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AD 474 255

MECHANICAL AND PHYSICAL PROPERTIES OF INVAR AND INVAR-TYPE ALLOYS

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Battelle Memorial Institute
Columbus, Ohio

31 August 1965

August 31, 1965
DMIC Memorandum 207

AD 474-255

MECHANICAL AND PHYSICAL PROPERTIES OF INVAR AND INVAR-TYPE ALLOYS

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1. ORIGINATING ACTIVITY (Corporate author) Battelle Memorial Institute Defense Metals Information Center 505 King Avenue, Columbus, Ohio 43201	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP --

3. REPORT TITLE

Mechanical and Physical Properties of Invar and Invar-Type Alloys

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

DMIC Memorandum

5. AUTHOR(S) (Last name, first name, initial)

McCain, William S., and Maringer, Robert M.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
August 31, 1965	70	207

8a. CONTRACT OR GRANT NO. AF 33(615)-1121 b. PROJECT NO. 8975 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) DMIC Memorandum 207 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) --

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11. SUPPLEMENTARY NOTES --	12. SPONSORING MILITARY ACTIVITY United States Air Force Research and Technology Division Wright-Patterson Air Force Base, Ohio 45433

13. ABSTRACT

This memorandum deals with the mechanical and physical properties of Invar and Invar-type alloys. Most of these are basically iron-nickel alloys which display unusual temperature dependencies of the thermal expansion and/or thermoelastic coefficients. This memorandum describes the compositions and properties of the most useful of these alloys, principally those which exhibit a constant modulus of elasticity or a very low thermal expansion over a significant temperature range. Specific alloys discussed are as follows: Invar, Super Invar, Stainless Invar, Elinvar, Ni-Span alloys, Vibralloy, Iso-Elastic, as well as some experimental alloys.

DD FORM 1 JAN 64 1473

Unclassified

Security Classification

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Mechanical properties	8	3				
Physical properties	8	3				
Invar	9	3				
Super Invar	9	3				
Stainless Invar	9	3				
Elinvar	9	3				
Ni-Span alloys	9	3				
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MECHANICAL AND PHYSICAL PROPERTIES OF INVAR AND INVAR-TYPE ALLOYS

W. S. McCain and R. E. Maringer*

SUMMARY

The need to eliminate or minimize the effects of temperature on elasticity and on the dimensions of precision-instrument components has led to the development of a host of alloys which display the "Invar Effect". Most of these are basically iron-nickel alloys which display unusual temperature dependencies of the thermal expansion and/or thermoelastic coefficients. This memorandum describes the compositions and properties of the most useful of these alloys, principally those which exhibit a constant modulus of elasticity or a very low thermal expansion over a significant temperature range.

Invar (an alloy with about 35.5 to 36 percent nickel) is the simplest of the Invar-type alloys. A number of other Invar-type alloys has been developed (primarily by the addition of other elements to the iron-nickel base) to achieve desired properties such as less sensitivity to variations in composition, better machinability, corrosion resistance, higher strength, etc.

The substitution of small amounts of cobalt for some of the nickel lowers the thermal-expansion coefficient of Invar. This improved alloy is called Super Invar. The minimum expansivity is reached at about 6 percent cobalt.

Improved machinability without loss of other desired properties can be achieved by adding selenium to the basic alloys of iron and nickel. Stainless Invar, so called because of its superior resistance to corrosion in NaCl, is remarkably stable with respect to time. It is reported to be three times better than conventional Invar.

Elinvar, which possesses a zero thermoelastic coefficient over a significant temperature range, is an Invar in which 12 percent of the iron has been replaced by chromium. Elinvar has other characteristics which enhance its usefulness in precision devices. It possesses a high degree of resistance to oxidation and corrosion; it has a low thermal expansivity, and it possesses a practical immunity to magnetic effects.

Ni-Span-C is essentially an Elinvar alloy with titanium added. The addition of titanium makes the alloy heat treatable by precipitation of an intermetallic compound of nickel and titanium. The most important uses of Ni-Span-C are to eliminate the effects of temperature variations on the responses to stress of elastically loaded members, such as helical and flat springs, Belleville washers, diaphragms, bellows, and Bourden tubes. Isoelastic is another alloy of the Elinvar class. This alloy is extensively used for precision extension springs.

Vibralloy consists of 9 percent molybdenum, 38 to 42 percent nickel, and the balance iron. The addition of the molybdenum to the iron-nickel alloys increases their mechanical strength. Also, the thermoelastic properties of these alloys are less sensitive to variations in nickel contents than those of an iron-nickel alloy.

Invar-type experimental alloys based on binary systems of Fe-Co, Fe-Pt, Ni-Co, and Fe-Pd, as well as ternary and quarternary systems containing these and other elements, also have been studied. The composite approach to the achievement of a low temperature coefficient of modulus springs has been and will continue to be a fruitful area for additional research.

Attention must be paid to the environment in which an Invar-type alloy is to be used, since it is known that a magnetic field causes a change in the dimensions of a ferromagnetic material. It is to be expected, though it is not always recognized, that the elastic moduli will also be affected.

INTRODUCTION

Just before the turn of the century, the French physicist Charles E. Guillaume discovered that the coefficient of thermal expansion of iron-nickel alloys depended strongly on the alloy composition, showing a minimum at about 36 percent nickel. The "invariable" dimensions of this alloy led to its name, Invar. Later, Guillaume reported that there were anomalies in the elastic moduli which corresponded closely to the anomalies in thermal expansion. In some cases, the elastic moduli were effectively constant over a significant range of temperature.

Obviously, such alloys were an important development, and found ready application in the precision apparatus of the day. Their usefulness inspired further research, until today we have available a whole series of alloys showing what has been called the Invar Effect. These alloys display unusual temperature dependencies of thermal-expansion coefficients and/or thermoelastic coefficients, and frequently have other unusual properties as well. Since the various aspects of the Invar Effect appear to be related, it is difficult to discuss one without referring to the others. Nevertheless, in order to keep this memorandum within reasonable bounds, the discussion will be limited as nearly as possible to those alloys which exhibit a constant modulus or a very low thermal expansion over a significant temperature range.

Background

There is, in our modern technology, a continuing and pressing need for ever-increasing precision. The demands put upon materials and equipment by designers are in many cases beyond the state of the art. This is not unrecognized, and as a result, a considerable amount of research has been undertaken during the last decade or so, aimed at various aspects of this need for precision. In particular, research has tried to develop designs and materials in which the effects

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of environment will be minimized. For example, consider a tuning fork which is designed to produce a given resonant frequency as a reference point. If an ordinary steel is used, the resonant frequency will be strongly temperature dependent. It is possible, however, by utilizing the Invar Effect to produce a fork whose frequency is independent of temperature over a moderate temperature range.

Related problems require a knowledge of some of the basic properties of metals and alloys. For this purpose, we will define some of the terms as they will be used throughout this memorandum.

Perhaps the most commonly recognized source of instability in materials and devices is thermal expansion. It is not uncommon to define a mean zero coefficient of thermal expansion ($\bar{\alpha}$) as

$$\bar{\alpha} = \frac{1}{L_o} \left(\frac{L_2 - L_1}{T_2 - T_1}\right), \qquad (1)$$

where L_o is the length at 0 C, L_1 is the length at temperature T_1, and L_2 is the length at temperature T_2. This expression introduces some inaccuracy, however, where the thermal expansion is not a linear function of the temperature. The thermal-expansion coefficient (α) can be defined more accurately as

$$\alpha = \frac{1}{L_o} \left(\frac{dL}{dT}\right), \qquad (2)$$

where L_o again is the length at 0 C, and dL/dT is the slope of the L vs T curve at some temperature T.

Similarly, the thermoelastic coefficient (γ) which is the temperature coefficient of the modulus of elasticity, can be defined as

$$\gamma = \frac{1}{E_o} \left(\frac{dE}{dT}\right), \qquad (3)$$

where E_o represents the modulus at 0 C, and dE/dT is the slope of the E vs T curve at the temperature T.

Since virtually all of the alloys to be discussed are ferromagnetic, a further property, magnetostriction, becomes of interest. Magnetostriction refers to the change in length of a ferromagnetic body which occurs during magnetization. The fractional change of length $\Delta l/l$ is represented by the symbol λ or, for saturation magnetization, by the symbol λ_s. It should be noted here that the inverse of magnetostriction exists. That is, the magnetic behavior of a ferromagnetic substance may be altered by the application of small stresses and strains.

The Invar Effect

As remarked earlier, there are a series of related anomalies which occur in iron-nickel alloys. The behavior of the average or mean thermal-expansion coefficient ($\bar{\alpha}$) as a function of nickel content is shown in Figure 1.* At nickel contents between about 34 and 36 percent, $\bar{\alpha}$ is less than 1×10^{-6} per F over the temperature range from -200 to +200 F.

*Figures begin on page 15.

The thermoelastic coefficient (at room temperature) also is a function of the nickel content, as shown in Figure 2, and reaches a maximum around 35 percent nickel. Between 27 percent and 44 percent nickel, the thermoelastic coefficient is positive, which means that the modulus is increasing with temperature. This is just the reverse of almost all other materials.

The magnetoelastic behavior of iron-nickel alloys is shown in Figure 3. The variation of the Curie point (θ) and the saturation induction (B_s) are shown in Figure 4. The variation of electrical resistivity with nickel content is shown in Figure 5.

Masumoto[(1)*] proposed an empirical rule that relates the anomalies in the magnetic properties of the iron-nickel alloys to the anomalies in the expansivities of the alloys. He observed that: "The circumstances whether a ferromagnetic alloys may have small expansivity depend merely on the ratio of the saturation magnetization to the transformation (Curie) temperature and the greater the ratio the smaller the coefficient of expansion becomes".

It is clear from various properties that some fundamental changes in the properties of the alloy are occurring. Consequently, a number of theories have been advanced to explain this behavior, beginning with that of Guillaume[(2)] in 1938. He assumed the formation of a compound, Fe_2Ni, but this has never been verified.

Numerous proposals, such as those of Dehlinger[(3)] and Zener[(4)], relate the anomalies to the magnetic behavior. All the commercially available constant-modulus alloys are ferromagnetic, and achieve their constant-modulus properties in the temperature range just below the Curie temperature. Thus, the theory suggests that the contraction is due to the loss of ferromagnetism compensates for the thermal expansion. Hence, the modulus tends to remain constant and the thermal-expansion coefficient tends to be low or even negative.

Other proposals, such as that of Benedicks,[(5-7)] suppose that if there is a temperature increase, a partial transformation occurs of the iron-rich alpha phase into the nickel-rich gamma phase. The differing volumes of the two phases provide the compensation to achieve a constant thermal expansion and presumably, constant modulus. These theories have never gained appreciable support.

The most modern of the theories (1963) is that of R. J. Weiss.[(8)] Earlier work showed that γ-iron has two electronic states (γ_1 and γ_2) separated by a small energy difference. The γ_2 is ferromagnetic with a magnetic moment per atom of 2.8 magnetons. The γ_1 state is antiferromagnetic with a magnetic spin per atom of 0.6 magneton. These two species will each form fcc structures, but with slightly different lattice parameters. Nickel in the fcc iron-base system stabilizes the higher lattice-parameter species. For such an alloy, raising the temperature tends to establish the lower lattice-parameter species. The growth of this phase will offset the normal temperature expansion that is associated with a single-phase alloy.

*References are given on pages 8-14.

Interestingly enough, Ananthanarayanan and Peavler[9] reported X-ray evidence of such a transition in 1961, although Weiss did not reference this work and apparently was not aware of it. Further, Weiss predicted that Fe-Pd alloys would show the Invar Effect, and this has been recently substantiated by Kussmann and Jesson.[10]

At present, it must be admitted that none of the early theories for the Invar Effect are completely satisfactory. That of Weiss appears promising, but it has not yet faced the test of scrutiny by the scientific community.

ALLOY PROPERTIES

The alloys to be considered in this section are listed in Table 1* along with their normal compositions as found in the literature. Table 2 gives a simple listing of references pertinent to each of the various alloys.

In the following sections, the data collected are presented essentially as they are found in the literature. Therefore, in many cases, there is some overlap and duplication among the various tables and graphs. This is believed preferable, however, to arbitrarily selecting data from any particular source.

Invar**

The simplest of the Invar-type alloys is Invar itself. Free-machining Invar, which contains a small amount of selenium, is included in the following data since the selenium has little effect on properties other than machinability. There is a great deal of literature concerning the physical and mechanical properties of Invar. Since these properties vary somewhat among different lots of material, after various amounts of deformation, with heat treatment, etc., different sources frequently report somewhat different properties. Indeed, one can distinguish several grades of Invar;[15] Standard, Superior, and Geodesic, each referring to successively more precise control of properties. This makes it difficult to present master plots which are not somewhat misleading. Therefore, in the interest of accuracy and expediency, the data appearing on subsequent pages are reproduced as they were taken from the literature. This leads to some duplication, but provides sets of self-consistent data.

For the most part, data on workability, weldability, machinability, pickling, plating, etc., are not included in this memorandum. These data are readily available in brochures put out by the vendors (see Reference 16).

Because of its low thermal-expansion coefficient, Invar is often used for precision applications where small temperature changes might otherwise produce unwanted dimensional changes. It must be recognized, however, that most materials have inherently unstable dimensions. Various processes such as stress relaxation, precipitation, ordering, etc., make the dimensions time dependent at most operating temperatures. This was recognized by Guillaume,[17] Invar's discoverer, who found that carbon was at least in part responsible for this instability. An example of these data are given in Figure 6. In this case, after about 8 years, the specimen had expanded some 10.8 microns per meter. This, however, was the change which followed after a very painstaking stabilization heat treatment. Ordinary cold-worked Invar, by comparison, might change by 150 microns per meter or more in a much shorter time period under service conditions.[18] Further, simply dropping a sample of quenched and annealed Invar on a hard surface might change its dimensions by as much as 100 microns per meter. These latter dimensional changes are all the more significant when it is realized that they are more than would be expected to result from a temperature change of 50 C (122 F).

The work of Lement, Averbach, and Cohen[19] indicates that both internal stress and carbon can be responsible for instability. Based on their experiments, they recommend the following heat treatment to achieve the optimum combination of low expansion coefficient and high dimensional stability:

(a) 830 C (1525 F), 30 minutes, water quench
(b) 315 C (600 F), 1 hour, air cool
(c) 95 C (205 F), 48 hours, air cool.

Instability may still result from magnetic effects as will be discussed in a later section.

Data on the various mechanical and physical properties of Invar are given in Tables 3 through 23 and in Figures 8 through 26.

Super Invar

The substitution of small amounts of cobalt for some of the nickel lowers the thermal-expansion coefficient of Invar. This was noted by several authors prior to 1930.[34-36] This improved alloy was called Super Invar. The minimum expansivity is reached at about 6 percent cobalt. Progressive amounts of cobalt above 10 percent tend to increase the minimum thermal-expansion coefficient of the ternary alloys, until the minimum disappears at about 40 percent cobalt (see Figure 27).

Cobalt additions increase the susceptibility of the alloy to the fcc to bcc transformations. This condition limits the ranges of useful compositions. For example, an alloy of the composition 63.5% Fe, 30.5% Ni, 6.0% Co will have low-expansivity properties, but will have an irreversible fcc to bcc transformation at about -10 C (14 F). This transformation would limit the usefulness of the alloys to temperatures above 14 F.

In addition to cobalt, the Super Invars will contain carbon, manganese, and silicon. It is necessary to add manganese and silicon to the ternary compositions when melted in air, to render them easily forgeable. Carbon is picked up from the furnace atmosphere during melting. Silicon is present in such small quantities that it has no important effects. On the other hand, carbon and manganese have considerable effects on the Super Invars.

*Tables begin on page 40.

**Also sold under the names Invar 36, Nilex, Nilvar, Indilitans, Uniloy-36, Nilo-36, Minvar, or Minovar.

On the favorable side, both carbon and manganese lower the fcc to bcc transformation temperature. Manganese tends to lower the inflection temperature and raise the minimum and mean values of the expansivity.

The ability of carbon and manganese to lower the Ar_3 temperature helps to counteract the opposite affect of cobalt, which tends to raise the alpha-to-gamma transformation temperature. Scott[36] found that an equivalent nickel content (percent L") could be established which could be used as a measure of the combined effectiveness of the three elements nickel, manganese, and carbon in the depression of the Ar_3 temperature:

$$\%L" = \%Ni + 2.5\ (\%Mn) + 18\ (\%C).$$

Scott was able to summarize the effects of carbon, manganese, nickel, and cobalt by devising a parameter be called the "merit index" (designated B)"

$$B = \ -\frac{\alpha}{A}\ ,$$

where is the inflection temperature in the expansion-versus-temperature curve and α is either the mean thermal-expansion coefficient, or the minimum thermal-expansion coefficient, and A is a constant. The parameter B is devised such that as the inflection temperature increases or the thermal-expansion coefficient decreases the merit index rises. Figures 28 and 29 show at a glance the harmful or useful effects of manganese C(Co + Ni) or cobalt. Figure 28 illustrates the effectiveness of cobalt additions in improving the thermal-expansive properties of ordinary Invar. This improvement is due to the dual effects of cobalt; namely, cobalt raises the inflection temperature and lowers the mean and minimum thermal-expansion coefficients. On the other hand, increases in the nickel content will raise the inflection temperature, but only by sacrificing the low expansivity.

Furthermore, Figure 29 demonstrates that carbon is only mildly harmful to the merit index and that manganese drastically reduces the merit index.

Unfortunately, no information on the mechanical properties of these alloys has been found.

Stainless Invar

Stainless Invar, so called because of its superior resistance to corrosion in NaCl, was apparently discovered by Masumoto[34] in the early 1930's. He investigated a portion of the Fe-Co-Cr ternary system, and showed that, for just over 35 percent iron, and for chromium contents between 9 and 10 percent, the thermal-expansion coefficient actually becomes negative. Some of these data are shown in Figures 30 and 31.

Hidnert and Kirby[33] did further work on the Fe-Co-Cr ternary, and verified some of Masumoto's findings. A series of alloys of the compositions shown in Table 24 was investigated. Some of the results are given in Figures 32 and 33. Some of these alloys tended to undergo a gamma-to-alpha phase change on cooling (see Figure 34), thus making them unsuitable as dimensionally stable materials. Lement, et al,[39] reported that they could not obtain reproducible expansion coefficients for the stainless Invar because of this phase change, Hidnert and Kirby's work indicates, however, that stable gamma alloys can be obtained.

Volet and Bonhoure[40] report that Stainless Invar is remarkably stable with respect to time, being some three times better than conventional Invar. They observed that, on drawing wire from a rod of the material, the thermal-expansion coefficient increased from about 0.7×10^{-6} per C to 8.2×10^{-6} per C. This is just the reverse of the behavior of ordinary Invar. On annealing the thermal-expansion coefficient decreases slightly with increasing annealing temperatures, rises to about 10.5×10^{-6} for an anneal near 750 C, then drops rapidly to zero for anneals near 900 C. The elastic modulus is also affected by annealing, being about 16,500 kg/mm^2 for the as-drawn wire and about 19,600 kg/mm^2 for a wire annealed at 750 C. There is a modulus minimum (14,800 kg/mm^2) for material annealed at 800 C. Higher annealing temperature result in a modulus of 17 to 18 kg/mm^2. The normal value of the thermoelastic coefficient is given as -300×10^{-6} per C, but this approaches zero for heat treatments in the vicinity of 800 C.

It is therefore possible to have either a low thermal-expansion coefficient, or a zero thermoelastic coefficient, depending upon the degree of working and the annealing schedule. This has been studied by Chevenard and Bouchet.[41] Some of their results are shown in Figure 35.

Some corrosion data as reported by Masumoto[34] are given in Figure 36.

Masumoto[33] measured the intensity of magnetization and the magnetostriction of one of his samples. These data are given in Figure 37. The electrical resistivity for this same specimen at 20 C was reported as 66.6×10^{-6}, while its mean temperature coefficient between 0 to 40 C was 0.832×10^{-3}. The units for the former property are presumably ohm-cm.

Elinvar

Guillaume is credited with the discovery and development of the first of the constant-modulus alloys, which he named Elinvar for invariant elasticity. Essentially, the original Elinvar is an Invar in which 12 percent of the iron has been replaced by chromium. Curve A of Figure 38 shows that the binary iron-nickel system has alloys of two compositions (at 27 and 44 percent nickel) which possess zero temperature coefficients of elastic modulus. It is difficult to take advantage of the constant moduli of alloys having either of these compositions, however, because both are so sensitive to nickel content that a small error in composition or even chemical inhomogeneities in the same casting would result in appreciable variations of the temperature coefficient of modulus. Guillaume discovered that the addition of 12 percent chromium, or its equivalent, were small quantities of manganese, tungsten, or carbon are also included, lowers thermoelastic-coefficient curve to the position shown in Curve B. In the ternary alloy, the zero temperature coefficient of modulus occurs at 36 percent nickel, and fortunately it is relatively insensitive to minor variations in composition.

It is now customary to modify the composition of Elinvar through the addition of elements such as tungsten, molybdenum, manganese, etc., in order to obtain or intensify specialized secondary properties and to increase ease of manufacturing.

Elinvar has other characteristics that enhance its usefulness in precision devices; namely, a high degree of resistance to oxidation and corrosion, low thermal expansivity, and practical immunity to magnetic effects.

Other constant modulus alloys for which Elinvar is the prototype will be discussed in the following sections of this memorandum.

Ni-Span Alloys

The Ni-Span Alloys, particularly Ni-Span-C, a are age hardenable and have considerably higher strengths than many of the other Invar types. Ni-Span-C has been developed specifically for its constant-modulus properties. Other alloys in the Ni-Span class are: Ni-Span Lo 42, Ni-Span Lo 45, Ni-Span Lo 52, and Ni-Span Hi. The first three are low thermal-expansion alloys, and the fourth a high-thermal-expansion alloy. The composition of these alloys can be found in Table 25.

Ni-Span C is an excellent sample of the benefits of age-hardenable alloys of the Invar types. It is essentially an Elinvar alloy with titanium added. The addition of titanium makes the alloy heat treatable by precipitation of an intermetallic compound of nickel and titanium. The heat treatment is normally carried out in two steps: a solution anneal, usually performed by the material supplier, and a precipitation-hardening treatment performed by the user after the forming operation.

The solution anneal is accomplished by heating to about 1700 to 1850 F, and quenching in water or oil. The material should be at temperature from 20 to 90 minutes depending upon size. Some applications may require additional stress-relieving and stabilizing treatment.(118)

The most important uses of Ni-Span C are to eliminate the effects of temperature variations on the responses to stress of elastically loaded members, such as helical and flat springs, Belleville washers, diaphragms, bellows, and Bourdon tubes. Within the range of -50 to 150 F, the modulus of Ni-Span C is almost constant. The temperature range can be widened (-90 to -240 F) with a slight deviation from the constancy-of-modulus property.

There is a marked effect of frequency on the thermoelastic coefficient of Ni-Span C. Experience has shown that the problems of producing a zero thermoelastic coefficient can be divided into two classes of applications: (1) low-frequency applications including springs and Bourdon tubes, and (2) high frequency applications, including tuning forks and vibrating reeds. Processing variables (cold-work level, time and temperature of heat treatment) can be adjusted to produce the desired thermoelastic coefficient for any frequency.

The available mechanical and physical properties of the Ni-Span alloys are given in Tables 26 to 36 and in Figures 39 to 71.

Vibralloy

Vibralloy consists of 9 percent molybdenum, 38 to 42 percent nickel, and the balance iron. In this alloy, molybdenum serves a dual purpose. First, the addition of 9 percent molybdenum to the iron-nickel alloys increases their mechanical strength. For example, the cold-worked 9 percent molybdenum alloy has a proportional limit of 110,000 pounds per square inch. On the other hand, the proportional limits of the iron-nickel alloys are only about 50,000 pounds per square inch. Second, the thermoelastic properties of the 9 percent molybdenum-containing alloy are less sensitive to variations in nickel contents than those of an iron-nickel alloy. Figures 72, 73, and 74 illustrate the effect of molybdenum on the thermal change in Young's modulus. The data are plotted such that changes in moduli of the alloys when heated from -40 C (-40 F) to temperature up to 80 C (176 F) relative to the moduli at 20 degress (4 F) are plotted as a function of temperature.

The slopes of these curves at a temperature T are proportional to the slopes of the corresponding modulus-temperature curves at the same temperature. That is, the occurrence of a negative slope at temperature T in Figures 73 or 74 indicates that the temperature coefficient of modulus of elasticity (γ) is also negative at that temperature. A positive slope indicates that γ is positive at T. The data in Figures 72 and 73 are summarized in Figure 74, which mean thermoelastic coefficients are obtained by dividing the relative change in modulus on heating from -40 to +80 C by 120 (the temperature range over which change is taken). The curves reveal that the additions of 9 percent molybdenum reduce by a factor of two the sensitivity of the mean temperature coefficient of elastic modulus to changes in nickel contents.

The curves in Figures 72 and 74 are valid only only for a definite amount of cold work. Figure 75 illustrates how cold work affects the thermoelastic properties of molybdenum-free and molybdenum-bearing alloys. Although the magnetic permeability of Vibralloy is lower than for a corresponding iron-nickel alloy, it is still sufficient for magnetic actuation and vibration. The work-hardened alloy has permeability values between 700 to 850 at 3500 gauss over the temperature range -40 to +80 C.

Iso-Elastic

Iso-Elastic is an alloy of the Elinvar class. It has a low-temperature coefficient of the modulus of elasticity, and is very adaptable for precision instruments, since drift error is less than 0.02 percent and hysteresis error is less than 0.01 percent of the total deflection. Iso-Elastic must be highly cold worked (up to 93.5 percent reduction in area) to obtain sufficient mechanical strength. Safe torsional stresses of 40,000 to 60,000 psi can be applied to Iso-Elastic after the suitable cold-working treatment. Iso-Elastic is not heat treatable, but the cold working is normally followed by a low-temperature 750 F stress-relief treatment.

The alloy is extensively used for precision extension springs. It is also used for torsion, spiral, or compression springs. The recommended range for obtaining Iso-Elastic's desirable low-temperature coefficient of modulus properties is

from -50 to +150 F. Some physical and mechanical properties for Iso-Elastic are given in Tables 38 and 39.

Experimental Alloys

The materials listed in the previous section do not by any means exhaust the possibilities of the Invar-type alloys. A great deal of research, particularly in Japan, has continued, and a wide variety of alloys has been investigated. Some of the summarized results follow.

Masumoto and his co-workers have done an enormous amount of work measuring moduli, thermal expansion, and thermoelastic coefficients in a wide variety of systems. This work led to the development of strainless Invar,(34) Co-elinvar,(54) Velinvar,(55) and a new alloy Moelinvar.(55) They have studied the properties of the binary systems Fe-Ni,(37) Fe-Co,(57) Fe-Pt,(58) Ni-Co,(59,60,57) Fe-Pd,(69) the ternary systems Fe-Ni-Co,(37) Fe-Co-Cr,(34,54,61) Fe-Co-Mo,(55) Fe-Co-V,(55) Co-Fe-Mn,(67) Co-Fe-W;(68) and the quaternaries Fe-Co-Cr-Ni,(1,62,63,64) Fe-Co-Cr-Cu,(65) Fe-Co-Ni-V,(66) Fe-Co-Mo-Ni,(56) Co-Fe-Mn-Ni,(67) and Co-Fe-W-Ni.(68) Some of these data are given in Tables 40 through 53, and in Figures 83 through 87.

The thermal-expansion characteristics of the Fe-Pt binary has also been studied in Germany.(70) Some of the results are shown in Figure 78.

Russian work in this area appears limited. The Russian papers encountered were restricted to three coauthored by Ivanushkino and Livshits,(71-73) and four papers authored by S. I. Doroshek.(74-77) Ivanushkino and Livshits studied the ternary systems of Fe-Ni-Cr, Fe-Ni-Mo, and Fe-Ni-Nb. It was shown in these studies that additions of the third element caused the hardness and the electrical resistivity to become functions of annealing time and temperature (Figures 79 and 80).

