving low thermal expansion characteristics through the addition of Fe to Cr
  - ✓ Control of Néel temperature by Mn addition
  - ✓ Impact of additive elements on thermal expansion characteristics
  - ✓ Magnetic properties of Cr-Fe-Mn alloy
- Conclusions

Customized Invars for specific temperature applications

Customized super Invar

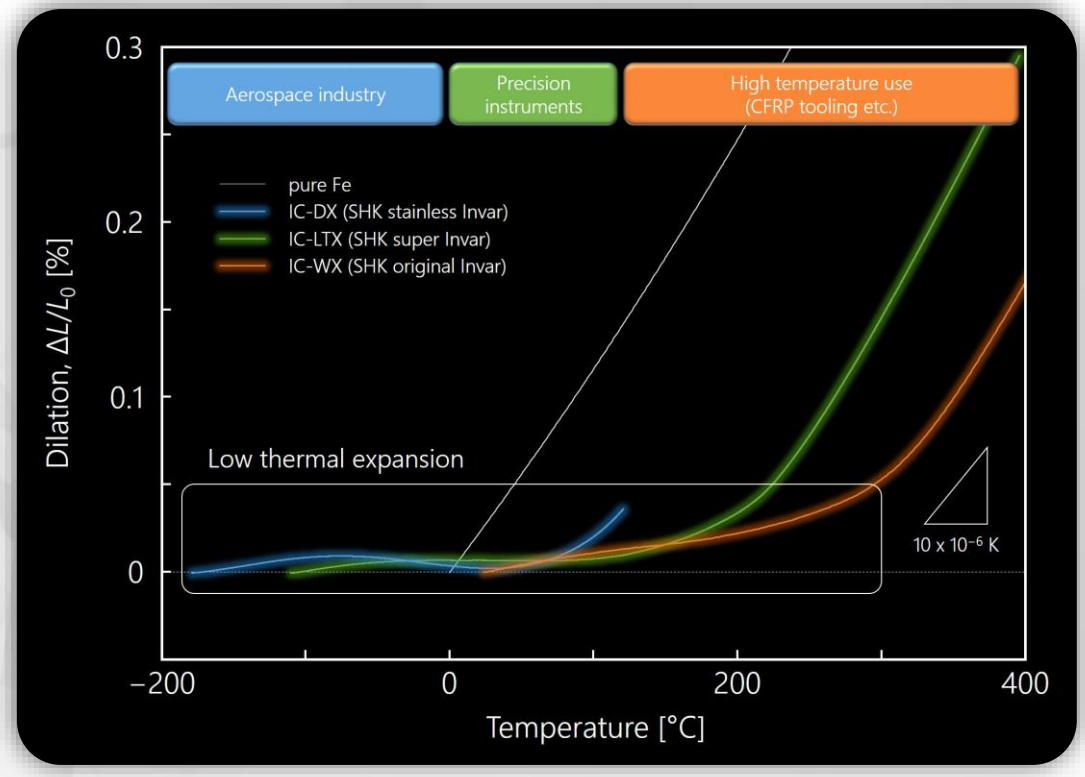
- ✓ Suitable for cryogenic temperatures (down to −100°C)
- ✓ Extremely low thermal expansion (< 0.015 x 10^{-6}/K)
- ✓ Dimensionally stable over years

World's only customized stainless Invar[1, 2]

- ✓ Zero-expansion
- ✓ Breaking new ground with the world's first zero-expansion stainless Invar (Patented)

