Synopsis of

Dimensional Stability: an overview
Roger A. Paquin

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Introduction

This paper, as the title implies, gives an overview of the problem of maintaining the dimensional stability of a system within specified tolerances. Maintaining dimensional stability requires that the sources of dimensional instability be understood and controlled. The author classifies instabilities into four categories based on the types of environmental change the system undergoes. Next, the sources of these instabilities are discussed. The article concludes with a general discussion of how to design with control of instabilities in mind.

Types of Instability

A very interesting aspect of this paper is the way in which instabilities are classified. Instead of classifying instabilities in terms of their specific sources, the author classifies them in terms of the response of the system to different types of environmental change:

- Temporal instability is the change in the system over time in a fixed environment. This change is permanent. This type of instability could be caused by the spontaneous relaxation of internal stress over time.
- Thermal/mechanical cycling instability is the permanent change in a system when it is cycled away from and then back to a fixed environment. This type of instability could be caused by the induced relaxation of internal stress as a result of thermal cycling.
- Thermal instability is the dimensional change of a system when the system is moved from one fixed environment to another (e.g. by a change in temperature). By definition this instability is both path-independent and reversible. An example of this would be a change in shape due to a temperature change.
- Hysteresis is the dimensional change of a system when the system is moved from one fixed environment to another that is dependent on the path between the two environments. This type of instability can be either reversible or irreversible. An example of this is the dependence of the length change of a heated bar on the cooling rate.

Sources of Dimensional Change

There are many sources of dimensional change. This paper discusses four of these in some detail. In some case a single source of dimensional change, such as a mechanical stress, can bring about different <u>types</u> of dimensional instability.

External stress. Every effort to model the behavior of a physical system results in a prediction of the behavior of that system that is only as good as the model itself. In optomechanical engineering, where the behavior of a system may need to be predicted to an accuracy of microns, this means that effects which would ordinarily be negligible may have to be accounted for. An excellent example of this is this paper's discussion of mechanical stress. The first-order model of the response of a system to mechanical stress is both linear and elastic - an applied force leads to a response that is proportional to the force, and the system returns exactly to it's original state when the force is removed. A real system may exhibit at least three additional types of response to an external force: 1) anelastic behavior (A), where the system approaches the elastic response only over time (any real system will exhibit this to some degree); 2) plastic behavior (P), where the system fails to return to it's initial state when the force is removed; and 3) creep (C), where the initial, linear response is followed by slow additional deformation. Any or all of these additional responses may be present depending on the magnitude and duration of the above stress, resulting in the behaviors shown in figure 1 below (figure 5 of the original paper):

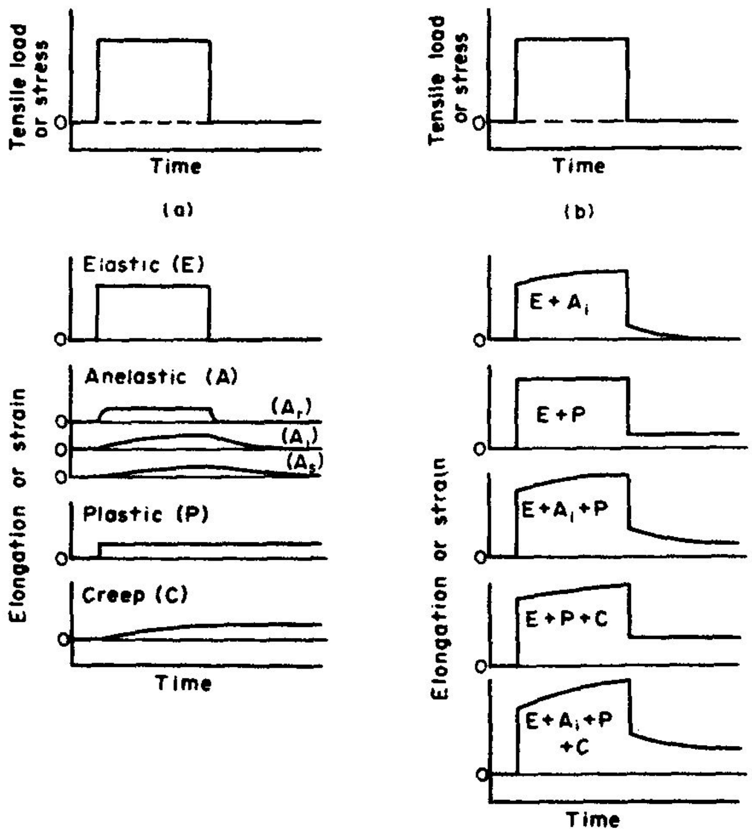

Figure 1: Possible responses to applied stress

To complicate matters even further, the response of the system may depend not only on the force currently applied, but also on the system's previous history. For example, the micro-yield strength of stainless steel, which if exceeded results in a plastic response, is strongly dependent on prior history. Thus an external stress can produce not only thermal instability but thermal/mechanical cycling instability and hysteresis as well.

