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THERMALLY STABLE MACRO-COMPOSITE STRUCTURES

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16. Abstract

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SUMMARY

A review of the mechanism providing small thermal expansivity in solids suggests the existence of macro-composite thermally stable gridworks. A kinematic theory of such gridworks is developed. Laboratory models of several titanium/aluminum composite gridworks are described, their thermal expansivity is measured and compared to theoretically predicted values. The existence of an essentially zero expansion construction is demonstrated experimentally.

CONTENTS

1. INTRODUCTION

Thermal expansion of structural materials are often detrimental to the proper functioning of advanced structures. They cause thermal stresses, for instance in supersonic and hypersonic aircraft and in thermodynamic propulsion plants. Such stresses may impair structural integrity and are difficult to control by conventional methods of design. Thermal expansion is also undesirable where very precise dimensional control must be maintained to satisfy functional requirements of the structure. Optical and radio-frequency sensors, timing devices, and multiple cavity RF-filters, for instance, require structures that retain their dimensions within very close tolerances while operating over a substantial temperature range.

The concept of using composite materials to achieve unidirectional low thermal expansion over a wide temperature range had been suggested in Reference 1. In Reference 2, a theoretical study of planar filamentary composites is reported in which the thermal strain tensor of the composite is related to the expansive and elastic properties of fibers and matrix. The present study deals with a macro-composite structure in which two types of metallic materials are combined in a binary trellis arrangement, configured to yield compensation of thermal expansion in a preferred direction.

2. MATERIALS OF LOW THERMAL EXPANSIVITY

Thermal expansivity of solids is primarily caused by molecular lattice vibrations. As temperature increases the amplitude of vibration increases and average interatomic distances changes accordingly. The result is an observable, macroscopic dimensional change. Molecular vibrations can take place in different modes depending on the vibrational frequencies. As the temperature changes, different modes can be excited preferentially and therefore the thermal expansion coefficient may be strongly dependent upon the temperature at which it is measured.

Materials of low thermal expansion are generally those of very strong interatomic bonding, i.e., those with high moduli of elasticity, and high melting points. Figure 1 shows a composite graph of data collected from Reference 3 - 8 for a variety of high modulus, low expansion materials plotted over a wide range of temperature.

Other materials exhibiting low thermal expansivity derive their characteristics from peculiar molecular arrangements, from anisotropic structure or from thermally induced crystallographic effects which tend to compensate for the vibrational lattice expansion. These three types are briefly discussed below.

Effects from pecular molecular arrangement are strongly evident in certain glassy materials. Examples are fused silica, titanium silicates such as ULE[1] (Ref. 9), and glass-ceramics such as CER-VIT[2]. These have thermal expansion coefficients that are close to zero or slightly negative over certain temperature ranges. They exhibit a covalently bonded "open" network structure, permitting rotational vibration modes in which atoms can vibrate laterally into vacant areas. Thus, an increase in vibrational energy of the rotational mode may tend to reduce the average interatomic distance and expansivity remains low in the temperature range where the rotational mode is dominant. Consequently, the effect is generally limited to a small range of temperatures.

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1 (ULtra Low Expansion): trademark Corning Glass Works

2 Registered trademark, Owen, Illinois, Inc.

Anomalous thermal expansivity can also arise from crystallographic transformations associated with volumetric changes. These may partially or completely negate the expansive effects of lattice vibrations.

In order to be useful for the construction of precise instruments and structures such crystallographic changes must be instantaneous and reversible. Certain nickel-iron (Invar) and nickel-titanium (Nitinol) alloys exhibit instantaneous, martensic transformations and related ferro-magnetic effects which effectively can compensate for thermal lattice expansion over a limited temperature range.

Highly oriented materials exhibit physical anisotropy. As a result the thermal expansion in a preferred direction may be extremely small (or negative). High modulus graphite fibers (Ref. 10) and thin films of vapor deposited carbon (Ref. 11), for instance, have been found to exhibit abnormally low and negative expansion coefficients in the direction of the fibers and in the directions parallel to the thin film surface. This effect is apparently always accompanied by abnormally large expansivity in perpendicular directions normal to fiber axis or film surface.

The concept of using a "composite" design in which thermal expansivity is compensated by judicious choice of geometrical configuration and materials selection is as old as the grandfather clock. There, the pendulum length, which determines the time beat of the clock, is held very nearly constant by a combination of brass and steel rods supporting the pendulum bob. Unfortunately, the structural efficiency of this arrangement is poor.

Taking a cue from the low thermal expansion observed in open molecular networks and highly oriented crystallographic structures, a composite texture can be devised in which axial expansivity is minimized at the cost of a high transverse expansion. Examples of such a structure made from conventional materials of construction are examined in the following section.

3. THERMAL STRAIN OF SYMMETRICAL BINARY GRIDS

Consider a gridwork consisting of two interconnected trellis constructions made from two sets, "A" and "B", of straight parallel rods as shown schematically in Figure 2. Each trellis is made from one of the two materials, and its geometry is characterized by the trellis angles $2\beta_A$ and $2\beta_B$. Two orthogonal principal directions, "1" and "2" are defined by the bisectors of the trellis angles. The composite gridwork is produced by pin connecting the two trellises at their points of intersection, such that the principal directions of both trellises coincide, and such that all joints are free to rotate.

