An Introduction to Invar

Scott Gibb
Graduate Student
College of Optical Sciences
University of Arizona
December 5, 2006

What is Invar?

- Metal used in applications in which a high degree of dimensional stability under changing temperatures is required
- Used in precision mechanical systems in many different industries; not limited to opto-mechanical engineering
- Invar is actually part of a family of low expansion iron-nickel alloys
  - Some metals in this family are
    - Invar (%64 Fe, 36% Ni) – also known as Invar 36 or FeNi36
    - SuperInvar (63% Fe, 32% Ni, 5% Co),
    - Kovar (54% Fe, 29% Ni, 17% Co)
      - Where Fe is iron, Ni is nickel and Co is cobalt
  - When uses the word Invar they almost always mean Invar 36
- This talk focuses on Invar and SuperInvar

CTE of Invar

- Most important property of Invar is that it has a low CTE
- In fact it has the lowest CTE of any metal at certain temperatures
- CTEs of common materials at room temperature
  - CTE of Invar is about 1ppm/K
  - Compared to steel and aluminum
  - CTE of SuperInvar is about 0.5ppm/K
    - Lower than Invar for narrow range of temperatures near room temperatures, but beware…it may not better for your application than Invar
  - CTE of Kovar is about about 5 ppm/K

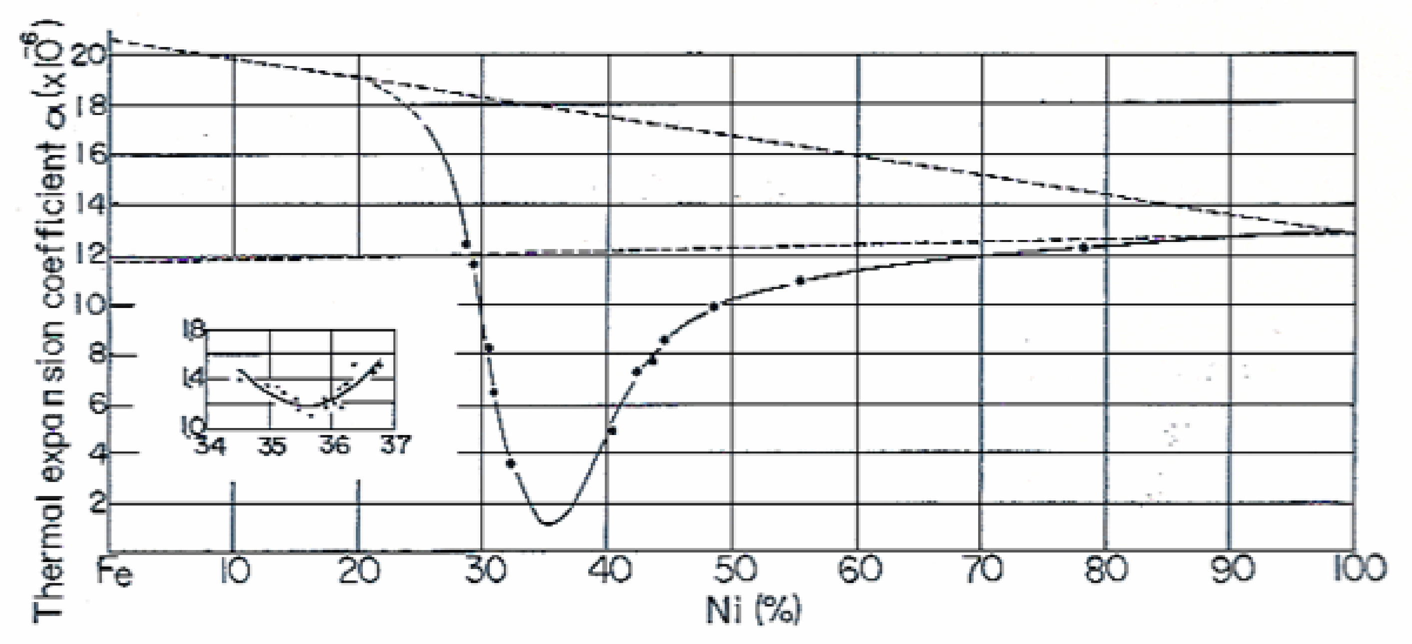
Material	CTE (x $10^{-6}K^{-1}$)
Metals	
Aluminum	23.6
Copper	17.0
Gold	14.2
Iron	11.8
Nickel	13.3
Silver	19.7
Tungsten	4.5
1025 Steel	12.0
316 Stainless Steel	16.0
Brass	20.0
Kovar	5.1
Invar	0.5 to 2.0
Super Invar	0.3 to1.0
Ceramics	
Fused Silica	0.4
BK7 glass	7.1
Borosilicate glass	3.3
Polymers (Plastics)	~100-200

