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Achievement of ultimate zero thermal expansion in super invar based alloy for stable optical systems

Hiromichi Fujii, Naoki Sakaguchi, Haruyasu Ohno, Kotaro Ona
Shinhokoku Mateiral Corp., 5-13-1 Arajuku-machi, Kawagoe, JAPAN 350-1124

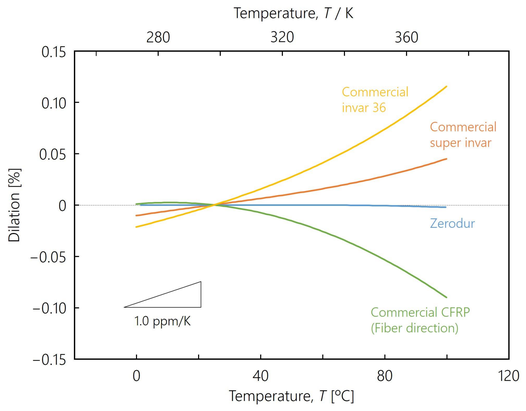
We developed a novel extremely low thermal expansion alloy with high temporal stability and high Young's modulus, which was based on the super invar ($Fe_{64}Ni_{31}Co_5$). The conventional super invar has been often used as the structural supporting components for stable optical systems and its average coefficient of thermal expansion (CTE) is approximately 0.5 ppm/K around room temperature. We clarified that there is a linear relationship between the average CTE and Fe content around room temperature in the super invar based alloys. According to the linear approximation between them, the average CTE was found to become zero when the Fe content is 62.5%. Based on this knowledge, we achieved an extremely low thermal expansion of 0.03 ppm/K average CTE in the temperature range between 18ºC and 28ºC (291 K and 301 K) by precise control of chemical composition. In case of a cast alloy, carbon content was reduced below 0.02% to suppress the carbon-dependent expansion with time that is known to occur in high carbon invar based alloy. As a result, dimensional change over the years of our developed cast alloy becomes lower than 0.05 ppm/year. Low Young's modulus due to coarse and columnar grains microstructure in the cast alloys can be improved by 30% with grain refinement technique using cryogenic and heat treatments.

INTRODUCTION

The demand for ultra-high dimensional stability of the structural supporting components is growing with the development of ultra-precision manufacturing technologies represented by semiconductor lithography equipment.

Comparison of technological benefits between Invar, Zerodur and CFRP

	Metal (Invar)	Glass (Zerodur)	Composite (CFRP)
Coefficient of thermal expansion (CTE) [/K]	10^{-6}	10^{-8}	10^{-6}
Young's modulus [GPa]	92 (cast) 130 (forged)	91	> 200 (fiber direction)
Machining	Easy	Difficult	Difficult
Ease of repair	Easy	Difficult	Difficult
Ductility	Ductile	Brittle	Brittle



Thermal expansion curves of commercial invar 36 and super invar, zero-expansion glass-ceramics (Zerodur) and commercial CFRP.

We develop an extremely low thermal expansion alloy by precise control of chemical composition based on super invar. In addition, dimensional stability over time and rigidity of the developed alloy are improved by metallurgical approaches.

EXPERIMENTAL

Sample preparation

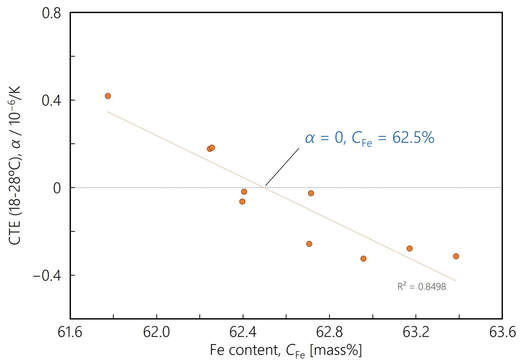
- ✓ Materials: $Fe_{64+x}Ni_{31+y}Co_{5-(x+y)}$
- ✓ Processes;
  Induction melting, Casting, Forging,
  Cryogenic and heat treatment

Evaluation of materials properties

- ✓ Precise dilatometer (Thermal expansion, Dimensional stability over time)
- ✓ Measurement of Young's modulus by resonance method

