

Dimensional stability: an overview

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ABSTRACT

In order to fabricate dimensionally stable components, the causes of dimensional instability must be understood and controlled to the level required by the specifications. This paper reviews four types of dimensional instability and the sources that cause dimensional change, including the effects of external and internal stress on both macro- and micro-levels. Stress relief and stress relaxation, as well as the use of low expansion materials are discussed. Examples are given of both unstable components and methods employed for fabricating stable components from materials such as aluminum, beryllium, glass and composites.

1. INTRODUCTION

In preparing to design and fabricate dimensionally stable components, it is important to realize that this implies controlling the sources of dimensional instabilities to a level such that any dimensional changes that occur are kept within specified tolerances. To be able to accomplish this requires an understanding of the sources of these instabilities. The primary purpose of this paper is to impart such an understanding.

Let me first define dimensional instability. By it I mean the time dependent dimensional change in response to internal or external influences. The problem at hand is that we want to control the dimensional change, a distortion or strain, of the component of interest. If we require stability on the order of machining tolerances, strain of approximately 10^{-3} , there is no serious problem. If parts must maintain dimensional tolerances to parts per million, e.g., microns/meter, then care and consideration must be given to materials selection and processing steps. This is the realm of precision instruments and optics. If nanotolerances are required, e.g., tens of Angstroms per meter, there is not much help available. The principles of controlling the sources of dimensional instability must be diligently applied - and then hope for the best.

Once a tolerance has been specified to bound the amount of allowable instability, the next step is to determine the potential sources of instability and control them to meet the specification. The balance of this paper presents examples of common types of instabilities, the sources of them, and some suggestions as to how they can be controlled. I have selected as much information to present as is practical; this is after all an overview with much that I can not cover. For more complete coverage of the subject of dimensional instability, but not necessarily for optics, I recommend Marschall and Maringer's excellent book¹, and I highly recommend the transcript of the dimensional stability workshop appended to these proceedings².

2. TYPES OF INSTABILITY

The evidence of dimensional instability is all around us and takes many forms, from the warping of a 2x4 which is readily apparent, to the figure change in a mirror subjected to a change in environment. I have chosen to classify instabilities into four categories which I call: temporal instability, thermal/mechanical cycle instability, thermal instability and hysteresis. Each of these can have magnitudes ranging from nanostrain to very large numbers as the following examples show.

Temporal instability is the change that takes place in a component as a function of time in a fixed environment. It is a permanent change. For example, figure 1 shows the behavior of two sets of nominally similar one inch gage blocks tested at NBS over a period of roughly thirty years³. The best sample, No.2 in set B, changed only one microinch in 22 years, while the worst changed 24 microinches in 25 years. Note that the worst sample was changing at the rate of 10^{-6} in./in./yr. That is a very small amount and yet it is totally unacceptable. This kind of behavior can be attributed to either relaxation of residual stress or microstructural change.

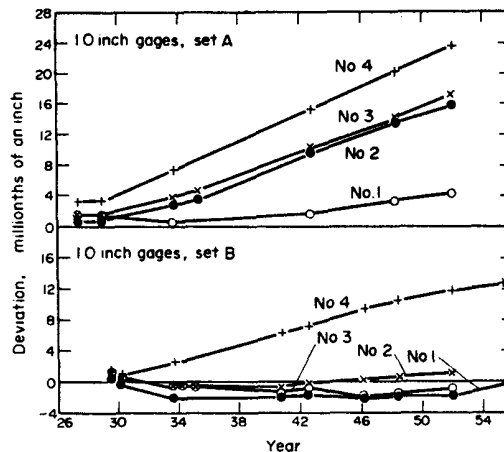


Figure 1. Example of temporal instability of two sets of nominally similar one inch steel gage blocks³.

Thermal/mechanical cycling instability is the change measured in a fixed environment after exposure to a variable environment. It too is a permanent dimensional change. A common example is the change that takes place in fiber reinforced composites as shown in figure 2 for boron reinforced aluminum⁴. The figure shows the behavior of three samples which changed length by over 0.02% on the first cycle, but the amount of change decreased with each succeeding cycle, approaching an asymptote. Later in this paper I show this kind of behavior in other materials. For composites, the cause for the dimensional changes is usually internal micro-cracking and in single phase materials it is usually some other form of internal stress relief. Similar behavior has been observed with mechanical cycling and vibration⁵.

Thermal instability, as I choose to define it, is the dimensional change measured in a fixed environment after a change from another fixed environment, independent of the environmental path. This dimensional change is reversible

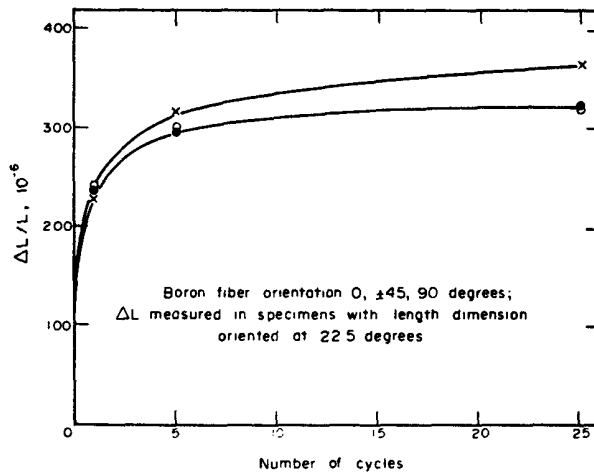


Figure 2. Example of thermal cycling instability of boron/aluminum composite samples thermally cycled from -55°C to $+55^{\circ}\text{C}$.

upon returning to the original conditions. Figure 3 shows evidence of just such a change. This beryllium (Be) mirror was made from an experimental billet produced in the late 60's which had a substantial amount of thermal expansion inhomogeneity⁶. It was interferometrically tested many times over a period of almost ten years and exhibited the same distortion shown in the figure when heated, and always returned to the same optical figure at room temperature, within the 0.02 wave accuracy of the instrument. This behavior has been virtually eliminated in modern Be materials.