It can be shown that the binary gridworks are hyperstatic, but that uniform temperature changes throughout the structure do not cause thermal stresses. Therefore, a purely kinematic analysis of the thermal strain tensor can be derived from the strain circle diagram shown in Figure 3.

A unit temperature change will produce thermal strains, α_1 and α_2, in the principal directions and a thermal shearing strain represented by the rotation at the pin joints proportional to the radius, r, of the circle. The relations between thermal strains of the grid and its properties are obtained by inspection from Figure 3.

$$\alpha_1 = \frac{\alpha_A \sin^2\beta_B - \alpha_B \sin^2\beta_A}{\sin^2\beta_B \cos^2\beta_A - \sin^2\beta_A \cos^2\beta_B}$$

$$\alpha_2 = \frac{\alpha_B \cos^2\beta_A - \alpha_A \cos^2\beta_B}{\sin^2\beta_B \cos^2\beta_A - \sin^2\beta_A \cos^2\beta_B}$$

$$r = \frac{\alpha_B - \alpha_A}{2(\sin^2\beta_B \cos^2\beta_A - \sin^2\beta_A \cos^2\beta_B)}$$

Note that the underlying assumption for the geometry of Figure 3 is that

$$\beta_B > \beta_A \quad \text{and} \quad \alpha_B > \alpha_A$$

The condition that $\alpha_1 = 0$ (i.e., a thermally stable structure in the "1" direction) requires that

$$\frac{\alpha_A}{\alpha_B} = \frac{\sin^2 \beta_A}{\sin^2 \beta_B}$$

Figure 4 shows the dependence between β_A and β_B for this case, assuming a thermal expansion ratio, $\alpha_A/\alpha_B = 0.365$ which is representative for the titanium-aluminum combination (see Fig. 6).

A somewhat surprising observation from this analysis relates to the anisotropy of these thermally compensated gridworks. As β_A decreases, β_B decreases also. Hence, a thermally stable gridwork can be constructed in which all trellis elements become nearly parallel and, therefore, also provide highest stiffness and strength in the "stable" direction. This concept is clearly limited by the extremely large transverse expansion coefficients, α_2, and rotations, r, that must be accommodated as both β_A and β_B approach zero.

From the foregoing analysis it is evident that the temperature range of stability depends on the range over which the ratio of expansion coefficients of the two materials is independent of temperature.

The variability of expansion coefficients for five conventional structural materials is plotted in Figure 5 over the range from -200 to +200 °C. The ratio of selected combinations of these materials is shown in Figure 6. Based upon these data, the combination titanium/aluminum is selected for the design of the test structures described in the following section.

4. EXPERIMENTS

4.1 Test Structures.

Four binary grid structures were made from aluminum 2024T3 and titanium Ti-6Al-4V alloy. To simplify the construction of the grids, $\beta_B = 90°$ was chosen for all models. The test models are shown in Figures 7 and 8. The three models shown in Figure 7 differ only by their angle β_A of the titanium grid. The strips for the grids are cut 3/16 in. wide from 1/16 in. titanium and aluminum alloy sheet stock. These strips are joined at their intersections with closely fitting screws to form the grids. The fourth model, shown in Figure 8, uses "zig-zag" strips 1/8 in. wide machined from 3/8 in. titanium alloy plate stock. Aluminum alloy rods of 1/4 in. diameter are used as transverse spacers. These rods are internally threaded at the ends and the whole model is assembled by cap screws and short threaded rods.

Table I lists the pertinent geometrical dimensions of the four models.

TABLE I.

Model	Distance Between Joints: Ti-Grid (in.)	Distance Between Joints: Al-Grid (in.)	β_A
I	0.75	0.75	30°
II	0.75	1.00	41°48'
III	0.75	1.25	56°24'
IV	1.60	2.00	50°40'

4.2 Experimental Methods.

The samples were immersed into a chamber containing a temperature controlled liquid (LEXAN*). The chamber is equipped with an optical quality window which permits optical measurements.

Temperature control was accomplished by circulating the liquid from a temperature controlled reservoir through the chamber and back into the reservoir. The temperature in the chamber was measured by laboratory mercury thermometers immersed in the chamber with their bulbs placed near the liquid inlet and outlet locations. Accuracy of temperature measurements is estimated to be $\pm$ 0.2°C.

A secondary thermal expansion standard in the form of a molybdenum strip was fixed to one end of the samples. The relative motion of bench marks on the other end of the sample and on the standard were observed with an optical image splitting dilatometer mounted on a Gaertner telemicroscope.

The optical image splitting dilatometer used in the experimental investigation was subjected to an error analysis. It was determined that it could reproducibly measure distances corresponding to $\pm$ 2 divisions, each division corresponding to a length of 81×10^{-6} in. For a typical sample of four-inch base length, measured over a 100°C temperature range, this provides a threshold sensitivity of 0.2×10^{-6}/°C for the thermal expansion coefficient derived from a single test run.

Each test consisted of a complete heating and cooling cycle between room temperature and 120°C, with dilatometer readings made at approximately 10°C intervals. Thermal expansion coefficient values were obtained from these measurements by plotting the data and determining the average slope of a best fitting line through the test points.