History and Relation to Steel

- Invar invented by a Swiss named Charles Edouard Guillaume in 1896 in Paris.
- The word Invar is capitalized because it is a trade name of a French company named Imphy Alloys.
  - This company originates from a small city near Nevers, France where the allow was initially industrialized after its invention.
  - The generic name for Invar® is FeNi36.
- Looks like and feels similar to steel
  - Pass around Invar sample
  - Invar is a ferrous alloy Ferrous alloys – those of which iron is the prime constituent - are produce in larger quantities than any other metal type
  - Remember that steels and cast irons are iron-carbon alloys (0.25% - 6.7% carbon, majority iron)
  - As already mentioned Invar is iron-nickel alloy

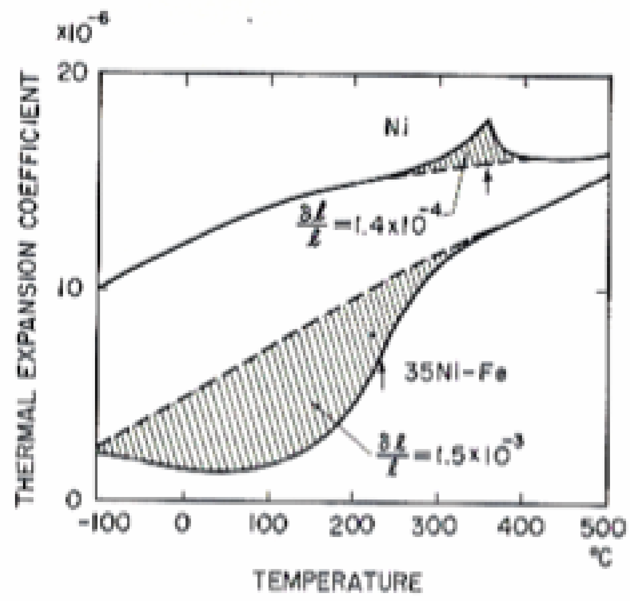
Composition of Invar

- Iron-nickel alloys have a minimum CTE when composition is 36% nickel, 64% iron



Where does the name Invar come from?

- Most would guess that it comes from its invariance to thermal expansion
- However Yoder writes that Invar "…has a virtually invariable (hence the name) and low CTE over a limited temperature range (typically 40 to 100 F [4 to 38 C])."



Mechanical Properties of Invar

- How do the mechanical properties of Invar 36 compare with those of 304 stainless steel?
- Invar has lower CTE, Young's modulus, specific stiffness, thermal conductivity and microyield strength