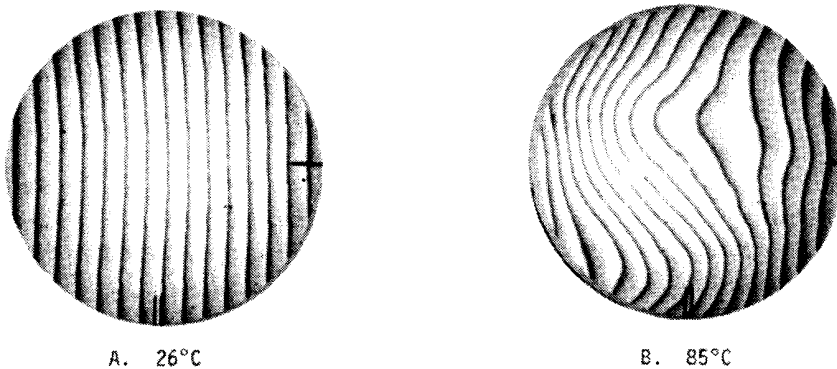


Figure 3. Optical interferograms of an electroless nickel coated experimental beryllium alloy mirror (ca. 1968) showing a reversible thermal instability of approximately two waves⁶.

What I call hysteresis is the change measured in a fixed environment and dependent on the environmental path to the fixed environment. This type of distortion can be permanent or reversible. For example, in figure 4, the length of Zerodur on cooling from 300°C to 20°C depends on the cooling rate⁷. This is typical behavior for glasses containing MgO . But note that the curves are parallel below 150°C indicating that the temperature range of sensitivity

is between 150°C and 300°C. This behavior has been eliminated in a new version of this material called Zerodur M.

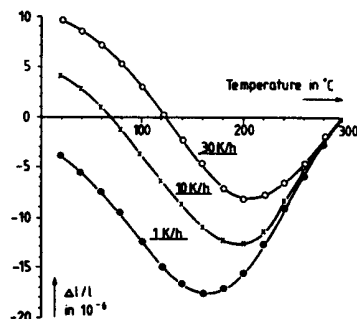


Figure 4. Thermal length contraction of Zerodur for three cooling rates from 300°C to 20°C illustrating a hysteresis type of dimensional instability⁷.

These are the major types of dimensional stability that can be encountered in optics and precision instruments. As will be seen later, many of the other commonly observed instabilities can be placed into one of these four categories.

3. SOURCES OF DIMENSIONAL CHANGE

The sources of dimensional changes such as those described above can be attributed to one or more of the following factors: externally applied stress, changes in internal stresses, microstructural changes and inhomogeneity/anisotropy of properties. I will describe each of these in some detail in the following sections.

3.1 External Stress

When an external stress is applied to a component, if it behaves according to Hooke's law, it should deform elastically no matter how long the stress is applied and return exactly to its original shape when the stress is removed. But this being an imperfect world, and most materials not being perfect, there are other responses to externally applied stress as shown in figure 5. If a load is applied suddenly, held for a length of time and then released as shown at the top of the figure, the elastic response is as shown for curve (E). A time dependent type of elastic response is shown in (A) and is called anelastic strain. The three curves show rapid, intermediate and slow response times. For this type of behavior there is no strain when the load is first applied, but it increases toward an asymptote with time; when the load is removed, the strain asymptotically returns to zero. Anelastic behavior has been observed in some glass ceramics at low temperature, but is more commonly observed in polymers, and particularly in polymer matrix composites where both the anelastic effect and mechanical properties are effected by moisture content and temperature. A combination of elastic and anelastic behavior is shown in the E+A curve. Plastic strain is permanent and does not decrease as the load is removed, as shown in P. The most common behavior for metals, a combination of elastic and plastic response to stress is shown in

the E+P curve. Time dependent plastic strain is called creep, C in the figure. Other possible combinations are also shown.

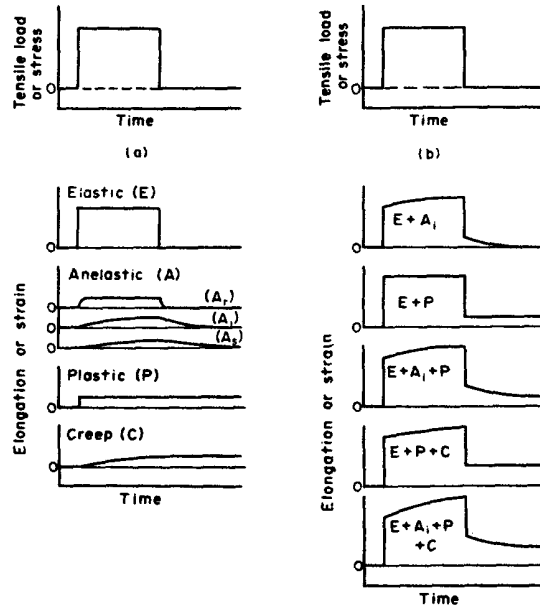


Figure 5. Schematic illustration of types of response to an instantaneously applied and removed tensile stress: (a) individual types of response, and (b) combined responses⁸.