The molybdenum secondary standard, the two forms of titanium materials, and the two forms of aluminum materials used in the Ti-Al grid structures were subjected to thermal expansion measurements by direct comparison with a primary silica standard supplied by the National Bureau of Standards. The grids were measured against the previously calibrated molybdenum secondary standard.

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*Trademark

4.3 Results.

Typical dilatometer data obtained during these tests are shown in Figure 9. An error analysis was performed for all tests as follows.

$$\text{Standard error} = \sqrt{\frac{\sum(\alpha - \bar{\alpha})^2}{n(n-1)}}$$

where n = number of tests

α, $\bar{\alpha}$ = individual and mean test value, respectively.

Results of the measurements and standard error are shown in Tables II and III. Table III also lists the predicted expansion coefficients for the four grids calculated from formulas given in the previous section.

TABLE II. THERMAL EXPANSION COEFFICIENT FOR BASIC MATERIALS.

Material	Thermal Expansion Coefficient $10^{-6}/°C$		
	Number of Tests	Mean Value $\bar{\alpha}$	Standard Error
Molybdenum (secondary standard)	6	4.15	± 0.29
Titanium Ti-6Al-4V:			
Sheet for grids I, II, III	4	7.90	± 0.56
Plate stock for grid IV	2	7.90	± 0.20
Aluminum 2024T3:			
Sheet for grids I, II, III	4	20.21	± 0.52
Rod stock for grid IV	3	23.42	± 0.65

TABLE III. THERMAL EXPANSION COEFFICIENTS
OF BINARY GRID STRUCTURES

Grid Type	No. of Tests	Thermal Expansion Coefficient $10^{-6}/°C$		
		Mean Value	Standard Error	Calculated Value
I	3	4.76	±0.12	3.8
II				
(Loose joints)	2	-0.95	±0.55	-1.95
(Tight joints)	2	0.11	±0.04	-
III	2	-14.64	±0.39	-20.08
IV	3	-0.01	±0.26	-2.79

The experimental results indicate expansivities generally somewhat larger than those calculated assuming freely rotating joints. Some hysteresis and scatter of data was observed in grids I, II, and III when tested with loose joints. Reproducibility was significantly improved by tightening the joint screws in Grid II. The resulting additional joint stiffness increased thermal expansivity of this model from -0.95 to +0.11 x 10^{-6} $°C^{-1}$. Grid IV was deliberately designed "over compensated" since joint rotation is absent. The effect of elastic restraint in the flexure motion was thereby compensated and an essentially zero expansion structures was obtained.

5. CONCLUSIONS

This program demonstrated that nearly perfectly compensated binary composite gridwork structures can be produced from titanium and aluminum. Best results have been obtained with a titanium grid assembled with aluminum spacers. The probable thermal expansion coefficient of this structure is of order $10^{-8}/°C$; sufficiently small to become comparable to microstrain effects inherent in conventional materials of construction. The measured expansivity is uniform within instrumental error over the measured range from room temperature to 120°C. The temperature coefficient variability of the materials used in the design are such that good temperature stability may be expected over a range from -200 to +250°C.

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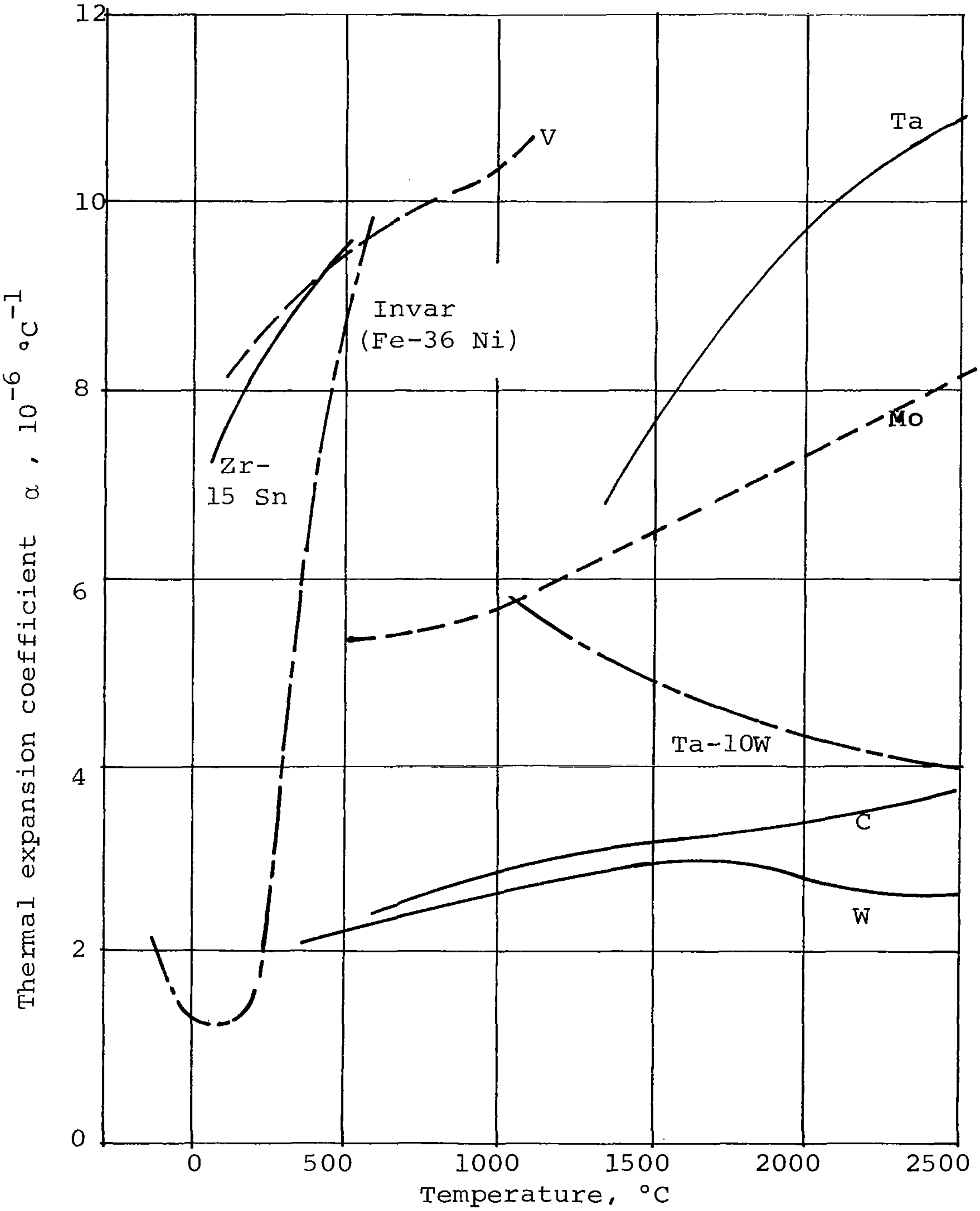