Challenges

- ✓ Dimensional change under a magnetic field due to large magnetostriction



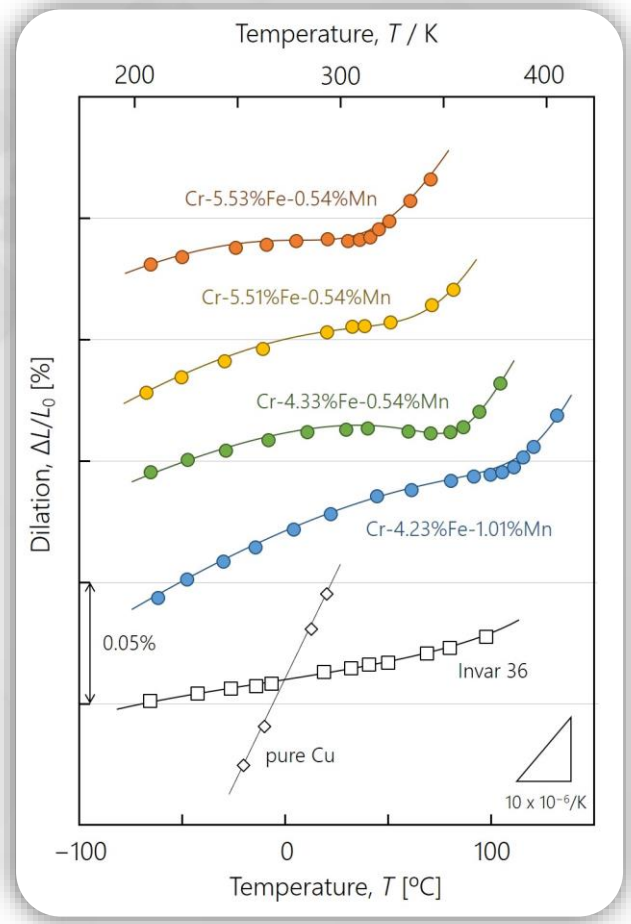
A range of low thermal expansion alloys is available across a wide temperature spectrum. (Coefficient of thermal expansion: Adjustable from 10^{-7} to 10^{-5} /K)

[1] H.T. Fujii *et al.*, *Proc. SPIE*, **11451** (2020), 1145118.
[2] H.T. Fujii *et al.*, *Proc. SPIE*, **12188** (2022), 1218806.

Non-nonferromagnetic Cr-based Invar-type alloy

Challenges associated with magnetism

- ✓ Dimensional changes due to magnetostriction
  - Semiconductor manufacturing equipment
- ✓ Magnetic noise
  - Electron microscope
  - Medical diagnostics
- ✓ Magnetic induction
  - Electrolytic refining furnace
  - Power transmission facilities



Thermal expansion curves of Cr-Fe-Mn alloys[1]. For comparison, the curves of typical Invar 36 and pure Cu are also shown.

[1] K. Fukamichi and H. Saito, *Phys. Stat. Sol. (a)*, **10** (1972), K129-131.

Purpose

By conducting a detailed analysis of the Cr-Fe-Mn non-ferromagnetic Invar-type alloy's thermal expansion behavior and magnetic response, we aim to enrich scientific understanding and pave the way for new industrial applications of non-ferromagnetic alloys with minimal thermal expansion.

Research issues

- ✓ Achieving low thermal expansion characteristics through the addition of Fe to Cr
- ✓ Control of Néel temperature by Mn addition
- ✓ Impact of additive elements on thermal expansion characteristics
- ✓ Magnetic properties of Cr-Fe-Mn alloy

Experimental

Sample preparation

- ✓ Materials: Cr-Fe, Cr-Fe-Mn and Cr-Fe-Mn-RE
- ✓ Methods: Arc melting

Measurement of thermal expansion characteristics

- ✓ Precise dilatometer with furnace and cooling bath
- ✓ Temp. range: 120 – 470 K
- ✓ Heating rate: 5.0 K/min

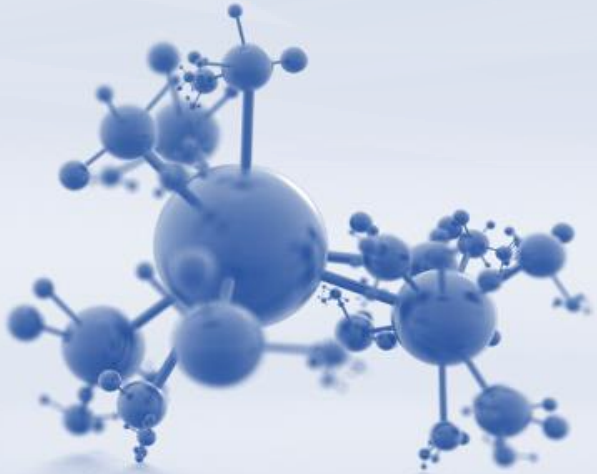
Evaluation of magnetic properties

- ✓ Vibrating sample magnetometer
- ✓ Specimen dimension: 5 mm x 5 mm x 1 mm
- ✓ Magnetic field direction: Parallel to the plate


