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Low thermal expansion at cryogenic temperature in $Fe_{39-x}Co_{49+x}Cr_{10}Ni_2$ alloy used for astronomical telescopes

Hiromichi T. Fujii[a], Naoki Sakaguchi[a], Kotaro Ona[a]
Fumihiro Uraguchi[b], Yutaka Hayano[b, d], Toshihiko Yokoyama[c]

[a] Shinhokoku Material Corporation
[b] National Astronomical Observatory of Japan
[c] Institute of Molecular Science
[d] Graduate University for Advanced Study (SOKENDAI)

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Shinhokoku Material Corporation

Outline

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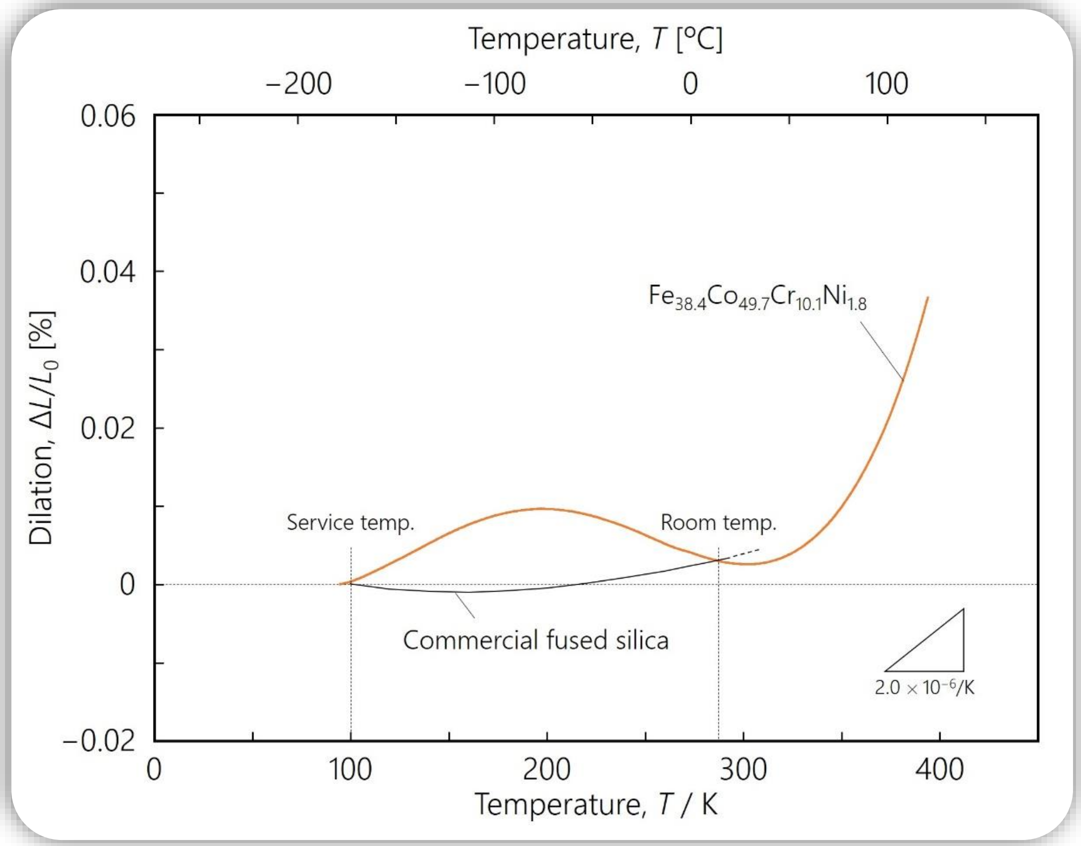
  - ✓ Precise control of thermal expansion
- Experimental procedure
- Results and discussion
  - ✓ Effect of Co content on microstructural evolution
  - ✓ Anomalously low thermal expansion at cryogenic temperature
  - ✓ Magnetic spin transition of Co atoms
- Conclusions