Doroshek investigated the properties of ternary Fe-Ni-Co,(74,77) Fe-Ni-Cu,(74) Fe-Ni-Ti,(76) and quaternary Fe-Ni-Mo-Ti.(75)

ALTERNATIVE APPROACHES

Composites

It is often possible, by balancing the temperature-dependent properties of two or more alloys, to achieve a degree of temperature independence. In keeping with the general intent of this memorandum, it is fitting to give a specific example of this approach.

Gascoigne, Enns, Kessel, and Ormondroyd(78) approached the problem of constant spring properties by attempting to balance the positive thermoelastic coefficient of Invar type iron-nickel alloys with the negative thermoelastic coefficients of Inconel X or 304 stainless steel. This was done both by nesting coil springs and by stacking Belleville springs. By these means they were able to achieve spring constants which varied by less than ±0.25 percent over the temperature range from -65 to +600 F.

Figure 91 shows nondimensional spring constants (ratio of spring constant at test temperature to reference spring constant taken at 750 F) for several bimetallic coil-spring nests.

It seems reasonable to believe that the composite approach to achievement of a low temperature coefficient of modulus springs will be a fruitful area for additional research.

Alternative Materials (Nonferromagnetic)

The materials previously listed cover most of the metallic materials which have been utilized or studied from the point of view of low thermal expansion or temperature-independent modulus. Although each of these materials has been ferromagnetic, this is not a necessity. The one major material which differs appreciably from the above is quartz. Quartz crystals, specially cut, are used in a wide variety of ways as frequency standards. Fused silica has an extremely low coefficient of thermal expansion (about 0.5×10^{-6} per C). Crystalline quartz has a considerably higher α, but it is anisotropic, having coefficient of expansion values of about 8×10^{-6} per C parallel to the crystal optic axis and 14×10^{-6} per C perpendicular to the axis. Its modulus also is anisotropic, being 10.3 $\times 10^{11}$ dynes/cm^2 perpendicular and 7.9×10^6 parallel to the optic axis. Because of this, it is possible to select a crystalline direction in which the thermoelastic coefficient is almost zero. Hence, quartz, properly cut, is an excellent material for reference frequency standards.

So far as the writers know, no such use has been made of metallic single crystals, although numerous examples of anisotropic metals and alloys exist. Uranium, for example, has thermal-expansion coefficients of 21, -1.4, and 22.6 x 10^{-6} per C in its three principal directions. Hence, depending upon the crystal axis, any α from -1.4 to 22.6×10^{-6} could be obtained as desired. Presumably a similar choice exists for a wide variety of thermoelastic coefficients. Other anisotropic metals of potential interest are listed in Table 55.

It is also possible for cubic metals to display anisotropy. Armstrong and Brown(79) have shown that this occurs in columbium. For the single columbium crystal, Young's modulus decreases with temperature in the [100] direction, but increases up to 16 percent between room temperature and 900 C (1652 F) in the [110] and [111] directions. Thus, increases in the measured moduli with increased temperature are possible for single crystals whose moduli are measured in a d[illegible]ction away from the [100]. Polycrystalline columbium also shows this anomalous modulus-temperature behavior.

Magnetic Effects

Almost all of the alloys discussed up to this point have been ferromagnetic. Since it is known that a magnetic field causes a change in the dimensions of a ferromagnetic material, it is to be expected that the elastic moduli will also be affected. This is indeed true, but not always recognized.

When a magnetic field is applied to a ferromagnetic material, its E modulus changes (it usually increases) by some amount called ΔE. Therefore, the effect has come to be known as the ΔE effect. The magnitude of the effect varies, of course, with the strength of the field. However, even minute fields can introduce a significant ΔE in precision measurements.

It has been shown, for example, that the period of an Invar pendulum (for gravity determinations) was altered by the earth's gravitational field.[81] This was eventually eliminated by shielding the instrument in a special box whenever it was moved.

Hibi[82] has shown the change in K/K_0, which is a measure of relative modulus, as a function of magnetic field for an Fe + 35 percent nickel sample (see Figure 92). Here the changes are of the order of several percent, and this is appreciable, even in less precise applications.

Katayev[83] has shown the same thing for Elinvar and Co-elinvar.(Figures 93 and 94). Koster[84] has studied this effect over a whole range of Fe-Ni alloys. Alers,[85] et al, have observed the ΔE effect in Fe-30Ni, and Yamamoto[86] has stated it in Ni-Cu alloys. The effect is also found in pure metals such as nickel and iron.[87] The point to be emphasized is that the ΔE effect is apparently a characteristic of ferromagnetic alloys.

At least in part, the modulus change is the result of the existence of a domain-wall structure. Because of magnetostrictive coupling, the application of a strain to a ferromagnetic system induces the domain walls to move. Thus, the total strain becomes the sum of the elastic and the magnetoelastic strains, and the modulus measured is lower than the pure elastic modulus. When a magnetic field is applied, the domain-wall density and orientation change, and consequently the measured modulus changes. At saturation magnetization, the domain-wall structure no longer exists, and the modulus reaches its maximum.

Because of the nature of domain-wall movement, it can further be anticipated that the modulus will be a function of stress. That is, E will not be a constant. This has been demonstrated in iron,[87] although the ferromagnetic origin of this dependence has not been verified.

T. S. Kê[88] has also observed an interesting and previously unreported effect. In most cases, the damping capacity of a vibrating body (damping is a measure of the area under the dynamic stress-strain loop) will decrease as a magnetic field is applied to the body. Ke found that, for an Armco Iron sample vibrating transversely in a magnetic field, the damping increased with the strength of the field, and reached a maximum at saturation magnetization. Since an increase in damping is normally accompanied by a decrease in dynamic modulus, this is the equivalent of saying that the modulus decreases as the field increases. The damping decreases with increasing magnetic field for longitudinal or torsional vibrations. Ke suggests that this effect may result from the stress-induced rotation of magnetic vectors.

An additional point deserves to be recognized. In some alloy systems (C in α-Fe is a good example) a solute element will tend to accupy a specific lattice position relative to the magnetization vector. Thus, if a piece of iron containing carbon in solution is magnetized (with a relatively small field), it will first increase in length due to magnetostriction, then it will decrease in length as a function of time as the carbon atoms diffuse to energetically more favorable positions.[89] This type of reaction is known as directional ordering, and seems to have many unexplored ramifications. A particularly pertinent one is reported by Kekalo and Livshits.[88,91] They report that the damping capacity of Invar changes with time, at temperatures below the Curie point, after thermal treatment, or after demagnetization. Once again, this means that the modulus (and probably also the length) is changing as a function of time. Thus, some attention must be paid to the environment in which an Invar-type alloy is to be used if its full potential is to be realized.

REFERENCES

(1) Masumoto, H., "On the Thermal Expansion of the Alloys of Iron, Nickel and Cobalt and the Cause of the Small Expansivity of Alloys of the Invar Type", Kinzokv no Kenkyu, 8, p. 237 (1931).

(2) Guillaume, C. E., "Discovery of the Anomaloy", Proc. Phys. Soc. (London), 32, pp 374-404 (1920).

(3) Dehlinger, U., "Alteration in Volume or Magnetization and the Invar Alloys", Z. Metallk., 28, pp 194-196 (July, 1936).

(4) Zener, C., "Impact of Magnetism Upon Metallurgy", Trans. Inst. AIME, Met. Div., 203, pp 619-630 (1955).

(5) Benedicks, C., "One-Phase or Two-Phase Conditions in the System Fe-Ni; Theories Concerning Meteoric Iron and Invar", Ark. Mat. Astr. Fys., A28 (14), 1-32 (1942).

(6) Benedicks, C., and Sederholm, P., "The Abnormal Expansion of Invar", Ark. Mat. Astr. Fys., B19 (1), 1-6 (1925).

(7) Benedicks, C., Metallographic Researches, McGraw-Hill Book Co., Inc.. New York, New York (1926).

(8) Weiss, R. J., "The Origin of the 'Invar' Effect", Technical Report AMRA TR-63-07, U. S. Army Materials Research Agency, Watertown, Massachusetts (June, 1963).

(9) Ananthanarayanan, N. I., and Peavler, R. J., "A New Reversible Solid-State Transformation in Iron-Nickel Alloys in the Invar Range of Compositions", Nature, 192, p. 962 (1961).

(10) Kussman, A., and Jesson, K., "Magnetic and Dilatometric Measurements of the Transformation Kinetics of FePd Alloys", Z. Metallk., 54 (9), 504-510 (1963).

(11) "Iron-Nickel and Related Alloys of the Invar and Elinvar Types (30% to 60% Nickel)", The International Nickel Company, Inc., New York, New York (1956, revised 1962).

(12) "Engineering Properties of Ni-Span-C, Alloy 902", Technical Bulletin T-31, Huntington Alloy Products Division, The International Nickel Company, Inc., Huntington, West Virginia (1963).

(13) Bozorth, R. M., Ferromagnetism, D. Van Nostrand Company, Inc., New York, New York, pp 102, 448, 642, 644 (1951).

(14) "Invar and Related Nickel Steels", Circular 58, U. S. National Bureau of Standards (June, 1923).

(15) "Alloys with a Fixed Rate of Dilatation", Aciers Fins and Speciaux Francais (13), pp 82-85 (March, 1953).

(16) "Technical Service Letter TL 1", International Nickel Company, Inc., New York, New York (1962).

(17) Marsh, J. S., Alloys of Iron and Nickel - Volume I, Special Purpose Alloys, McGraw-Hill Book Co., Inc., New York, New York, pp 135-183 (1938).

(18) Eberly, W. S., "How to Make Invar Stay Put", Prod. Eng., 28 (D9), 80-81 (1957).

(19) Lement, B. S., Averbach, B. L., and Cohen, M., "The Dimensional Behavior of Invar", Trans. ASM, pp 1072-1097 (1951).

(20) Lyman, T., Metals Handbook, 1, 8th Edition, The American Society for Metals, Metals Park, Ohio, 816-819 (1961).

(21) "Carpenter Alloys for Electronic, Magnetic, and Electrical Applications", The Carpenter Steel Company, Reading, Pennsylvania (1963).

(22) Schwartzberg, F. R., Osgood, S. H., Keys, R. D., and Kiefer, T. F., "Cryogenic Materials Data Handbook", Report ML-TDR-64-280, PB 171809 (Revised) and PB 171809-6, The Martin Company, Denver, Colorado, under Air Force Contract AF 33(657)-9161 (January 15, 1964, and August, 1964).

(23) Johnston, H. L., and Brooks, H. E., "Impact Strength of Various Metals at Temperatures Down to 20° Absolute", Tech. Report 264-17, The Ohio State University Research Foundation, Columbus, Ohio.

(24) Bornemann, A., and Gela, T., "Studies in the Behavior of Certain Non-Ferrous Metals at Low Temperatures", Final Report, Stevens Institute of Technology, Hoboken, New Jersey, under U. S. Army Contract DA-36-039-SC-15393 (December 31, 1953).

(25) "Mechanical Properties of Uniloy 36 at Temperatures from 75 F to -300 F", R&D Memo 15, Universal-Cyclops Steel Corporation (April 24, 1962).

(26) Schummer, A., and Bladwin, W. M , Jr., "Investigation of the Brittleness of Non-Sensitized Stainless Steels at High Deformation Speeds", preliminary information by Case Institute of Technology, Cleveland, Ohio, in cooperation with American Iron and Steel Institute.

(27) "Latrobe Steel Company Data Sheet - Invar", Latrobe Steel Company, Latrobe, Pennsylvania.

(28) Schetky, L. M., "The Properties of Metals and Alloy of Particular Interest in Precision Instrument Construction", Report R-137, Massachusetts Institute of Technology, Cambridge, Massachusetts (January, 1957).

(29) Rosenfield, A. R., and Averbach, B. L., "Effect of Stress on the Expansion Coefficient", J. Appl. Phys., 27 (2), 154-156 (February, 1956).

(30) Sands, J. W., "Invar, Elinvar, and Related Iron-Nickel Alloys", Metals and Alloys, 3 (6), 131-135, 150, 156-165 (June, 1932).

(31) Sefing, F. G., and Nemser, D. A., "Low-Expansion High Nickel Alloy for Precision Parts; Minvar", Prod. Eng., 16, pp 799-801 (November, 1945).

(32) "Technical Information Bulletin No. 210", Driver-Harris Company, Harrison, New Jersey.

(33) Lement, B. S., and Averbach, B. L., "Measurement and Control of the Dimensional Behavior of Metals", Summary Report No. 1 R-95, Massachusetts Institute of Technology, Cambridge, Massachusetts, under Air Force Contract AF 33(616)-2039 (December, 1955).

(34) Masumoto, H., "On the Thermal Expansion of Alloys of Cobalt, Iron, and Chromium, and a New Alloy 'Stainless Invar'", Sci. Rept. Res. Inst., Tohoku University, 23, pp 265-280 (1934-1935).

(35) Brace, P. H., U. S. Patent 1,689,814.

(36) Scott, H., "Expansion Properties of Low-Expansion Fe-Ni-Co Alloys", Trans. AIME, Inst. Metal Div., 89, pp 506-537 (1930).

(37) Masumoto, H., "On the Thermal Expansion of the Alloys of Iron, Nickel, and Cobalt, and the Cause of the Small Expansibility of Alloys of the Invar Type", Sci. Rept., Res. Inst., Tohoku University, 20, pp 101-123 (1931).

(38) Hidnert, P., and Kirby, R. K., "Thermal Expansion and Phase Transformations of Low-Expanding Cobalt-Iron-Chromium Alloys", J. Res. Nat. Bur. Std., Res. Paper 2602, 55 (1), 29-37 (July, 1955).

(39) Lement, B. S., Roberts, C. S., and Averbach, B. L., "Determination of Small Thermal Expansion Coefficients by a Micrometric Dilatometer Method", Rev. Sci. Instr., 22, pp 194-196 (March, 1951).

(40) Volet, C., and Bonhoure, A., "Some Properties of Stainless Invar", Compt. Rend., 216, pp 734-735 (1943).

(41) Chevenard, P., and Bouchet, P. J., "Sur l'anamalie dilatometrique et l'anomaoe thermo-elastique de l'invar Japanais", Compt. Rend., 220, pp 774-776 (1945).

(42) "Spring Materials High and Low Temperature Applications", Report No. AL-2606, North American Aviation, Inc., under Air Force Contract AF 33(600)-28469 (September 16, 1957).

(43) Mudge, W. A., and Talbot, A. M., "Ni-Span", Iron Age, 157, pp 66-70 (1946).

(44) Ward, M., "Constant Modulus Alloy for Elastic Elements", Prod. Eng., 27, p. 135 (1956).

(45) Ochsner, F. C., "Age-Hardening Nickel Alloys", Prod. Eng., 19, pp 126-128 (October, 1948).

(46) Burnett, H. C., "Thermoelastic Properties of Alloys", Second Progress Report from the National Bureau of Standards to U. S. Navy Bureau of Aeronautics.

(47) Mooradian, V. G., Gosch, D. R., and McIsaac, D. F., "Development of Improved Metallic Materials for Electronic Components Operating at High Temperatures", Final Report, Engelhard Industries, Inc., Union, New Jersey, under U. S. Navy Bureau of Ships Contract NObs 77085 (September 30, 1965).

(48) Favor R. J., Gideon, D. N., Grover, H. J., Hayes, J. E., and McClure, G. M., "Investigation of Fatigue Behavior of Certain Alloys in the Temperature Range from Room Temperature to -423 F", Report WADD-TR-61-132, Battelle Memorial Institute, Columbus, Ohio, under Air Force Contract AF 33(616)-6888 (June, 1961).

(49) "Wilco Ni-Span-C - Constant Modulus Alloy", Engelhard Industries, Inc., H. A. Wilson Division.

(50) Fine, M. E., "Vibralloy - A New Ferromagnetic Alloy", Bell Lab. Record, 30 (9), 345-348 (September, 1952).

(51) Fine, M. E., and Ellis, W. C., "Thermal Variation of Young's Modulus in Some Fe-Ni-Mo Alloys", J. Metals, Trans. AIME, 3, pp 761-764 (September, 1951).

(52) "Technical Information on Vibralloy - A Controllable Modulus Ferromagnetic Alloy", Data Sheet from the Arnold Engineering Company, Marengo, Illinois.

(53) "Iso-Elastic Spring Alloy", Engineering Bulletin, John Chatillon and Sons, New York, New York.

(54) Masumoto, H., and Saito, H., "On Young's Modulus and Its Temperature Coefficient of the Alloys of Cobalt, Iron, and Chromium, and a New Alloy 'Co-Elinvar'", Sci. Rept. Res. Inst., Tohoku University, A1, pp 17-22 (1949).

(55) Masumoto, H., Saito, H., and Kobayashi, T., "On the Thermal Expansion, Rigidity Modulus and Its Temperature Coefficient of the Alloys of Cobalt, Iron, and Vanadium, and a New Alloy 'Velinvar'", Sci. Rept. Res. Inst., Tohoku University, A4, pp 255-260 (1952).

(56) Masumoto, H., et al, "New Elinvar-Type Alloy 'Moelinvar' in the Ternary System of Cobalt, Iron, and Molybdenum, and the Characteristics Dependent on the Addition of Nickel", Trans. Japan Inst. Metals, 3, pp 4-9 (1962).

(57) Masumoto, H., and Nara, S., "On the Coefficient of Thermal Expansion in Ni-Co and Fe-Co Alloys, and the Magnetostriction of Fe-Ni Alloys", Sci. Rept. Res. Inst., Tohoku University, 16, pp. 333-341 (1927).

(58) Masumoto, H., and Kobayashi, T., "On the Abnormality in the Thermal Expansion of Iron-Platinum Alloys", Sci. Rept. Res. Inst., Tohoku University, A2, p. 856 (1950).

(59) Masumoto, H., Saito, H., and Takahashi, M., "Magnetization, Magnetostriction, and Relaxation Phenomena During Isothermal Magnetic Annealing at High Temperatures in Ni-Cb Alloys", Sci. Rept. Res. Inst., Tohoku University, A9, pp 293-308 (1957).

(60) Masumoto, H., Inoue, S., and Ukaji, I., "On a New Anomaly in the Alloys of Nickel and Cobalt. I. The Effect of Heat Treatment in Magnetics on Their Magnetic Properties", Sci. Rept. Res. Inst., Tohoku University, A6 (4), 375-383 (August, 1954).

(61) Masumoto, H., and Saito, H., "On the Rigidity Modulus and Its Temperature Coefficient of the Alloys of Cobalt, Iron, and Chromium", Sci. Rept. Res. Inst., Tohoku University, A4, p. 245 (1952).

(62) Masumoto, H., Saito, H., and Sugai, Y., "Influence of Addition of Nickel on the Thermal Expansion, Rigidity Modulus and Its Temperature Coefficient of the Alloys of Co, Fe, and Cr, Especially of Co-Elinvar. II. Additions of 30 and 40% Ni", Sci. Rept. Res. Inst., Tohoku University, A7, pp 533-540 (1955).

(63) Masumoto, H., Saito, H., and Kono, T., "Influence of Nickel on the Thermal Expansion, Rigidity Modulus and Its Temperature Coefficient of the Alloys of Co, Fe, and Cr, Especially of Co-Elinvar. I. Additions of 10 and 20% of Nickel", Sci. Rept. Res. Inst., Tohoku University, A6, pp 529-538 (1954).

(64) Masumoto, H., Saito, H., and Kono, T., "Thermal Expansion Coefficient, Shear Modulus, and Its Temperature Coefficient of the Alloys of Iron, Nickel, Cobalt, and Chromium. I. Thermal Expansion and the Relation Between Super Invar and Stainless Invar; II. Shear Modulus and Its Temperature Coefficient, and the Relation between Co-Elinvar and Elinvar", Nippon Konzoku Gakkai-Si, 19 (8), (I), 478-480, (II), 481-484 (1955).

(65) Masumoto, H., Saito, H., and Sugai, Y., "Influence of Addition of Copper on the Characteristics of an Elinvar Type Alloy 'Co-Elinvar'. I. Alloys Containing 5% of Copper", Sci. Rept. Res. Inst., Tohoku University, A9, pp 170-175 (1957).

(66) Masumoto, H., Saito, H., and Goto, K., "Influence of Addition of Nickel on the Thermal Expansion, the Rigidity Modulus and Its Temperature Coefficient of the Alloys of Cobalt, Iron, and Vanadium", Sci. Rept. Res. Inst., Tohoku University, A9, pp 159-169 (1957).

(67) Masumoto, H., Saito, H., and Sugai, Y., "New Elinvar Type Alloy 'Mangelinvar' in the Ternary System of Cobalt, Iron, and Manganese", J. Japan Inst. Metals, 28 (2), 96-101 (1964), in Japanese.

(68) Masumoto, H., Saito, H., and Sugai, Y., "New Elinvar-Type Alloy 'Tungelinvar' in the Tenrary System of Cobalt, Iron, and Tungsten, and the Characteristics Dependent on the Addition of Nickel", Res. Inst. Iron, Steel, Other Metals (July 24, 1963).

(69) Masumoto, H., Saito, H., and Kobayashi, T., "The Thermal Expansion Coefficients and the Temperature Coefficients of Young's Modulus of the Alloys of Iron and Palladium", Trans. Japan Inst. Metals, 4 (2), 114-117 (April, 1963).

(70) Kussman, A., Anwärter, M., and von Rittberg, G., "The Iron-Platinum Invars and Their Expansion Anomalies", Ann. Phys., Leipzig (Folge 6), 4 (3-4), 174-182 (1948), in German.

(71) Ivanushkina, A. Z., and Livshits, B. G., "Invar Can be Made Heat-Treatable by Alloying", Fiz. Metal. i Metalloved, 4 (1), 150-151 (1957), in Russian.

(72) Ivanushkina, A. Z., and Livshits, B. G., "Study of the Properties and Structure of Invar Alloys Containing Molybdenum, Chromium, and Niobium", Fiz. Metal. i Metalloved., 5 (3), 527-535 (1957), in Russian.

(73) Ivanushkina, A. Z., and Livshits, B. G., "Alloying of a 36% Invar Leads to a Change of Its Properties After Quenching and Tempering", Fiz. Metal. i Metalloved., 4 (1), 184-185 (1957), in Russian.

(74) Doroshek, S. I., "Influence of the Third Elements and Structure on Elasticity Modulus and Physical Anomalies in Invar", Fiz. Metal. i Metalloved., 17 (4), 638-640 (1964), in Russian.

(75) Doroshek, S. I., "Influence of Molybdenum on the Properties and Anomalies of Dispersion Hardening Invar-Type Alloys", Fiz. Metal. i Metalloved., 17 (2), 243-251 (1964), in Russian.

(76) Doroshek, S. I., "Physical Anomalies and Properties of Dispersion Hardened Invar Alloys", Fiz. Metal. i Metalloved., 17 (1), 122-131 (1964), in Russian.

(77) Doroshek, S. I., "The Effect of Cobalt on the Mechanical, Electrical, and Elastic Properties of Iron-Nickel Alloys", 17 (2), 317-320 (1964). in Russian.

(78) Gascoigne, H., Enns, J. H., Kessel, P., and Ormondroyd, J., "Wide-Temperature-Range Spring", Report ASD-TR-61-566, The University of Michigan, Ann Arbor, Michigan, under Air Force Contract AF 33(616)-6284 (May, 1962).

(79) Armstrong, P. E., and Brown, H. L., "Anomalous Temperature Dependence of Elastic Moduli of Niobium Metal", Trans. ASM Quarterly, pp 30-35 (March, 1965).

(80) Gray, D. E., American Institute of Physics Handbook, McGraw-Hill Book Company, Inc., New York, New York, pp 4-154 (1957).

(81) Bullard, E. C., "The Effect of a Magnetic Field on Relative Gravity Determinations with Invar Pendulums", Proc. Cambridge. Phil. Soc., 29, pp 288-296 (May 10, 1933).

(82) Hibi, T., "On the Change of Torsional Modulus of Some Ferromagnetic Substances With Temperature and with the Magnetisation", Sci. Rept. Res. Inst., Tohoku University, First Series, 28, pp 435-449 (1939-1940).

(83) Katayev, G. I., "Ferromagnetic Anomaly in Young's Modulus and the Shear Modulus in Alloys fo the Invar Class", Fiz. Metal. i Metalloved., 11 (3), 375-381 (1961).

(84) Koster, W., Elasticity Modulus and ΔE-Effect or Fe-Ni Alloys", Z. Metallk. 35 (10), 194-199 (October, 1943), in German.

(85) Alers, G. A., Neighbours, J. R., and Sato, H., "Magnetic Contributions to the Elastic Constants of Nickel and an Fe-3% Ni at High Magnetic Fields", J. Appl. Phys., 30 (4), 231S (1959).

(86) Yamamoto, M., "The Change of Young's Modulus of Elasticity by Magnetization in Iron and Carbon Steels", Sci. Rept. Res. Inst., Tohoku University, 27, pp 115-136 (1938).

(87) Engler, O., "Modulus of Elasticity of Ferromagnetic Substances in Dependence on the Temperature and on the Magnetic Field", Ann. Physik, 31 (2), 145-163 (January, 1958).

(88) Ke, T. E., and Chow, P. L., "A Study on the Acoustic Internal Friction of Iron Vibrating Transversely in a Steady Magnetic Field by Piezo-Electric Crystal Plates", Sci. Sinica, 6, pp 237-246 (1957).

(89) Maringer, R. E., "Magnetoelastic Damping in Zone-Melted Iron", J. Appl. Phys., 35, pp 2375-2381 (1964).

(90) Kekalo, I. B., and Livshits, B. G., "Magnetic Diffusion Effect in Invar, Studied by the Damping Capacity Method II", The Phys. Metals Metallog., 12, pp 19-23 (1961).

(91) Kekalo, I. B., and Livshits, B. G., "A New Magnetodiffusion Effect in Invar, Studied by the Damping Capacity Method I", The Phys. Met Metals Metallog., 12, pp 9-15 (1961).

(92) Masumoto, H., Saito, H., Kono, T., and Sugai, Y., "Thermal Expansion Coefficient, Rigidity Modulus and Its Temperature Coefficient of the Alloys of Iron, Nickel, Cobalt, and Chromium, and Relations of Super Invar to Stainless Invar and of Elinvar to Co-Elinvar", Sci. Rept. Res. Inst., Tohoku University, A8, pp 471-483 (1956).

OTHER ARTICLES OF INTEREST

(93) Alers, G. A., Neighbours, J. R., and Sato, H., "Temperature Dependent Magnetic Contributions to the High Field Elastic Constants of Nickel and an Fe-Ni Alloy", J. Phys. Chem. Solids, 13, pp 40-55 (1960).

(94) Ayurzanayn, B. A., "Study of Magnetization and Magnetostriction Saturation in Elinvar Alloys, Subject to Plastic Deformation", Akad. Nauk SSSR - Ser. Fer. Fiz., 28 (1), 206-210 (1964).

(95) Bando, Y., "The Magnetization of the Face Centered Cubic Iron-Nickel Alloys in the Vicinity of Invar Region", J. Phys. Soc. Japan, 19 (2), 237 (February, 1964).

(96) Bates, L. F., and Weston, J. C., "Thermal Expansion of Invar", Nature, 145 (3675), 550-551 (1940).

(97) Belov, K. P., and Agasyan, O. N., "Temperature Dependence of the Magnetostriction of the Invar-Type Alloys", Izv. Akad. Nauk SSSR, Ser. Fiz, 11, pp 655-659 (1947).

(98) Belov, K. P., "Ferromagnetic Nature of Invar and Elinvar Type Alloys", Izv. Akad. Nauk SSSR, Ser. Fiz., 11, pp 649-653 (1947).

(99) Belov, K. P., and Shmidt, V. V., "Magnetostriction and Thermal Expansion of Invar Alloys Near the Curie Point", Zh. Tekhn. Fiz., 23, pp 44-49 (1953).