Internal stress. A piece of material free from any source of external stress, either mechanical or thermal, can still have internal stresses. These can be either microscopic or macroscopic. An example of microscopic stress is that which occurs in beryllium. The CTE of an individual beryllium grain is anisotropic, since its lattice structure is hexagonal. Since the orientation of individual grains in a macroscopic sample is random, there will be short-range stresses at the grain boundaries.

Macroscopic stress is generally caused by processing of the sample. Figure 2 below shows the effect of quenching aluminum 7075-T6 at different temperatures (figure 10 of the original paper):

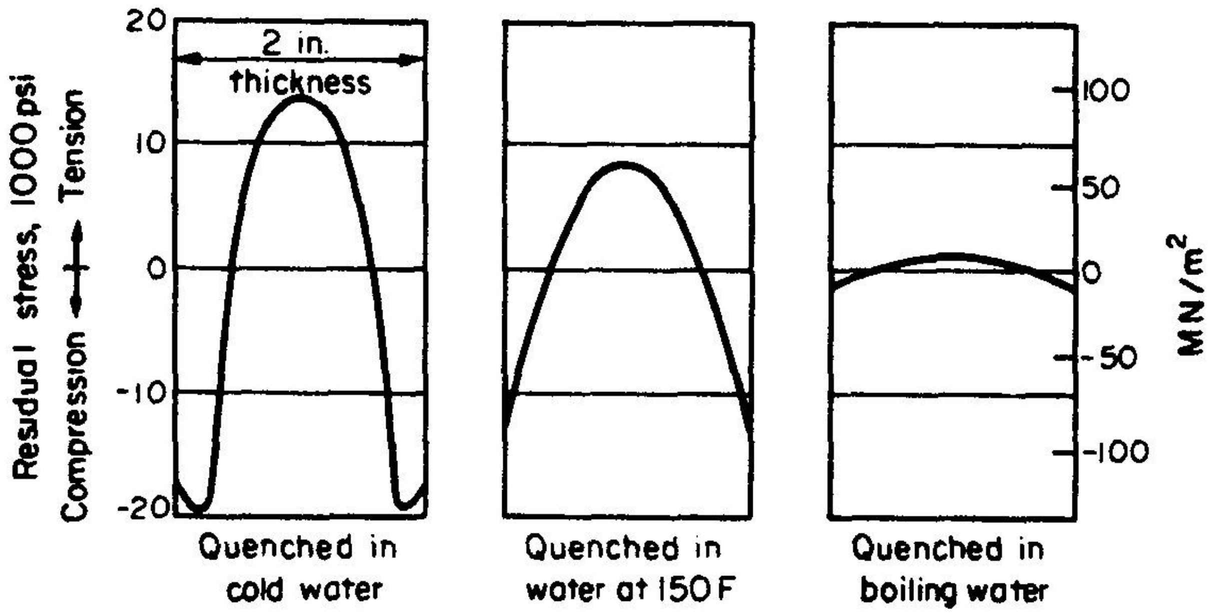

Figure 2: Stress induced by quenching

(Cold water quenching greatly increases the internal macroscopic stress of the sample, but the yield strength is also increased.)

Internal stresses are problematic because they can lead to both temporal and thermal/mechanical cycling instabilities, so for critical applications these stresses should be reduced if possible. The paper suggests several ways to do so:

- Isothermal exposure of thermal cycling
- Mechanical treatment
- Surface treatment
- Time

Microstructural changes. This term refers to the many chemical and physical changes that can occur in a material over time. For example, a phase transition can occur in steel where one allotrope of iron (austenite) transforms to a lower density form (martenite). This result in an expansion of the material over time. Such changes can result in temporal instability.

Inhomogeneity and anisotropy. Anisotropy is a fundamental property of pure crystals of many materials. For example, the Young's modulus of a crystal of pure iron varies with direction, and we have previously discussed the anisotropy of the CTE of beryllium. Thus, at the molecular level, most materials are anisotropic (glass is an exception). Fortunately the average behavior of a macroscopic piece of material with a fine-grained, randomly oriented microstructure is effectively isotropic. Anisotropy can be a problem when modeling the dimensional instability of components made of single crystals if the anisotropic behavior of the component is not taken into account.

Inhomogeneity results from variations in composition, grain size and grain orientation, or other factors. These variations can result from limitations in the manufacturing process, such as the small variations in glass composition that result in index variations within a lens, or can occur deliberately, for example during the heat treatment of metals. Inhomogeneities can result in either anomalous thermal instability.

Low Expansion Materials

Low expansion materials have become a popular way to reduce dimensional instability in systems where the primary source of instability is due to thermal variations. The paper briefly discusses the advantages and disadvantages of some of the materials. This section is somewhat dated; substantial advances in low CTE have been made in the 20 years since this paper has been published.

Promoting Dimensional Instability

In this section the author gives his thoughts on the design process as it relates to controlling the dimensional stability of a system:

- Establish an appropriate error budget.
- Consider the types of dimensional instability that the system will actually have to contend with, and relate the sources of instability to those types.
- Carefully consider the sources of instability that can be introduced during fabrication.

Conclusion

Because this paper is twenty years old, some of the specific examples given in it will seem dated, but the concepts discussed are still very relevant. Any optical engineer would find the concepts presented in this paper useful as he or she designs an optical system.