There are a number of material properties that are important to dimensional stability. Among these are thermal properties such as the coefficient of thermal expansion (CTE) and thermal conductivity, and mechanical properties: elastic modulus (Young's Modulus), a measure of stiffness and the slope of a stress vs. strain curve as shown in figure 6; Poisson's ratio, the rela-

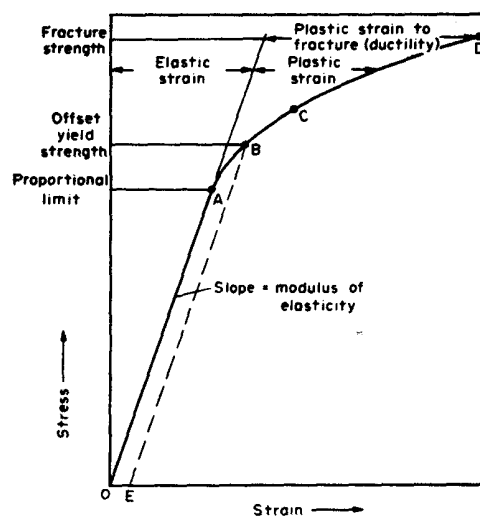


Figure 6. Schematic stress-strain diagram to illustrate typical material behavior⁹.

relationship between tensile (or compressive) and shear strain; yield strength (at 0.2% offset), the stress to cause 2×10^{-3} permanent or plastic strain; ultimate or fracture strength; microyield strength, the stress to cause 1×10^{-6} plastic strain (one microstrain); and microcreep strength, which has no acceptable definition other than that it is less than the microyield strength and is a constant stress that produces microstrain after some period of time.

Microyield behavior can not be inferred from the macro-mechanical properties of either yield strength or modulus. For example, in figure 7 the behavior of I-400 Be and 2024-T4 aluminum (Al), metals with approximately the same yield strength, are compared. The Be sample exhibits a microyield strength of only 6.8 ksi, but with increased stress yields little more whereas the Al alloy resists yielding for a high microyield strength of 38.8 ksi but then continues yielding readily.

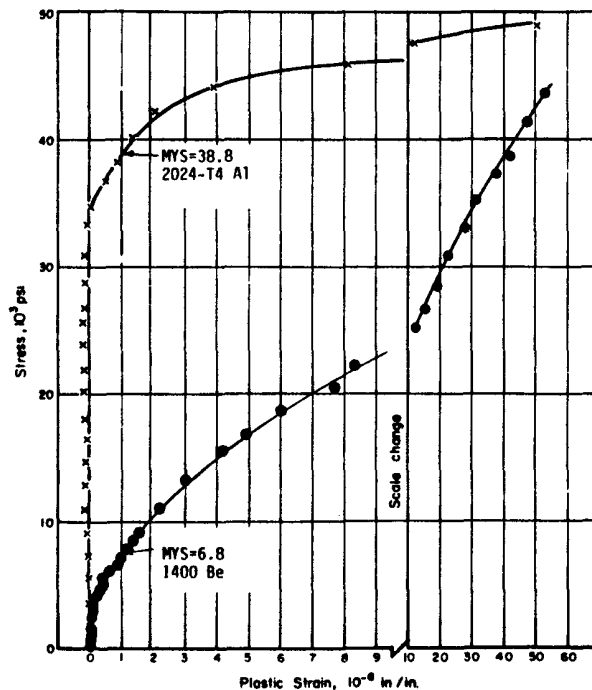


Figure 7. Comparison of a beryllium and an aluminum alloy that have similar yield strengths but very different microstrain behavior².

Microyield strength is strongly dependent on the prior history of the material. If it has been annealed, the microyield will be lower than in almost any other condition. Conversely, if there has been prior straining, either through intentional or inadvertent applications, the microyield will be raised as demonstrated for a stainless steel in figure 8. While prestraining produces a stronger material, it also leaves a level of residual stress which may be detrimental. Residual stress is discussed further in the next section.

Since high microyield strength (MYS) is a desirable property, and since many materials have relatively low MYS, it is important to know that there are methods for increasing it. Prestrain, as mentioned above, is one method, but

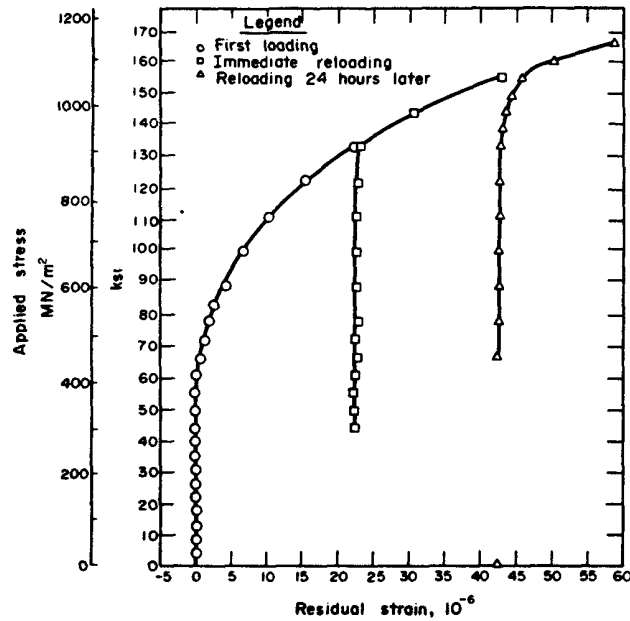


Figure 8. Effect of prestrain on microyielding behavior of 440 C stainless steel¹⁰.