(100) Bellware, M. D., "How to Weld Invar", Welding Engr., 49 (11), 41 (1964).

(101) Belov, K. P., "Magnetostriction of Ferromagnetic Alloys in the Region of the Paraprocess", J. Exp. Theoret. Phys., USSR, 20, pp 54-61 (January, 1950), in Russian.

(102) Belov, K. P., Katayev, G. I., and Levitin, R. Z., "On Internal Friction Anomaly in Ferromagnetics and Antiferromagnetics Near the Curie Point", J. Appl. Phys., 31, pp 153S-156S (1960).

(103) Belov, K. P., and Agasyan, O. N., "The Nature of the Elastic Anomalies in Alloys of the Invar and Elinvar Type", Dokl. Akad. Nauk SSSR, 80 (6), 881-883 (1951), in Russian.

(104) Belov, K. P., Magnetic Transformation, Moscow, Fizmatgiz, 259 pp (1959).

(105) Belov, K. P., Elastic, Thermal and Elastic Phenomena in Ferromagnetic Metals, Moscow, 2nd Edition, p 279 (1957).

(105) Blomqvist, E. A., "An Investigation of the Physical Properties of Some Nickel-Iron Alloys of the Invar Group", Engineering and Science Series No. 13, Rensselear Polytechnic Institute, Troy, New York (1926).

(107) Bouchard, J., "Effect of Reversible and Irreversible Changes of Magnetization on the Thermo-Electric Power of Ferromagnetics", Compt. Rend. Acad. Sci., 226, pp 1895-1897 (June 7, 1948), in French.

(108) Borodkina, M. M., "Investigation of Ageing of Spring Alloys", Fiz. Metal. i Metalloved., 6 (4), 700-705 (1958).

(109) Guillaume, C. E., "Chemical Equilibrium in Solids and in Nickel Steels", Rev. Gen. Sci., 9, pp 282-286 (1898).

(110) Boulanger, C., "Internal Friction Due to Ferromagnetism", Physica, 15, pp 266-271 (April, 1949), in French.

(111) Bozorth, R. M., and Walker, J. G., "Magnetic Crystal Anisotropy and Magnetostriction of Iron-Nickel Alloys", Phys. Rev., 89, pp 624-628 (February 1, 1953).

(112) Broniewski, W., and Smolinski, J., "The Structure of the Iron-Nickel Alloys", Compt. Rend., 196, pp 1793-1796 (1933).

(113) Chatillon, John & Sons, British Patent 495,562.

(114) Chevenard, P., "Anomaly of the Correlative Elasticity of the Magnetic Transformation of Nickel and of Solid Solutions Rich in Nickel", Compt. Rend., 212, pp 535-537 (1941).

(115) Chevenard, P., and Crussard, C., "Influence of Temperature on Poisson's Ratio in Fe Alloys. Anomaly of This Ratio Associated with the Magnetic Transformation of Reversible Ferronickels", Compt. Rend., 215, pp 58-61 (1942).

(116) Chevenard, P., Hugenin, L., Wache, and Villachon, A., "New Alloys of the Elinvar Type Susceptible to Structural Hardening", Compt. Rend., 204, p. 1231 (1931).

(117) Chevenard, P., et al., "New Alloy of the Elinvar Type", Engineer, 163, Sup. [Metallurgist], pp 38-39 (June 25, 1937).

(118) Chino, Y., "Thermal Hysteresis in Irreversible Iron-Nickel Alloys", J. Phys. Soc. Japan, 4 (1-2), 24-29 (1949).

(119) Clark, C. A., "The Dynamic Magnetostriction of Nickel-Cobalt Alloys", Brit. J. of Appl. Phys., 7 (10), 355-360 (October, 1956).

(120) Davis, L. G., "Low-Expansion Co-Fe-Cr Alloys", Iron & Steel, 29, pp 396-397 (1956).

(121) Davies, R. M., and Thomas, I. H., "Dynamical Method for the Measurement of Young's Modulus for Imperfectly Elastic Metals and the Application of the Method to Nickel and Some of Its Alloys", Phil. Mag., 23, pp 361-397 (1937).

(122) DeVinney, R. G., "Thermoelastic and Thermal Expansion Properties of Iron-Nickel Alloys", Strain Gage Readings, 5 (4), 23-30 (October/November, 1962).

(123) Doring, W., "Effect of Temperature on Elastic Modulus of Ferromagnetic Substances", Ann. Physik, 32 (5), 465-470 (July, 1938).

(124) Eberly, W. S., "Temperature Compensator (Nickel) Alloys", Machine Design, 26 (5), 152-156 (1954).

(125) Eberly, W. S., "Design Properties of Controlled-Expansion Alloys", Machine Design, 35 (11), 235-242 (1963).

(126) Fahlenbrach, H., and Meyer, H. H., "Materials with Elasticity Modulus of Particular Temperature Characteristic", Z. Technische Physik, 21 (2), 40-44 (1940), in German.

(127) Fangemann, M. G., "Precision Springs", Machine Design, 24, pp 154-158 (November, 1952 1952).

(128) Fangemann, M. G., "Spring Alloys", Machine Design, 28, pp 121-125 (May 31, 1956).

(129) Fine, M. E., and Ellis, W. C., "Young's Modulus and Its Temperature Dependence in 36 to 52% Nickel-Iron Alloys", Trans. AIME, J. Metals, 188 (9), 1120-1125 (1950).

(130) Fritz, J. F., and Clark, J. J., "Effects of Temperature on Magnetic Properties of Nickel-Iron Alloys", Elec. Mfg., 62 (5), 135-139 (November, 1958).

(131) Graf, L., and Kussman, A., "Composition and Magnetic Characteristics of Pt/Fe Alloys", Phys. Zeit., 36, pp 544-551 (August 15, 1935), in German.

(132) Harris, J. E., "Alloy for Vibratory Devices Such as Springs and Tuning Forks", Bell Telephone Laboratories, U. S. Patent 2,251,356.

(133) Heidenreich, R. D., and Nesbitt, E. A., "Stacking Disorders in Nickel Base Magnetic Alloys", Phys. Rev., 105 (5), 1678 (March 1, 1957).

(134) Herpin, A., "Hysteresis of Inverse Magnetostriction", Compt. Rend., 217, pp 475-476 (1943).

(135) Hibi, T., "Change of Damping Coefficient of Ferromagnetic Substances Due to Magnetization", Sci. Rept. Res. Inst., Tohoku University, 28, pp 450-457 (March, 1940).

(136) Hibnert, P., "Thermal Expansion of Some Nickel Alloys", J. Res. Nat. Bur. Std., 58 (2), 89-92 (1957).

(137) Hidnert, P., and Kirby, R. K., "A New Method for Determining Linear Thermal Expansion of Invar Geodetic Surveying Tapes", J. Res. Nat. Bur. Std., 50 (4), 179-185 (1953).

(138) Hiemenz, H., "The Thermal Expansion of Some Alloys of the System Ni-Fe and the Effect of the Heat-Treatment Thereon", Festschr. 70. Geburtstag von W. Heraeus, pp 69-79 (1930).

(139) Hill, W. J., Shimmin, K. D., and Wilcox, B. A., "Elevated-Temperature Dynamic Moduli of Metallic Materials", ASTM Preprint No. 74 (1961).

(140) Hoselitz, K., and Sucksmith, W., "A Magnetic Study of the Two-Phase Iron-Nickel Alloys", Proc. Roy. Soc., A181, pp 303-313 (May 6, 1943).

(141) Hunter, M. A., "Low Expansion Alloys", ASM Metals Handbook Cleveland, Ohio, pp 601-606 (1948).

(142) Josso, E., "Interpretation of the Instability of Invar and the Reversible Ferronickels", Compt. Rend., 242 (17), 2148-2150 (1956).

(143) Kekalo, I. B., and Livshits, B. G., "Dependence of the Damping Capacity and Shear Modulus of Nickel on the Magnetizing Field", Phys. Metals Metallog., 13 (4), 599-608 (1962).

(144) Kimura, R., "Elastic Moduli of Ferromagnetic Materials. I. Iron Crystals", Proc. Phys. Math. Soc. Japan, 21, pp 686-706 (November, 1939).

(145) Kondorsky, E. I., "On the Cause of the Peculiarities in the Physical Properties of Invar Alloys", Soviet Physics, J. Exp. Theoret. Phys., 37 (6), 10 (1959).

(146) Kondorsky, E. I., and Sedov, V. L., "Anti-ferromagnetism of Iron in Face-Centered Crystalline Lattice and the Causes of Anomalies in Invar Physical Properties", J. Appl. Phys., 31, p. 331S (1960).

(147) Burlaki, S. F., and Korolev, M. I., "Heat Treatment of Invar Type Alloys", Metalloved. i Term. Obrabotka Metal., (8), pp 39-41 (1941).

(148) Koster, W., "On the Damping of Nickel and Iron-Nickel Alloys", Z. Metallk., 35, pp 246-249 (1943).

(149) Koster, W., "The Temperature Dependence of the Elastic Modulus of Pure Metals", Z. Metallk., 39, pp 1-12 (1948).

(150) Kruger, G., "Temperature-Compensated Hair-Springs", Engineers' Digest, 20, pp 448-450, 466 (1959).

(151) Kuritsyna, E. F., "Temperature Dependence of the Magnetic Viscosity of Some Ferromagnetics", Izv. Akad. Nauk SSSR, Ser. Fiz., 16, pp 471-480 (1952).

(152) Kuritsyna, E. F., "Temperature Dependence of the Magnetic Viscosity of Ferro-Nickel Alloys", Dokl. Akad. Nauk SSSR, 84 (4), 687-688 (1952), in Russian.

(153) Kussmann, A., and Jessen, K., "Invar Behaviour and Magnetic Moments of the Gamma-Phase of Iron-Palladium Alloys", Physical Society of Japan, Proceedings - International Conference on Magnetism and Crystallography, 1, pp 136-139 (1962).

(154) Lohr, J. M., and Hopkins, C. H., "Thermal Expansion of Nickel-Iron Alloys", Trans. AIME, 135, pp 535-541 (1939).

(155) Luerssen, G. V., "Iron-Nickel Alloys and Their Characteristics", Elec. Mfg., 36 (1), 126-128 (July, 1945).

(156) Manley, J. J., "The Use of Invar for Precision Behavior", Proc. Phys. Soc., London, 38, pp 473-481 (1926).

(157) Merica, P. D., "Iron-Nickel Alloys", Chem. Met. Eng., 24, pp 375-378 (1921).

(158) Mooradian, V. G., "Development of Improved Metallic Materials for Electronic Components Operating at High Temperature", Bimonthly Progress Report No. 3, from Engelhard Industries, Inc., H. A. Wilson Division to Bureau of Ships, USN (August 1 - September 6, 1954).

(159) Cobalt Monograph, edited by the Centre d'Information du Cobalt, Brussels, Belgium, prepared in cooperation with the staff of Battelle Memorial Institute, Columbus, Ohio (1960), 515 pp.

(160) Mulquin, P., "Les Ferronickels Reversibles", Echo des mines et de la Metallurgie, (3371), pp54-55 (April, 1947); (3372), pp 70-71 (May, 1947); (3373), pp 86-87 (June, 1947).

(161) Nakajima, T., "Effect of Pressure on the Curie Temperature in Inv[illegible]e Iron-Platinum Alloys as a Ph[illegible]nsition of the Second Kind", J. Phys. [illegible]an, 19 (4), 520-529 (1964).

(162) Nakamura, K., "Effect of Magnetization on Young's Modulus of Ferromagnetic Substances", Sci. Rept. Res. Inst., Tohoku University, 24, pp 303-331 (August, 1935).

(163) Nakamura, Y., Shiga, M., Shikazono, N., "Mossbauer Study of Invar-Type Iron-Nickel Alloy", J. Phys. Soc. Japan, 19, pp 1177-1181 (July, 1964).

(164) Ochsenfeld, R., "The Damping of Iron-Nickel Alloys", Z. Physik, 143 (3), 357-373 (1955).

(165) Ochsenfeld, R., "The Magneto-Elastic Properties of Some Ferromagnetic Iron-Nickel Alloys", Z. Physik, 143 (4), 375-391 (1955).

(166) Owen, E. A., Yates, E. L., and Sully, A. H., "An X-Ray Investigation of Pure Iron-Nickel Alloys. Part 5: The Variation of Thermal Expansion with Composition", Proc. Phys. Soc., London, 49, P. 323 (1937).

(167) Page, B. L., "Relative Dimensional Stabilities of a Selected Series of Stainless-Steel Decimeter Bars", J. Res. Nat. Bur. Std., Research Paper 2742, 58 (3), 119-124 (1957).

(168) Pawlek, F., "Nickel and Nickel Alloys. II. Nickel Alloys", F.I.A.T. Rev. Ger. Sci. (1939-1946): Non-Ferrous Metallurgy-II (1948), pp 1-8, in German.

(169) Pilling, N. B., and Talbot, A. M., "Dispersion-Hardening Alloys of Nickel and Iron-Nickel-Titanium", ASM, Symposium on Age Hardening of Metals, pp 231-256 (1939).

(170) Pridantsev, M. V., and Shcherbakov, B. N., "Properties and Technology of Manufacturing Geodetic Invar", Stal', 11 (1), 62-68 (1941).

(171) Pupke, G., "Anisotropy of the Thermal Expansion of Iron-Nickel Alloys. I", Z. Physik. Chem., 2-7, pp 91-110 (1957), in German.

(172) Straumann, R., "Nickel and Iron Alloys Adapted for Springs in Thermocompensated Oscillating Systems", U. S. Patent 2,466,285 (April 5, 1949).

(173) Propastina, V. V., "On the Problem of the Effect of Heat Treatment on the Shear Modulus and the Curie Point of the Elinvar Alloy", Fiz. Metal. i Metalloved., 6 (6), 1105-1109 (1958).

(174) Raduebaugh, R. J., "Structural Property Relationships in 30 to 80% Nickel-Iron Alloys", Metals Eng. Quart., 2, pp 41-48 (1962).

(175) Reimer, L., "Irreversible Change of the Remanent Magnetization of Plastically Deformed Nickel", Z. Physik, 137, pp 588-594 (1954).

(176) Russell, H. F., "Low-Expansion Nickel Steel", Engineering, 128, pp 400-402 (1929).

(177) Scheil, E., and Reinacher, G., "Elastic Modulus and Damping Characteristics of Irreversible Iron-Nickel Alloys", Z. Metallk., 36 (3), 63-69 (1944).

(178) Scheil, E., and Thiele, W., "Change in Modulus of Elasticity and Damping of Iron-Nickel Alloy with γ-α Transformation", Arch. Eisenhuttenw., 12 (2), 103-105 (August, 1938).

(179) Schulze, A., "Thermal Expansion of Cobalt-Nickel, Cobalt-Iron, and Iron-Nickel Alloys", Z. Physik., 28, pp 669-773 (1927).

(180) Scott, H., "Expansion Characteristics of Low-Expansion Nickel Steels", Trans. Am. Soc. Steel Treating, 13, p. 829 (1928).

(181) Scott, H., "Iron-Nickel Alloys (Stable Invar)", U. S. Patent 2,050,387, to Westinghouse Electric and Manufacturing Company, (August 11, 1936).

(182) Yamamoto, M., "The ΔE-Effect, Young's Modulus, and Magnetic Properties in Ferromagnetic Nickel-Copper Alloys", Sci. Rept. Res. Inst., Tohoku University, A6, pp 446-457 (1954).

(183) Shozi, Y., Takahashi, T., and Shibata, S., "Temperature Characteristics of Springs for Scales", Central Inspection Institute of Weights and Measures, Report, Tokyo, 8 (1), 42-49 (1959).

(184) Spretnak, J. W., "Development of New Mechanisms for Obtaining Steels in the Ultrahigh Strength Range", Final Report, from The Ohio State University Research Foundation, Columbus, Ohio, for WADC (August, 1956).

(185) Spinner, S., Reichard, T. W., and Tefft, W. E., "A Comparison of Experimental and Theoretical Relations Between Young's Modulus and the Flexural and Longitudinal Resonance Frequencies of Uniform Bars", J. Res. Nat. Bur. Std., 64A (2), 147 (1960).

(186) Street, R., and Woolley, J. C., "A Note on the ΔE Effect in Alnico", Proc. Phys. Soc., 61, pp 391-392 (October, 1948).

(187) Suda, P., and Paces, J., "The Influence of Plastic Deformation on the Magnetostriction Constant of Iron-Nickel Alloys", Czech. J. Phys., 11, pp 602-608 (1961).

(188) Sutoki, T., "On an Anomalous Thermal Expansion in Hardened Irreversible Nickel Steels", Sci. Rept. Res. Inst., Tohoku University, 10, pp 94-99 (1921).

(189) Talbot, A. M., "Age-Hardenable, Low-Expansion Nickel-Iron-Titanium Alloys", U. S. Patent 2,266,481, to International Nickel Company.

(190) Thompson, J. G., "Nickel and Its Alloys", NBC Circular 592 (1958).

(191) Tino, Y., "The Invar Problem", J. Sci. Res. Inst. (Tokyo), 46, pp 141-146 (1952).

(192) Tino, Y., "On Disappearance of the Hopkinson Effect", J. Sci. Res. Inst. (Tokyo), 49, pp 97-102 (1955).

(193) VanNeste, A., and Dubé, A., "Effect of Temperature on the Elastic Modulus of Ferromagnetic Metals (Nickel)", Compt. Rend., 255, pp 1732-1734 (1962).

(194) Vigoreux, P., and Booth, C. F., Quartz Vibrators and Their Applications, His Majesty's Stationery Office (1950).

(195) Vlasov, A. Ya., Laptei, D. A., Aurzanain, B. A., and Smolin, R. P., "Temperature Dependence on Magnetic Properties of Elinvar", Izv. Akad. Nauk SSSR, Ser. Fiz., 26, pp 287-290 (1962).

(196) Watson, T. W., and Robinson, H. E., "Thermal Conductivity of Some Commercial Iron-Nickel Alloys", Trans. ASME, J. Heat Transfer, Series C, 83, pp 403-408 (1961).

(197) Voskoboynikov, S. I., "Magneto-Striction and Magnetization of Ternary Iron-Nickel-Cobalt Systems of Iron-Nickel Base and Iron-Cobalt Base Alloys", Fiz. Metal. i Metalloved., 6 (6), 1011-1016 (1958).

(198) Williams, H. J., Bozorth, R. M., and Christensen, H., "Magnetostriction, Young's Modulus and Damping of 68 Permalloy as Dependent on Magnetization and Heat Treatment", Phys. Rev., 59, pp 1005-1012 (June 15, 1941).

(199) Wise, E. M., "Nickel Alloys for Controlled Thermal Expansion", Product Engineering, 28, pp 68-71 (October 28, 1957).

(200) Yanaguchi, S., "Thermomagnetic Study of Metals by Electron Diffraction", Il Nuovo Cimento, 22, pp 447-493 (November 1, 1961).

(201) "Thermal Expansion of Invar Tapes Tested by Electrical Resistance", Civil Eng., 23, p. 568 (August, 1953).

(202) "Expansion Properties of Ni-Fe Alloys", Nickel Bull., 10 (11), 237 (1937).

(203) "Nickel and Nickel Base Alloy Tubing", Superior Tube Catalog 13, Norristown, Pennsylvania.

(204) "Preliminary Data on Ni-Span-C Tubing", Special Analysis Memo 111, Superior Tube Company, Norristown, Pennsylvania.

(205) "Magnetostriction", Development and Research Division, The International Nickel Company, Inc., New York, New York.

(206) "Nickel and Nickel Alloy Tubing", Catalog 12, Superior Tube Company, Norristown, Pennsylvania (1956).

(207) "The Nilo Series of Controlled Expansion Alloys", Publication 2098, Henry Wiggin and Company, Ltd., Birmingham, England.

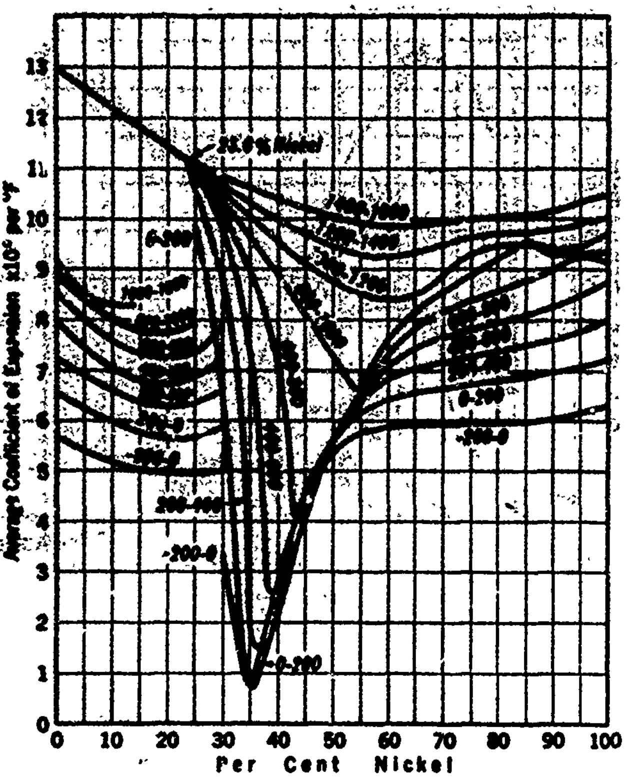


FIGURE 1. AVERAGE COEFFICIENTS OF EXPANSION OF IRON-NICKEL ALLOYS OVER THE FAHRENHEIT TEMPERATURE RANGES INDICATED[11]

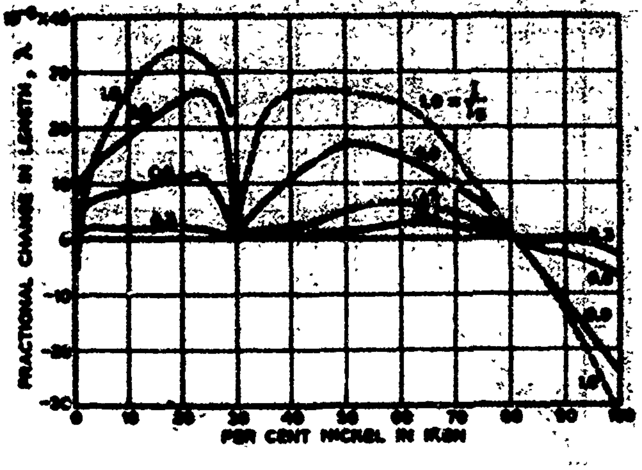


FIGURE 3. MAGNETOSTRICTION OF IRON-NICKEL ALLOYS AT VARIOUS FRACTIONS OF SATURATION[13]

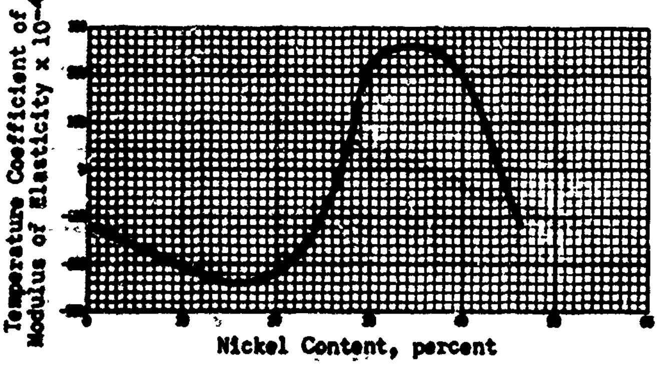


FIGURE 2. EFFECT OF COMPOSITION ON THE TEMPERATURE COEFFICIENT OF MODULUS OF ELASTICITY OF IRON-NICKEL ALLOYS[12]

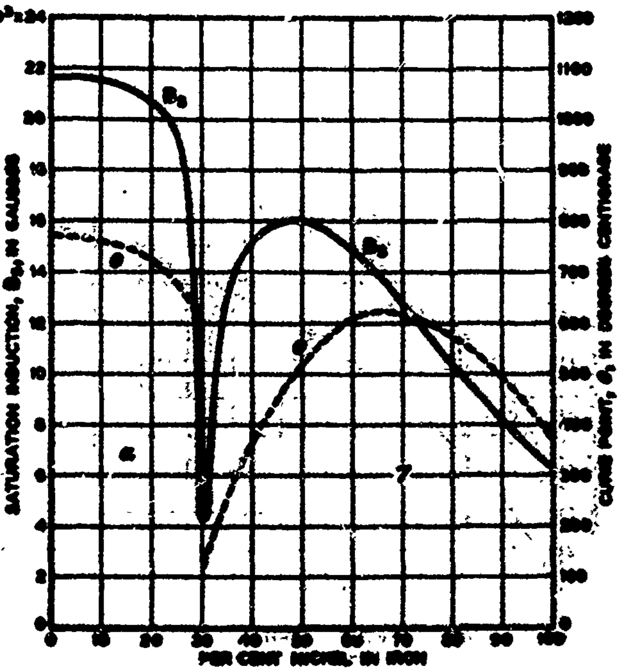


FIGURE 4. VARIATION OF B_s AND θ WITH THE COMPOSITION OF IRON-NICKEL ALLOYS[13]

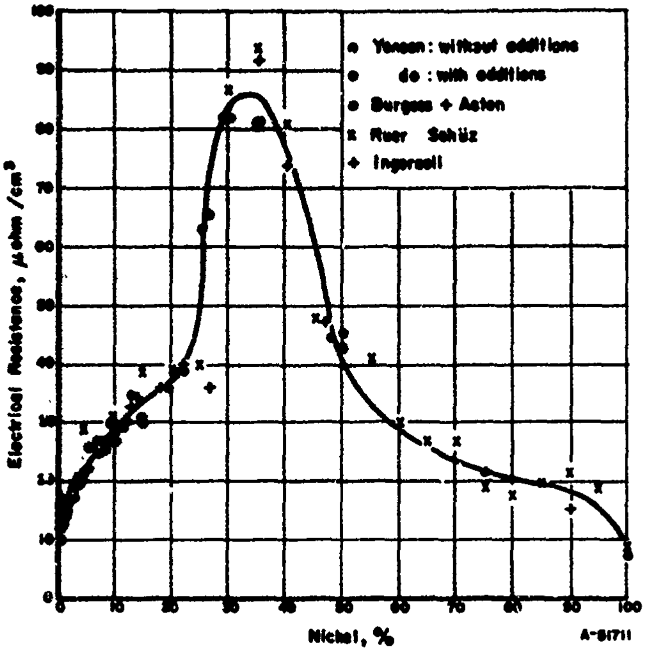


FIGURE 5. ELECTRICAL RESISTIVITY OF PURE FERRO-NICKELS[14]

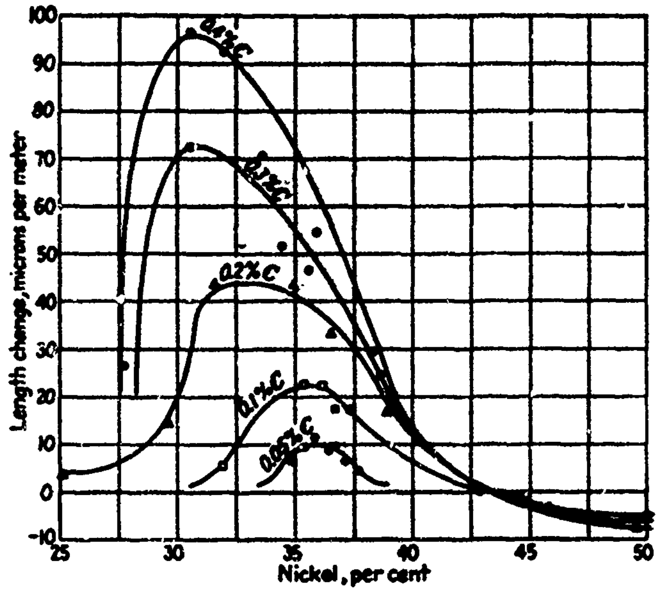


FIGURE 7. INFLUENCE OF CARBON ON THE DIMENSIONAL STABILITY OF IRON-NICKEL ALLOYS[17]