Figure 1. Linear Thermal Expansion Coefficient from Room Temperature to Indicated Temperature for Various Materials.

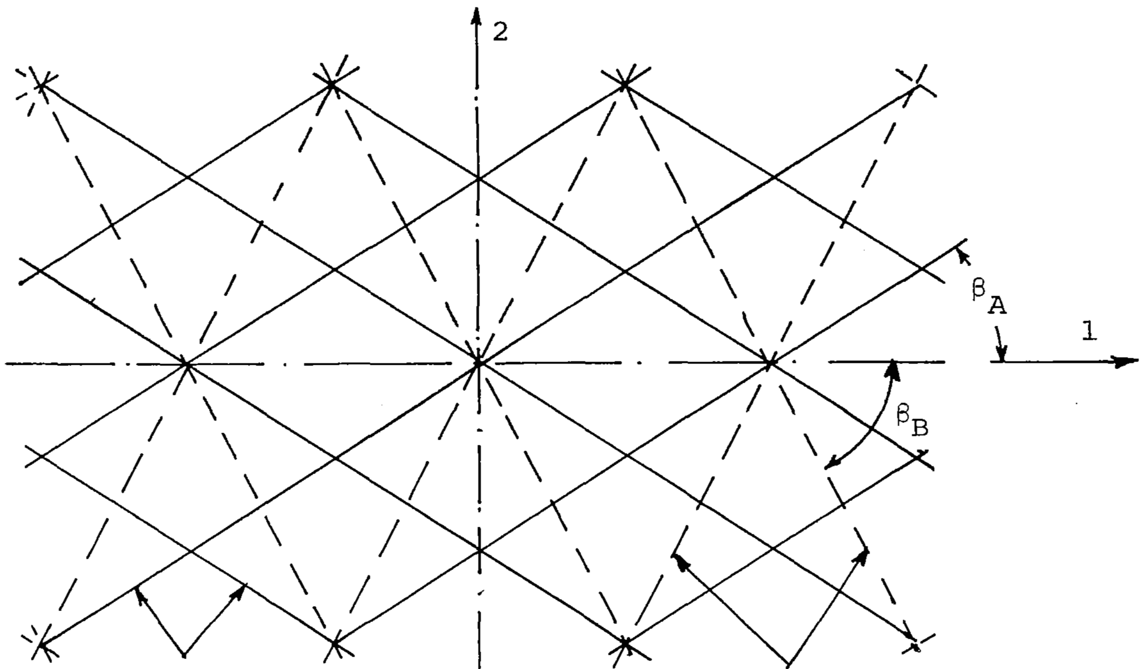


Figure 2. Binary Gridwork.