Observation accuracy in large astronomical telescopes

- **Thirty meter telescope (TMT)**
  - ✓ New class of extremely large telescope
  - ✓ Observation of cosmic objects with unprecedented sensitivity
- **Infrared imaging spectrograph (IRIS)**
  - ✓ Cooling down to cryogenic temperature to reduce the thermal noise
  - ✓ Reduction of dimensional change down to cryogenic temperature
- **Low thermal expansion alloys**
  - ✓ Invar alloy (Fe-36mass%Ni)
  - ✓ CTE at cryogenic temperature is still not low enough for infrared instruments

Thirty meter telescope (TMT) planned for construction in Hawaii
(Courtesy of NAOJ)

Precise control of thermal expansion



A relative thermal expansion curve obtained from the $Fe_{38.4}Co_{49.7}Cr_{10.1}Ni_{1.8}$ alloy with precisely controlled CTE between 100 K and room temperature. For comparison, the curve obtained from the commercial fused silica is also shown.

Previous research results*

- ✓ $Fe_{39}Co_{49}Cr_{10}Ni_2$ was found to have controllable low thermal expansion at cryogenic temperature by subtle adjustment of chemical composition
- ✓ Dimensional change between 100 K and room temperature of a developed alloy was matched with that of a fused silica

Detailed investigations of magnetic spin transition, which is origin of low thermal expansion (invar effect), are essential for the further development of low thermal expansion alloys used at cryogenic temperatures.

* Fujii H.T. *et al.*, *Proc. SPIE*, **11451**, 1145118 (2020).

Objective

We clarify the magnetic spin transition of Fe and Co atoms in the $Fe_{39}Co_{49}Cr_{10}Ni_2$ alloy to establish academic foundation for the development of the Fe-based low thermal expansion alloys used at cryogenic temperature for infrared instruments mounted on astronomical telescopes.

Research issues

- ✓ Microstructural characterization of $Fe_{39+x}Co_{49-x}Cr_{10}Ni_2$ alloys
- ✓ Effect of Co atom on thermal expansion characteristics at low temperature
- ✓ Origin of low thermal expansion

Experimental procedure

- **Sample preparation**
  - ✓ Materials: $Fe_{39-x}Co_{49+x}Cr_{10}Ni_2$ ($-1.0 \le x \le 2.3$)
  - ✓ Methods: Induction melting, casting and forging
  - ✓ Chemical analysis: Titration method
- **Microstructural characterization**
  - ✓ Optical microscopy
  - ✓ X-ray diffractometry
- **Evaluation of material properties**
  - ✓ Precise dilatometer with cooling bath
  - ✓ SQUID magnetometer

Results and discussion

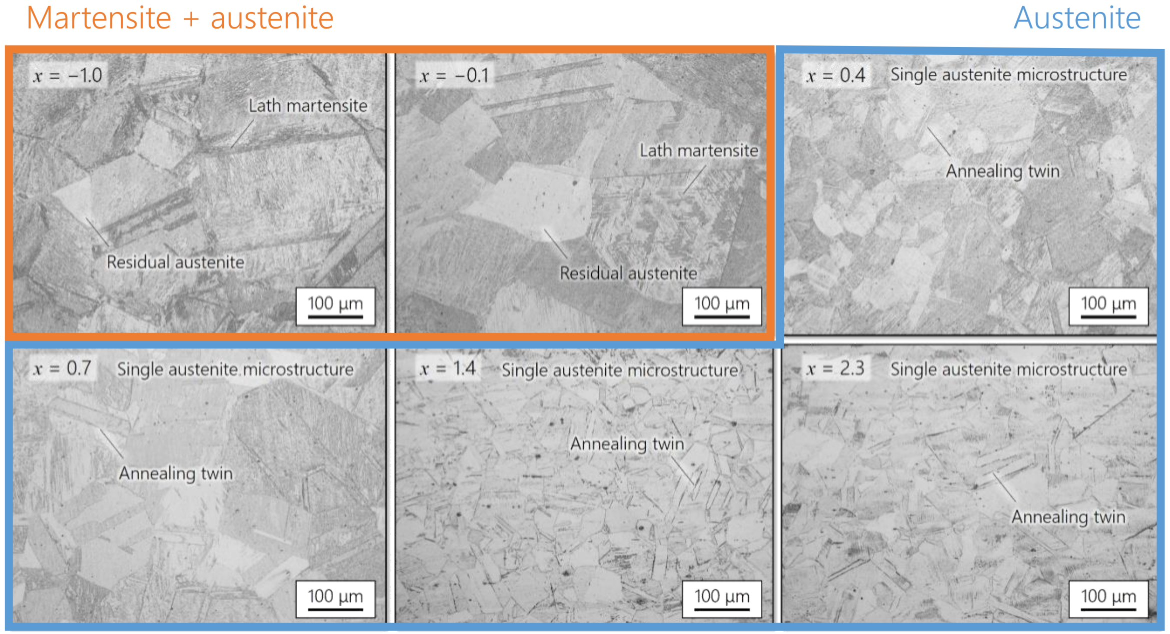
Effect of Co content on microstructural evolution

