SILICON CARBIDE

- Forms:
  - CVD - can be solid or coated on a substrate
    100% β SiC, 100% dense, prone to high stress
    Can be superpolished to < 3 Å rms
  - Sintered and/or hot-pressed
    α SiC, not 100% dense
    used as substrate for CVD
  - Reaction bonded
    10-40% Si + α SiC - 100% dense
    Inexpensive - useful as substrate for CVD
    Can be cast to near net shape - complex shapes possible
    Non uniformity of material prevents superpolish
- Hard and difficult (expensive) to engineer
- Not produced in quantity - mirror-sized pieces are hard to make and are produced specially for each mirror
- Introduced to solve the high power mirror problem but has so far only been used in “brick” shapes with indirect cooling

SILICON

- Single crystal (intrinsic) - widely used for SR optics
- Produced in tonnage quantities with outstanding QA for semiconductor fab
- Many uses:
  can be superpolished
  UHV compatible
  large GI mirrors with internal or indirect cooling
  bent optics (epoxy on metal endpieces)
    no chips! - radius < 1000 times thickness
  gratings
  crystal optics
  Multilayer optics
- Can be soldered and brazed - best use metal coating eg Cr/Au
  low temp solder for Bragg reflectors
  high temp braze for plumbing connections (before polishing!)
- Best all-round SR optic material

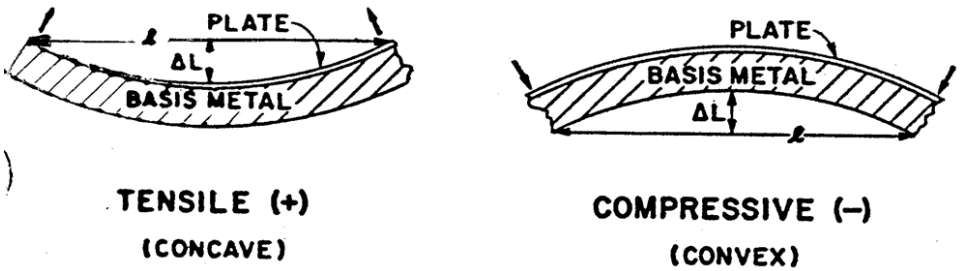
ELECTROLESS NICKEL GENERAL PROPERTIES

- Electroless nickel is a chemically-applied coating that is applied mostly to metals to gain corrosion and wear resitance - it is now a huge industry since its commercial beginnings in the 1950's - ASM Handbook lists 140 applications and hardly mentions optics!
- Provides a superpolishable surface for essentially any metal substrate
- Alloy of nickel and 5-13% phosphorus
- For SR substrates (other than Al), 9-11% is normally used which gives the desired hard amorphous coating
- Propietary solutions contain Ni and P ions and a reducing agent (usually sodium hypophosphite) plus various control additives
- The Ni and P concentration and the temperature and pH are normally monitored: T = 90°C and pH = 4 to 5 are typical values
- For optics a coating of about 100 µm is typical which takes about 10-40 hours and is intended to allow for sufficient material removal during polishing - note this implies a flatness requirement!

PLATING ISSUES FOR INVAR MIRRORS

- Electroless nickel plating issues represent the main difference between making an optic out of invar compared to any other type of steel
- The main issue is stress which is always present for three reasons
  1, intrinsic depending on %P and deposition parameters
  2. CTE missmatch on cooling bath to room temperature
  3. shrinkage on bakeout
- The problem is similar to plating Al which has an equally big thermal missmatch with nickel but in the opposite direction - for invar the nickel will be in tension, for Al in compression
- In practice it is not easy to get an exact balance among the above stress factors nor is it necessary. Measured values of the stress show a wide variation and 10-30 ksi is not unusual even for materials that appear to have CTE's that are well-matched to nickel

STRESS MEASUREMENT



$$\text{STRESS} = \frac{4}{3} E_2 \left(\frac{t^2 + td}{d\ell^2} \right) \Delta L$$