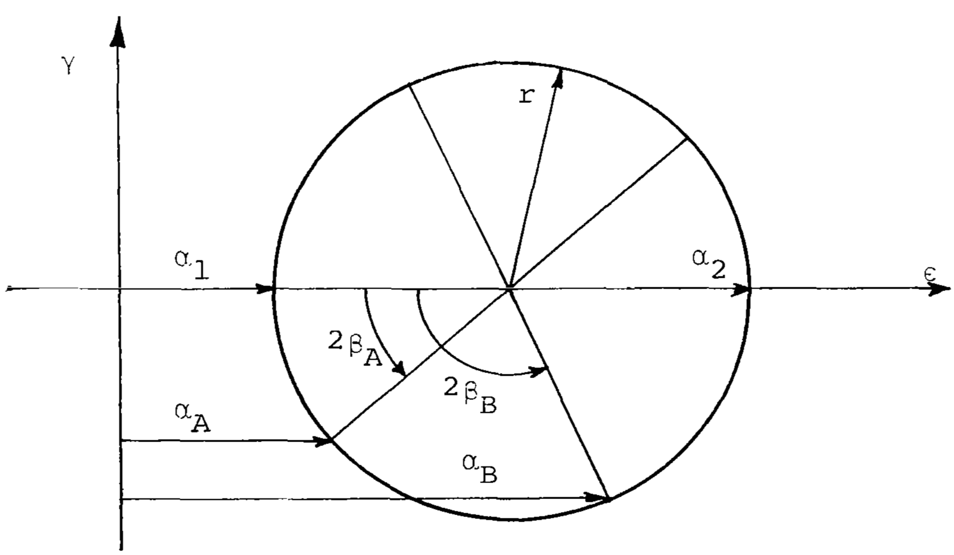


Figure 3. Diagram for Thermal Strains of Binary Gridwork Due to Unit Temperature Change.

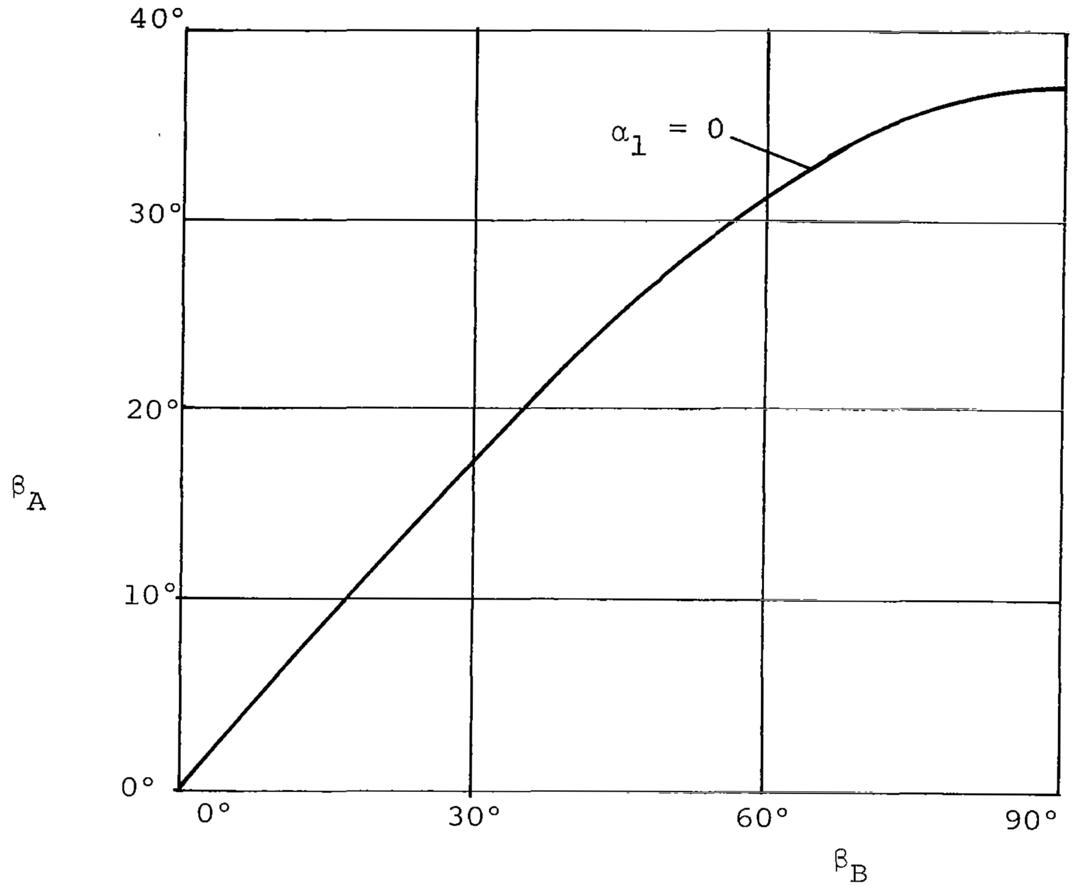


Figure 4. Geometrical Condition for Gridwork.