Invar effect

- ✓ Remarkable in the ferromagnetic Fe fcc phases with chemical composition near to a boundary between bcc and fcc phases
- ✓ Fe lattice contraction with increasing temperature caused by spin transition

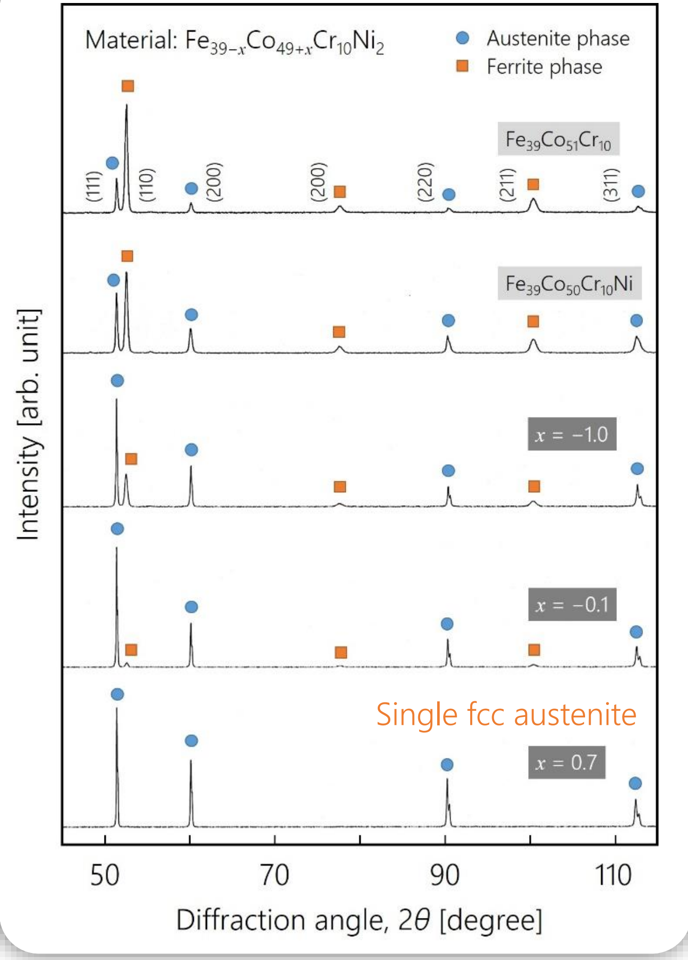
Microstructural characteristics

- ✓ Lath martensite: bcc (Dark regions)
- ✓ Residual austenite: fcc (Bright regions)
- ✓ Single austenite: $C_{Co} \geq 49\%$



Optical micrographs taken from the annealed $Fe_{39-x}Co_{49+x}Cr_{10}Ni_2$ (x = −1.0, −0.1, 0.4, 0.7, 1.4 and 2.3) alloys. Dark and bright regions indicate lath martensite and austenite phases, respectively.

Quantitative evaluation of fcc phase fraction



XRD profiles obtained from the annealed $Fe_{39-x}Co_{49+x}Cr_{10}Ni_2$ (x = −1.0, −0.1, and 0.7), the $Fe_{39}Co_{51}Cr_{10}$ and the $Fe_{39}Co_{50}Cr_{10}Ni$ alloys.