Magnetometer


Dilatometer

Results and discussion



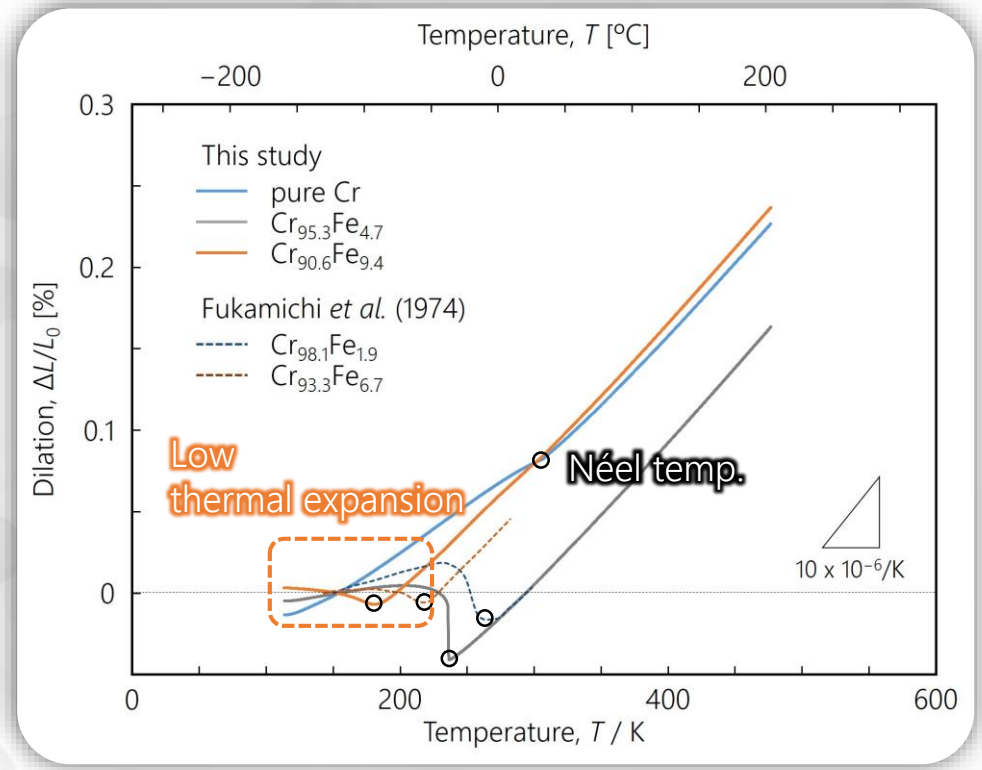
Manifestation of low thermal expansion characteristics

Anomalous thermal expansion in Cr-based alloys

- ✓ Distinct inflection points, known as Néel temperature (T_N), are revealed by the Fe addition
- ✓ Low thermal expansion characteristics are observed below T_N
- ✓ T_N is lower than 0ºC and decreases with increasing Fe content

Nature of low thermal expansion

- ✓ Reduced lattice vibrations due to stronger antiferromagnetic ordering below T_N



Thermal expansion curves obtained from pure Cr and Cr-Fe alloys. For comparison, previously reported curves by Fukamichi *et al.*[1] are also included.

[1] K. Fukamichi and H. Saito, *AIP Conf. Proc.*, **17** (1974), 45-55.