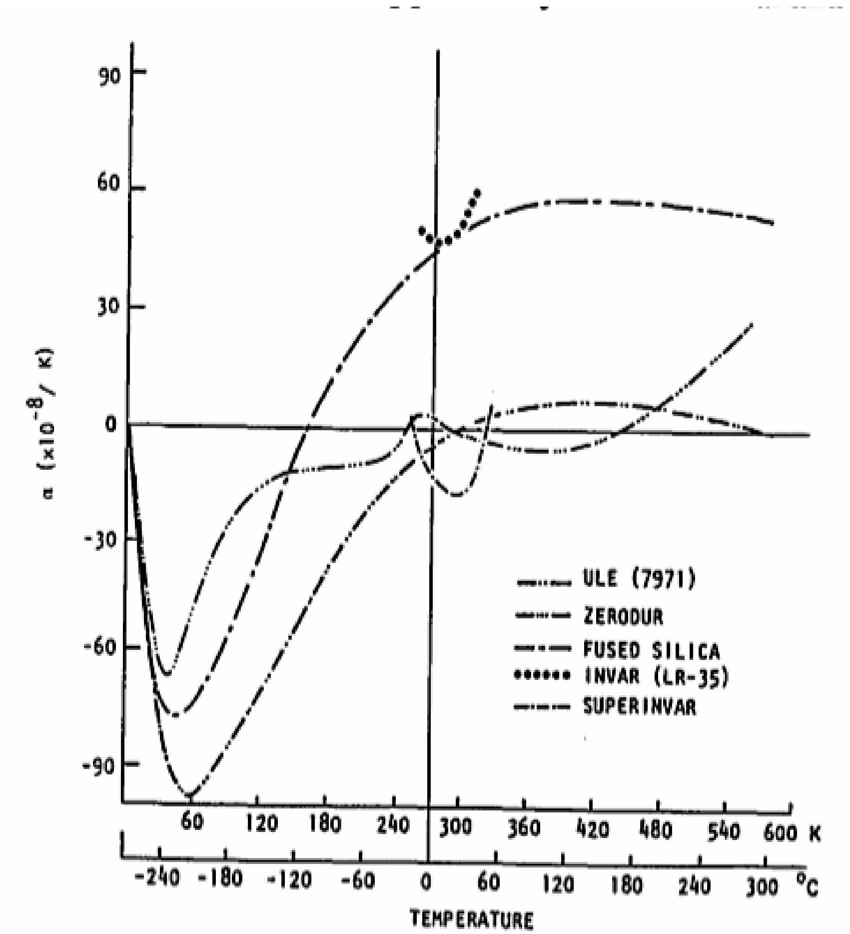
Material	Units	Invar 36	304 Stainless Steel
Density	g/cm^3	8.05	8.00
Young's Modulus	GPa	141	193
Poisson's Ratio	-	0.26	0.27
Microyield Strength	MPa	70	>300
Thermal Expansion Coefficient	$\times 10^{-6} K^{-1}$	1	14.7
Thermal Conductivity	W/m K	10.4	16.2
Specific Heat	W s/kg K	515	500
Specific Stiffness	-	17.5	24.1
Thermal Diffusivity	10^{-6} m^2/s	2.6	4.1
Thermal Distortion (Steady State)	µm/W	0.10	0.91
Thermal Distortion (Transient)	s/m^2K	0.38	3.68

Dimensional Stability

- As stated at the outset I said that Invar is
  - Metal used in applications in which a high degree of dimensional stability under changing temperatures is required
- What is dimensional stability? Or Instability?
  - Dimensional stability refers to how a part of a given material changes shape with changes in environment
    - Typically: time, stress, and/or temperature variation
  - We'll focus on temporal and temperature variation
  - Invar expands with increasing temperature as many materials do
    - From an atomic perspective, thermal expansion is reflected by an increase in the average distance between atoms
  - Invar expands with age, even at constant temperature