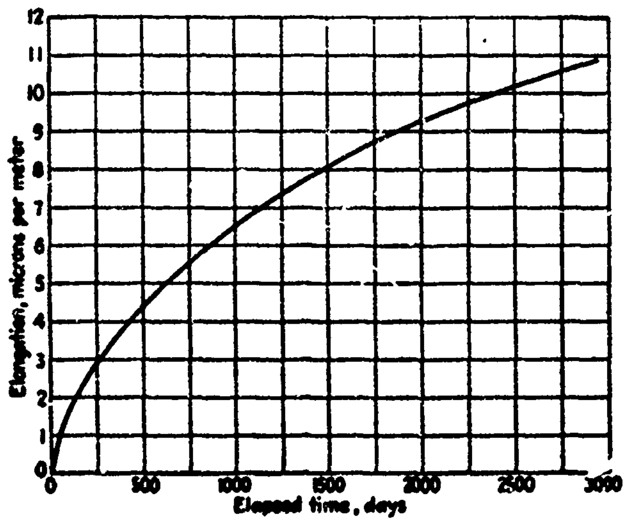


FIGURE 6. ELONGATION OF INVAR WITH TIME AFTER COOLING FROM 100 TO 25 C (210 TO 75 F) OVER PERIOD OF 3 MONTHS[17]

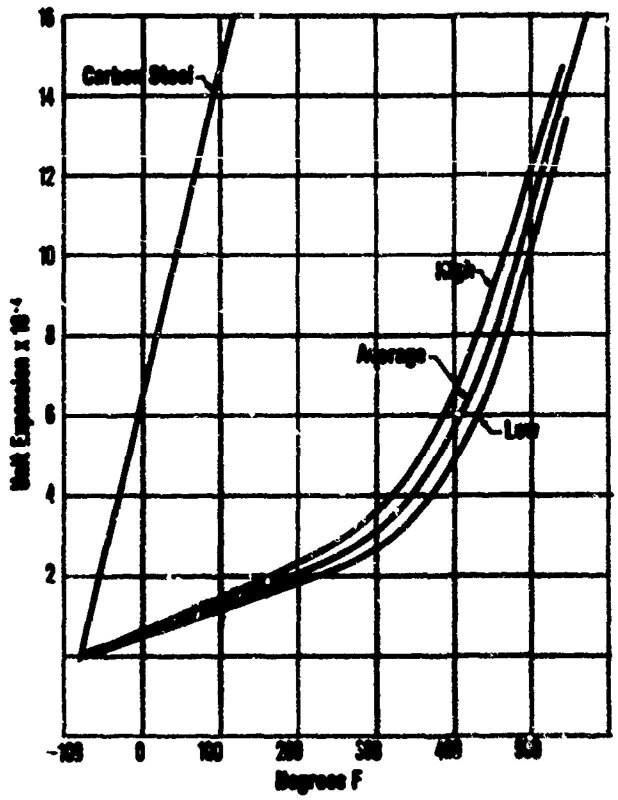


FIGURE 0. EXPANSION CURVES SHOWING COMPARISON BETWEEN CARBON STEEL AND CARPENTER INVAR 36 OR FREE-CUT INVAR 36[21]

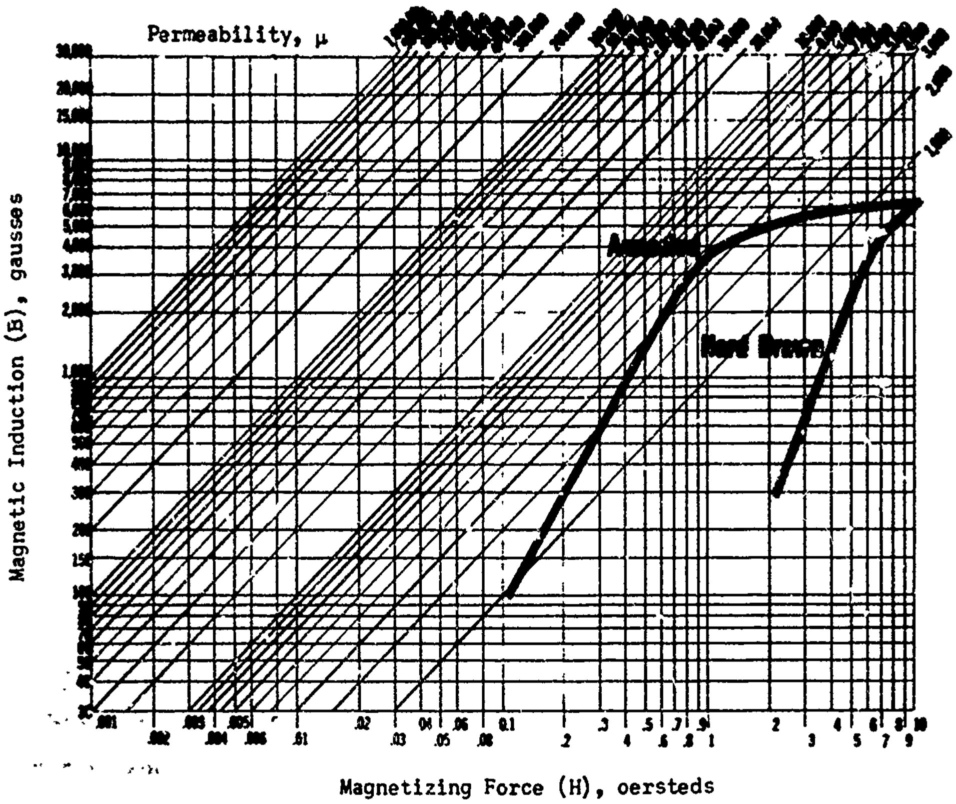


FIGURE 9. D-C MAGNETIC PERMEABILITY CURVES FOR ANNEALED AND COLD-DRAWN INVAR 36[21]

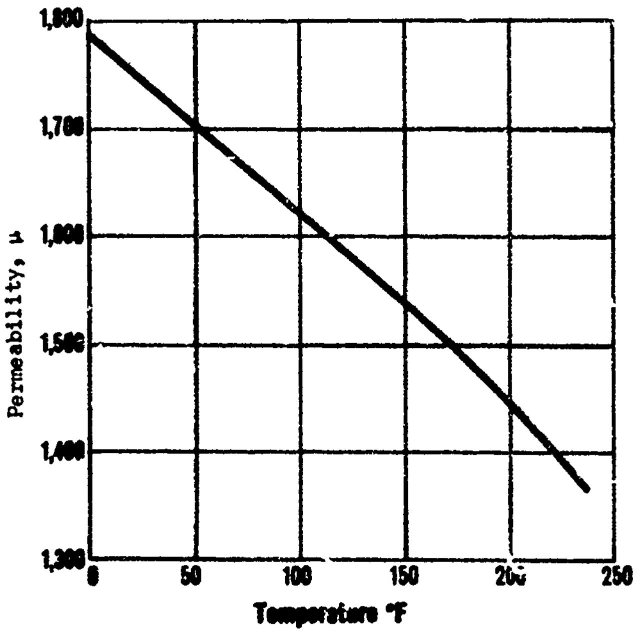


FIGURE 10. TEMPERATURE CHARACTERISTICS OF CARPENTER FREE-CUT INVAR 36 IN THE ANNEALED CONDITION. (H = 5 Oersteds)[21]

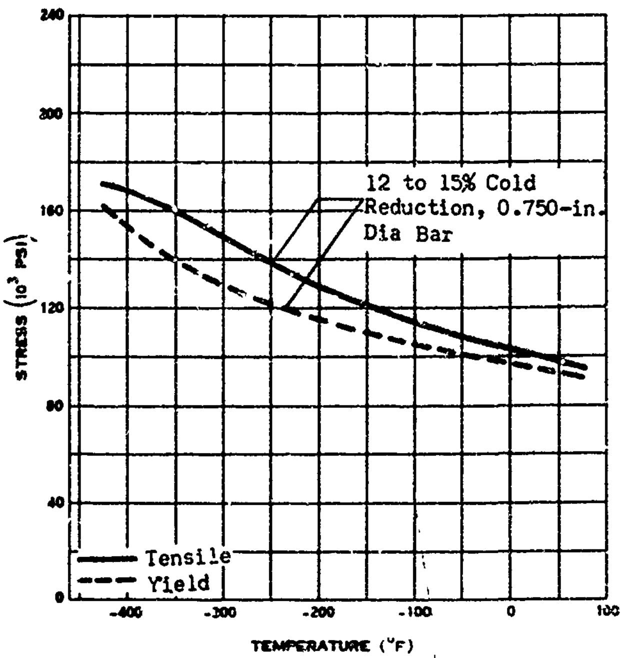


FIGURE 11. STRENGTH OF INVAR[22]

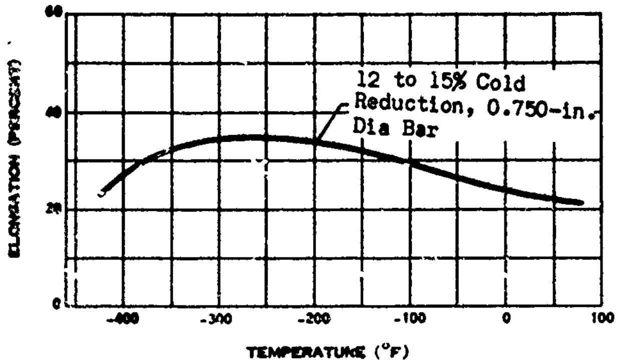


FIGURE 12. ELONGATION OF INVAR(22)

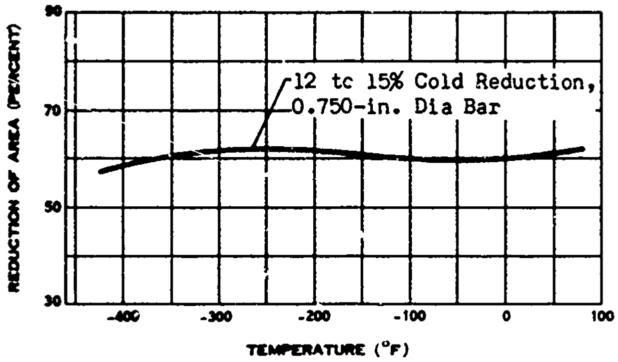


FIGURE 13. REDUCTION OF AREA OF INVAR(22)

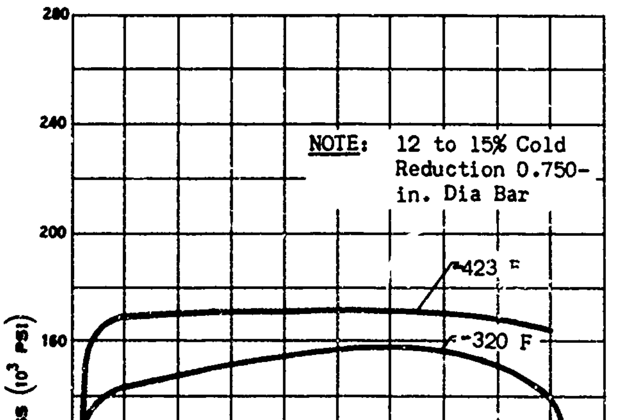


FIGURE 14. STRESS-STRAIN DIAGRAM FOR INVAR(22)

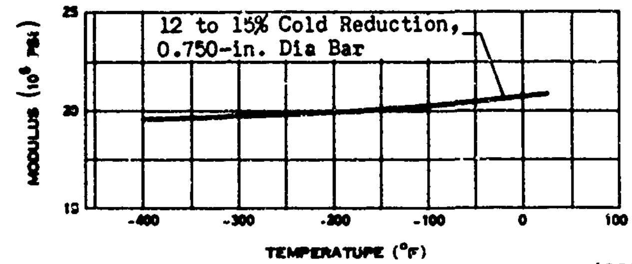


FIGURE 15. MODULUS OF ELASTICITY OF INVAR(22)

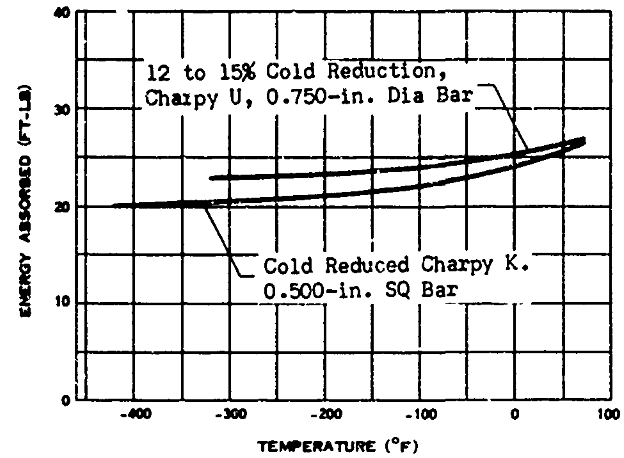


FIGURE 16. IMPACT STRENGTH OF INVAR(22)

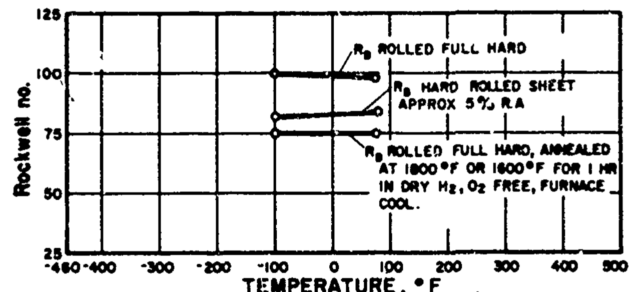


FIGURE 17. HARDNESS OF INVAR 36(22)

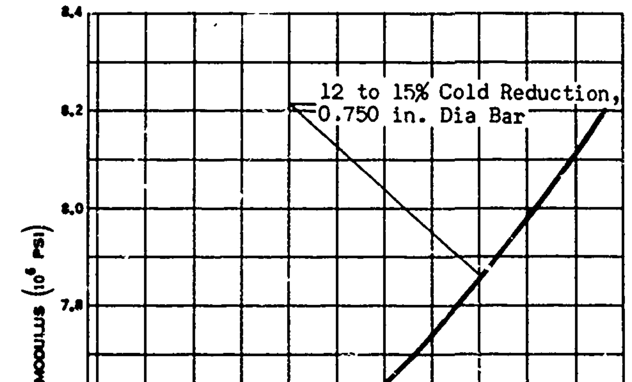


FIGURE 18. MODULUS OF RIGIDITY OF INVAR(22)

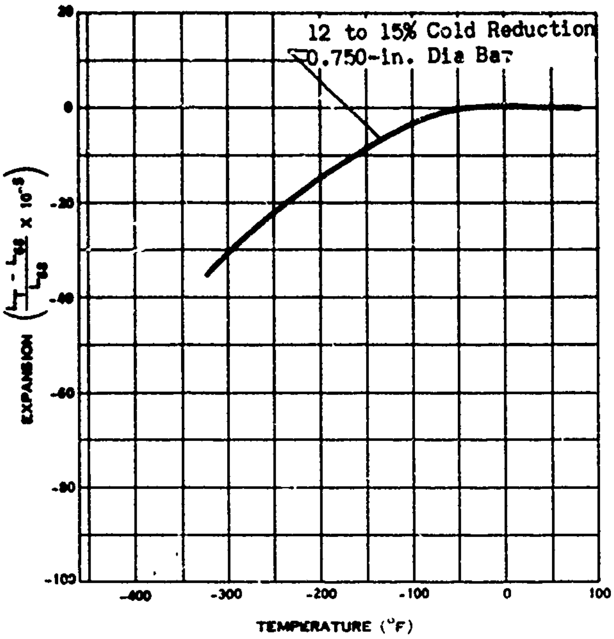


FIGURE 19. THERMAL EXPANSION OF INVAR[22]

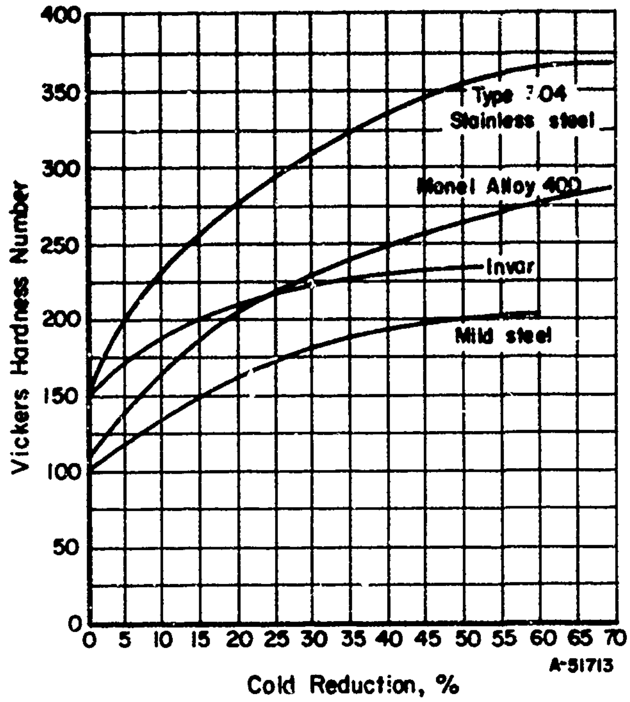


FIGURE 21. WORK-HARDENING RATE FOR COLD-ROLLED STRIP[16]

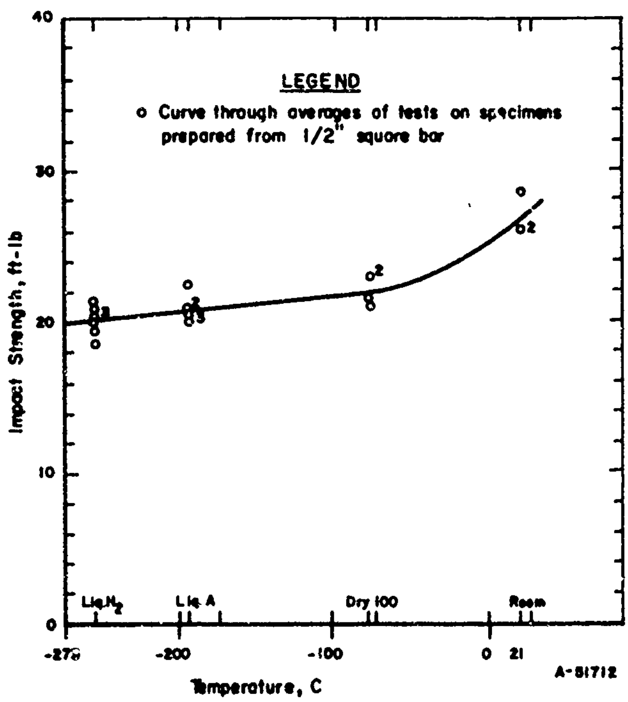


FIGURE 20. CHARPY IMPACT TESTS ON STANDARD SPECIMENS OF INVAR STEEL, COLD-DRAWN BAR ON AMSLER IMPACT-TESTING MACHINE (110 FT-LB MAX)[23]

(10 mm x 10 mm x 50 mm, keyhole type, 0.394 x 0.394 x 2 .)

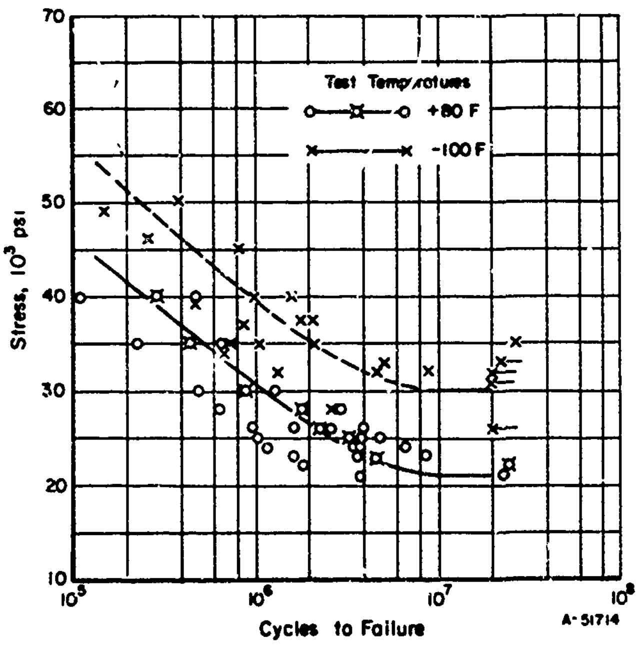


FIGURE 22. FATIGUE CHARACTERISTICS OF 0.040-IN.-THICK NILVAR SHEET[25]

Tested at +80 and -100 F

Condition: rolled on pass hard (approx 5% reduction in area

Specimen Designation: AN - 1 to 36 (+80 F)
AN - 37 to 72 (-100 F)

Tests made on Sonntag Universal Fatigue Machines (Model SF-2).

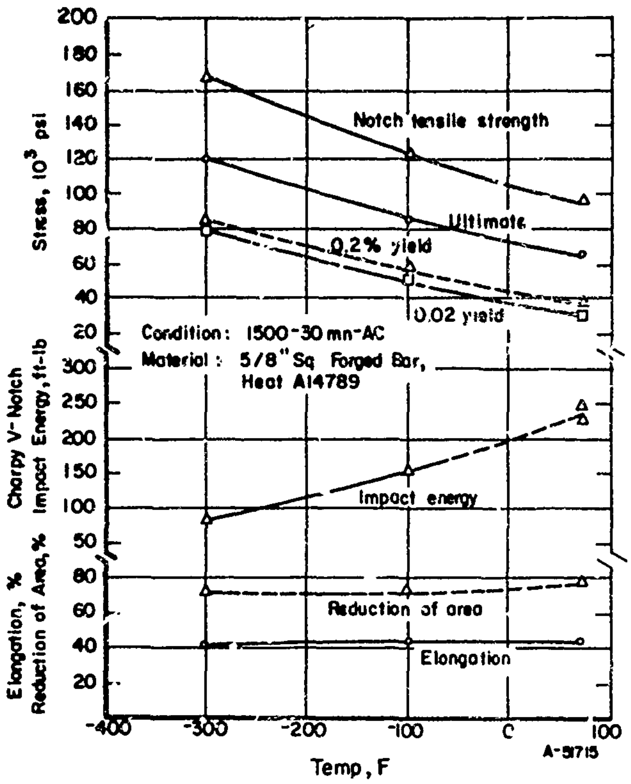


FIGURE 23. MECHANICAL PROPERTIES OF UNILOY 36 FORGED BAR AT TEMPERATURES FROM 75 F TO -300 F[25]

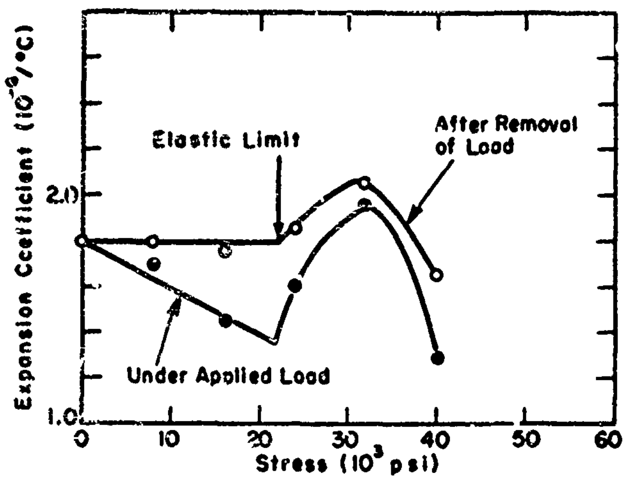


FIGURE 25. EFFECT OF STRESS ON THE EXPANSION COEFFICIENT OF AN INVAR[29]

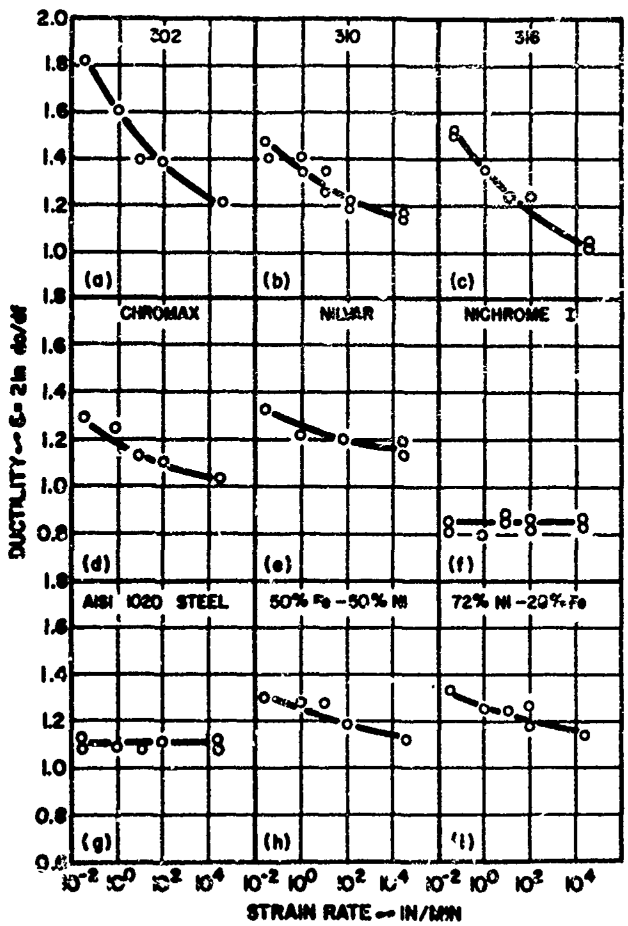


FIGURE 24. DUCTILITY VERSUS STRAIN RATE FOR VARIOUS Fe-Ni-Cr ALLOYS[26]

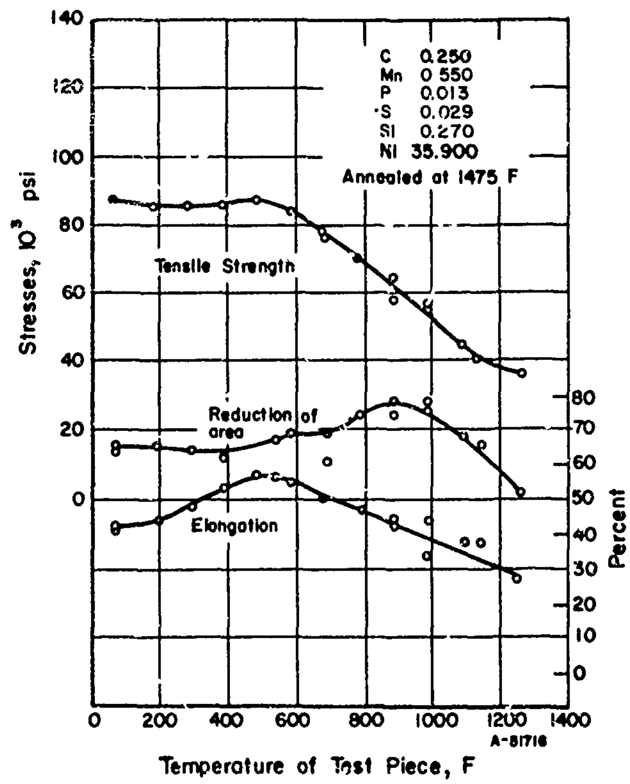


FIGURE 26. TENSILE PROPERTIES AT HIGH TEMPERATURES OF A FORGED 34% NICKEL STEEL[30]