Evaluation of area fraction

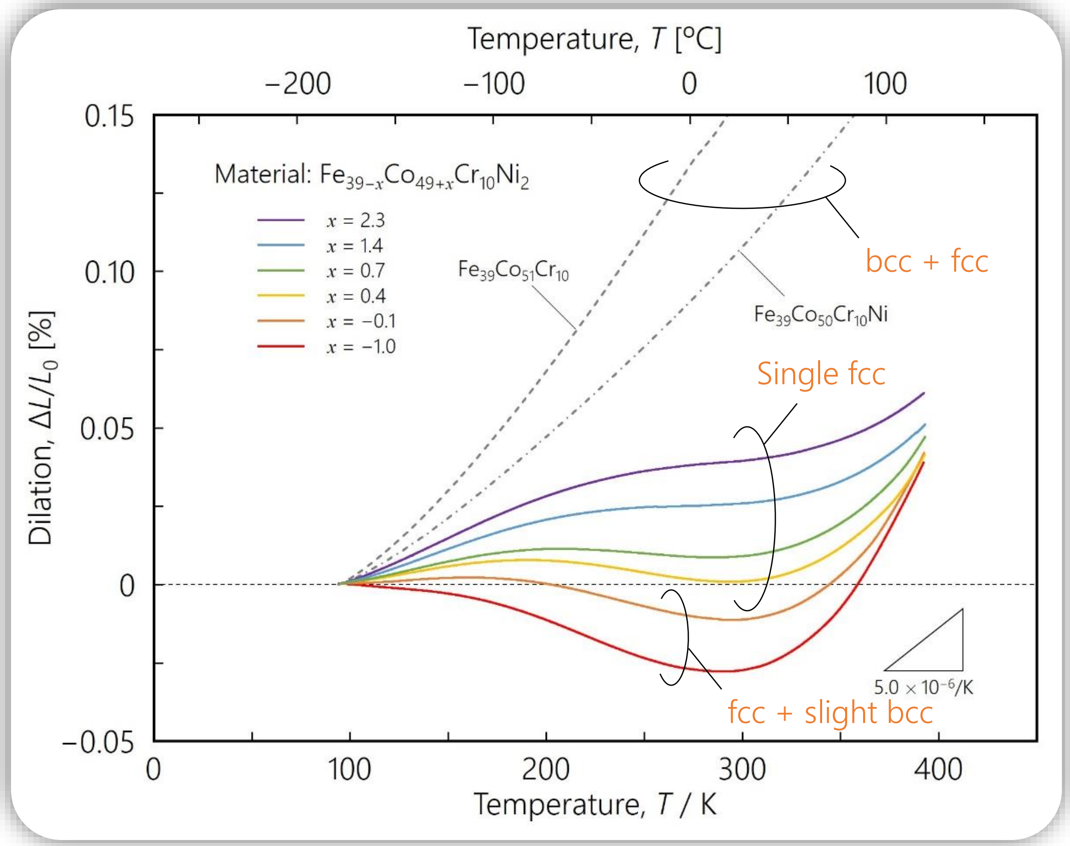
- ✓ Integrated peak intensity ratio between martensite and austenite phases
- ✓ C_{Co} < 49%: Martensite + austenite
- ✓ 49% ≤ C_{Co}: Austenite

Materials	Area fraction of phases [%]	
	bcc martensite	fcc austenite
$Fe_{39}Co_{51}Cr_{10}$	71	29
$Fe_{39}Co_{50}Cr_{10}Ni$	57	43
$Fe_{39-x}Co_{49+x}Cr_{10}Ni_2$		
x = −1.0	34	66
x = −0.1	12	88
x = 0.7	0	100