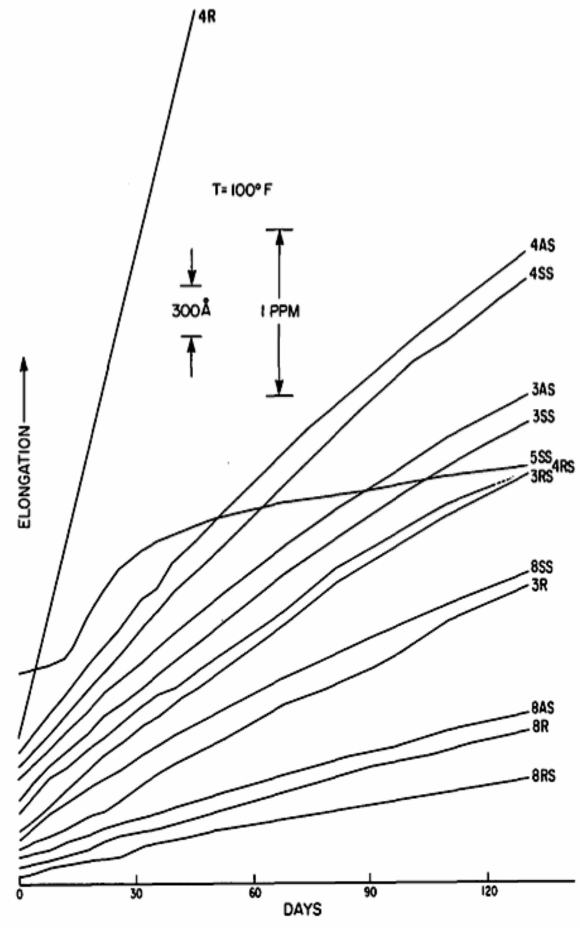
Thermal Stability

- Linear thermal expansion
  - $\Delta L = CTE(T) \times L \times \Delta T$
  - Remember CTE is a function of temperature
- Invar
  - CTE varies from -0.6 to 3.0 ppm/K between -70 to 100 C
  - CTE varies from 0.8 to 1.6 between 30 and 100 C by careful control of material during processing
  - Matches CTE of fused silica
- SuperInvar
  - Lower CTE than Invar
  - Matches CTE of ULE and Zerodur
- Kovar
  - Not shown, but CTE designed to match the CTE of borosilicate (Pyrex)



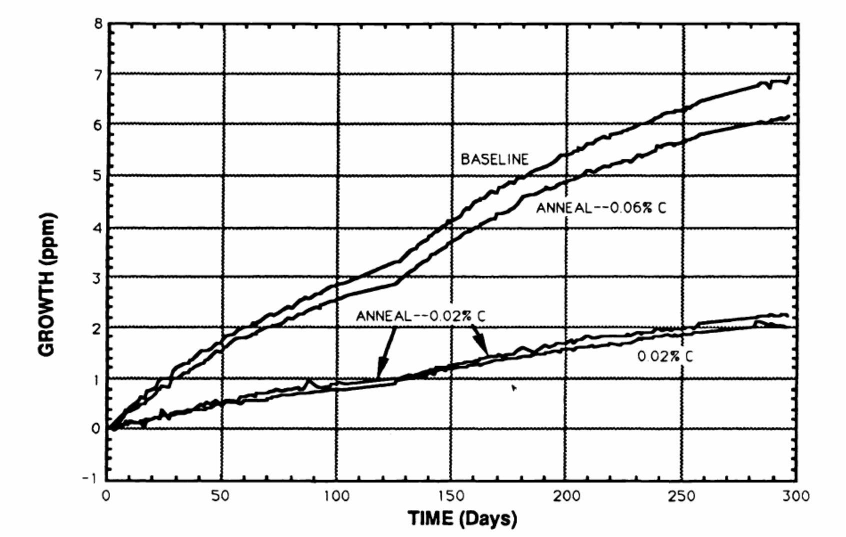
Temporal Stability

- Plot showing temporal stability variation for different compositions and heat treatments
- Factors with affect temporal stability of Invar
  - time since final machining
  - carbon content
  - heat treatment
  - ambient temperature
- I'll show you a widely used heat treatment