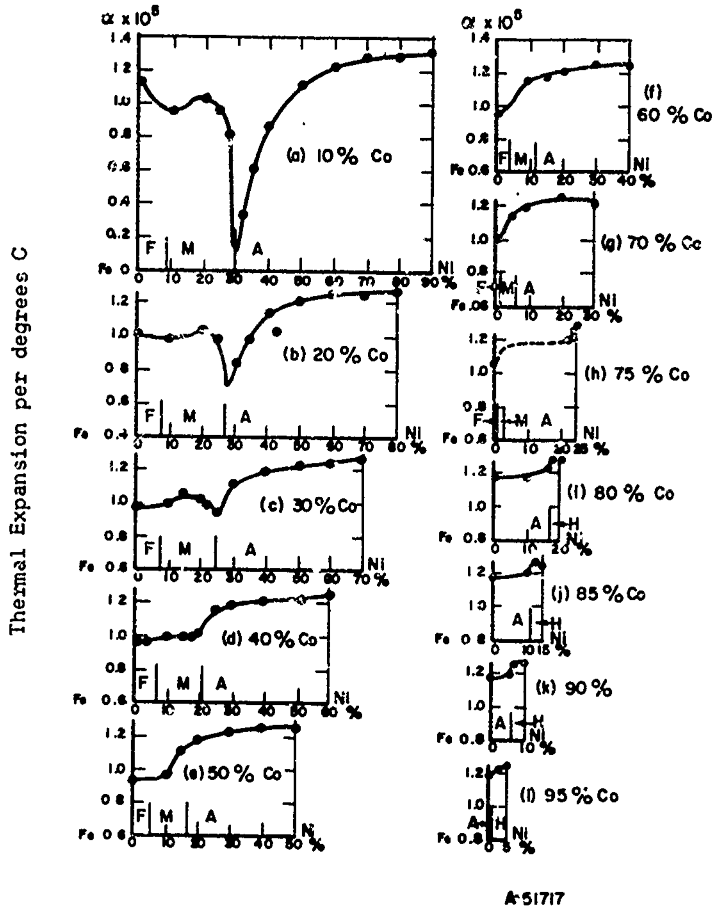


FIGURE 27. COEFFICIENT OF THERMAL EXPANSION AS A FUNCTION OF CONCENTRATION IN TERNARY IRON-NICKEL-COBALT ALLOYS (37)

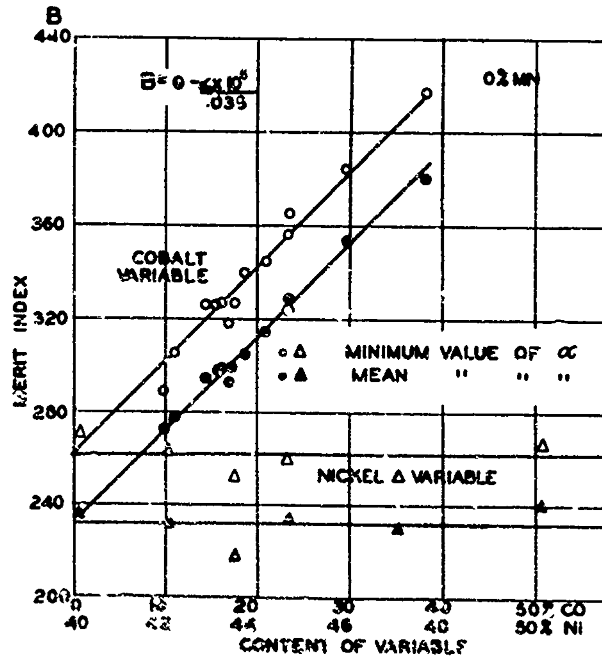


FIGURE 28. VARIATION OF MERIT INDEX WITH NICKEL AND COBALT CONTENT, OTHER ELEMENT CONSTANT(36)

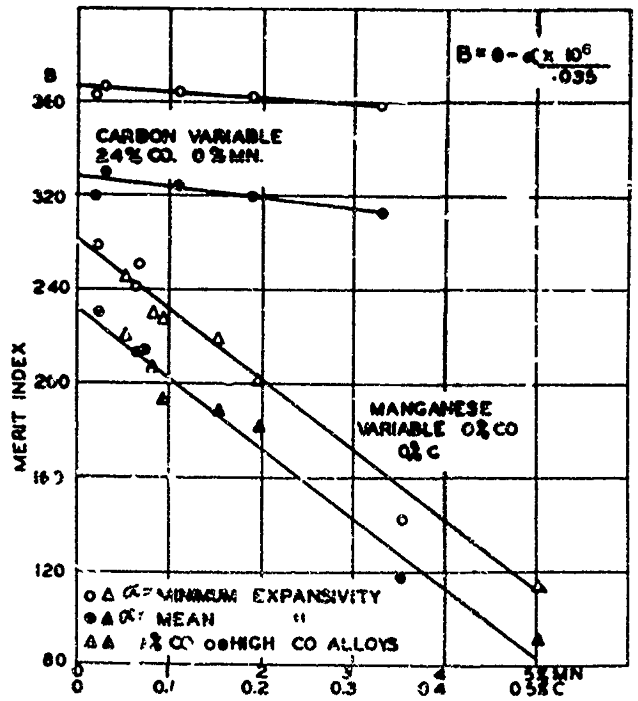


FIGURE 29. VARIATION OF MERIT INDEX WITH MANGANESE AND CARBON CONTENTS, OTHER ELEMENTS CONSTANT(36)

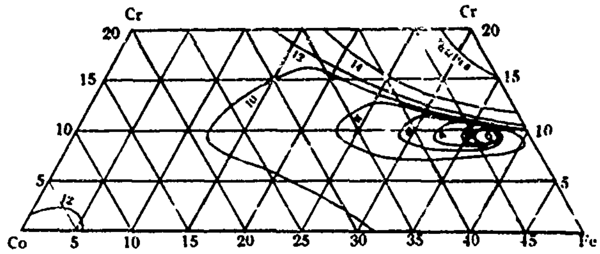


FIGURE 30. MASUMOTO'S DETERMINATION OF ISOTHERMAL-EXPANSION-COEFFICIENT COMPOSITIONS(34)

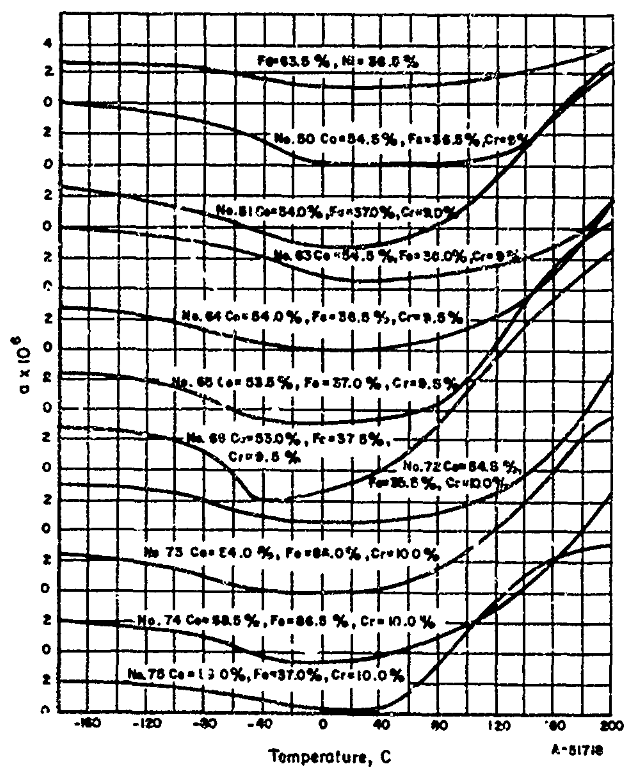
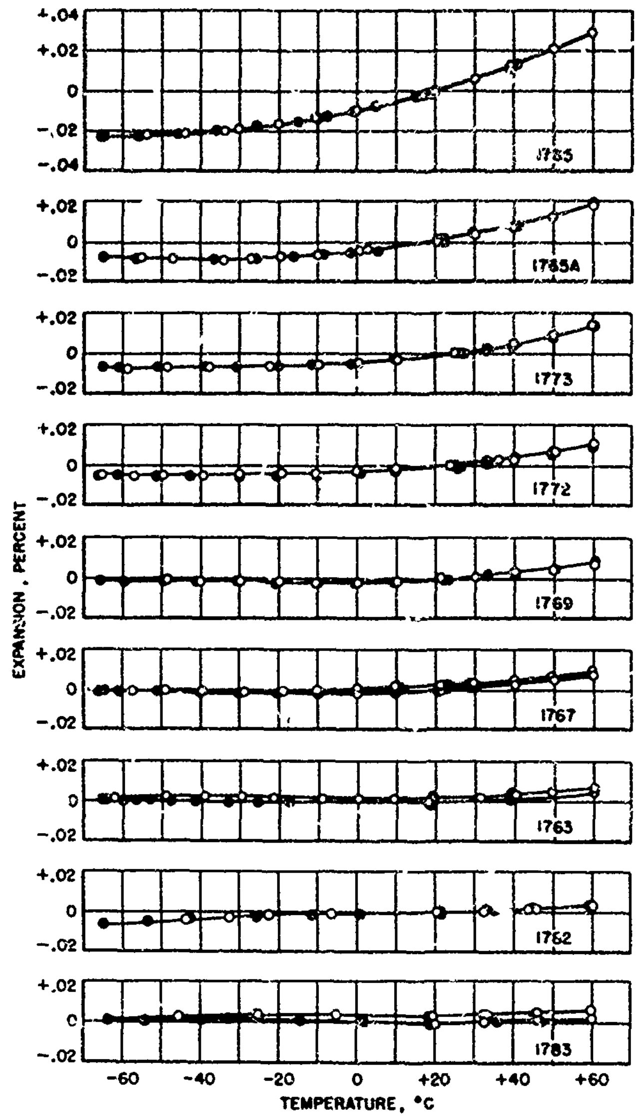


FIGURE 31. THERMAL-EXPANSION COEFFICIENTS FOR VARIOUS Fe-Co-Cr ALLOYS(34)



o, Heating; •, Cooling

FIGURE 32. LINEAR THERMAL EXPANSION OF NINE ANNEALED COBALT-IRON-CHROMIUM ALLOYS (Fe 36.2_2 to 36.9_2, Cr 9.0_9 to 9.8_7%)(38)

(The initial observation for each alloy was taken at about 20 C and is plotted on the zero ordinate.)

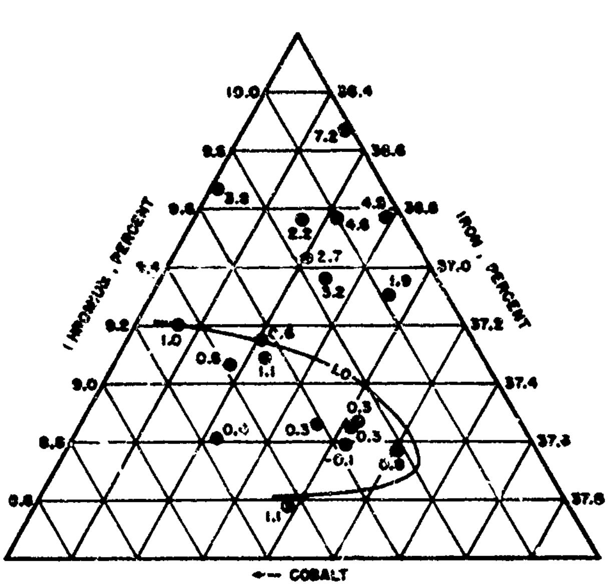
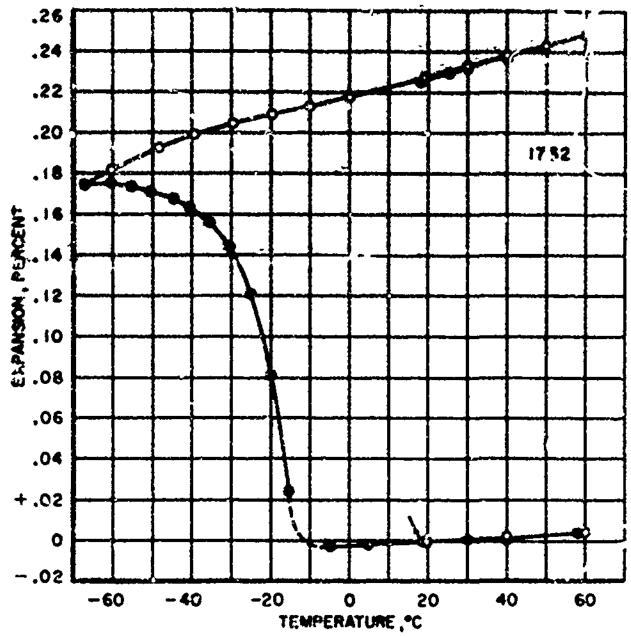


FIGURE 33. PORTION OF TERNARY DIAGRAM INDICATING THE EFFECTS OF COMPOSITION (PERCENTAGE BY WEIGHT) ON THE COEFFICIENTS OF LINEAR EXPANSION (IN MILLIONTHS PER DEGREE C) OF ANNEALED COBALT-IRON-CHROMIUM ALLOYS FOR THE RANGE 20 TO 60 C(38)



o, Heating; ●, Cooling; ⟶ Initial Observation

FIGURE 34. LINEAR-THERMAL-EXPANSION CURVE OF ANNEALED COBALT-IRON-CHROMIUM ALLOY (Fe 36.9_8, Cr 8.5_6%) SHOWING γ---->α TRANSFORMATION ON COOLING(38)

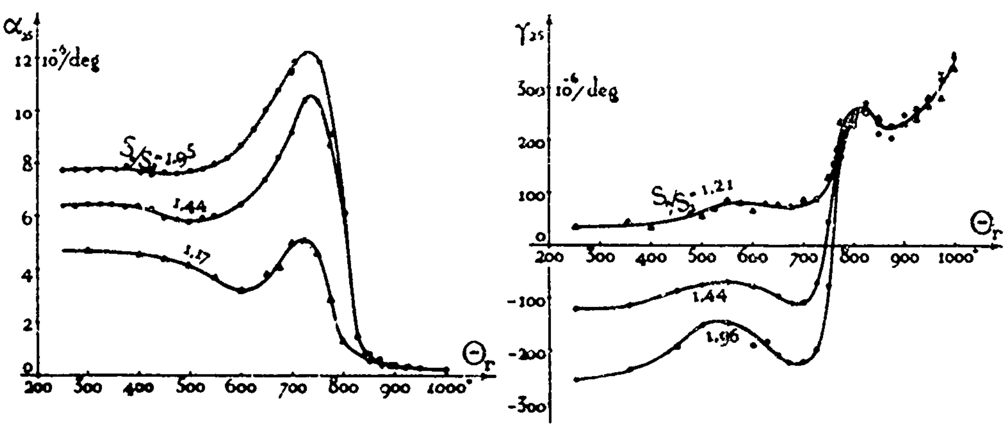


FIGURE 35. VARIATION OF THERMAL-EXPANSION COEFFICIENT (α) AND THERMOELASTIC COEFFICIENT (γ) AS A FUNCTION OF ANNEALING TEMPERATURE (θ_r) AND DRAWING RATIO (S_0/S_1)(41)

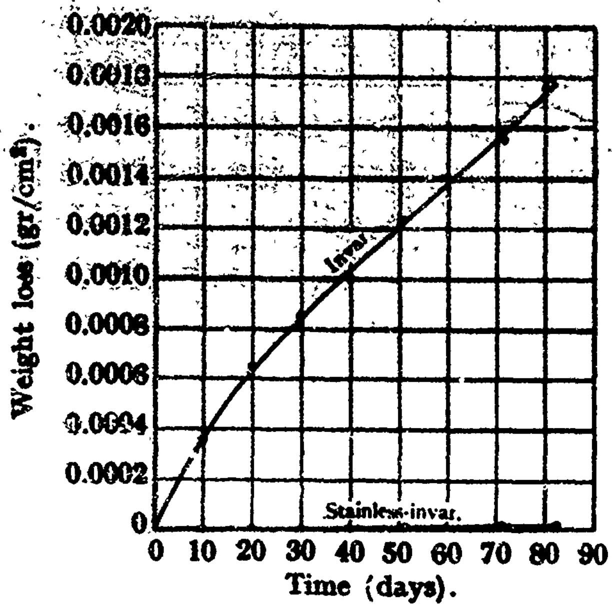


FIGURE 36. CORROSION OF INVAR AND STAINLESS-INVAR IN 0.1 MOLAR NaCl[34]

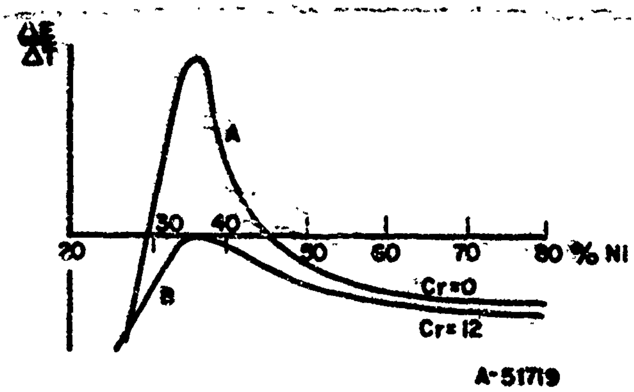


FIGURE 38. VARIATIONS IN THE TEMPERATURE COEFFICIENT OF MODULUS OF ELASTICITY OF NICKEL STEELS WITH NICKEL CONTENT AT 20 C (68 F) (Guillaume)

Magnetization (20°)		Magnetic expansion (20°).	
H	I	H	$\frac{\delta l}{l}\times10^6$
0.25	44	1.55	0.46
0.41	90	10.5	0.58
0.86	180	39.5	0.13
1.14	272	67.2	−0.61
3.50	427	128	−1.12
8.60	540	190	−1.17
21.4	628	250	−0.97
48.4	680	400	−0.29
77.9	694	678	0.82
137.8	706	927	2.85
198.3	710	1170	4.23
258.9	718	1415	6.20
380.7	720		
563.4	724		
745	726		
927	727		
1170	728		
1474	729		

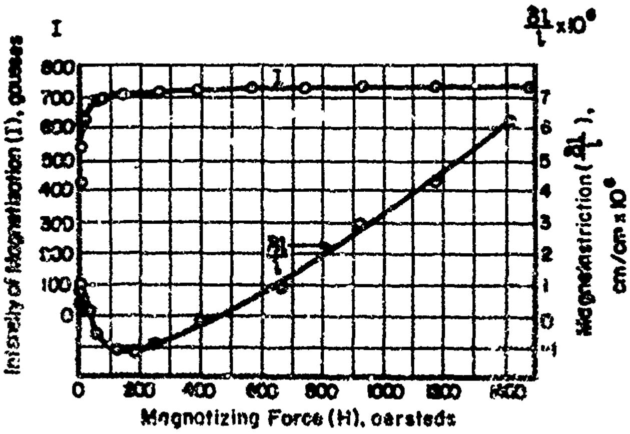


FIGURE 37. SOME MAGNETIC PROPERTIES OF AN ALLOY OF 54%Co, 36.5%Fe, AND 9.5%Cr MEASURED AT 20 C (68 F)[34]

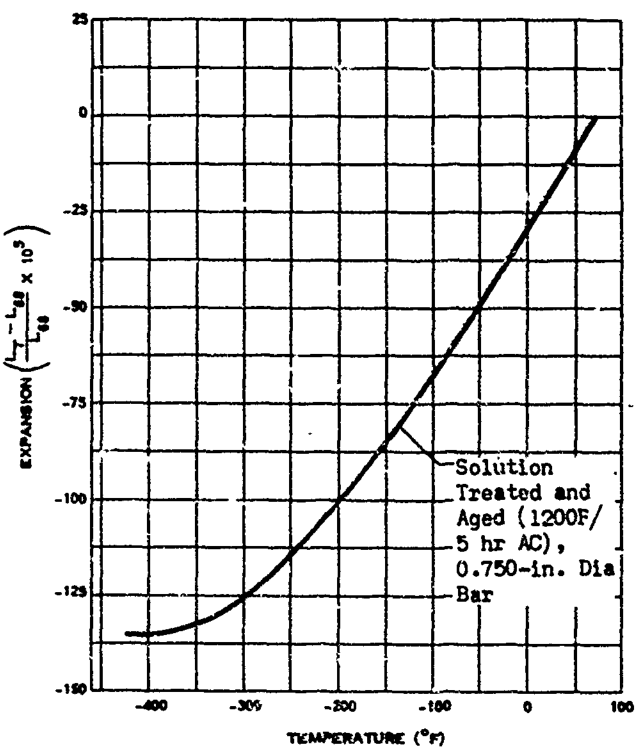


FIGURE 39. THERMAL EXPANSION OF NI-SPAN C[22]

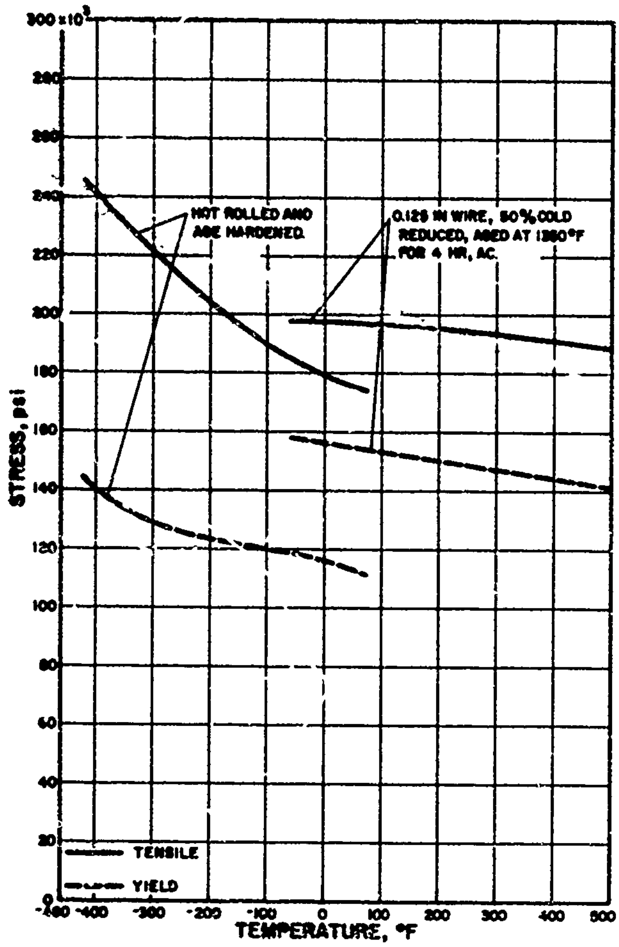


FIGURE 40. STRENGTH OF NI-SPAN C[22]

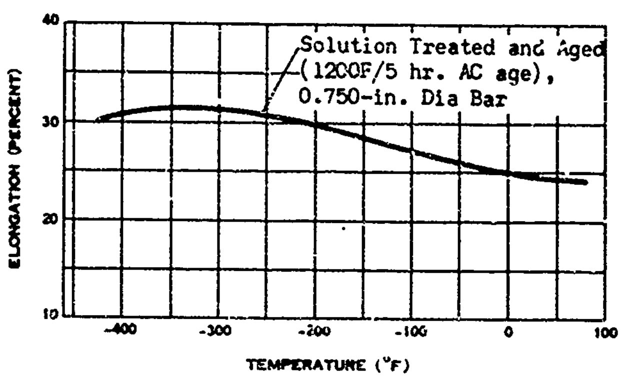


FIGURE 41. ELONGATION OF NI-SPAN C[22]

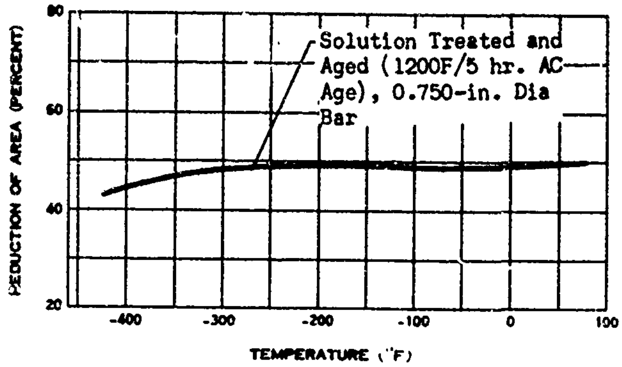


FIGURE 42. REDUCTION OF AREA OF NI-SPAN C[22]

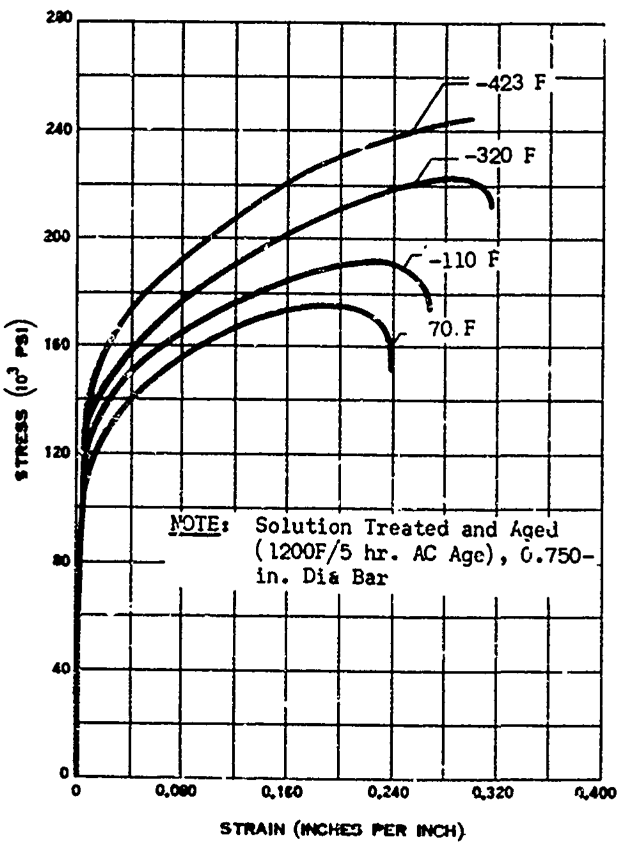


FIGURE 43. STRESS-STRAIN DIAGRAM FOR NI-SPAN C[22]

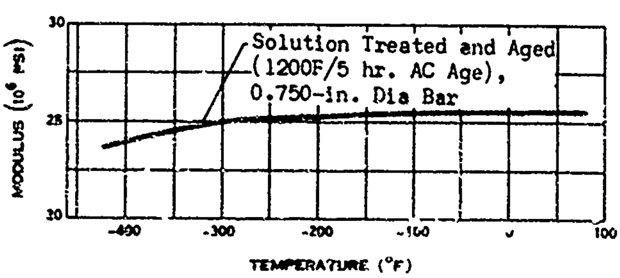


FIGURE 44. MODULUS OF ELASTICITY OF NI-SPAN C[22]

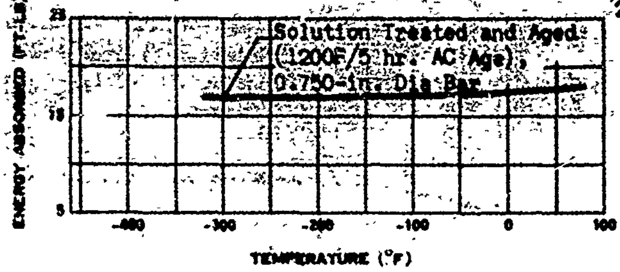


FIGURE 45. IMPACT STRENGTH OF NI-SPAN C(22)

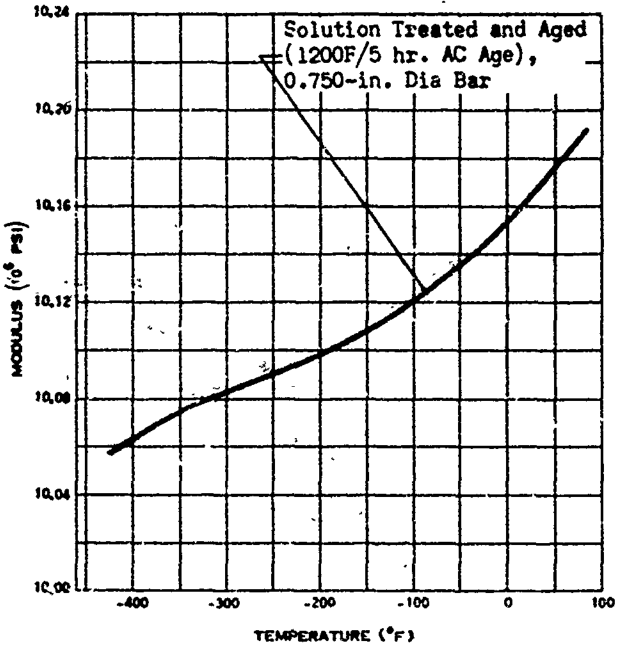


FIGURE 46. MODULUS OF RIGIDITY OF NI-SPAN C(22)