it has its disadvantages. Many aluminum alloys, after rolling to plate form, are stretched a few percent to both straighten and level the stress through the thickness of the plate, which also increases MYS; but this process also seems to lower microcreep strength. Since the process of microyielding occurs, at least in the early stages, by movement of dislocations, anything that pins or prevents dislocation movement will increase MYS. By reducing the grain size of a material, dislocations are more readily pinned, as they are when particle or fiber reinforcement is added to a single phase material. Multi-phase materials almost always have higher MYS than similar single phase alloys. Thermal treatments that precipitate a second phase or produce a metastable phase tend to increase strength and alloying a pure material usually produces dislocations and lattice strains that likewise increase MYS.

3.2 Changes in Internal Stress

While external stress is applied and removed from a component and is readily observed and measured, internal stress is not obvious. A component can be free of external attachments, even floating in a zero-g environment, and have internal stresses. They are in equilibrium and consist of balanced tensile and compressive stresses.

There are two types of internal stress called short range and long range. The spatial extent of these is, as the name implies, microscopic and macroscopic respectively. The long range internal stress is also called residual stress. An illustration of both types is shown in figure 9 for a machined Be cross-section. The micrograph shows a heavily deformed layer below which is a region of twinned grains (grains with contrasting bands) where there would be long range internal stress of perhaps 40,000 psi. The bulk of the Be shows grains of many shades of gray indicating differing crystallographic orientations. Since there is a substantial difference in thermal

expansion for different orientations in Be, there will be short range internal stress between grains, at the grain boundaries.

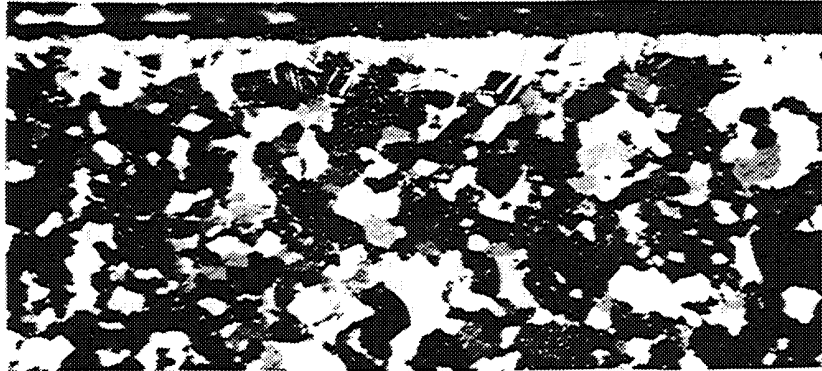


Figure 9. Micrograph of machined beryllium showing plastically deformed layer, twinned grains and differing contrast of grains. (200X, polarized light)

Short range internal stress can result from unequal amounts of distortion between neighboring crystals in plastically deformed material. It can also arise from inhomogeneous coefficient of thermal expansion (CTE): in a two phase material, between adjacent crystals with anisotropic CTE, or in a matrix with a dispersed phase or reinforcing particles, whiskers or fibers. Table 1 lists the theoretical maximum values of thermally induced microstrain due to CTE mismatch between adjacent grains of a few non-cubic materials^{11,12}. In practice, the average values are approximately one third of these calculated maxima. You can see that for Be, one third of 63.8 psi/°C over a 100°C temperature change results in a short range stress of over 2000 psi, a value that exceeds the microyield strength of some Be alloys.

Table 1. Theoretical Maximum Values of Short Range Internal Stresses Due to Thermal Expansion Anisotropy^{11,12}

<u>Material</u>	<u>Lattice</u>	<u>psi/°C</u>
Zinc	Hexagonal	177.
Calcite	Rhombohedral	165.
Cadmium	Hexagonal	91.4
Beryllium	Hexagonal	63.8
Quartz	Rhombohedral	43.1
Indium	Tetragonal	32.6
Magnesium	Hexagonal	2.74
Graphite	Hexagonal	0.944

Long range internal stress, residual stress, is usually the result of processing operations such as forming, heat treating, welding, machining or plating. As you would expect, the level of the stress is dependent on the severity of the operation, as shown in the following examples. Figure 10 shows how the temperature of the quench water effects the residual stress in Al alloys. The yield strength also drops when the water quench is less severe. Polymer quenchants are available that can provide the low residual

stress of a boiling water quench with the strength of the cold water quench.

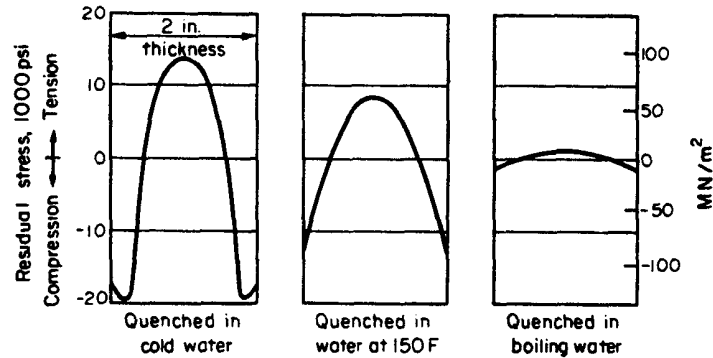


Figure 10. Residual stresses in specimens of 7075-T6 aluminum plate quenched in water at different temperatures¹³

The effects of grinding parameters on residual stress in steel are shown in figure 11. Abusive conditions, heavy feed, high speed and no coolant, produce a highly stressed (tensile) deep layer, while gentle cuts yield shallow layers with much less stress (compressive)¹⁴. Sharp milling cutters produce compressive stresses with conventional machining parameters, but dull tools yield a surface layer with high tensile stress¹⁵.