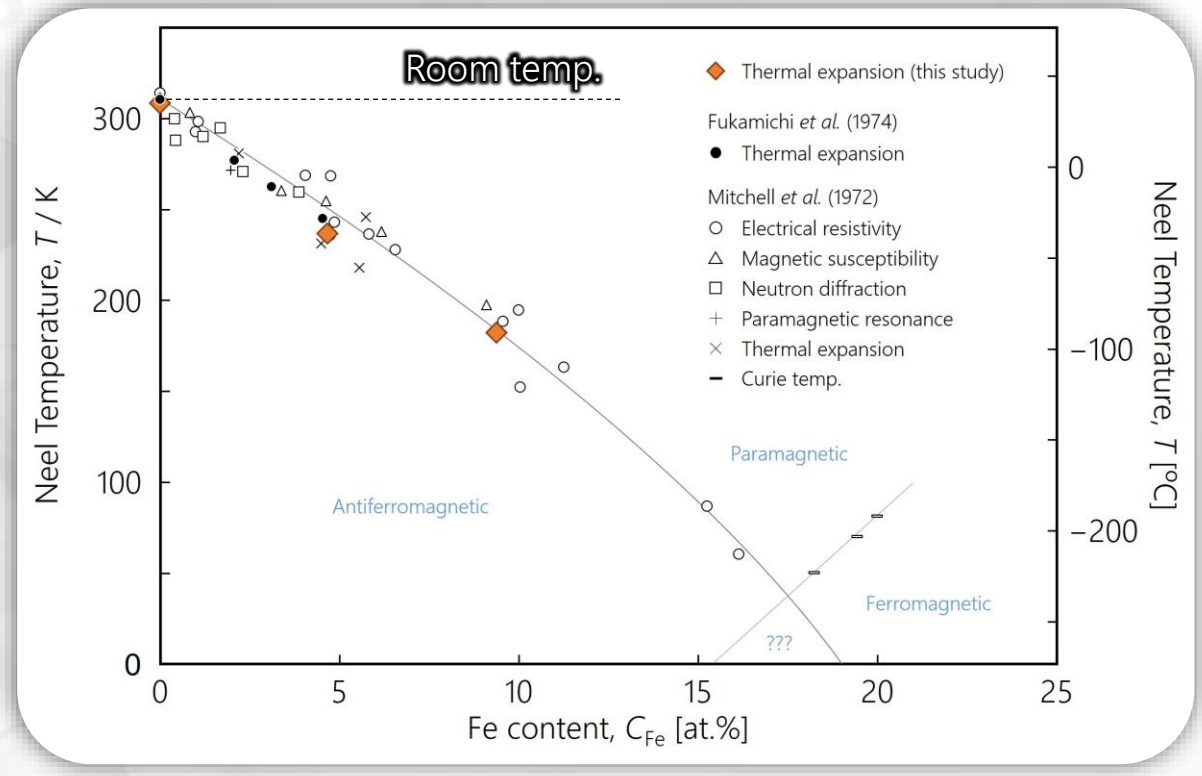
Potential applications and limitations of Cr-Fe alloys

Applicable temperature range

- ✓ Measured T_Ns are good agreement with previous data estimated by various methods
- ✓ Cr-Fe alloys can be used as low thermal expansion materials only below room temperature

CTE estimated at specific temperatures

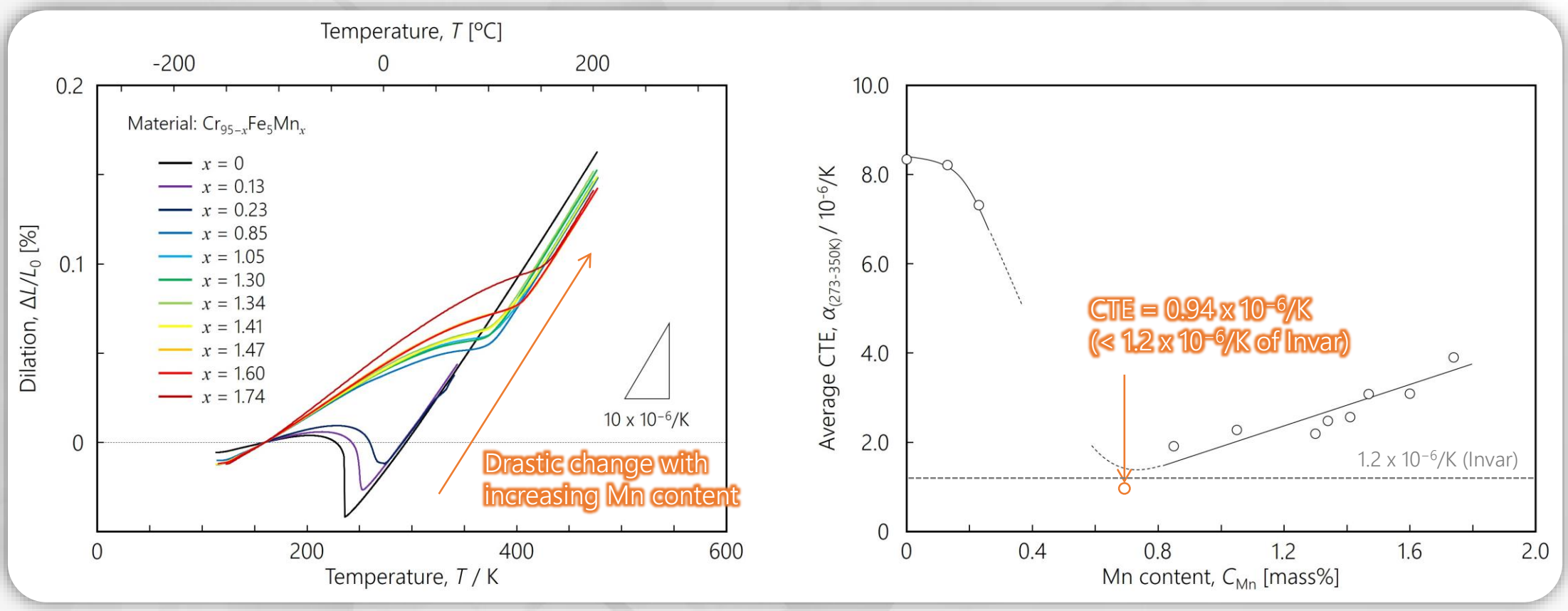
Material	CTE at each temperature [10^{-6}/K]				
	150 K	200 K	250 K	300 K	350 K
pure Cr	4.39	5.83	5.63	3.81	8.62
Cr95Fe5	1.25	0.19	6.50	8.96	8.82
Cr90Fe10	−1.43	7.45	7.82	8.44	9.07