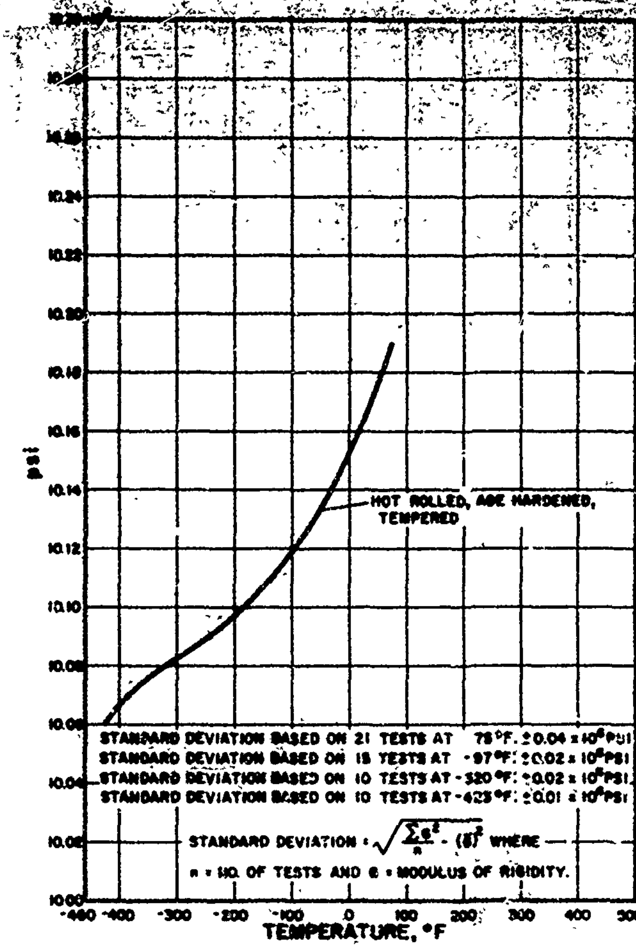


FIGURE 47. MODULUS OF RIGIDITY OF NI-SPAN C(22)

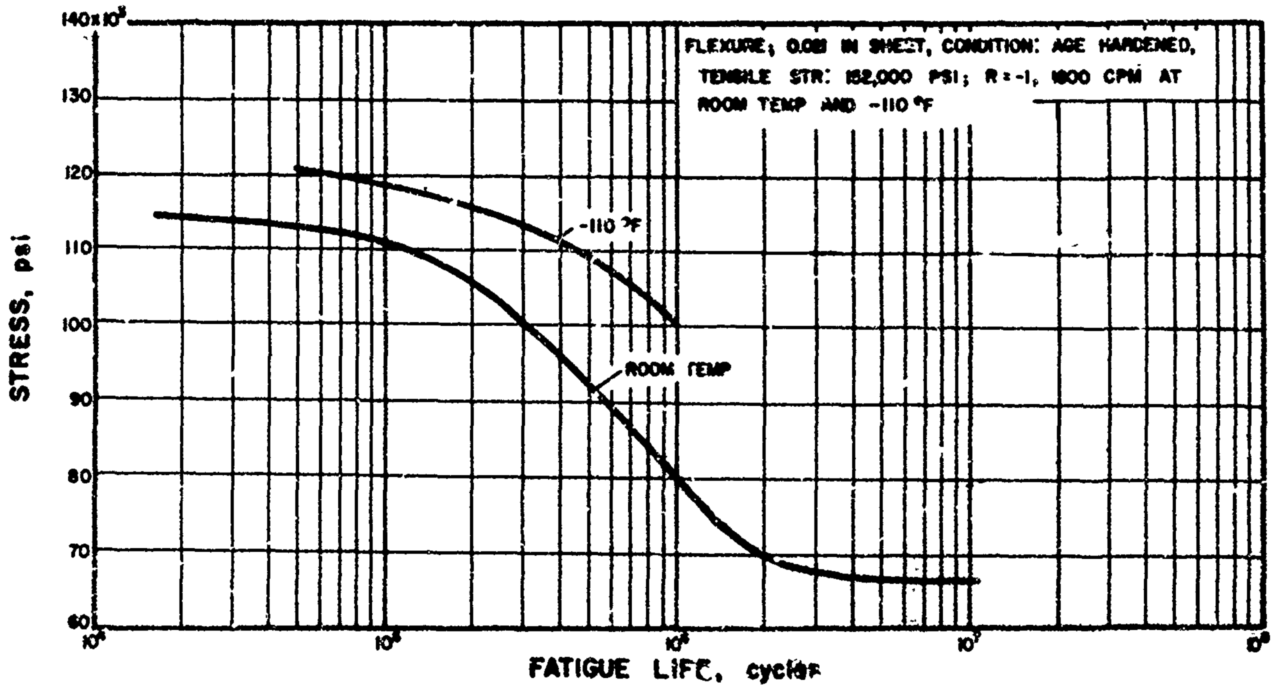


FIGURE 48. FATIGUE BEHAVIOR OF NI-SPAN C(22)

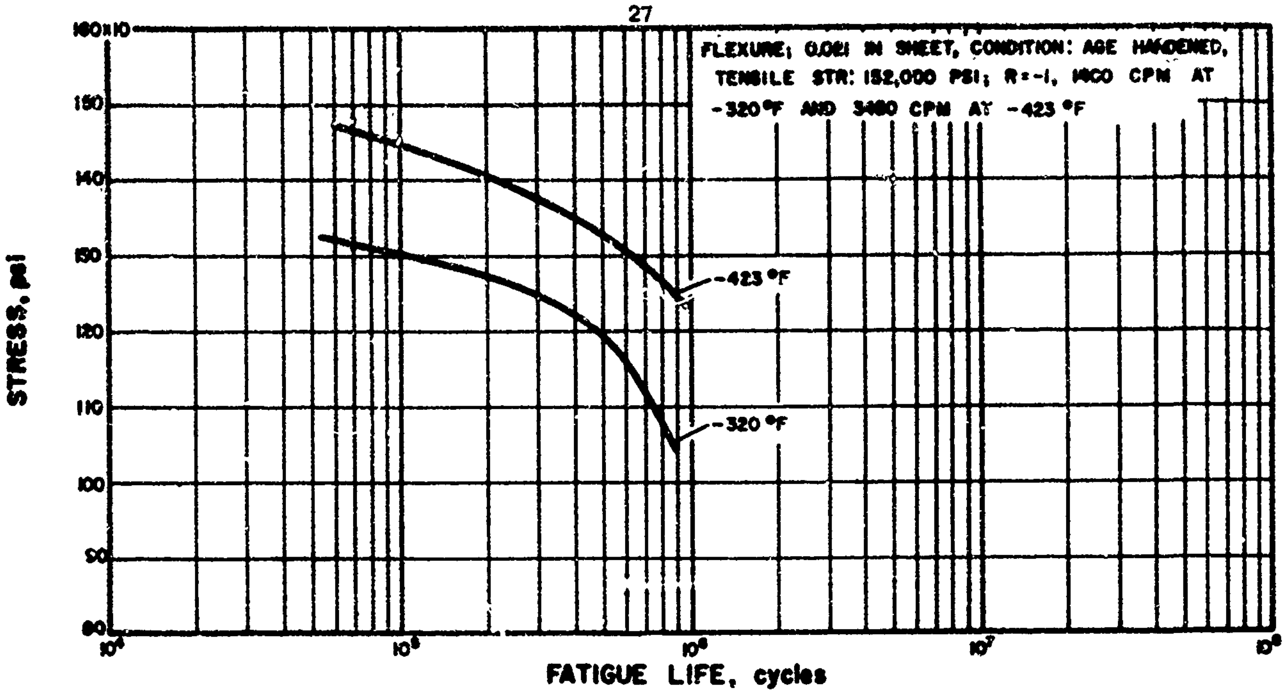


FIGURE 49. FATIGUE BEHAVIOR OF NI-SPAN C[22]

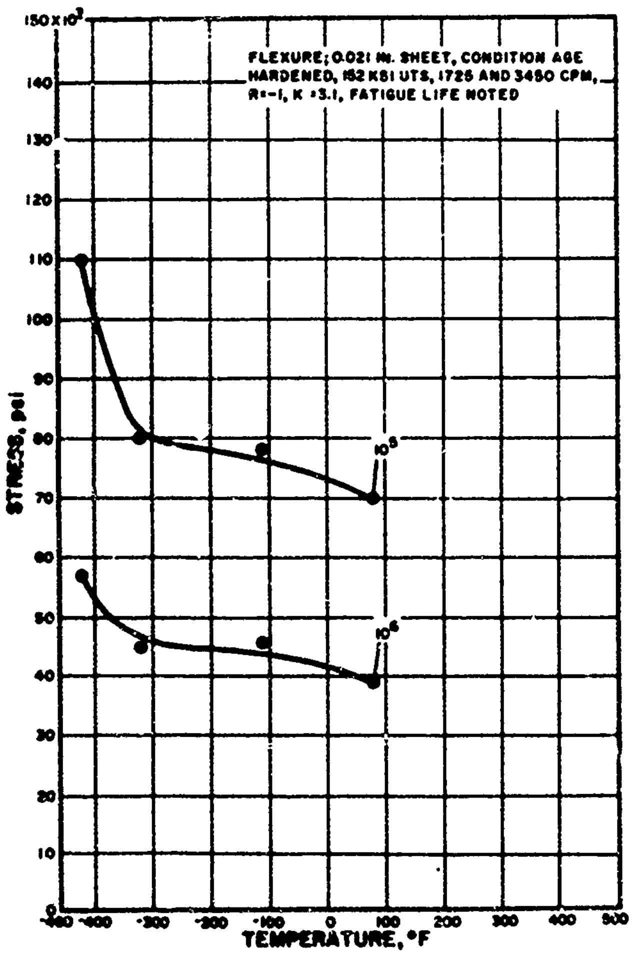


FIGURE 50. FATIGUE STRENGTH OF NI-SPAN C[22]

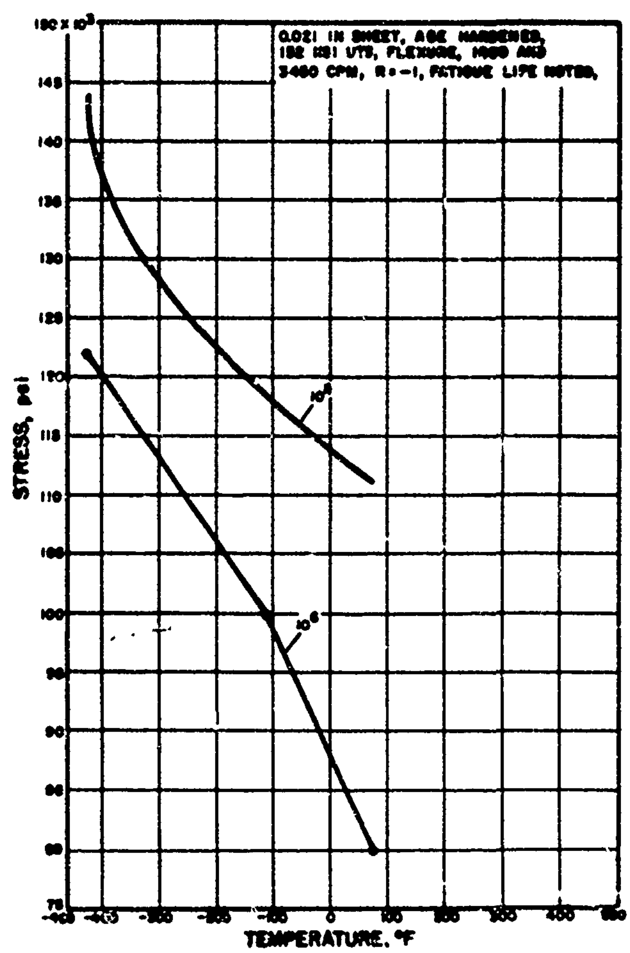


FIGURE 51. FATIGUE STRENGTH OF NI-SPAN C[22]

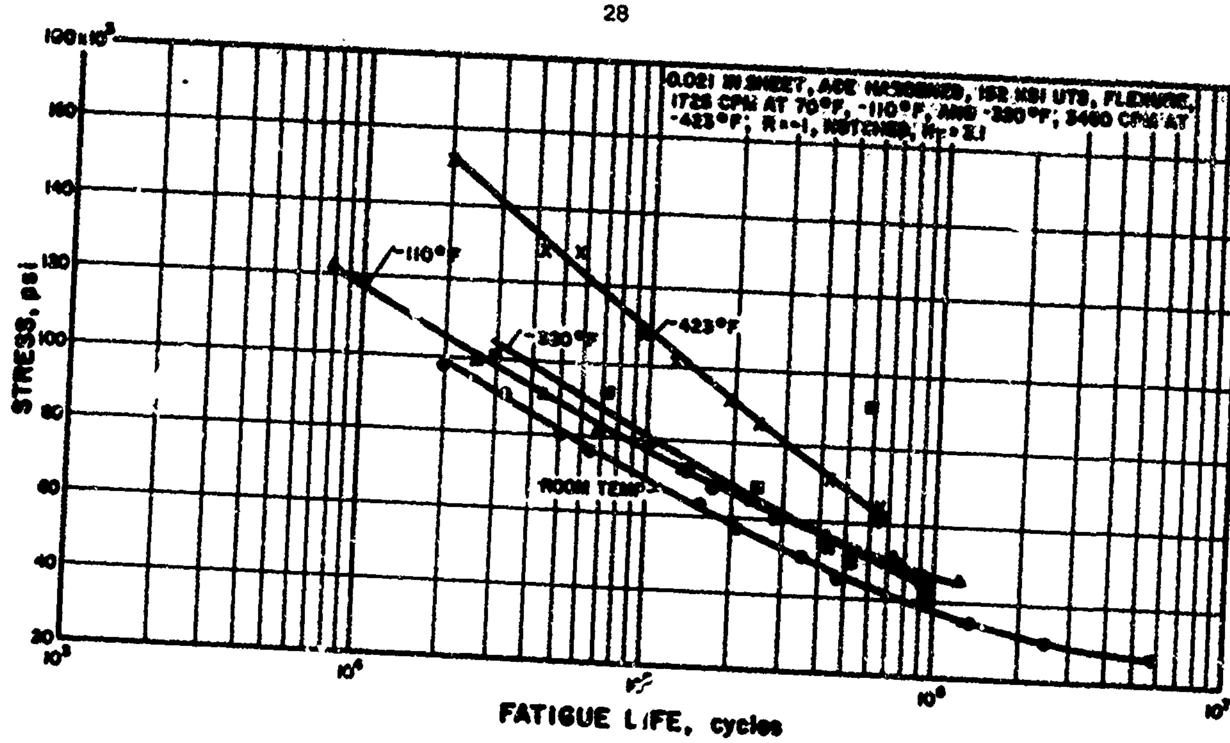


FIGURE 52. FATIGUE BEHAVIOR OF NI-SPAN C(22)

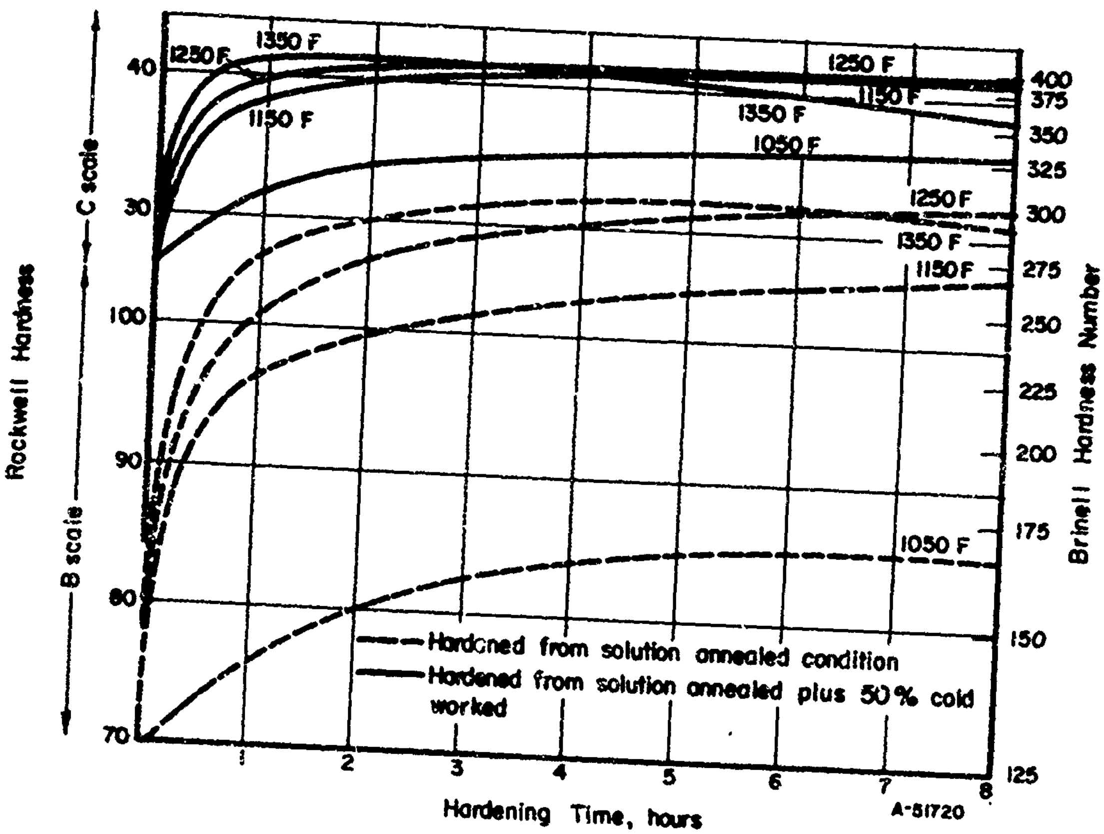


FIGURE 53. RATE OF HARDENING AT VARIOUS TEMPERATURES FOR BOTH ANNEALED AND 50% COLD-WORKED MATERIAL(44)

(Note that higher temperatures give much faster hardening as well as higher strength. Hardening rate for intermediate amounts of cold work or for parts having varying degrees of cold work are between the two extremes shown. When requirements for a specific modulus coefficient and maximum hardness are in conflict, the optimum hardening time and temperature will depend on the specific application.)

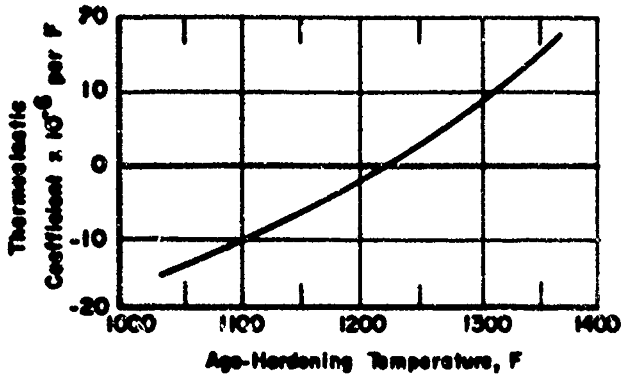


FIGURE 54. EFFECT OF HARDENING TEMPERATURE ON THERMO-ELASTIC COEFFICIENT(44)

(Curve shown is for a typical lot; position of curve to left or right along zero coefficient line depends on composition. Precise heat-treating conditions are specified for each lot of material.)

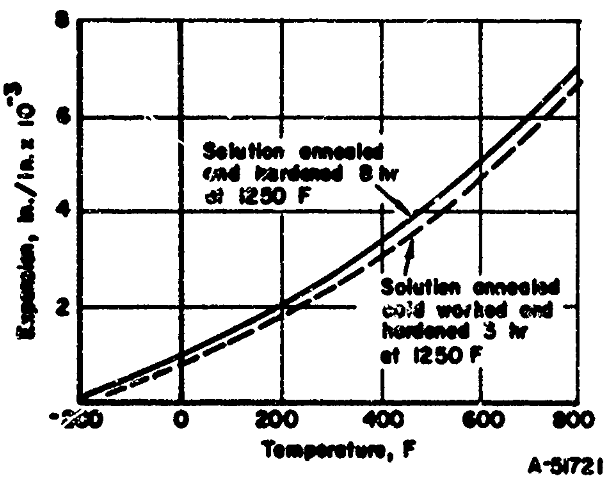


FIGURE 55. THERMAL EXPANSION OF NI-SPAN C(44)

(Thermal expansion of Ni-Span C is moderately high; cold work prior to hardening has a slight effect on the expansion rate.)

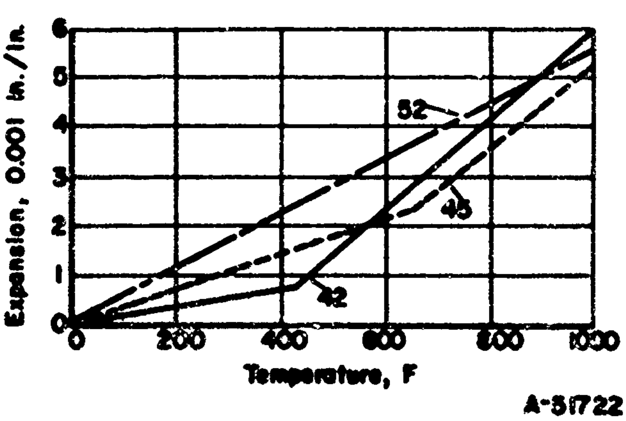


FIGURE 56. EXPANSION CHARACTERISTICS AND INFLECTION TEMPERATURES OF LOW-EXPANSION ALLOYS CONTAINING THREE DIFFERENT AMOUNTS OF NICKEL(45)

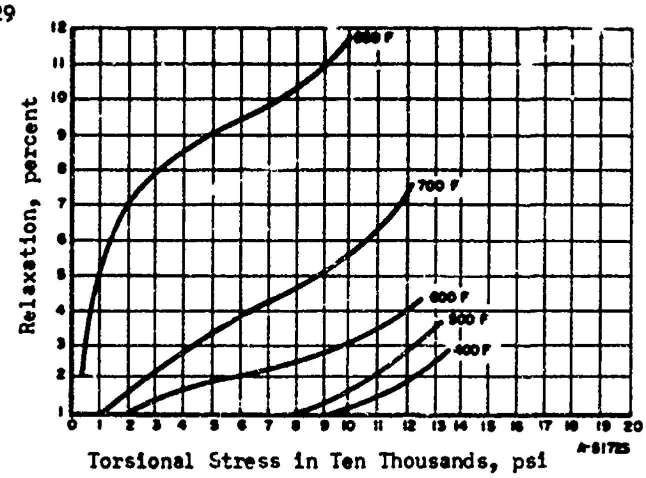


FIGURE 57. RELAXATION OF NI-SPAN C AT ELEVATED TEMPERATURES(42)

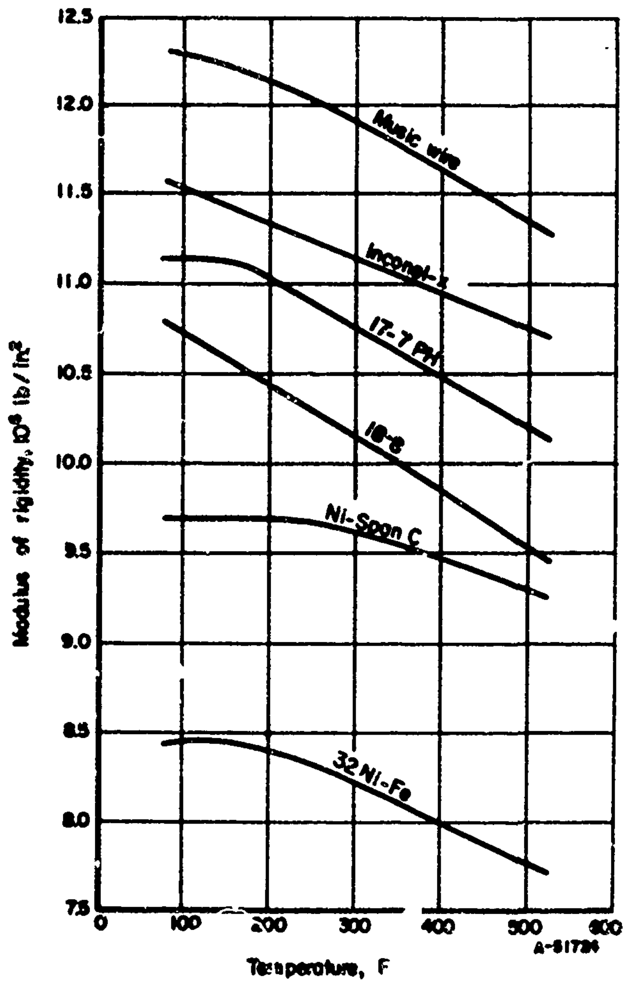


FIGURE 58. EFFECT OF TEMPERATURE ON THE SHEAR MODULUS OF SEVERAL ENGINEERING ALLOYS(46)

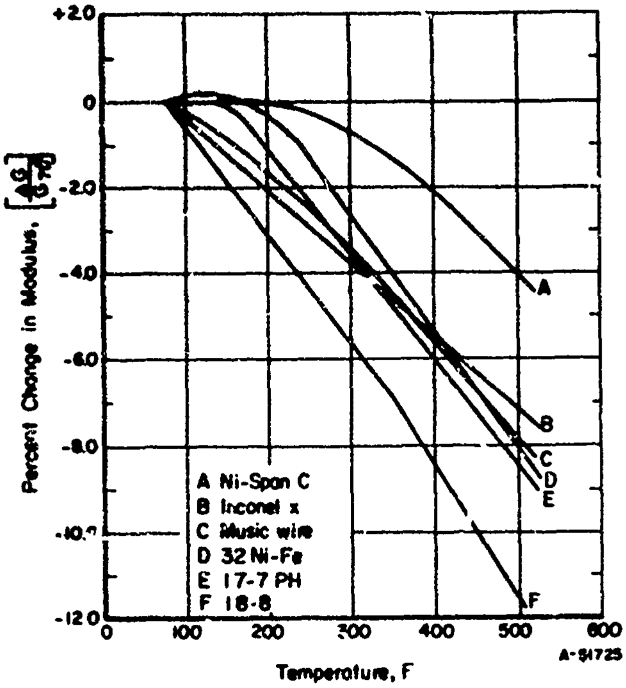


FIGURE 59. PERCENT CHANGE IN SHEAR MODULUS VERSUS TEMPERATURE FOR THE ALLOYS SHOWN IN FIGURE 58[46]

