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Magnetostriction in Invar-type alloys: The role of Co substitution for Ni and dimensional stability under magnetic field

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Blooming innovation in metal casting

Invar-type alloys, renowned for their low coefficients of thermal expansion (CTE), are widely used in optical devices due to their dimensional stability. However, their significant magnetostriction under magnetic fields poses challenges for precision applications. This study investigates the magnetostrictive behavior of Invar and super Invar alloys with varying Co contents for Ni. Results show magnetostriction increases exponentially up to 150 mT, transitioning to linear behavior beyond this point. Dimensional changes are suppressed below 1.0 × 10^{-7} when magnetic fields are under 100 mT. Comparisons with non-ferromagnetic Cr-based Invar provide insights into improving dimensional stability for optical and semiconductor applications.

INTRODUCTION

The advancement of ultra-precision manufacturing technologies has heightened the demand for materials with exceptional dimensional stability.

Invar alloy

Widely used in optical components due to its extremely low thermal expansion

Key limitations

- Invar-type alloys exhibit magnetostrictive behavior, causing dimensional changes under magnetic fields

Challenges associated with magnetostriction

Dimensional changes

- Magnetostriction-induced deformation can exceed thermal expansion

Impact on performance

- Magnetic fields disrupt dimensional accuracy
- Reduced reliability in optical systems

Knowledge gap

- Co's influence on magnetostriction still remains unclear

By systematically varying the Co content and analyzing the resulting magnetostrictive properties, we seek to provide a comprehensive understanding of the relationship between alloy composition and magnetostrictive performance.

EXPERIMENTAL

Sample preparation

- ✓ Materials: Fe-Ni-Co Invar-type alloys
- ✓ Processes;
  Induction melting, casting and forging

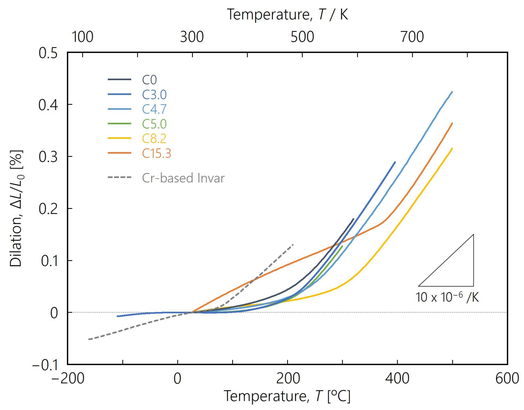
Sample ID	Chemical composition (mass%)						
	C	Si	Mn	Al	Ni	Co	Fe
C0	–	0.23	0.23	0.01	36.2	–	Bal.
C3.0	0.02	0.06	0.17	0.04	33.5	3.0	Bal.
C4.7	0.02	0.16	0.49	0.06	32.1	4.7	Bal.
C5.0	0.01	0.09	0.22	0.02	31.8	5.0	Bal.
C8.2	0.01	0.10	0.21	0.03	32.6	8.2	Bal.
C15.3	0.01	0.75	0.47	–	30.3	15.3	Bal.

Evaluation of materials properties

- ✓ Precise dilatometer
  (Thermal expansion)
- ✓ Strain gage method and magnetic measurement
  (Magnetostriction, Magnetization)

RESULTS

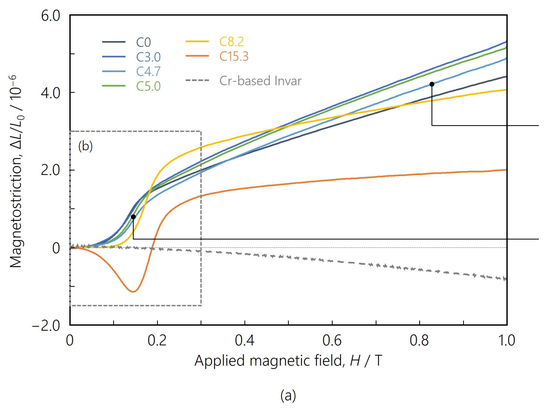
Thermal expansion characteristics of Fe-Ni-Co Invar-type alloys



Thermal expansion curves of Fe-Ni-Co Invar-type alloys with varying Co contents. For comparison, the thermal expansion curve of a Cr-based Invar alloy is shown as a dotted line.

The thermal expansion characteristics were found to be controllable by Co content, suggesting that magnetostriction, closely related to thermal expansion, could be suppressed through precise control of Co content.