RESULTS

Effect of Fe content on thermal expansion

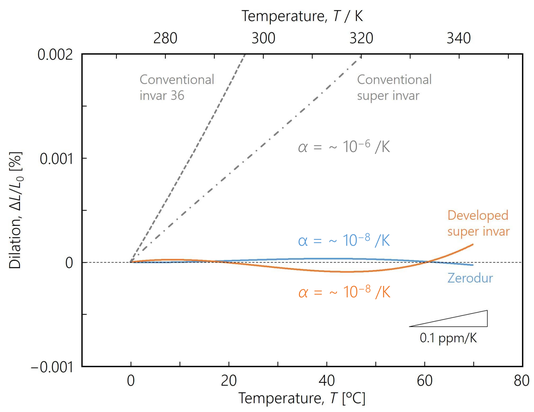


Effect of Fe content in Fe-Ni-Co alloys on average coefficients of thermal expansion between 18ºC and 28ºC.

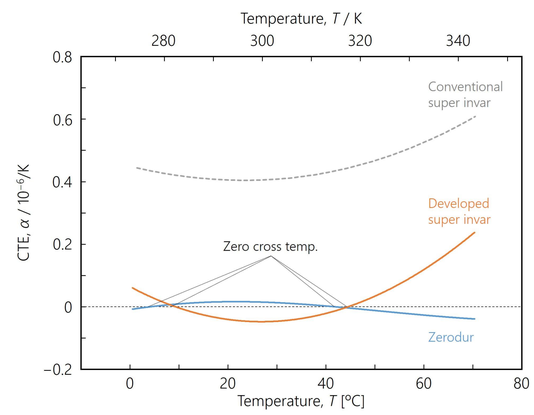
A linear relationship between CTE and Fe content was clarified. CTE α could be determined by using the following equation;

$$\alpha\ (18\text{-}28ºC) = -0.4789\ C_{Fe} + 29.927$$

Achievement of ultimate zero thermal expansion



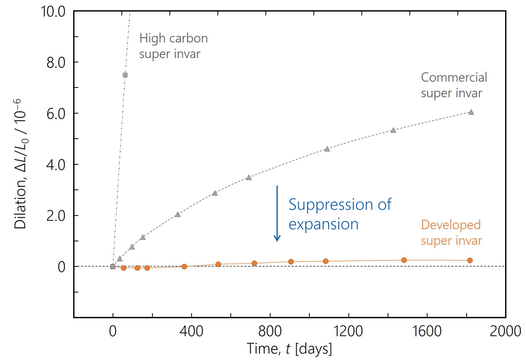
Thermal expansion curves of conventional invar 36 and super invar, developed super invar and zero expansion glass-ceramics (Zerodur).



Temperature dependence of the coefficients of thermal expansion estimated from thermal expansion curves.

Based on knowledge on a linear relationship between CTE and Fe content in Fe-Ni-Co super invar based alloy, ultimate zero thermal expansion can be achieved by precise control of Fe content.

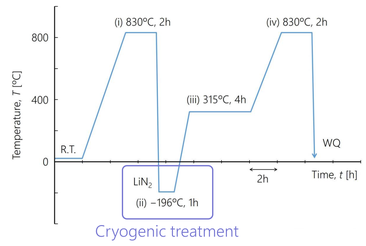
Enhancement of dimensional stability over years



Dilation curves over years obtained from high-carbon, commercial and developed super invars. The measurements were conducted by AIST.

Y expansion over years is known to be a phenomenon caused by carbon atoms in super invar. We clarified that this can be drastically suppressed by reducing carbon content.

Improvement of Young's modulus



Cryogenic treatment

Young's modulus of as-cast and cryogenic and heat treated super invars

Process	Microstructure	Young's modulus
As-cast		93 GPa
Cryogenic and heat treatments		130 GPa

Young's modulus of cast super invar based alloy can be improved by 30% with grain refinement technique using proprietary cryogenic and heat treatments.

CONCLUSIONS

1. A linear relationship between the average CTE around room temperature and Fe content is clarified in Fe-Ni-Co super invar based alloy. According to this relationship, ultimate zero expansion can be achieved.
2. Dimensional stability over years can be drastically improved by reducing C content in cast super invar based alloy.
3. Young's modulus of cast super invar can be improved with grain refinement technique using cryogenic treatment.

These are important understandings for the future development of EUV lithography equipment by the application of super invar based alloys with extremely high dimensional stability.

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

fujii@shst.co.jp
www.shst.co.jp

email
webpage