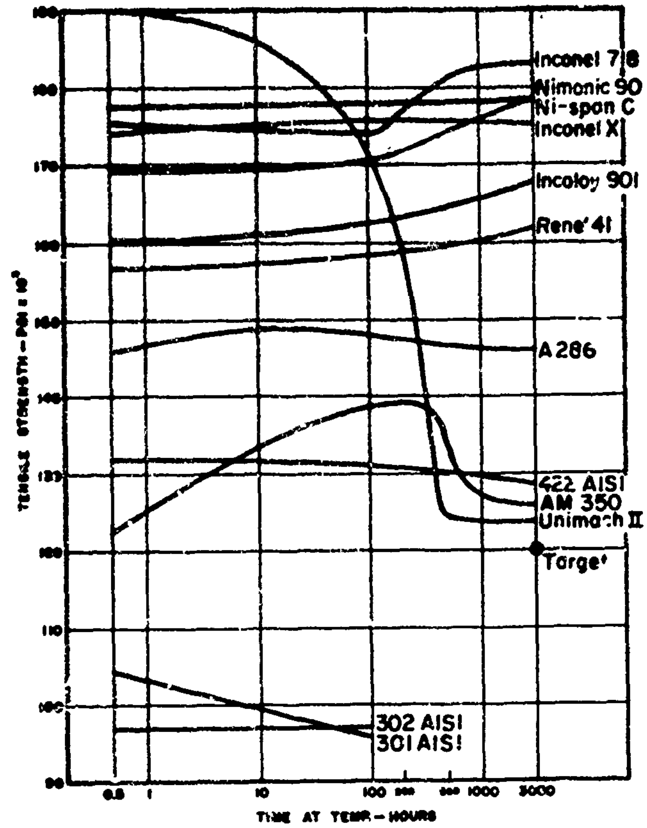


FIGURE 60. TENSILE STRENGTH OF SPRING MATERIALS AT 500 C (TEST RESULTS)[47]

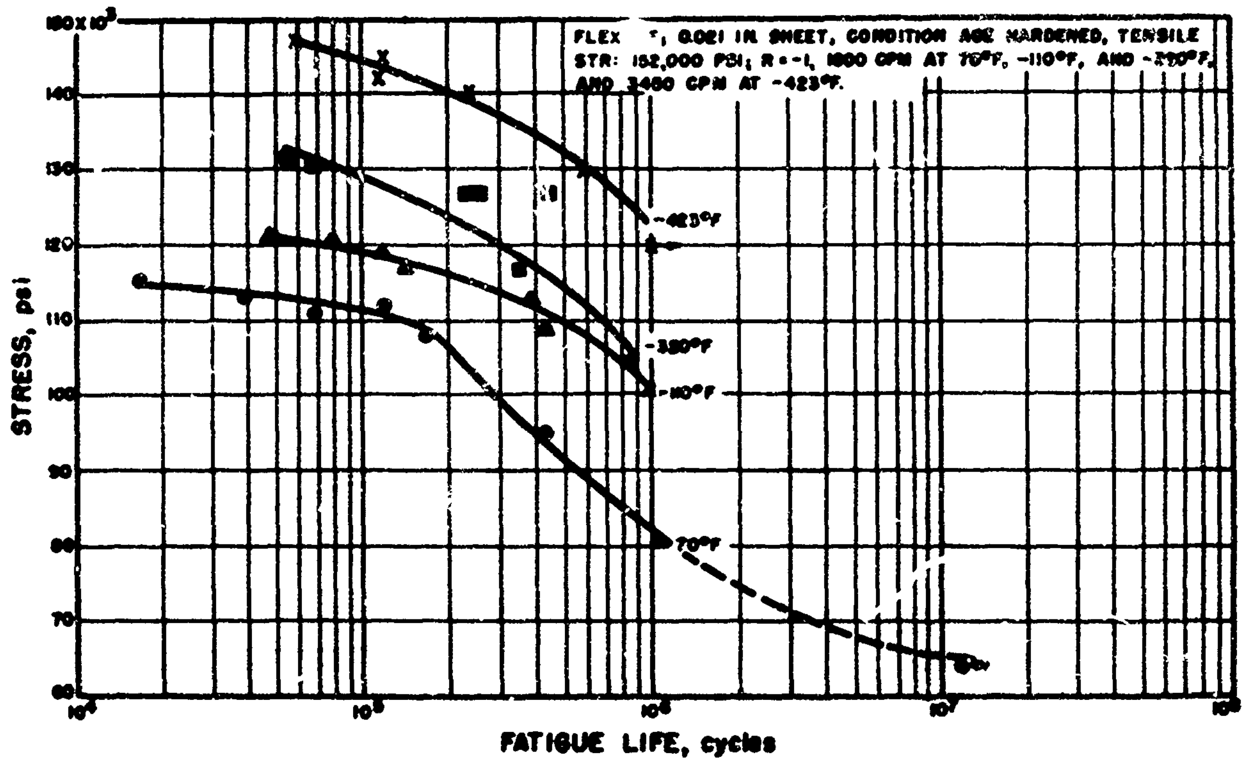


FIGURE 61. FATIGUE BEHAVIOR OF NI-SPAN C[48]

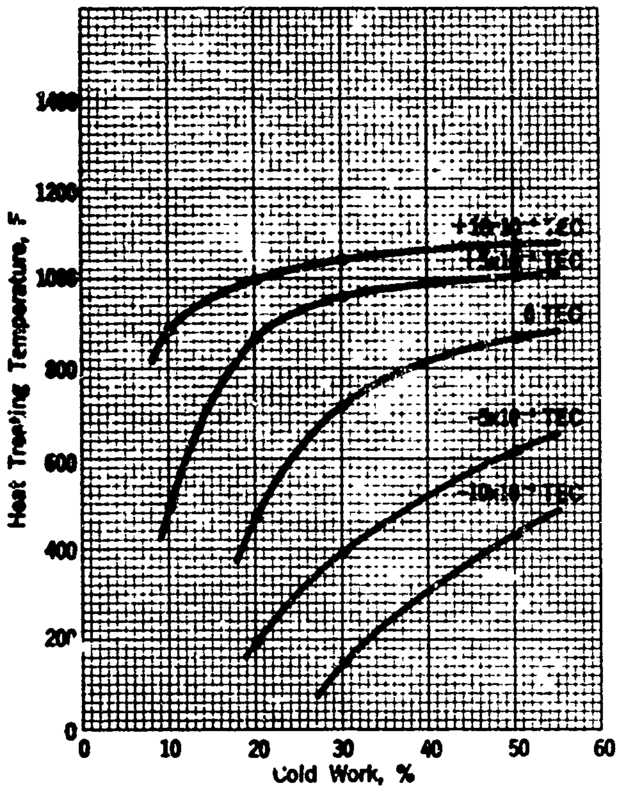


FIGURE 62. COLD WORK AND 5-HOUR HEAT TREATMENT REQUIRED TO PRODUCE VARIOUS THERMOELASTIC COEFFICIENT LEVELS(12)

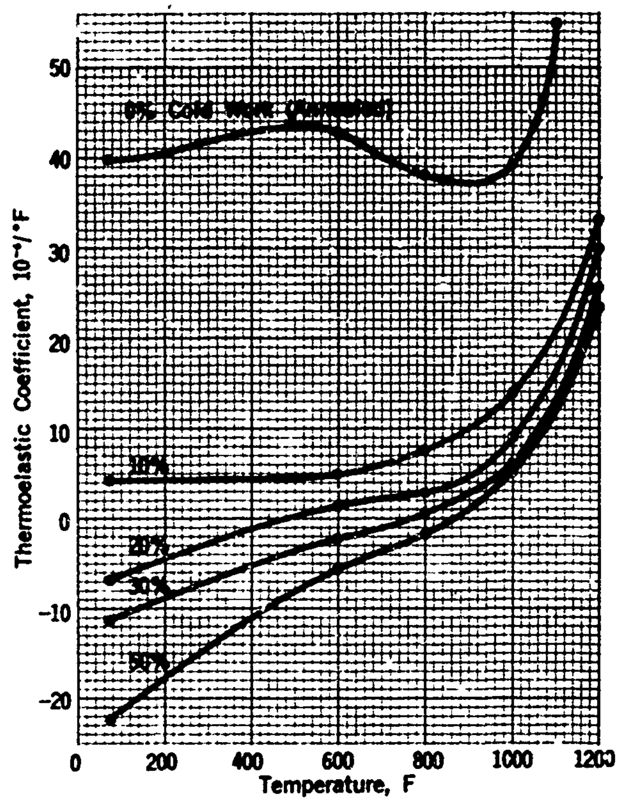


FIGURE 63. EFFECT OF COLD WORK AND 5-HOUR HEAT TREATMENT AT TEMPERATURE SHOWN ON THERMOELASTIC COEFFICIENT(12)

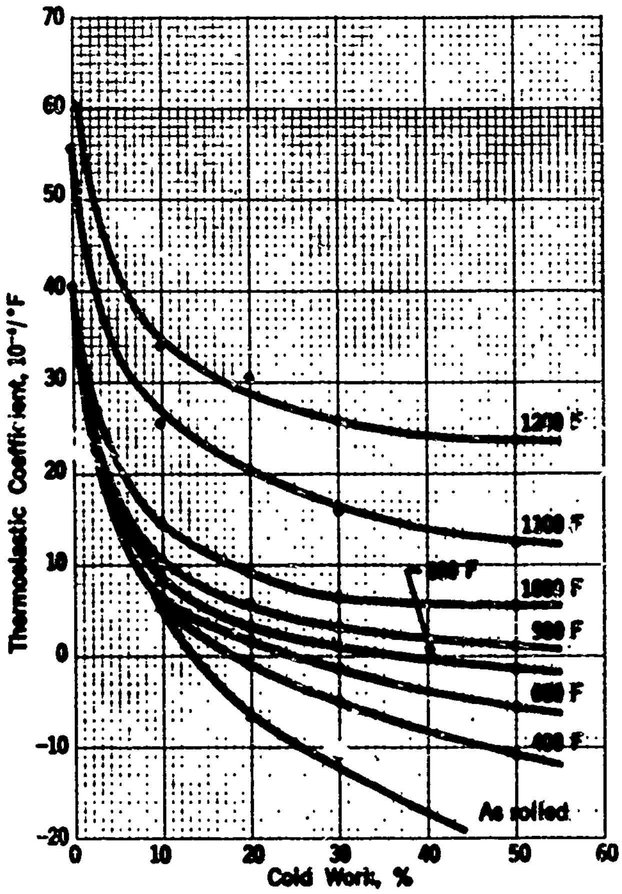


FIGURE 64. EFFECT OF COLD WORK AND 5-HOUR HEAT TREATMENT AT TEMPERATURE SHOWN ON THERMOELASTIC COEFFICIENT(12)

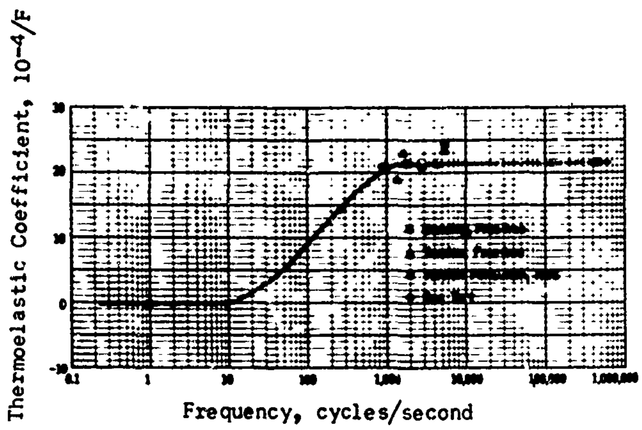


FIGURE 65. EFFECT OF OPERATING FREQUENCY ON THERMO-ELASTIC COEFFICIENT OF NI-SPAN C(12)

(Free-free specimens heat treated at 1200 F for 5 hours, pendulum specimens at 1285 F for 3 hours. All specimens cold worked 50 percent before heat treatment.)

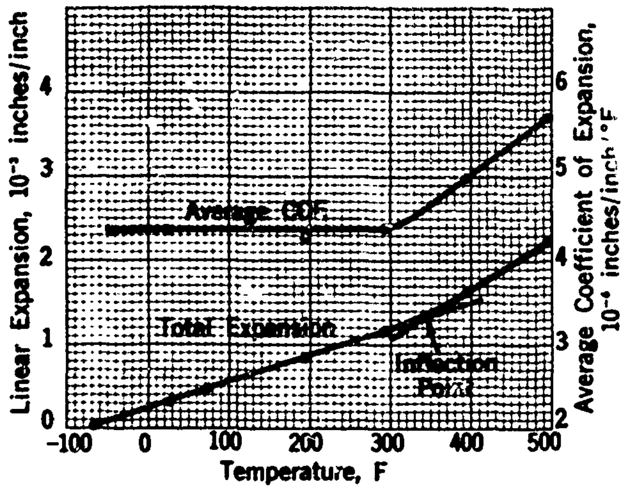


FIGURE 66. THERMAL-EXPANSION CHARACTERISTICS OF NI-SPAN C(12)

(Hot-rolled material, heat treated at 1850 F for 1 hour, water quenched and aged at 900 F for 5 hours, air cooled.)

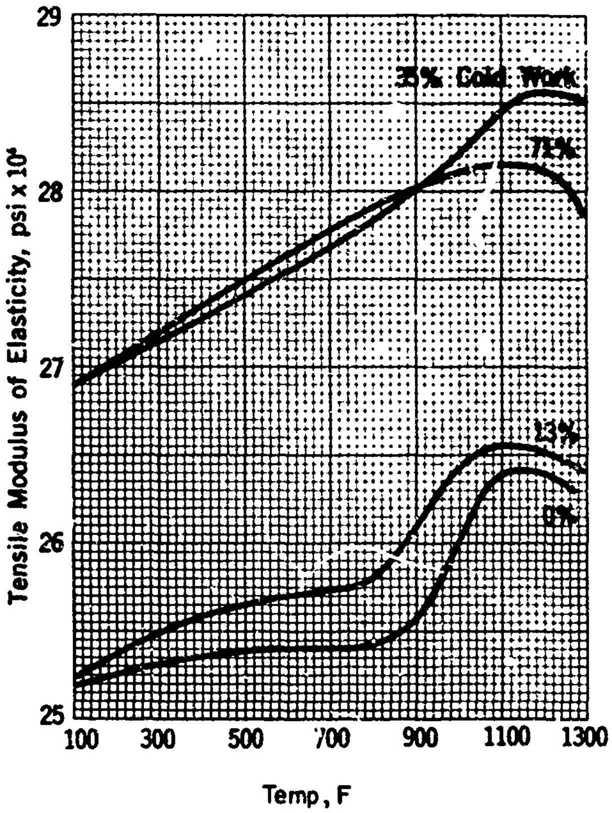


FIGURE 67. EFFECT OF COLD WORK AND HEATING FOR 5 HOURS AT TEMPERATURE SHOWN ON THE ROOM-TEMPERATURE MODULUS OF ELASTICITY FOR NI-SPAN C(12)

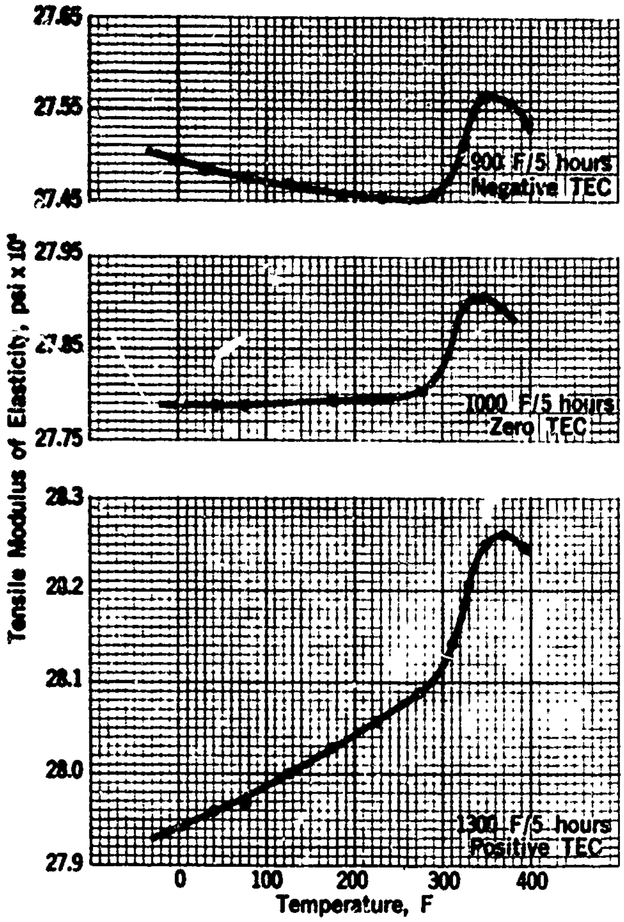


FIGURE 68. EFFECT OF VARIOUS HEAT TREATMENTS ON THE TENSILE MODULUS OF ELASTICITY OF NI-SPAN C AT DIFFERENT TEMPERATURES(12)

(Material cold worked 50 percent prior to heat treatment.)

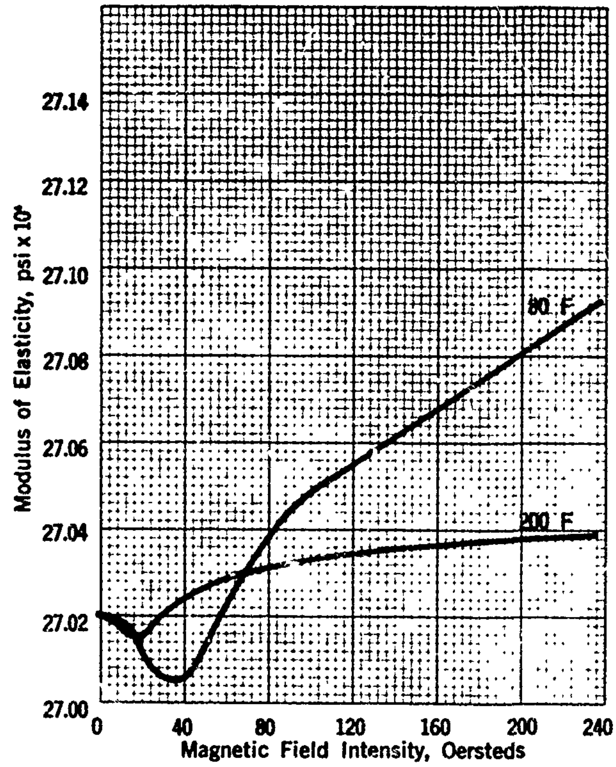


FIGURE 70. EFFECT OF MAGNETIC FIELD INTENSITY ON MODULUS OF ELASTICITY (AT TWO TEMPERATURES) OF NI-SPAN C(12)

(Material cold rolled 40 percent and treated at 1000 F for 5 hours.)

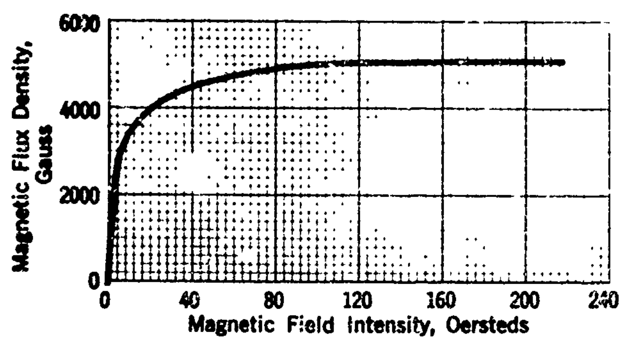


FIGURE 69. NORMAL MAGNETIZATION CURVE FOR NI-SPAN C(12)

(Material cold rolled 40 percent and heat treated at 1000 F for 5 hours prior to testing. Magnetic Field Intensity is also known as Magnetizing Force (H), and Magnetic Flux Density as Magnetic Induction (B).)

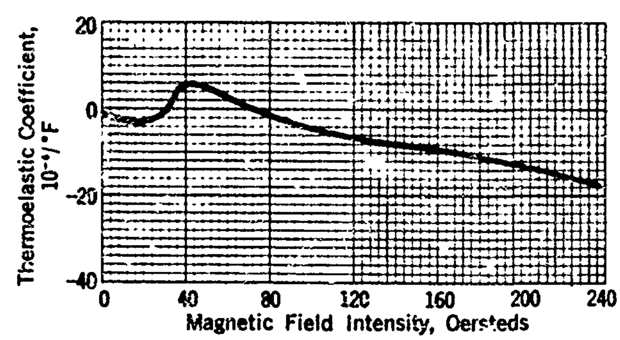


FIGURE 71. EFFECT OF MAGNETIC FIELD INTENSITY ON THE THERMOELASTIC COEFFICIENT OF NI-SPAN C(12)

(Material cold worked 40 percent and heat treated at 1000 F for 5 hours.)

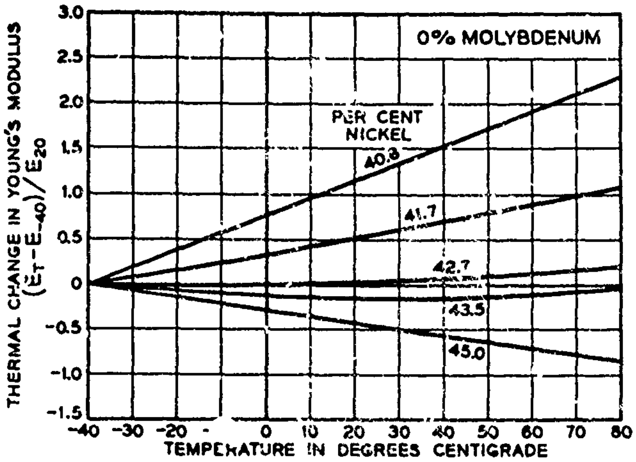


FIGURE 72. A PLOT OF $(E_T-E_{-40})/E_{20}$ AGAINST TEMPERATURE FOR COLD-WORKED IRON-NICKEL ALLOYS OF DIFFERENT PERCENTAGES OF NICKEL(50)

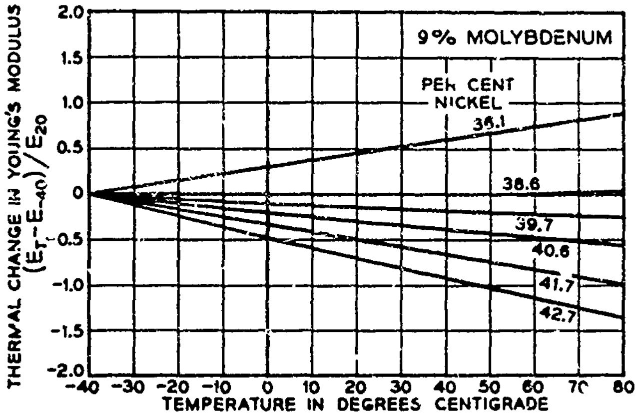


FIGURE 73. PLOT OF $(E_T-E_{-40})/E_{20}$ AGAINST TEMPERATURE FOR A NUMBER OF COLD-WORKED IRON-NICKEL ALLOYS CONTAINING 9 PERCENT MOLYBDENUM(50)

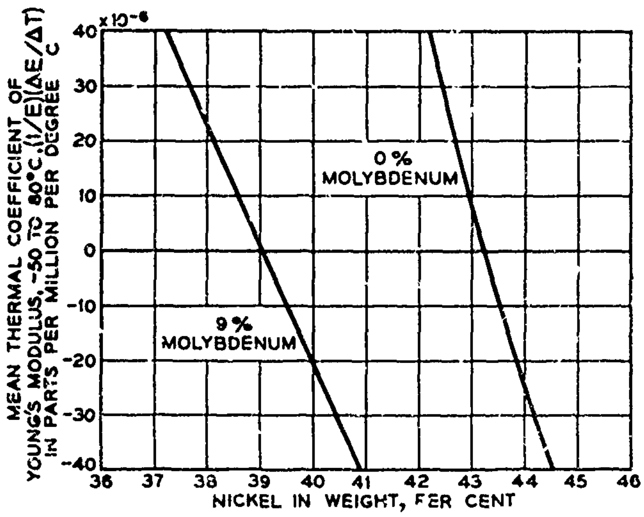


FIGURE 74. PLOT OF MEAN THERMAL COEFFICIENT OF YOUNG'S MODULUS AGAINST NICKEL CONTENT FOR IRON-NICKEL ALLOYS(50)

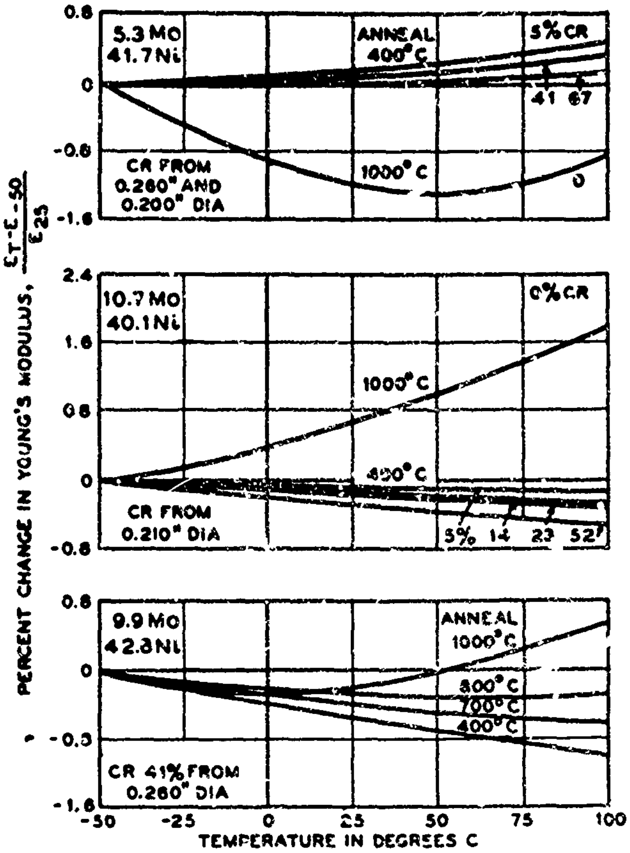


FIGURE 75. PERCENTAGE THERMAL CHANGES IN YOUNG'S MODULUS AS AFFECTED BY VARIATION IN DEGREE OF COLD WORK AND ANNEALING TEMPERATURE(51)

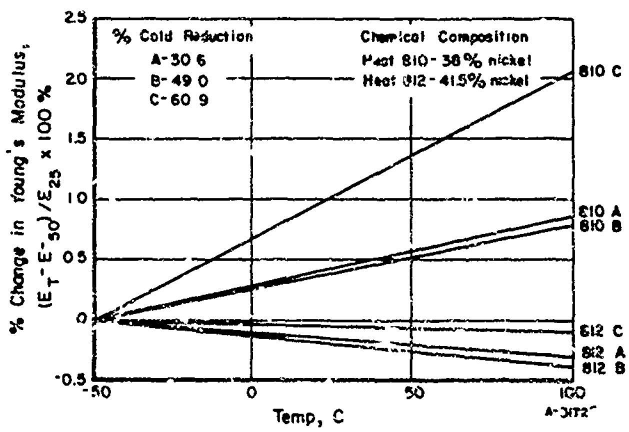


FIGURE 76. PERCENT CHANGE IN YOUNG'S MODULUS VERSUS TEMPERATURE OF VIBRALLOY FOR DIFFERENT CHEMICAL COMPOSITIONS AND PERCENT COLD REDUCTIONS(52)

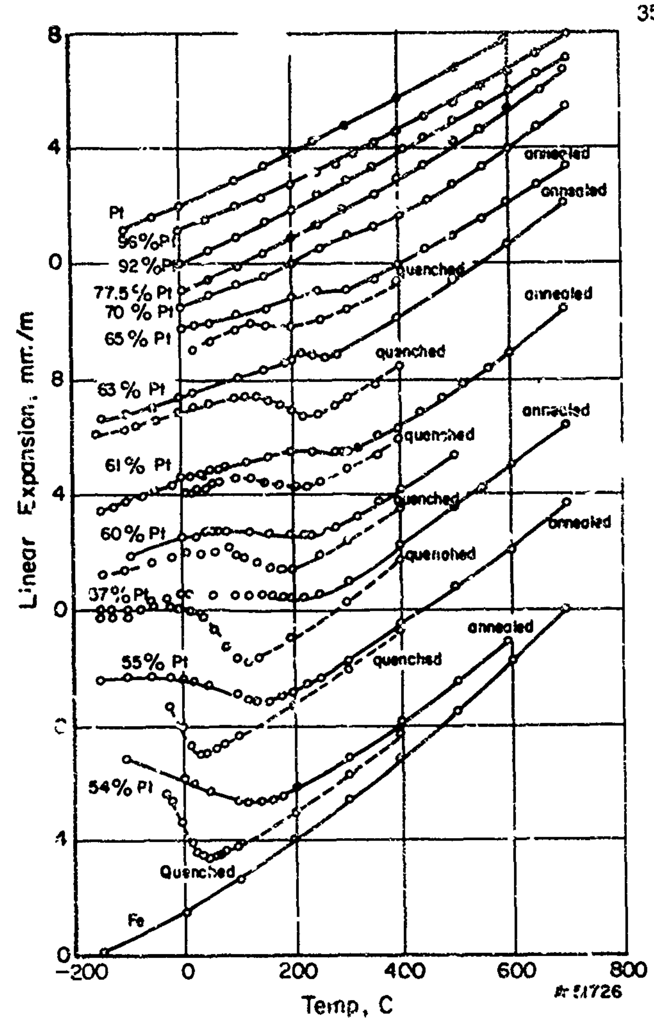


FIGURE 77. THERMAL EXPANSION OF PLATINUM-IRON ALLOYS(70)