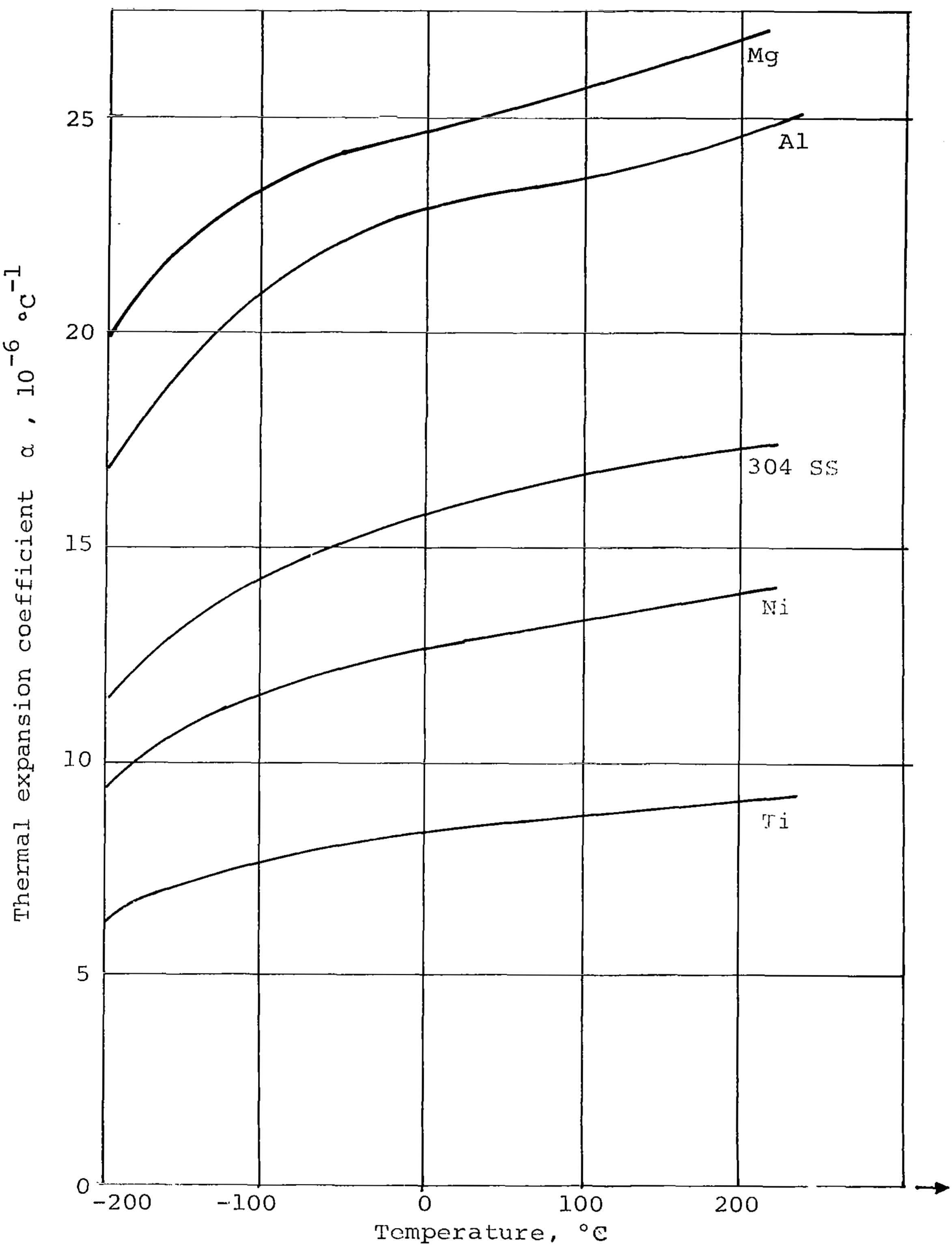


Figure 5. Linear Thermal Expansion Coefficient from Room Temperature to Indicated Temperature for Some Metals.