The impact of Fe addition on the Néel temperature of Cr alloys, as determined from thermal expansion measurements. For comparative purposes, the graph also includes data previously estimated by various experimental[1, 2].

[1] K. Fukamichi and H. Saito, *AIP Conf. Proc.*, **17** (1974), 45-55.
[2] M.A. Mitchell and J.F. Goff, *Phys. Rev. B*, **5** (1972), 1163-1170.

Tailoring thermal expansion characteristics of Cr-Fe-Mn alloys



Thermal expansion curves obtained from Cr-based Invar-type alloys with varying Mn contents and the impact of Mn content on the average CTE between 273 and 350 K in Cr-based Invar-type alloys. The average CTE values were derived from the thermal expansion curves.

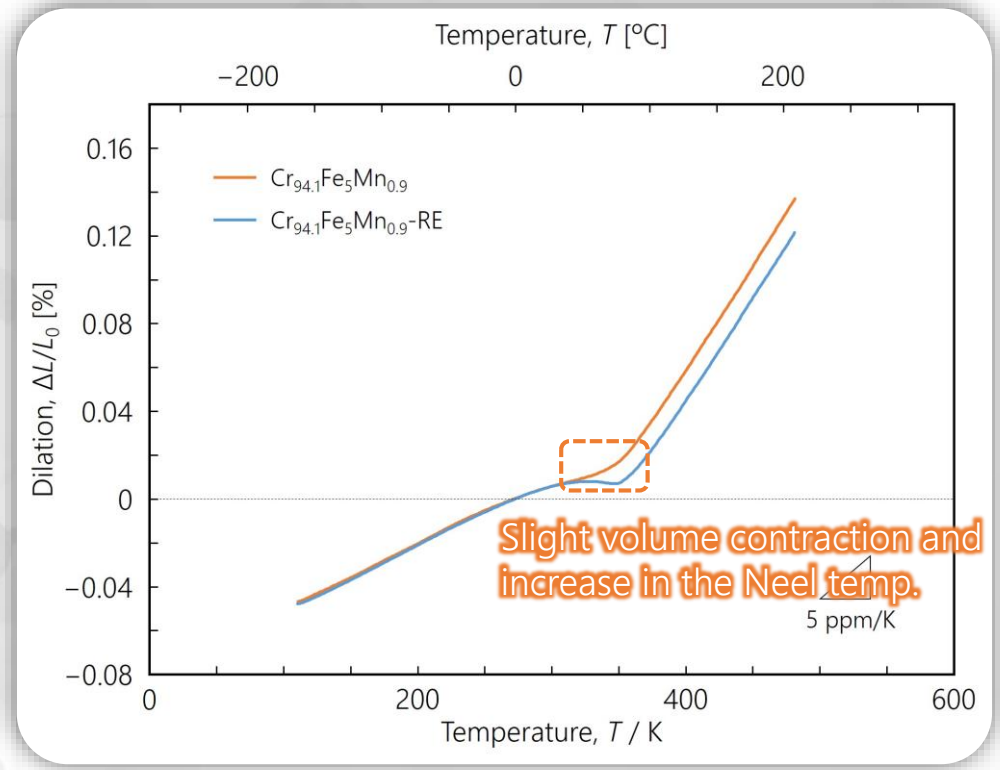
Impact of rare earth elements on thermal expansion

Role of rare earth elements

- ✓ Cr-based alloys face challenges in formability, hindering mass production use
- ✓ Incorporating rare earth elements has shown promise in improving machinability

Change in thermal expansion behavior

- ✓ Overall thermal expansion behavior of the alloy remains consistent even with the addition of rare earth elements, preserving its fundamental thermal properties



Thermal expansion curves obtained from Cr-based Invar-type alloys with and without rare-earth elements.