Low thermal expansion caused by invar effect

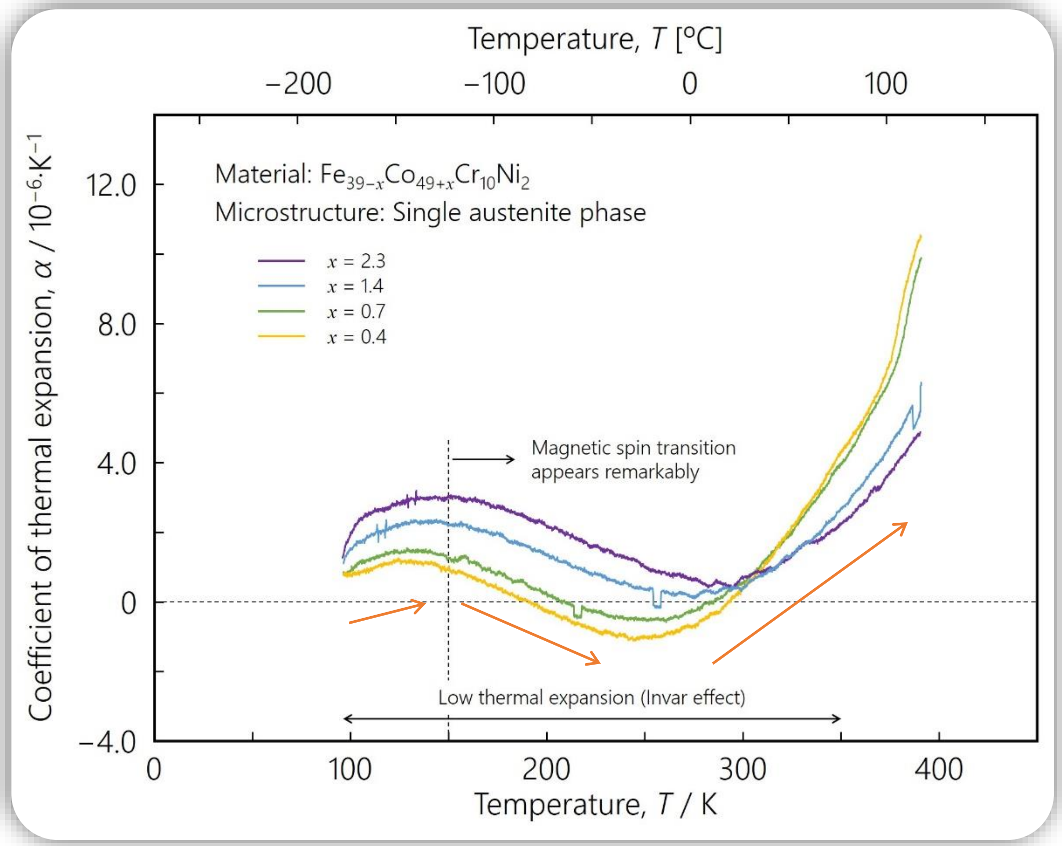
Thermal expansion characteristics

- ✓ The alloys with a lot of bcc phases show normal thermal expansion.
- ✓ Thermal expansion of single fcc alloys is suppressed by lattice contraction caused by magnetic spin transition.
- ✓ Average CTE between 100 and 300 K of the $Fe_{38.6}Co_{49.4}Cr_{10}Ni_2$ alloy is 0.0 × 10^{-6}/K.



Thermal expansion curves obtained from the annealed $Fe_{39-x}Co_{49+x}Cr_{10}Ni_2$ (x = −1.0, −0.1, 0.4, 0.7, 1.4 and 2.3) specimens. For comparison, the curves of the $Fe_{39}Co_{51}Cr_{10}$ and the $Fe_{39}Co_{50}Cr_{10}Ni$ alloys are also shown by dotted line.