E_2 – YOUNG'S MODULUS BASIS METAL

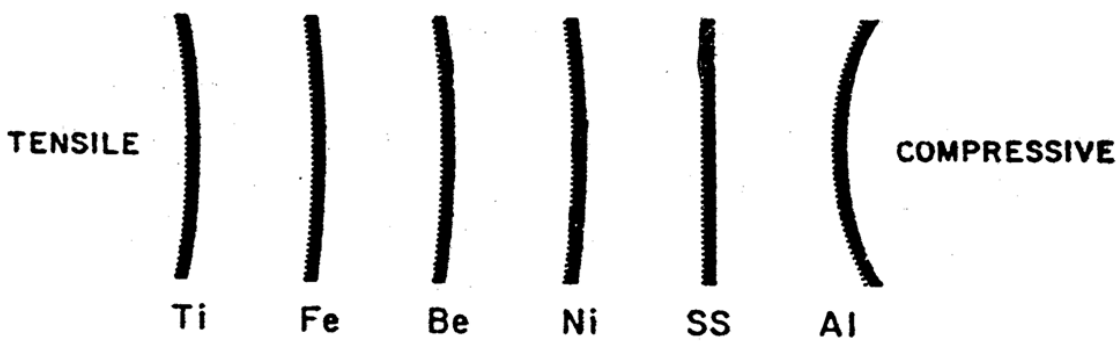
d – DEPOSIT THICKNESS

t – STRIP THICKNESS

ℓ – LENGTH OF PLATED STRIP

ΔL – NET CHANGE IN BOW AT CENTER OF STRIP

Stoney Equation (1909)



- Standard to use witness strips with every plating bath
- Invar would be to the left of Ti on the bottom diagram
- Can also use optical measurements of the curvature of actual mirrors - eg BL 7 grating substrate gives 20 ksi

STRESS IN ELECTROLESS NICKEL PLATED LAYERS

K. Parker 1981

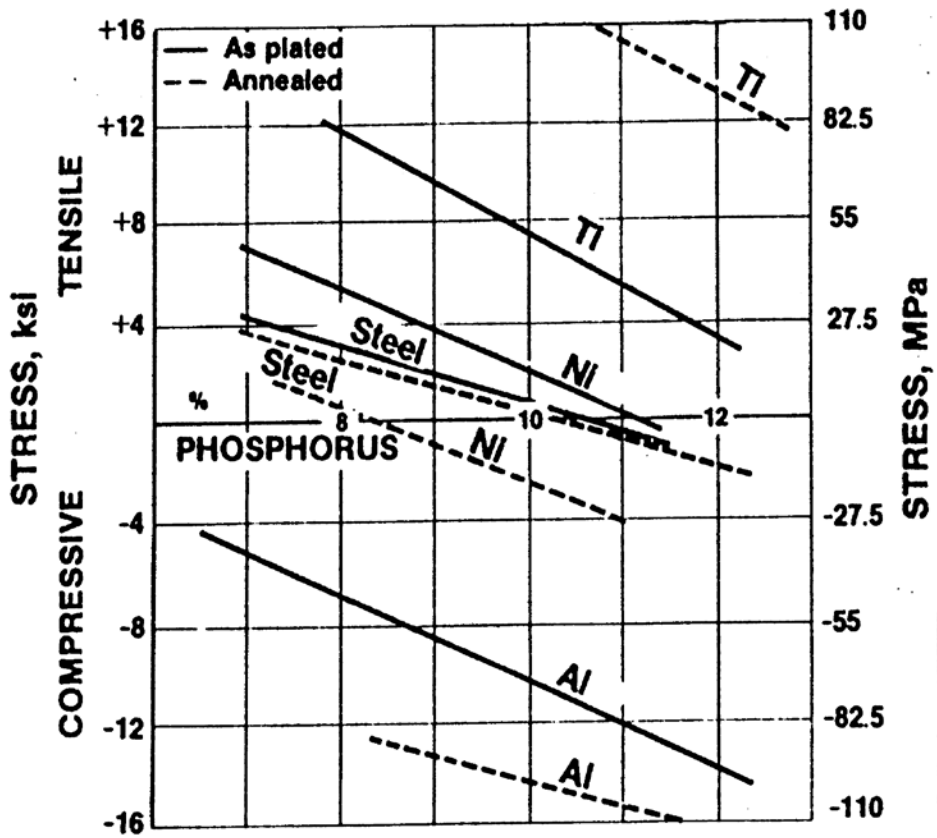
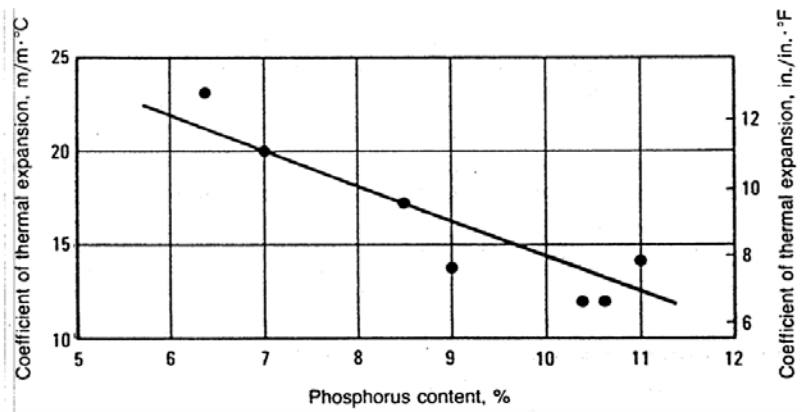