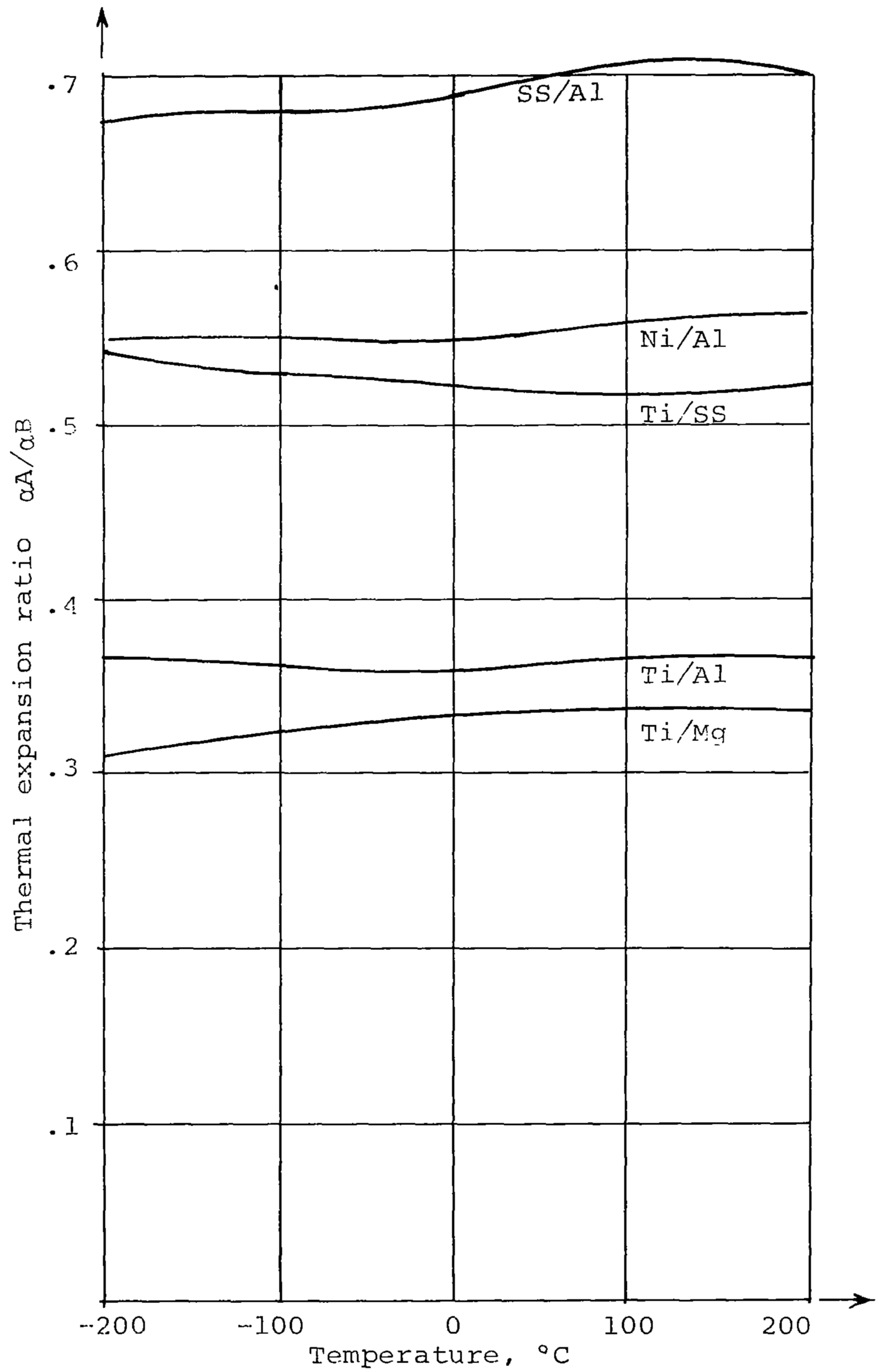
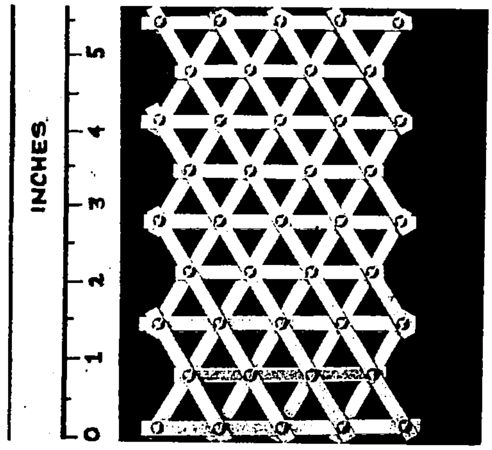
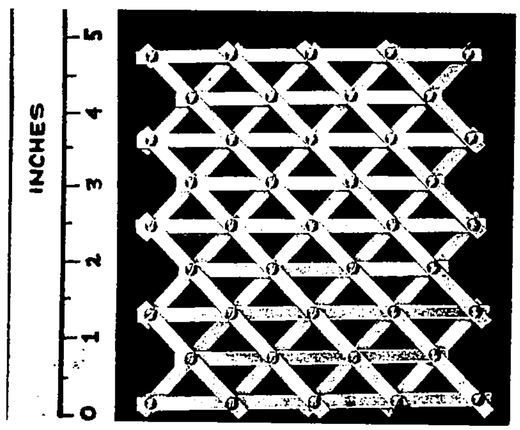


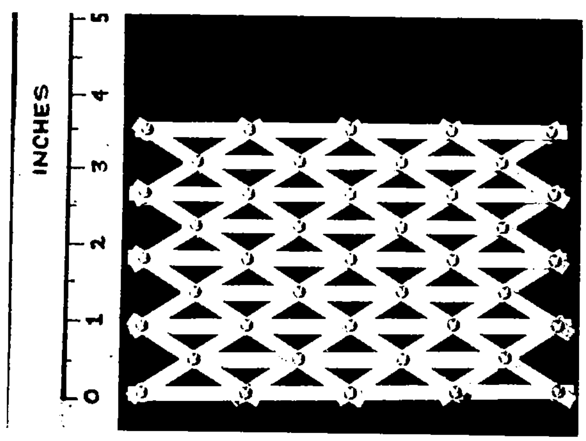
Figure 6. Thermal Explansion Ratios for Five Metal Combinations.