Decrease in CTE caused by lattice contraction

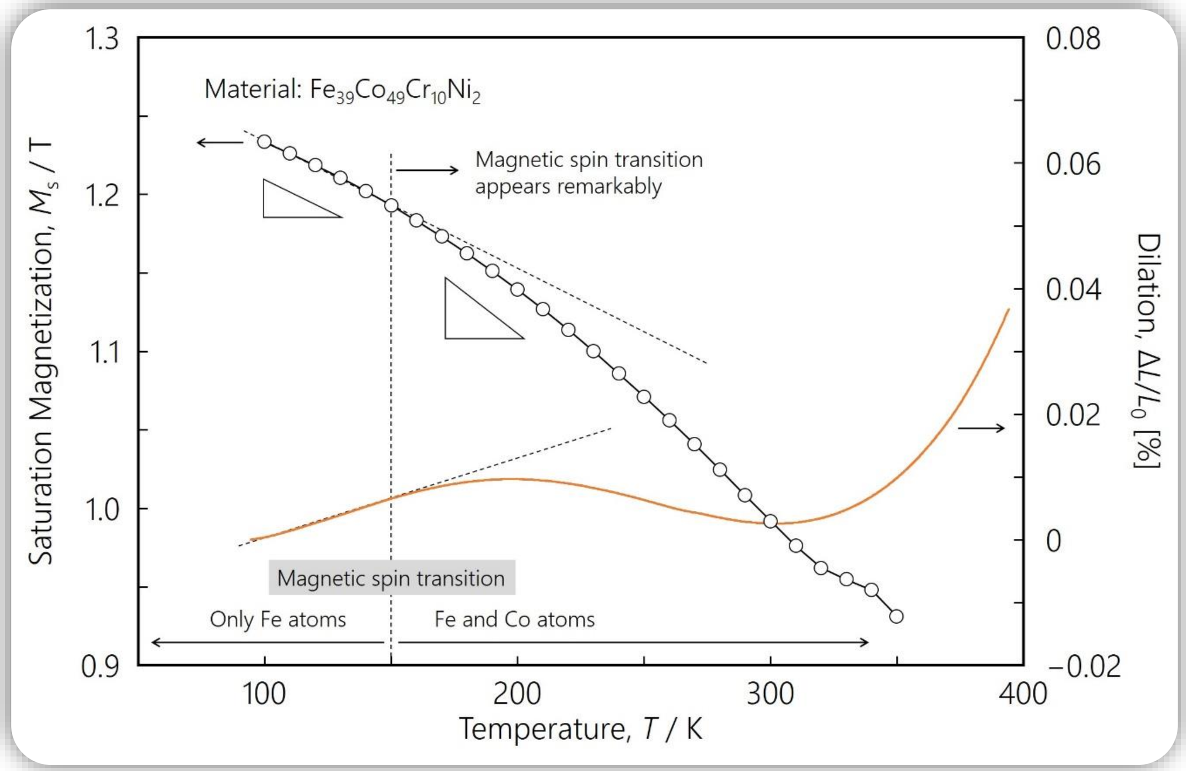


Temperature dependence of the CTEs in the $Fe_{39-x}Co_{49+x}Cr_{10}Ni_2$ (x = 0.4, 0.7, 1.4 and 2.3) specimens. The CTEs were derived from the temperature derivative of the relative dilation in the measured thermal expansion curves.

- Temperature dependence of CTE
  - ✓ The CTEs modestly increase with temperature up to 150 K and decrease up to around 300 K.
  - ✓ Lattice contraction owing to the magnetic spin transition occurs more significantly above 150 K.
  - ✓ Lattice contraction of Co atoms contributes to the low thermal expasnion.

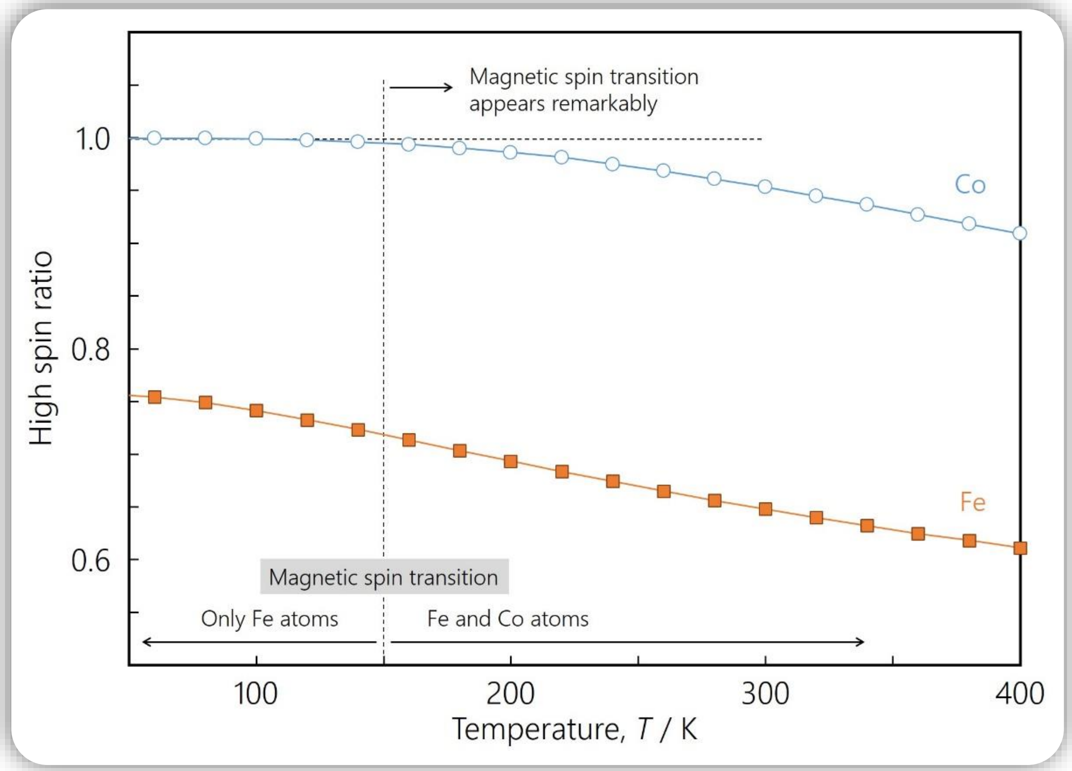
Effect of Co spin transition on thermal expansion