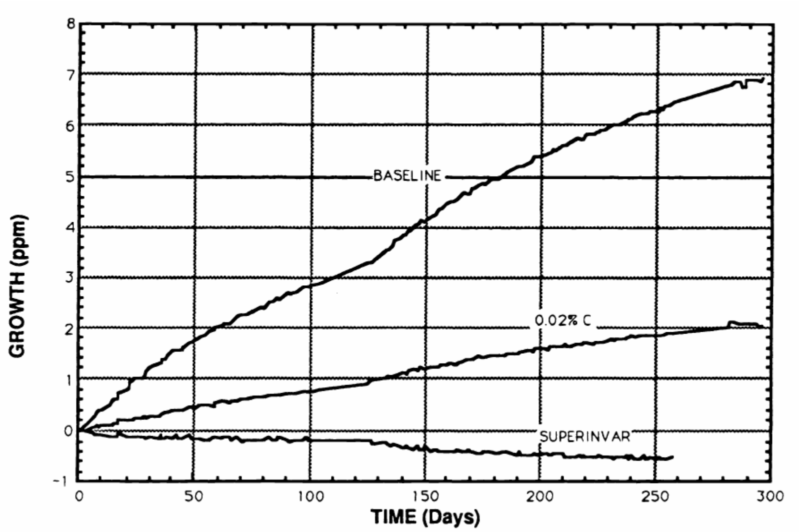
Temporal Stability

- Lower carbon content is better
- The dimensional stability of Invar can be less than 1-2 ppm/yr. This requires very low carbon content, < 0.02%
- In 1993 JPL had great success in obtaining possibly the most dimensionally stable (lowest CTE plus lowest temporal change) Invar 36 ever produced
  - HP Invar – high purity Invar, very low carbon content
  - CTE was 1 ppm/K
  - Temporal was 1 ppm/year
- Determine the composition of your Invar
- Pay close attention to the heat treatment Talk more about this later



SuperInvar

- SuperInvar is less common than Invar in opto-mechanical engineering
- SuperInvar has lower CTE than Invar, and has been shown to be more temporally stable
- JPL design of imaging system for Cassini – "it was eliminated as a possible material for the metering rods because of
  - its highly composition-dependent irreversible phase transformation
  - temperature-dependent temporal stability
  - difficulties in fabrication
- Low temperature use of Super-Invar should be avoided as it will permanently destroy its low CTE properties. The exact temperature at which this change in the CTE occurs varies depending on the composition
- See references to find out more



Practical Topics

- Cost
  - Invar 36 is about five times more expensive than 304 steel (for a 1in round of 100lb)
- Machining
  - Invar is relatively difficult to machine
  - Cutting tools will wear relatively quickly and cutting speeds will be slow
  - This requires more patience on the part of the machinist, longer lead-time and greater cost for the engineer

Heat Treatment and Fabrication

- To obtain the best balance between temporal and temperature stability use the “MIT” or “Lement” heat treatment
  - Anneal by holding part at 830 C for 30 minutes. Cool by water or polyalkaline glycol quench. (An alternative cooling would be a slow furnace cool, which gives marginally better stability, but higher CTE).
  - Stress relieve by holding the part at 315 C for 1 hour and then cooling to 95 C and holding for 48 hours. Air cool.
- Greater than 100μm cuts, may disturb the heat treatment of Invar and reduce the temporal stability
- Machining procedure which incorporates annealing at various steps
  - Rough machine part, then heat treat
  - Semi-finish machine part very close to final dimensions, then heat treat
  - Final machine
- These machining procedures may be proprietary at some companies

Vendors and Specifications

- Need to carefully specify Invar in engineering drawing
  - There are various specifications and vendors and each will have different compositions
  - A good place to start is the vendor websites
    - Each of these vendors provide detailed spec sheets which contain
      - Composition information
      - CTE vs temperature plots or tables
      - Heat treatment recommendations
    - Carpenter Corporation (I’ve heard most Invar comes from this supplier)
    - Allegheny Ludlum
    - Electronic Alloys (no specification)
  - Specifications to look into
    - AMS-I-23011, Class 7, annealed.
    - ASTM F1684 (UNS K93603)

References

- This presentation accompanies a paper located on the opto-mech website:www.optics.arizona.edu/optomech
- Paper contains all the references and more detail
- A good place for further reading on Invar is Carpenter Corporation Website: www.cartech.com