Fig. 6—Stress of 25-μm-thick electroless nickel deposits.

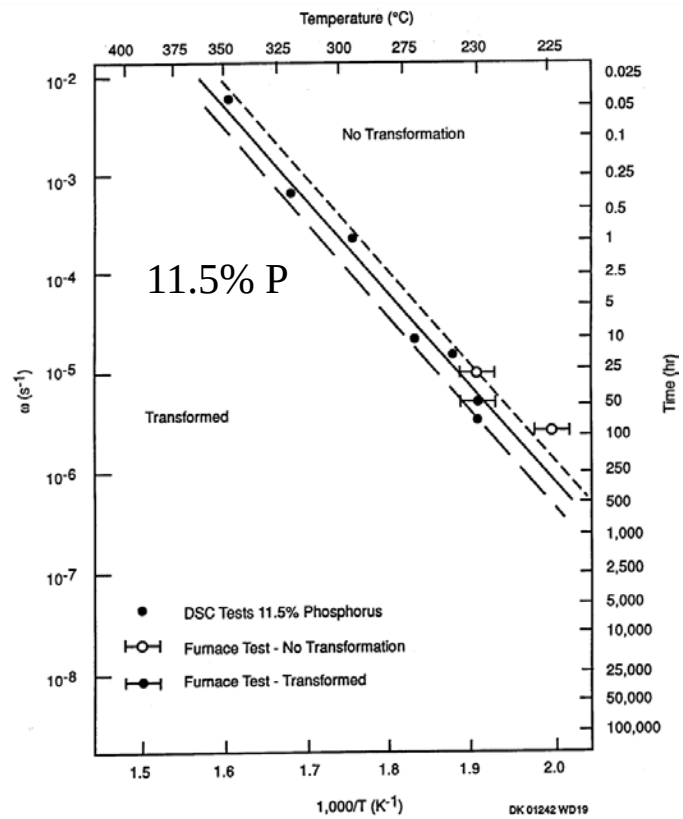
Mat'l	CTE (ppm/°C)
Invar	1.0
Ti	8.35
Steel	12.2
Ni	13.3
Al	22.5

- Diagram shows the general trend toward lower tensile stresses at higher %P
- We see why we are at around 12%
- Invar would be roughly at the blue lines which makes our observed stress of 30 psi on test strips seem quite reasonable