Magnetostriction dynamics under controlled fields



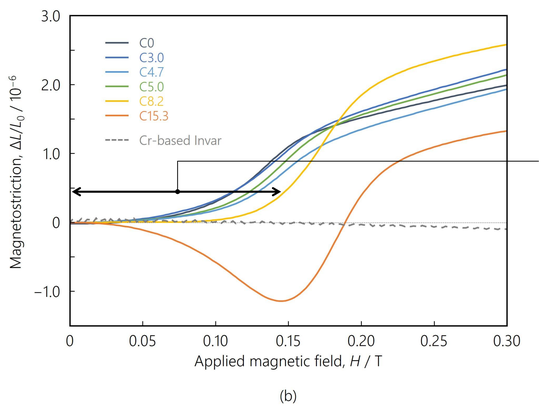
(a)

Linear relationship
(Magnetostriction dominated by fully aligned magnetic moments: Forced magnetostriction)

$$\frac{\Delta L}{L_0} = \frac{1}{c}\frac{\partial M}{\partial \omega}H$$

Quadratic function
(Progressive alignment of magnetic domains)

$$\frac{\Delta L}{L_0} = \frac{NH^2}{2c\mu_0}$$



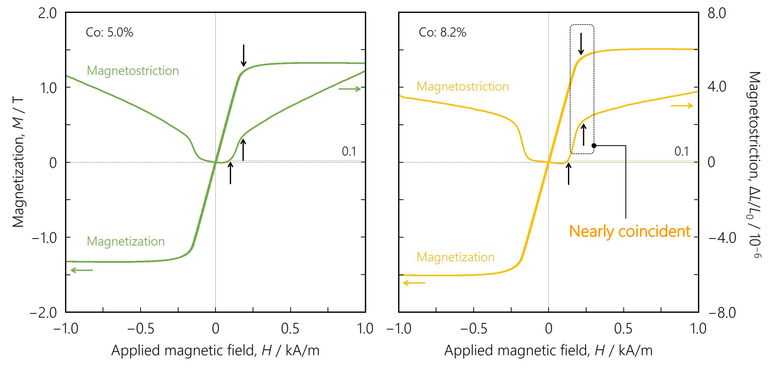
(b)

Expansion of the low magnetostriction region through Co addition

(a) Magnetostriction behavior of Fe-Ni-Co Invar-type alloys with varying Co contents and a Cr-based Invar alloy as a function of applied magnetic field. (b) Enlarged view of the low magnetic field region from (a).

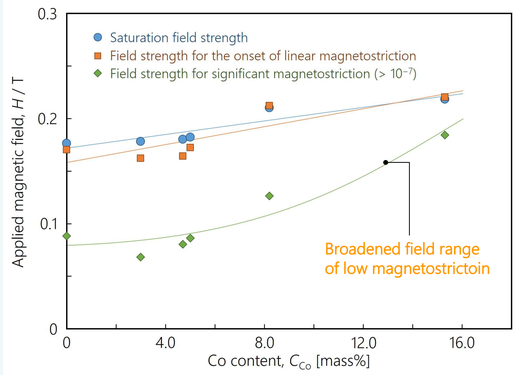
The influence of Co content on the magnetostrictive properties of Fe-Ni-Co Invar-type alloys was revealed for the first time, offering a versatile strategy to optimize these materials for specific optical applications.

How Co substitution shapes magnetostrictive behavior



(a) (b)

Magnetostriction and magnetization curves for Fe-Ni-Co Invar-type alloys with Co contents of (a) 5.0% and (b) 8.2%. Arrows indicate the saturation field strength, the field strength at the onset of linear magnetostriction, and the field strength where significant magnetostriction begins.



KEY POINTS

Effect of Co content on key magnetic field thresholds in Fe-Ni-Co Invar-type alloys: saturation field strength, onset of linear magnetostriction, and significant magnetostriction (10^{-7}) field strength.

The range of magnetic field strengths exhibiting low magnetostriction was found to expand with Co addition, and it was revealed that the low magnetostriction region corresponds to the range before magnetic saturation.

CONCLUSIONS

The study revealed that the thermal expansion and magnetostrictive properties of Fe-Ni-Co Invar-type alloys can be effectively controlled by Co substitution. Increasing Co content expands the range of magnetic field strengths exhibiting low magnetostriction, which corresponds to the pre-saturation region. These findings provide valuable insights for optimizing Fe-Ni-Co alloys for high-precision optical applications requiring dimensional stability under varying magnetic fields.

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