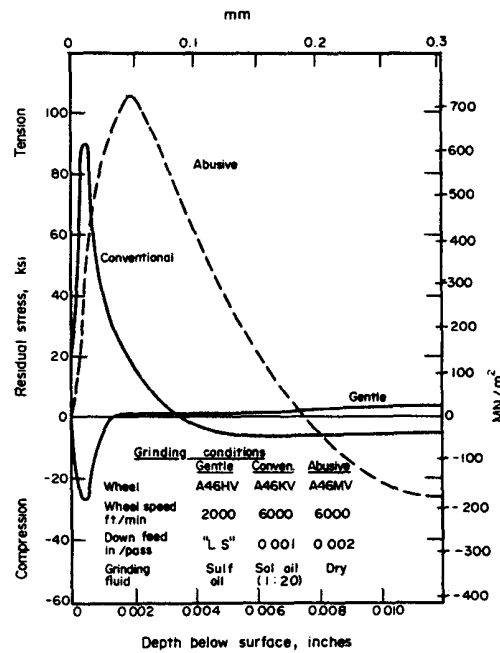


Figure 11. Residual surface stress in AISI 4340 steel produced by surface grinding¹⁴

The introduction of residual stress, or any change in the balance of the stress will cause changes in dimensions of the component. This means that removal of a stressed layer will cause dimensional changes as demonstrated in

figure 12. When two specimens with surface residual stress are acid etched, they both shrink, the one with the higher stress (deeper cut) shrinking more. This principle is used in the manufacture of dimensionally stable components where after heavy material removal operations the surfaces are acid etched to restore unstressed dimensions to the part.

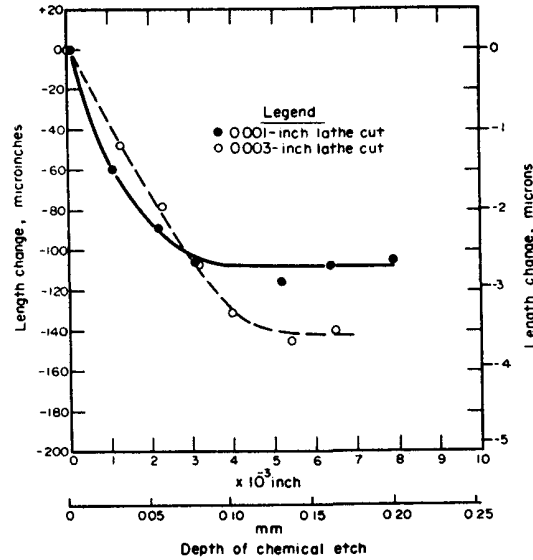


Figure 12. Dimensional changes in 3.0" long specimens of Ni-Span-C on chemical removal of residual stresses due to machining¹⁶

Residual stress can also decrease spontaneously with time with a related change in dimensions. This effect is called stress relaxation and the rate of stress decrease ($-ds/dt$) is proportional to the stress level as shown in equation (1), where s is stress, t is time and τ is relaxation time.

$$(-ds/dt)\tau = s. \quad (1)$$

This can be written to show that stress decreases exponentially with time.

$$s = s_0 e^{-t/\tau}. \quad (2)$$

Note that when t is equal to the relaxation time, τ , the ratio of stress to original stress, s/s_0 , is equal to $1/e$, 0.37. This behavior is shown in figure 13, where a Be mirror was fabricated with no treatment for stress relief after annealing the rough blank. Note the exponential shape to the optical figure change curve.

Stress relaxation is also a thermally sensitive process, behaving according to the Boltzmann equation (3), where E is the activation energy, k is Boltzmann's constant and T is absolute temperature.

$$1/\tau \propto e^{-E/kT} \quad (3)$$

This phenomenon can be used to reduce the stress levels with thermal treatment - stress relief. The question often raised however is whether an isothermal

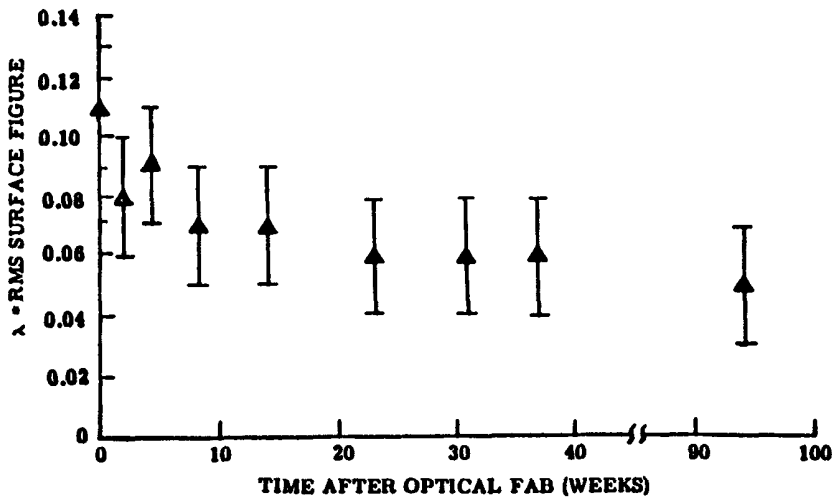


Figure 13. Temporal stability of a commercial 13" diam. beryllium mirror fabricated from vacuum hot pressed block.