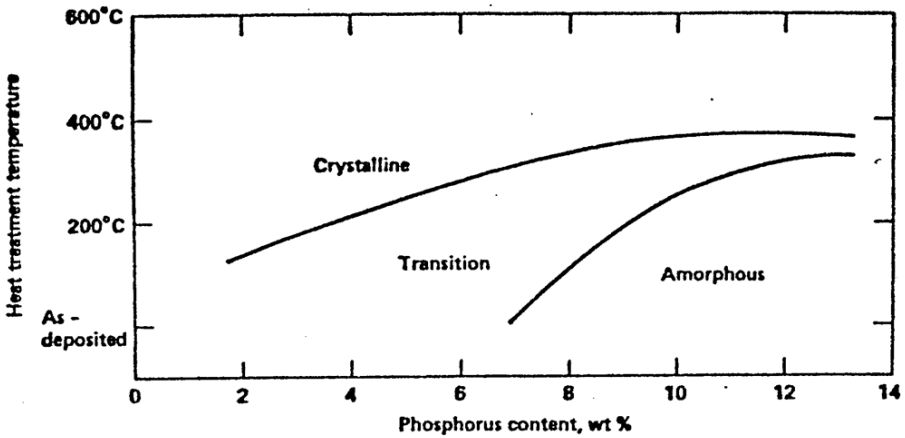


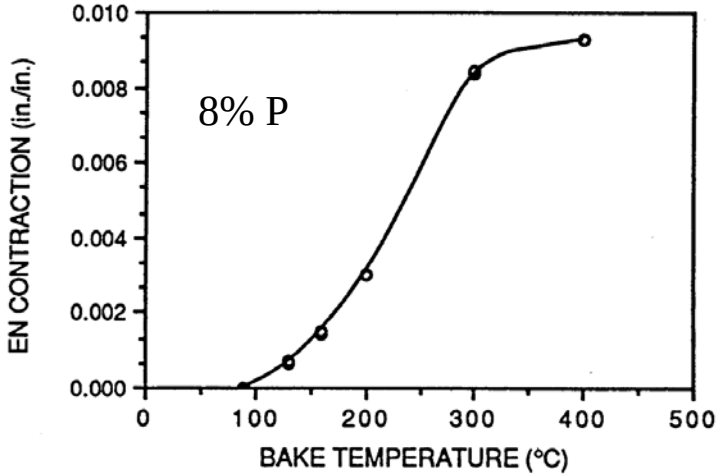
BAKING ISSUES FOR ELECTROLESS NICKEL

- A roughly 200°C bake is usually done for the following reasons
  - remove hydrogen and (in some cases) prevent embrittlement
  - improve adhesion
  - increase hardness (good for polishing)



- There is a phase transition to $Ni+Ni_3P$: high shrinkage, loss of amorphous character and worse polishability
- Therefore limit bake time and temperature to around 200°C - 300°C too high





GLIDCOP™ AL-15 (UNS C15715)

- Dispersion-strengthened copper alloy with 0.3% alumina in small (10 nm) particles - has 90% of the thermal conductivity of pure copper
- Provides similar strength to cold working or precipitation hardening even after high temperature processes such as brazing
- Material is extruded and usually has high stress upon delivery - thus it must be stress-relieved either by braze or otherwise
- A low oxygen version is recommended for brazing
- Recommended for high-power intensively internally-cooled mirrors to be engineered as brazements
- We usually use silver-based wire brazes but gold foil brazes are also successful

ALUMINUM ALLOYS

- Readily available, low cost, easy to engineer
- EN coating required
- Prefered are alloys
  6061 in T-6 or T-7 condition
    most versatile - stocked in all machine shops
  5083/5086
    not heat-treatable
    Cannot be brazed or soldered
- Becoming competitive with Glidcop™
- Al Matrix composites
  SXA™ and Lanxide™ - 2024 T-6 with about 30%SiC particles
  CTE matched to EN
  Higher modulus and strength than Al
  VERY hard to machine and impossible to braze or weld except with plated layer

Thermal cycling treatments for stabilization of aluminum alloy optics [a]

Material	After rough machining	Cycle high temperature	Cycle low temperature	Total # of cycles	Notes
6061	Solution treat at 530, quench in PG[c], overageage 175, 8-16 hr in stages (T7 temper)	150 for 0.5 hr	<-40 for 0.5 hr	3	Rate <3°C/min (<1°C/min during figuring)
SXA	Solution treat at 495, quench in PG[c], age at 190 for 12 hr	180 for 0.5 hr[b]	Quench to -195[b]	until no dimension change	These cycles after finish machining
SXA	Same	170 for 4 hr[b]	-75 for 0.5 hr[b]	until no dimension change (>5)	These cycles after ELN plating, rate <5°C/min
5000 series	Anneal at 350, slow cool	150 for 1 hr	<-40 for 0.5 hr	3	Rate <3°C/min (<1°C/min during figuring)

[a] all temperatures in °C
[b] cycling as recommended by manufacturer
[c] PG=20% polyalkylene glycol solution