- **SQUID measurements**
  - ✓ The saturation magnetization monotonically decreases with increasing temperature.
  - ✓ Decreasing rate of saturation magnetization is larger above 150 K.
- **Magnetic spin transition**
  - ✓ 150 K is the onset temperature of the magnetic spin transition of Co atoms.
  - ✓ The lattice contraction seems to become large above 150 K.



Temperature dependence of saturation magnetization of the $Fe_{39}Co_{49}Cr_{10}Ni_2$ alloy measured by SQUID magnetometer. For comparison, the thermal expansion curve is also shown.

Magnetic spin transition of Fe and Co atoms



Temperature dependence of high spin ratio of Fe and Co atoms calculate by the PIECP MC simulations.

Temperature dependence of spin ratio

- ✓ HS state ratio was calculated by the PIECP MC simulations.
- ✓ The magnetic spin transition of Fe atoms from the HS to the LS states occurs at a constant rate.
- ✓ All Co atoms are HS states below 150 K and the spin transition occurs above 150 K.

Both Fe and Co atoms in the $Fe_{39-x}Co_{49+x}Cr_{10}Ni_2$ alloys show the invar effect, which can be characterized by the magnetic spin transition between 100 and 300 K.

Conclusions

1. The average CTEs between 100 and 300 K are less than 0.5×10^{-6}/K in the chemical composition around the $Fe_{39}Co_{49}Cr_{10}Ni_2$. The temperature dependence of CTE has been characterized as the modest increase up to 150 K and decrease up to 300 K.

2. The saturation magnetization of the developed alloy decreased with increasing temperature ranging from 100 to 350 K and its decreasing rate in the temperature range above 150 K is larger than that below 150 K.

3. It is found for the first time that the magnetic spin transition of Co atoms from the HS state with large volume to the LS state with small volume strongly contributes to the low thermal expansion characteristics.

These are important understandings for the future development of the low thermal expansion alloys used at cryogenic temperature as the structural components for astronomical telescopes.

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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

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著　者： Hiromichi T. Fujii, Naoki Sakaguchi, Kotaro Ona, Fumihiro Uraguchi, Yutaka Hayano, Toshihiko Yokoyama
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概　要：

$Fe_{39}Co_{49}Cr_{10}Ni_2$ has exhibited ultra-low thermal expansion with its average coefficient of approximately 0.13×10^{-6}/K between 100 K and 300 K from cryogenic to room temperatures. This value is extremely close to that of the fused silica used for cameras and spectrographs mounted on astronomical telescopes. The nature of the low thermal expansion of $Fe_{39-x}Co_{49+x}Cr_{10}Ni_2$ has been clarified by the measurements of the magnetic properties and the numerical simulations based on the path-integral effective-classical-potential theory. The saturation magnetization is found to decrease with increasing temperature in the range from 100 K to 350 K. The rate of decrease becomes larger at temperatures over 150 K. The numerical calculation has shown that this magnetic behavior is attributed to the electronic state changes from high spin state to low spin state in the Co atoms, which occurs at temperatures over 150 K. The electronic state changes in Co atoms are found to strongly contribute to the low thermal expansion for the first time in $Fe_{39-x}Co_{49+x}Cr_{10}Ni_2$.

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