treatment for some reasonable time or thermal cycling between elevated and reduced temperatures is the more effective stress relief treatment. Much has been written on this subject and has been summarized in Chapter 6 of Marschall and Maringer¹ and the answer is, "it depends". It depends on the crystal structure and purity of the material; it depends on the prior thermo-mechanical history of the component; it depends on the temperature, time and rate of change of temperature of the treatment; and of course it depends on the level, type and distribution of the internal stresses. One example of what can happen is given in figure 14 where both isothermal and thermal cycling treatments were given to Be specimens previously stressed to 11.2 ksi¹⁷. In this case, the low temperatures of 100° and 190° do very little but relieve peak stresses. The best treatment is a 600°C stress relief treatment, but this is higher than most designers would want to subject a semifinished optic. A temperature of 400°C still only removes 40% of the stress, but note that thermal cycling from 400°C to either -70°C or -196°C provides a 55% reduction. The cycling is more effective than the isothermal treatment to the

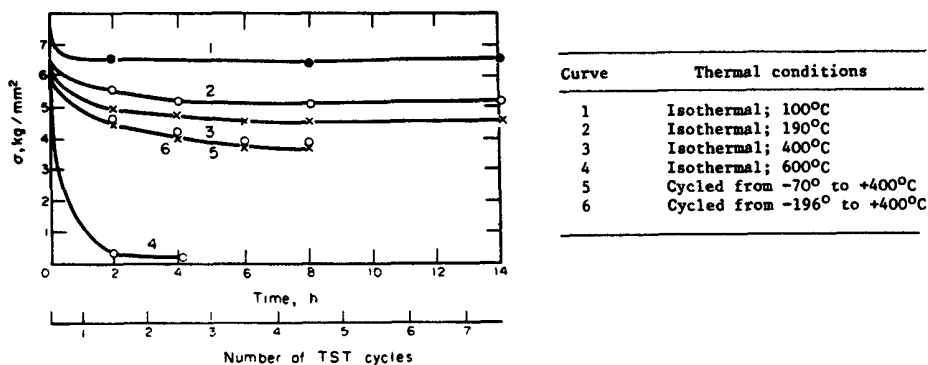


Figure 14. Comparison of the effects of thermal cycling and isothermal exposure on stress relaxation of pure beryllium¹⁷

same upper temperature. This effect may only hold for non-cubic materials with reasonably high expansion anisotropy as listed above in table 1, or for materials with more than one phase such as the composite materials shown in figure 2. There is conflicting evidence in the literature on the effect of thermal cycling on stress relief of homogeneous cubic or amorphous materials.

For those materials where thermal cycling is more effective than isothermal exposure at the same elevated temperature for reduction of residual stress, the proposed mechanism is as follows. These materials develop short range internal stress when the temperature is changed due to the expansion mismatch between adjacent grains and/or phases. When this stress is added to the long range, or residual stress, the yield, or microyield strength is exceeded locally and plastic strain results. When the temperature is returned to room temperature, the plastic strain remains, but the level of the residual stress is reduced. Holding at the elevated temperature provides no further benefit unless it is close to the annealing temperature. When the temperature is then reduced, the sign of the short range stress is reversed, exercising the material further and providing more stress relief. In a similar manner, vibration, or mechanical cycling can provide stress relief although, as for thermal cycling, there are resulting dimensional changes.

For reducing stress levels in critical components we then have a number of options:

1. Thermal treatments such as isothermal exposure or thermal cycling,
2. Mechanical treatments such as vibration or mechanical working,
3. Removal of surface material by chemical etching, controlled grinding and/or polishing or other stress-free methods and
4. Time.

3.3 Microstructural Changes

Microstructural changes in materials can result in both induced dimensional change and internal stress. The type of response depends on the material type and the kind of microstructural change. The changes that can take place in materials used in optical and precision instrument systems include devitrification in glasses and glass ceramics; phase transformations, recrystallization and grain growth in metals and ceramics; and devitrification, phase transformations, recrystallization and grain growth in coatings. This cause of dimensional instability is quite common, but can not be covered adequately here. I will only discuss a few examples to illustrate the principle. The first example is the dimensional change that takes place in heat treatable aluminum alloys during precipitation heat treatment, also called precipitation hardening, and is illustrated in figure 15. This example illustrates that a component which is aged from the solution treated and quenched condition to obtain maximum mechanical properties, normally 4 to 8 hours, will undergo a dimensional change due to the precipitation of the second phase. The change is small for 6061, a significant shrinkage for 7075 and a significant expansion for 2014. But notice that additional hours of aging, often performed for stress relief, induces additional significant dimensional change, particularly for the 2014 alloy. The 6061 alloy, most often used for precision optical structures and mirrors, changes the least, verifying its applicability for these applications.