MILD STEEL 1010 OR 1006 (0.06% C)

- An approach to dimensional stability - plain-carbon steel fully annealed (and thus stress-relieved) with very low carbon
- EN coating required - all surfaces preferably
- Simple, low cost - good CTE match to EN
- Almost pure iron - higher thermal conductivity than high-alloy steels
- Magnetic easy to machine and grind
- Good for large uncooled mirror
- Not very strong but this is rarely an issue even for benders (mirror stress is usually < 1000 psi)

ALS ONE-METER-CLASS 10:1 ELLIPTICAL CYLINDER

- Parameters: r=20 m, r'=1.85 m, incidence angle 87.5 °
- Overall size: 1.25×0.1×0.015 m^3
- Material: Electroless-nickel-plated mild steel type 1006 (fully annealed)
- Bending stress: 20 MPa (maximum curvature 50 m radius)
- Advantages of 1010 substrate:
  - Inexpensive
  - Stable microstructure (proved by gage-block experiments)
  - Low carbon
  - High conductivity
  - Magnetic
  - No quenches
  - Thermal match to electroless nickel

- Manufacturing procedure:
  1. Cut and rough machine
  2. Anneal between flat ceramic plates (heat/cool < 100 °C/hour)
  3. Fine machine including NC machine mirror edges
  4. Repeat 2.
  5. Grind both sides to 20-micron flatness
  6. Repeat 2.
  7. If 20-micron flat then proceed to polish, if not then back to 5