Model I



Model II



Model III

Figure 7. Binary Grid Test Structures, Models I, II, and III

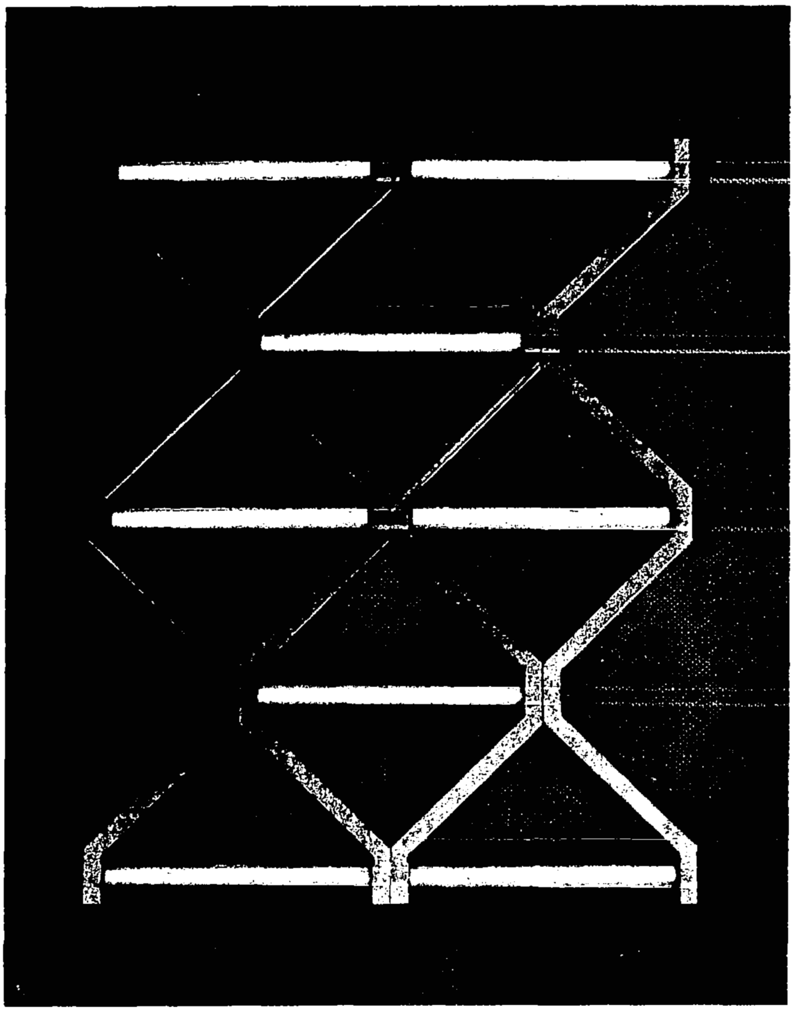


Figure 8. Binary Grid Test Structure, Model IV

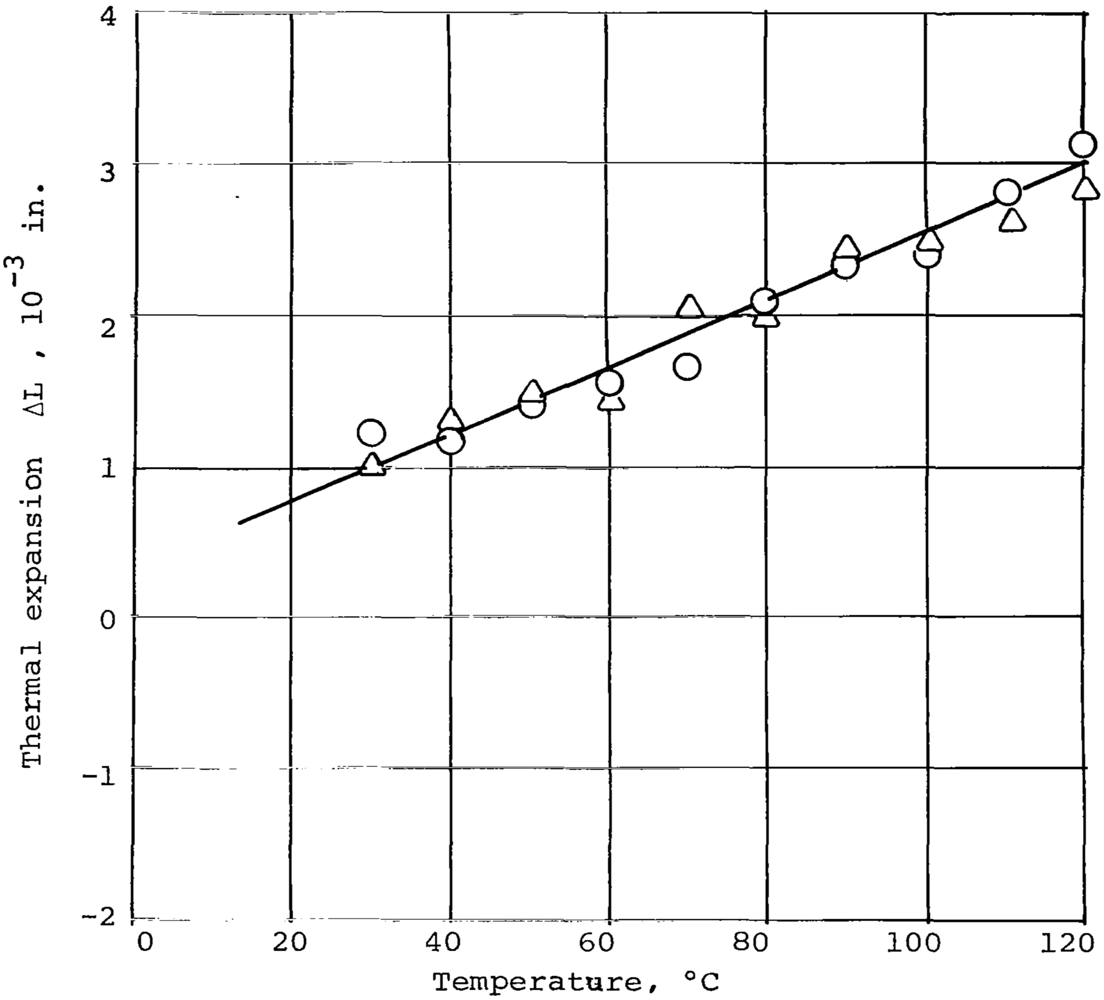


Figure 9. Length Changes as a Function of Temperature, Grid I
Base Length = 5.386 in.