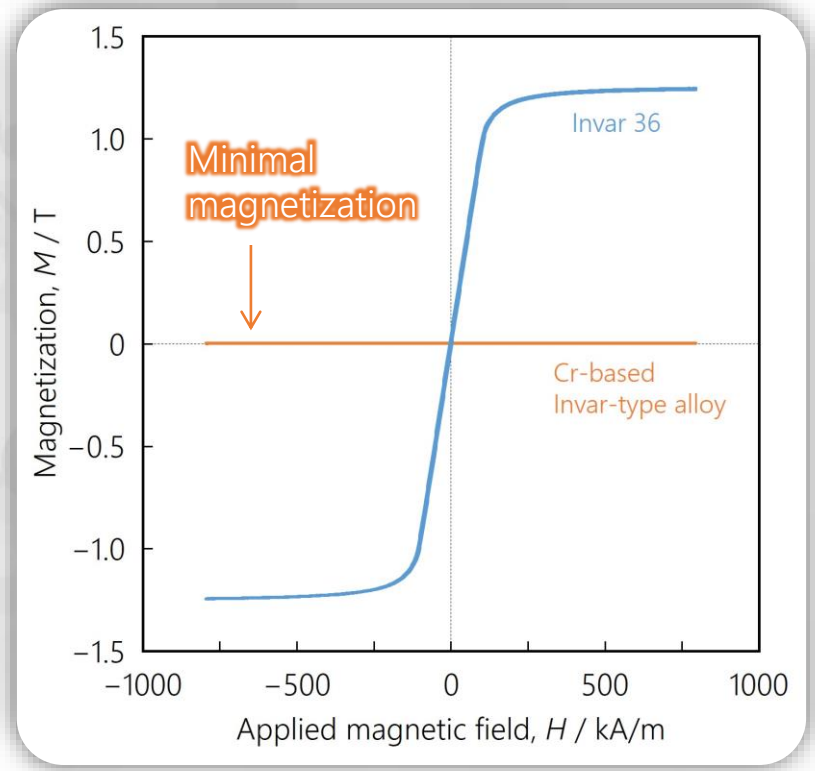
Magnetic properties of Cr-based Invar-type alloy

Magnetization curve

- ✓ Magnetization is nearly zero
- ✓ Magnetostriction would be significantly lower compared to standard Invar 36

Magnetic properties

Magnetic properties	Cr-based Invar	Invar 36
Residual magnetization [T]	3.7×10^{-6}	3.5×10^{-2}
Permeability [H/m]	6.3×10^{-11}	9.4×10^{-6}



Magnetization curves obtained from Cr-based Invar and Invar 36 using vibrating-sample magnetometer (VSM).

Conclusions

1. Incorporating Fe into Cr significantly reduces thermal expansion below the Néel temperature, making these alloys suitable for cryogenic applications.

2. The addition of Mn further enhances these properties by increasing the Néel temperature, thereby extending the low thermal expansion characteristics to temperatures closer to room temperature. This makes Cr-Fe-Mn alloys promising candidates for applications requiring dimensional stability over a broader temperature range.

3. Magnetic measurements confirmed the non-ferromagnetic nature of Cr-based Invar-type alloys, which exhibit minimal magnetization and magnetostriction, making them ideal for high-precision applications where magnetic neutrality is essential.

Our comprehensive analysis highlights the potential of Cr-Fe-Mn alloys as superior alternatives to conventional Invar alloys, particularly in fields such as aerospace, precision instrumentation and other engineering applications requiring minimal thermal expansion and magnetic interference.

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e-mail

THANK YOU

新報国マテリアル株式会社
SHINHOKOKU MATERIAL CORPORATION

Hiromichi T. Fujii
+81-49-242-1955
fujii@shst.co.jp
www.shst.co.jp