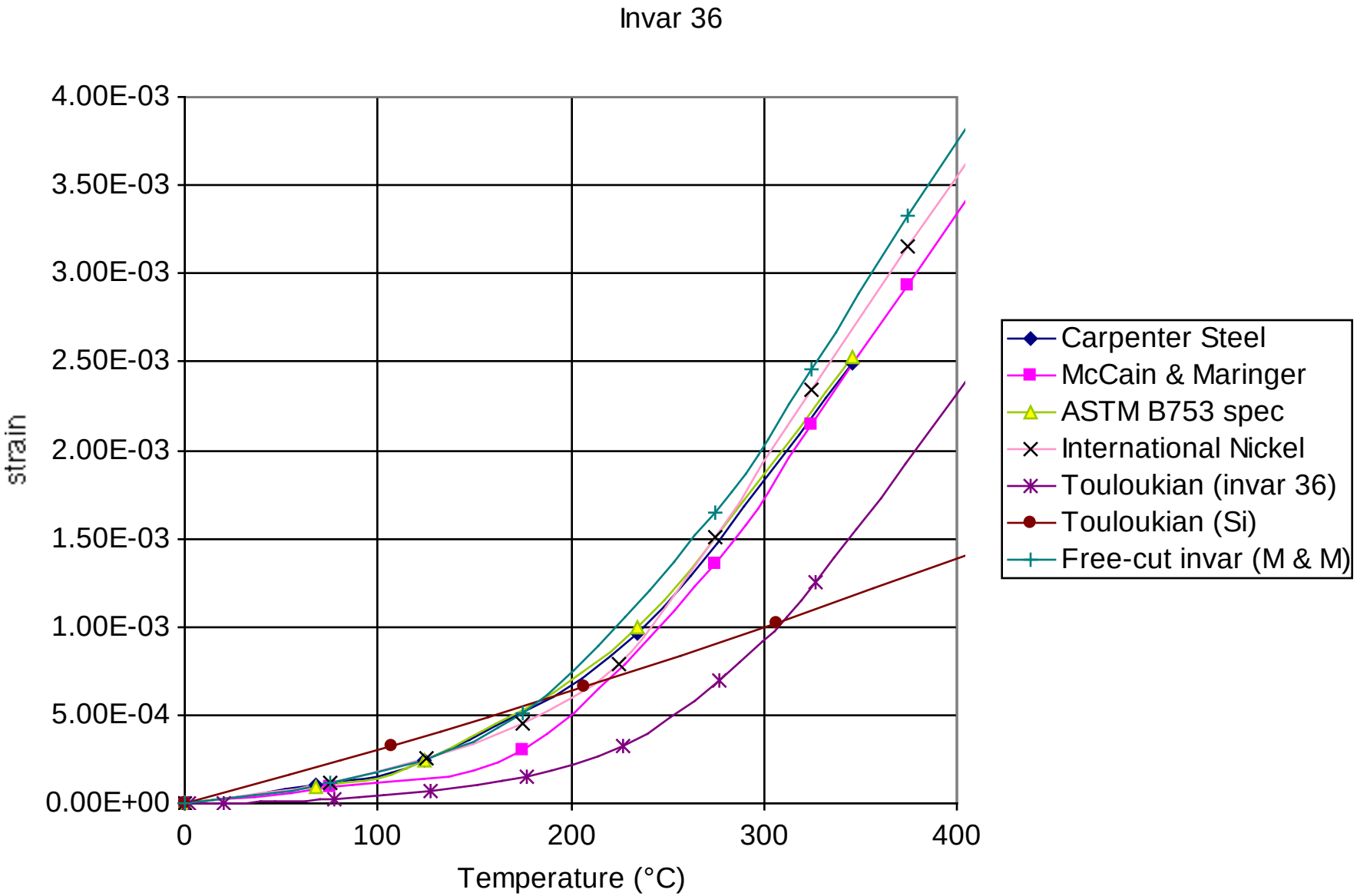
INVAR AS AN OPTICAL-SUBSTRATE MATERIAL

- Invar (36% Ni+64%Fe) has good thermal parameters compared to other metals in the temperature range 0-80°C
- It has most of the advantages of a steel alloy
  - widely available with good quality control
  - weldable, brazeable
  - machinable like other steels
  - magnetic - easy to grind
  - almost stainless
- Discovered in Paris by Charles Guillaume in 1886
  - it is an austenitic (fcc) material which is ferromagnetic at room temperature with a Curie temperature of 260°C
  - the invar property results from a balance between a decrease of atomic spacing due the loss of magnetic ordering as the Curie temperature is approached and the normal increase in atomic spacing with temperature
  - the invar property is compromised by impurities especially C which should be below 0.01% and Mn
- Invar can only be used for optics if the problem of dimensional instability can be addressed - much studied by Guillaume - γ expansion - 50 ppm total over 20-30 yrs

THE DIMENSIONAL STABILITY ISSUE

- The γ expansion was first understood in a landmark paper by Lement, Averbach and Cohen in 1951 - the problems were recognized to be:
- A. Stress relief
  B. The γ expansion
  C. Graphite formation
- The solution for best compromise between dimensional stabilty and low expansion coefficient is “The MIT triple treatment”
  1. Solution treatment: heat to 830°C for 0.5 hour, quench (polyalkylene glycol is best)
  2. Stress relief: heat to 315°C for 1 hour in air, air cool
  3. Stabilization: heat to 95°C in air for 48 hours, air cool
- The stabilization is intended to get the γ expansion completed quickly
- Step 2 can be repeated as often as needed during manufacture but after stabilization the part must be held below 90°C thereafter
- The expansion coefficient obtainable with low C after this is around 1 ppm/°C

INVAR THERMAL EXPANSION DATA



GLASSES AND CERAMICS

- Good for lowest heat loads - thermal conductivity is terrible
- Opticians love it
- Can be polished to “multilayer” smoothness
- Zerodur not recommended due to radiation sensitivity in spite of other good properties
- Best are pure fused silica and ULE™ (silica-7.5% titania)
- ULE has CTE=0 at room temperature and it stays low for a wider range than invar
- OK for mild bending but avoid chips especially on edges

CONCLUSIONS: CURRENT PRACTICE

- Most demanding heat loads and distortion specifications - use internally-cooled EN-plated Glidcop™ or single-crystal silicon
- Less severe demands - same materials or CVD SiC with either direct or indirect cooling
- Lowest heat loads use silicon or fused silica or ULE ™

RECOMMENDATIONS (HOWELLS + PAQUIN)

1. Highest heat loads:
   - Internally-cooled Glidcop™ **
2. Tightest distortion specs:
   - Internally-cooled silicon **
   - Invar may be better and cheaper with some development
3. Moderate specifications but still cooled:
   - Metals are cost effective
   - Glidcop™, Al or Invar with EN coating
4. Uncooled applications:
   - Silicon, ULE™

**hex or square cellular pin post are best but most expensive