The second example I previously cited in figure 1. The change taking

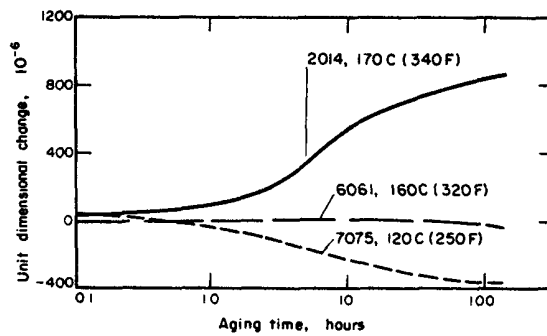


Figure 15. Dimensional change as a function of time at the precipitation heat treating temperature employed to produce the T6 temper for three aluminum alloys¹⁸

place in this material is typical of many tool steels where there is a sluggish phase transformation taking place from retained austenite to martensite, a transformation accompanied by a net expansion. The relatively stable parts, numbers 1-3 in set B, were sub-zero cooled to drive the reaction to completion.

Electroless nickel coatings are used extensively, both for polishable coatings and for corrosion protection of Be and Al mirrors and Be and iron alloy structural components. As deposited, the coatings may be amorphous and are thermodynamically unstable. Figure 16 shows that the coatings can have significant residual stress depending on phosphorous content and substrate thermal expansion coefficient¹⁹. By performing an anneal, hydrogen is driven off, adhesion improves, and the coating becomes polycrystalline. There is a shrinkage that takes place during thermal treatment, the magnitude of which depends on the annealing conditions. For higher temperatures and longer times, nickel phosphide (NiP), which has a smaller specific volume than pure nickel, forms as a precipitate in the coating. The annealing temperature used in the referenced studies is 190°C, with four hours at temperature for Be²⁰ and one hour for the other materials¹⁹. Stress goes from tensile to compressive with increasing phosphorous content and increasing substrate expansion coefficient, annealing changes the stress toward compression for high expansion

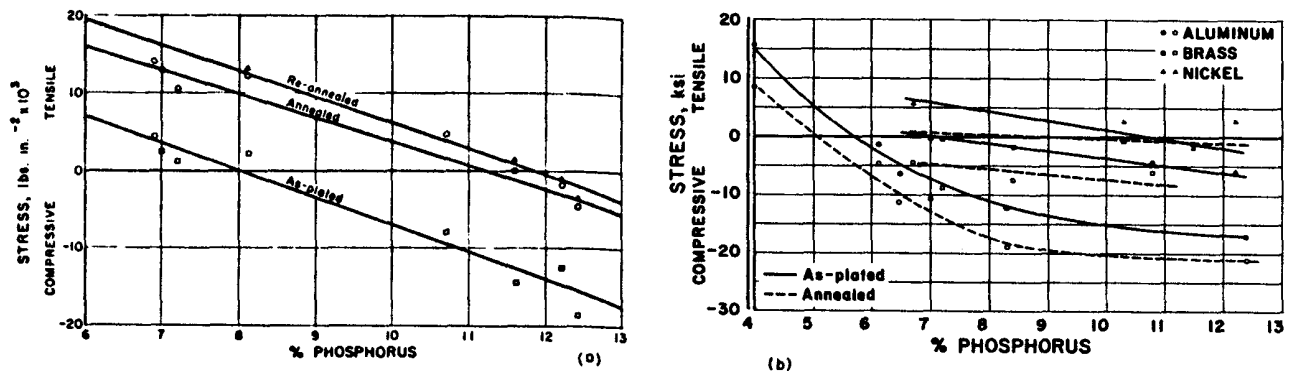


Figure 16. Stress of electroless nickel on (a) beryllium²⁰ and (b) on aluminum, brass and nickel¹⁹ as a function of phosphorous content.

sion materials and toward tension for low expansion materials. What this all means is that for a particular substrate, to obtain zero stress at room temperature after annealing, the right phosphorous content must be chosen, e.g., 5% on Al and 11.5% for Be. For use at lower or higher temperatures, different phosphorous contents should be chosen to minimize the stress.

3.4 Inhomogeneity/Anisotropy of Properties

Most materials, as fabricated, are neither completely isotropic nor homogeneous. By that I mean that they are to some level anisotropic, i.e., having some preferred directionality of properties, and/or inhomogeneous, i.e., having a spatial variation in properties. Anisotropy of properties exists in pure single crystals of materials. Inhomogeneity of properties occurs in bulk and is a function of raw material fabrication processes.

Cubic materials generally have anisotropy in their elastic properties. For example, the Young's modulus of elasticity of pure iron varies with crystallographic direction from 19.2 Msi to 41.2 Msi. Similar variations in shear modulus and Poisson's ratio are also present. Comparable variations in these properties occur in other cubic materials such as Cu, Ni, Si, beta SiC, etc. When these materials are used in polycrystalline form, the variations average out and are not noticed. In components that are fabricated from single crystals, or applications that have crystallographic texture such as plated or chemically vapor deposited materials, there can be substantial elastic property anisotropy and this should be included in any detailed deformation modeling of such components. Thermal properties such as coefficient of thermal expansion (CTE) and thermal conductivity are isotropic for cubic materials.

In a similar manner to the cubic materials, there are variations in elastic properties in non-cubic materials, i.e., hexagonal, rhombohedral, tetragonal, orthorhombic, etc. However the thermal properties of the non-cubic materials are anisotropic. For example, the CTE of Be is 38% higher in the basal plane than it is in the axial direction of a Be crystal or grain. This anisotropy leads to the microstructural strains listed above in Table 1. Some materials such as graphite and quartz have negative CTE in some directions and positive in others. The effects of thermal properties anisotropy, for the various crystalline materials that exhibit it, can be minimized with a fine-grain, randomly oriented microstructure.

Inhomogeneity can be attributed to spatial variations in chemistry, grain size and/or grain orientation, and many other factors. In general, CTE inhomogeneity in glasses and glass ceramics is due either to compositional variations or can be related to annealing history; for metals, ceramics and salts, it is due to compositional or microstructural variations where the latter can be due to crystal orientation differences and/or the presence of other phases. For composites, CTE inhomogeneity is a given due to the presence of multiple phases. The inhomogeneity can be caused by variations in orientation of the reinforcement, or from variations in the concentration of the reinforcement. Care should be exercised in selection of multiphase materials that will be used over a temperature range to insure dimensional stability.

Components having CTE inhomogeneity can behave in the manner shown in figure 3 at the beginning of this paper. In this particular case, the cause is a combination of Be powder with basal plane cleavage, a poor distribution

of grain sizes and inappropriate consolidation parameters. Current Be fabrication processes have virtually eliminated these types of inhomogeneities through the use of impact ground or spherical powder with well controlled chemistries combined with hot isostatic pressing of the powder^{21,22}.

4. LOW EXPANSION MATERIALS

Low expansion materials have been used for many years for precision instrumentation to minimize thermal dimensional changes in service. For optics, fused silica and fused quartz have replaced borosilicate glasses in many applications, and in recent years ULE and the low expansion glass ceramics have been used extensively for more critical applications. Invar alloys have been used in precision metering applications for many years, especially in combination with fused silica optics because of the excellent CTE match at room temperature. More recently composite materials, particularly graphite-epoxy composites, have been used for precision structures since they can be tailored for near zero expansion over a fairly wide temperature range. However each of these material types has distinct advantages and disadvantages.

Borosilicate glasses have been used for large mirror substrates, e.g., the 200 inch Hale telescope primary on Mt. Palomar, but these glasses have relatively high CTE, 3.0 ppm/°C, and are no longer considered low expansion glasses. Lightweight mirror blanks continue to be fabricated from these glasses due to the relatively low fabrication temperature and the utilization of more sophisticated blank fabrication methods^{23,24}. All of the glasses and glass ceramics are chemically inert, can be highly dimensionally stable and can be used over fairly wide temperature ranges, although each material has a range where it performs best. ULE and the glass ceramics have essentially zero expansion at room temperature and fused silica has zero CTE at a lower temperature. All of these materials are brittle and have very low fracture toughness and fracture strength in tension, have low Young's modulus and relatively high density. Fabrication can be difficult for complex shapes, and attachments require clever methods and thermal compensation. Zerodur can have an instability in the range of 150°C to 300°C⁷, but use of Zerodur M or careful control of heating and cooling in this temperature range eliminates any change in dimensions or CTE.

The invar alloys can have near zero CTE with special processing, but only over a limited temperature range. Components can be readily fabricated using conventional metalworking processes and the materials have high fracture toughness but relatively low strength and almost all invar specimens measured have temporal dimensional instabilities. In addition, invar alloys are ferromagnetic, have high density and a relatively low elastic modulus for one of the lowest specific stiffnesses of any material used for precision applications. Super invar can have a phase transition at low temperatures that is irreversible and changes properties substantially if the composition departs much from the nominal.

Composite materials, by their very nature have the disadvantage of having built in residual stress at the phase boundaries which usually lead to temporal dimensional instability. Graphite-epoxy composites can be designed and fabricated with CTE near zero, low density and high modulus. The properties can be tailored to the application, but are usually anisotropic due to

the fabrication methods which require a preferred fiber direction or at best, a pseudoisotropic layup. The biggest drawback of graphite-epoxy is its moisture sensitivity which effects dimensions, CTE and mechanical properties.

A number of the papers in this conference address the issues raised here for the dimensional stability of low expansion materials. The two invited papers of Professors Jacobs and Wolff are particularly recommended.

5. PROMOTING DIMENSIONAL STABILITY

Now that I have given you some insight into the causes of dimensional instability, you should see that there are many potential pitfalls in the design and fabrication of dimensionally stable components. In order to avoid these pitfalls there is a sequence of actions that can be taken that should lead to stable components.

The first step is to establish a budget for the allowable dimensional change for each component in the system and allocate a tolerance to each element. Structural components probably will not have as tight a tolerance as optical components and all components of each type will not necessarily have the same requirements. Then consider the sources of dimensional change as they relate to the components to be fabricated. For example, if the system is to operate at reduced or elevated temperatures, then both thermal instability and thermal cycling instability are potential types of instability and the sources for such behavior are changes in internal stress, inhomogeneity and/or anisotropy, and microstructural changes. Consider the fabrication options and how they relate to the dimensional instability sources and the component performance requirements. With all these factors in hand, select the candidate materials and reevaluate the sources and fabrication methods for each material with respect to meeting the budgeted dimensional tolerances in the specified use environment.

In order to make the final materials and fabrication method selection, you need to demonstrate that external stresses will not cause excessive strain in the component; that internal stresses in the component due to fabrication methods or inhomogeneities and/or anisotropies will not change excessively; and that any microstructural changes will not cause excessive strains. While this method sounds complicated, once you understand the basic sources of potential instability and the magnitude of the possible changes for each of the common candidate materials and their respective fabrication methods, the selection process becomes almost intuitive. The difficult part is when you must produce a component that operates in an environment for which properties information is severely limited, or when designing components to nanotolerances.

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