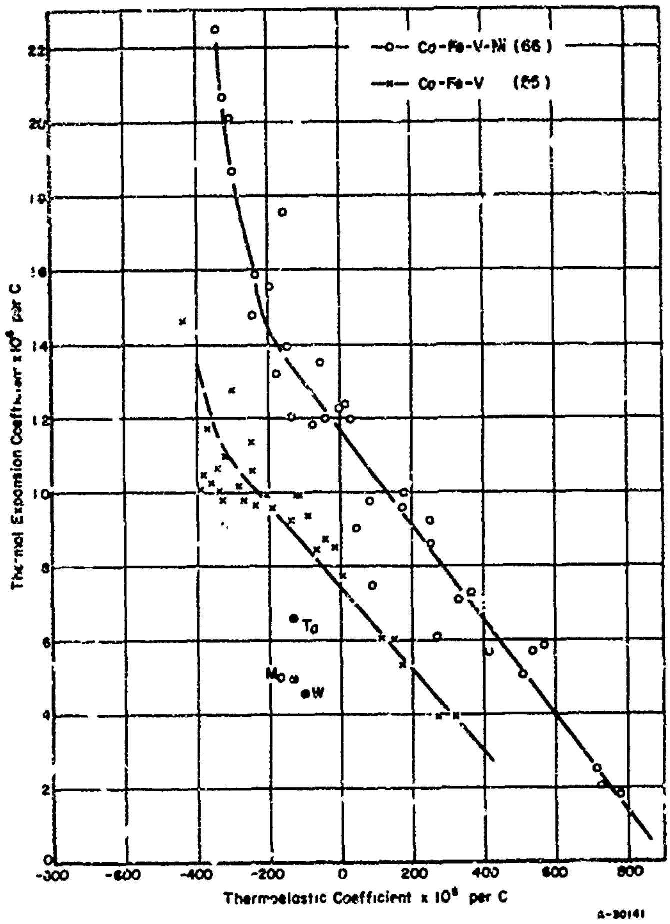


FIGURE 78. RELATION BETWEEN THERMOELASTIC AND THERMAL-EXPANSION COEFFICIENTS IN SOME MASUMOTO ALLOYS

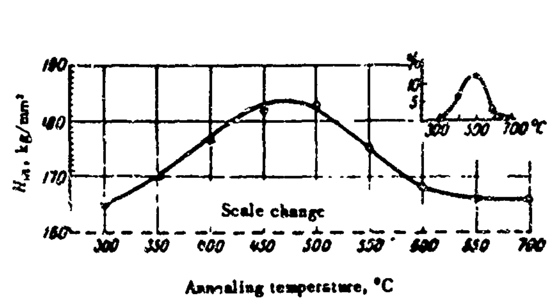


FIGURE 79. CHANGE IN MICROHARDNESS IN RELATION TO TEMPERATURE OF ANNEAL(72)

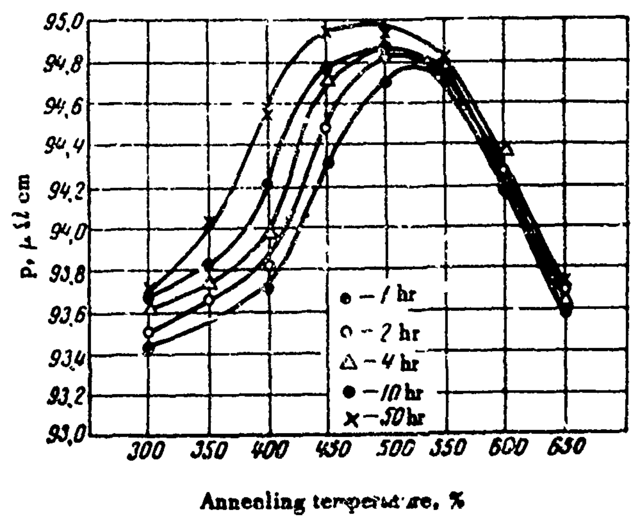


FIGURE 80. RELATION OF SPECIFIC ELECTRICAL RESISTANCE OF A FERRO-NICKEL ALLOY WITH COLUMBIUM TO ANNEALING TEMPERATURE(72)

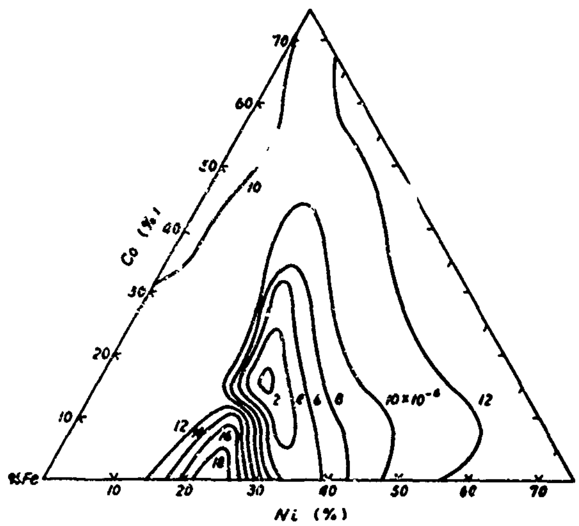


FIGURE 81. THERMAL-EXPANSION COEFFICIENT OF Fe-Ni-Co-Cr ALLOYS CONTAINING 5PERCENT OF CHROMIUM(92)

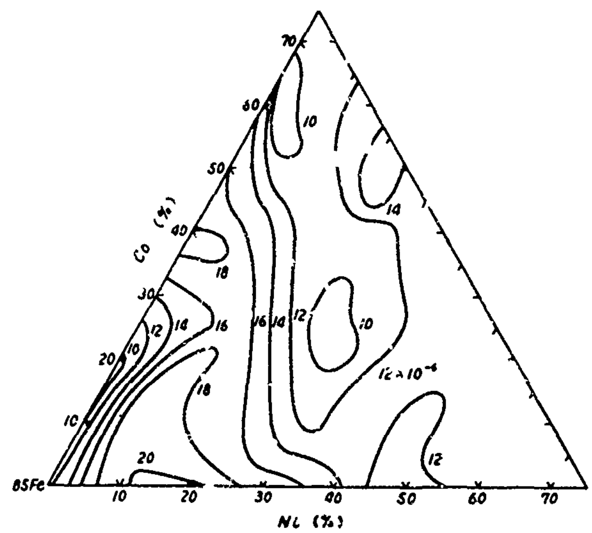


FIGURE 83. THERMAL-EXPANSION COEFFICIENT OF Fe-Ni-Co-Cr ALLOYS CONTAINING 15 PERCENT OF CHROMIUM(92)

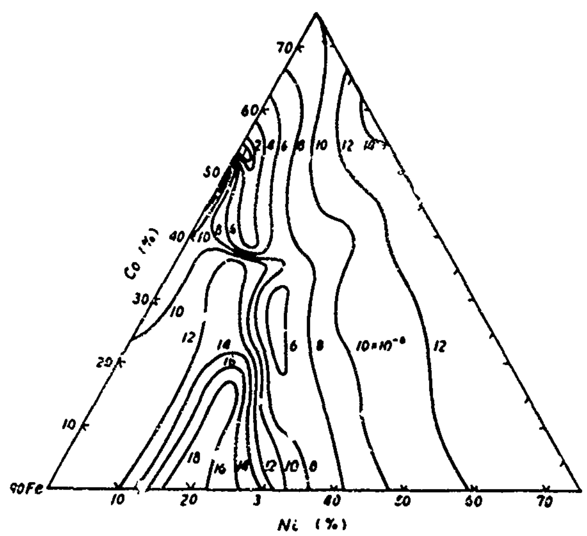


FIGURE 82. THERMAL-EXPANSION COEFFICIENT OF Fe-Ni-Co-Cr ALLOYS CONTAINING 10 PERCENT OF CHROMIUM(92)

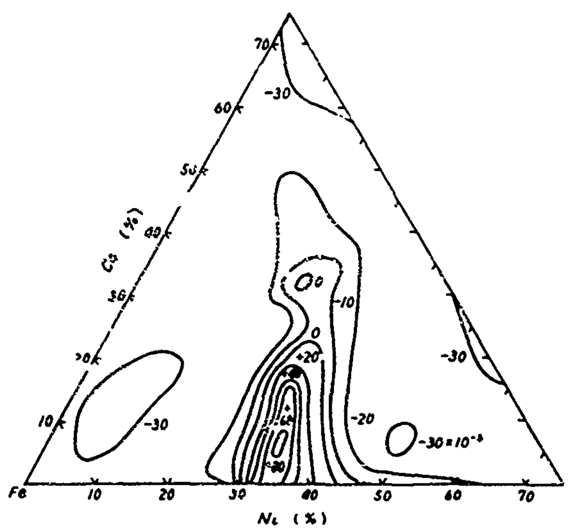


FIGURE 84. TEMPERATURE COEFFICIENT OF RIGIDITY MODULUS OF Fe-Ni-Co ALLOYS(92)

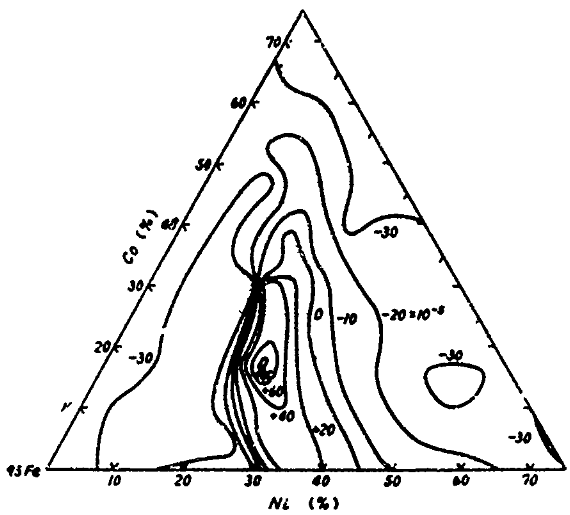


FIGURE 85. TEMPERATURE COEFFICIENT OF RIGIDITY MODULUS OF Fe-Ni-Co-Cr ALLOYS CONTAINING 5 PERCENT OF CHROMIUM(92)

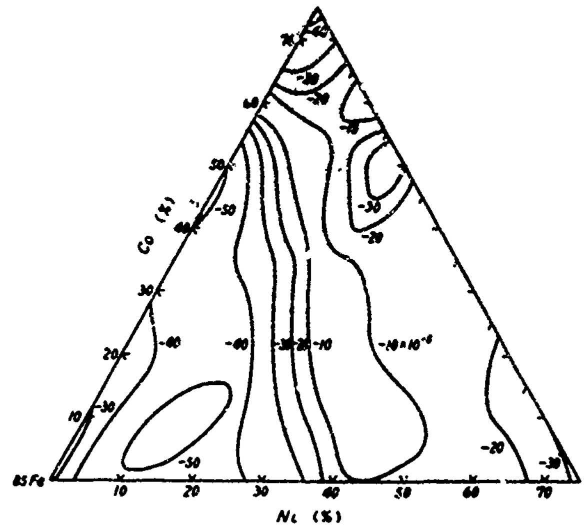


FIGURE 87. TEMPERATURE COEFFICIENT OF RIGIDITY MODULUS OF Fe-Ni-Co-Cr ALLOYS CONTAINING 15 PERCENT OF CHROMIUM(92)

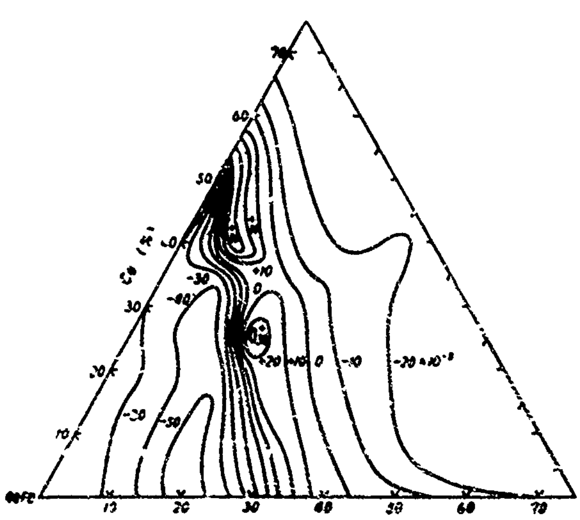


FIGURE 86. TEMPERATURE COEFFICIENT OF RIGIDITY MODULUS OF Fe-Ni-Co-Cr ALLOYS CONTAINING 10 PERCENT OF CHROMIUM(92)

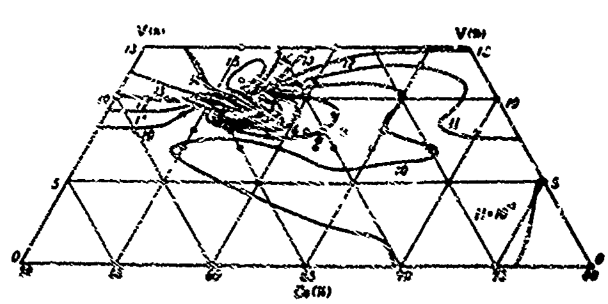


FIGURE 88. COEFFICIENT OF THERMAL EXPANSION OF THE ALLOYS OF COBALT, IRON, AND VANADIUM(55)

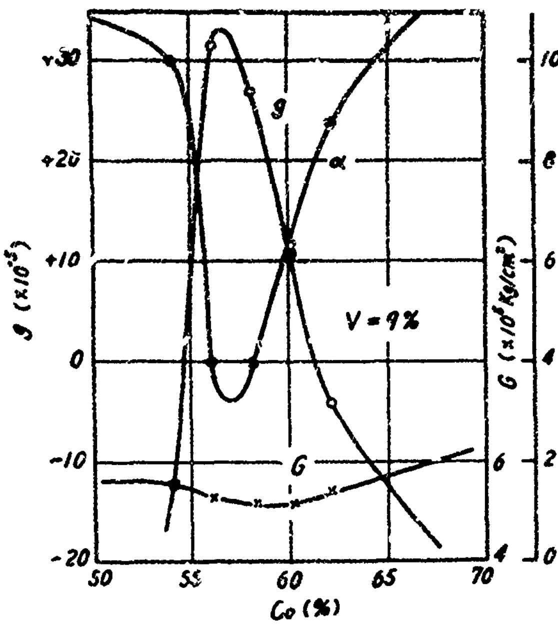


FIGURE 89. RELATIONS BETWEEN THE THERMAL-EXPANSION COEFFICIENT, THE RIGIDITY MODULUS AND ITS TEMPERATURE COEFFICIENT, AND THE CONCENTRATION IN THE SECTION OF 9 PERCENT OF VANADIUM(55)

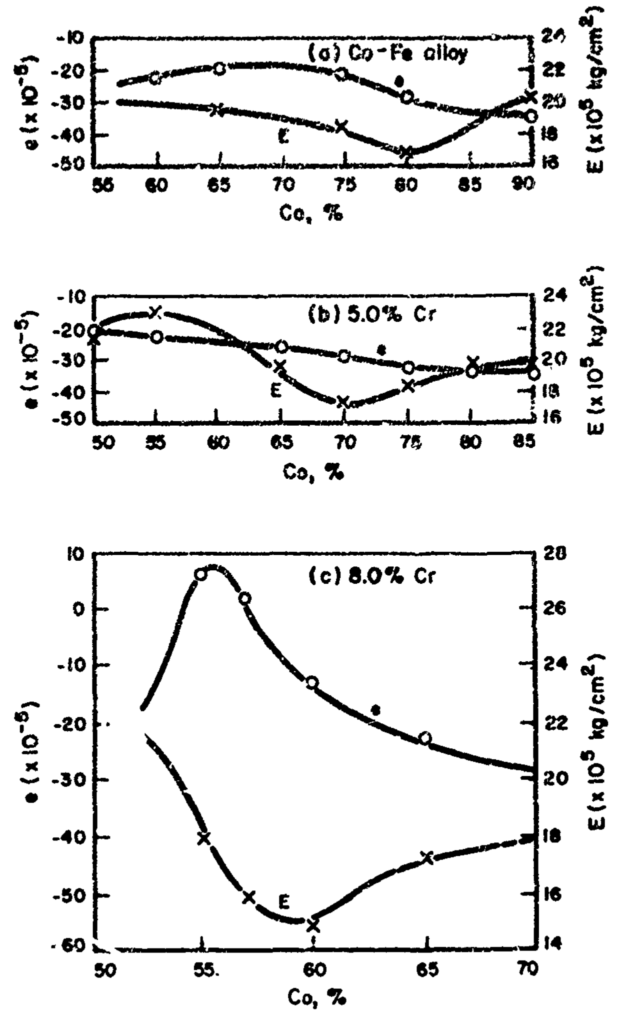


FIGURE 90. RELATION BETWEEN YOUNG'S MODULUS OR ITS TEMPERATURE COEFFICIENT AND THE CONCENTRATION OF Co-Fe-Cr ALLOYS[54]

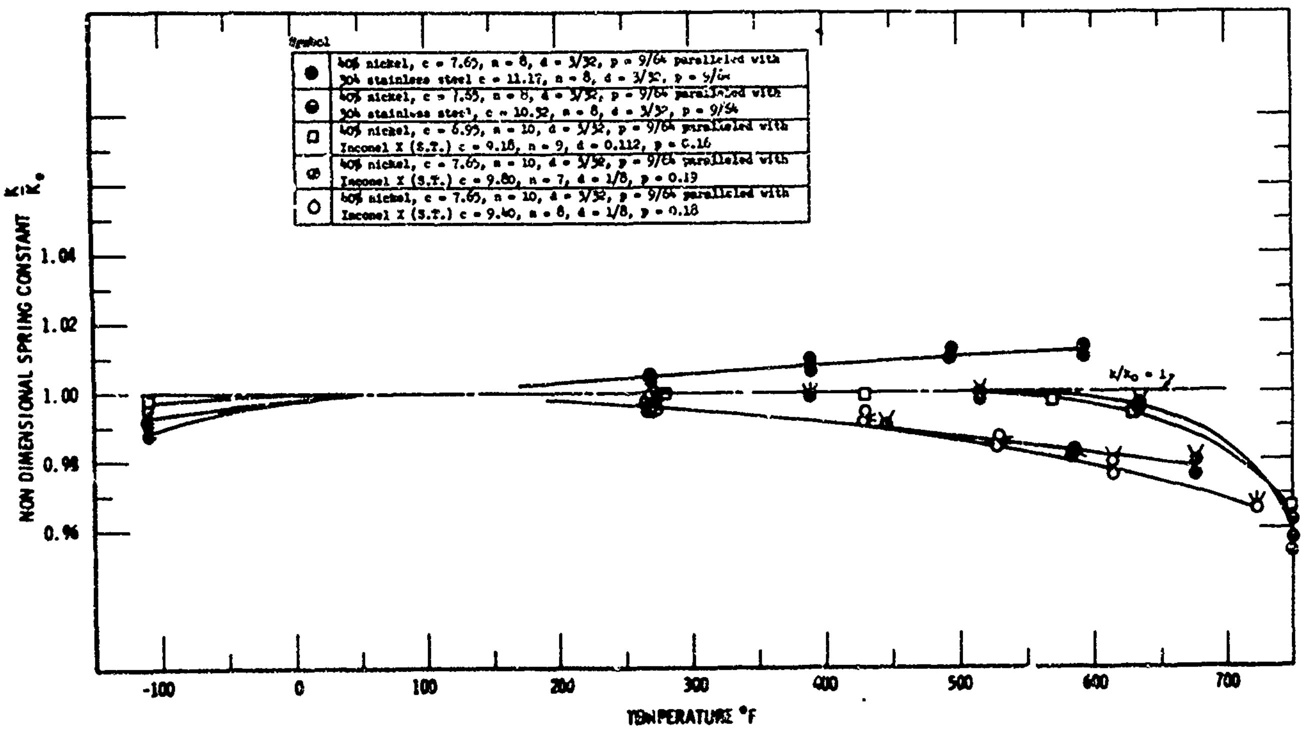


FIGURE 91. NONDIMENSIONAL SPRING CONSTANT VERSUS TEMPERATURE FOR BIMETAL COIL SPRING SYSTEMS TESTED[78]

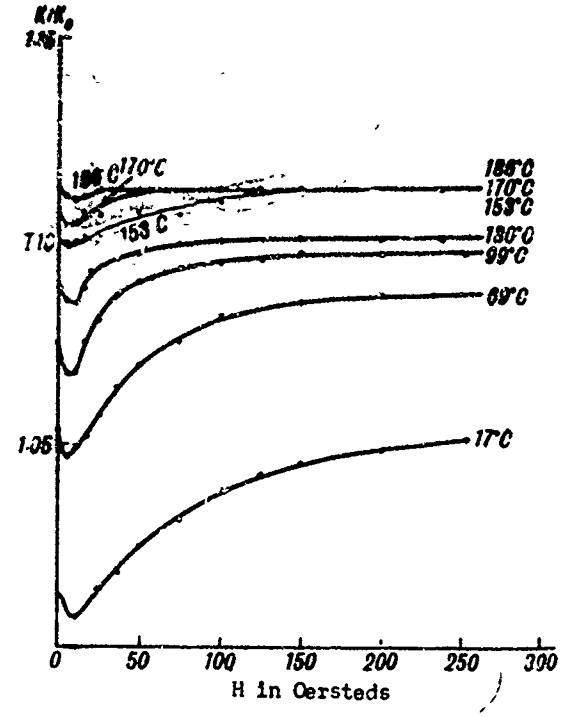


FIGURE 92. THE TORSIONAL MODULUS AT 0 C RELATIVE TO THE TORSIONAL MODULUS AT THE TEMPERATURES AND MAGNETIC FIELDS INDICATED FOR Fe65% - Ni35%(82)

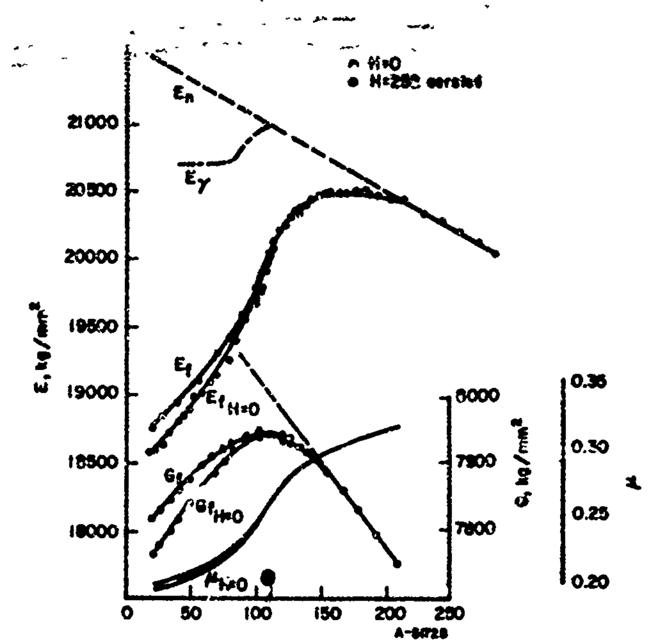


FIGURE 94. THE SAME AS IN FIGURE 93 FOR ALLOY 2, CONTAINING 53.5% Co, 8.7% Cr, and 37.8% Fe(83)

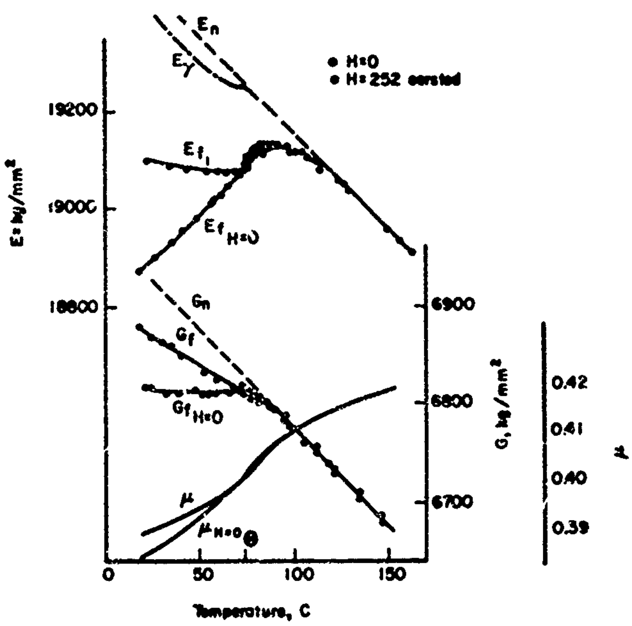


FIGURE 93. TEMPERATURE DEPENDENCE OF YOUNG'S MODULUS E, THE SHEAR MODULUS G, AND POISSON'S RATIO μ FOR ALLOY 1, CONTAINING 36%Ni, 12%Cr, and 52% Fe, IN THE DEMAGNETIZED STATE (H=0) AND IN A FIELD OF 252 OERSTED(83)

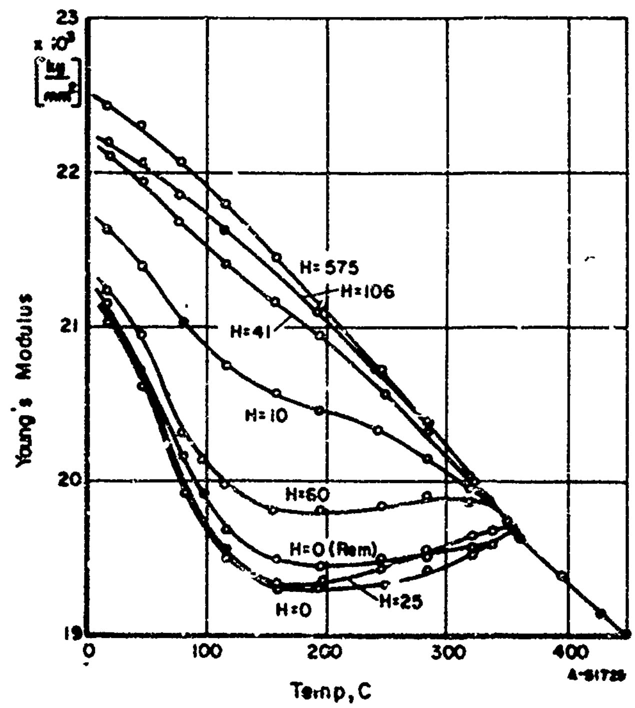


FIGURE 95. THE DEPENDENCY OF YOUNG'S MODULUS OF NICKEL ON MAGNETIZATION (H IN OERSTEDS) AND TEMPERATURE(87)

TABLE 1. COMPOSITIONS OF VARIOUS INVAR-TYPE ALLOYS

	N	Co	Ti	Cr	C	Mn	Si	Al	P	S	Se	W	Mo	Cb	V	Fe
Niles, Minvar	36				.10 max	.50 max	.20-.35									Bal
Invar Nilvar	36.8				0.07	0.44	.24									Bal
Indilitans	35.5				0.08	0.42										Bal
Invar, free machining	38				0.12	0.8					0.25					Bal
	33-35			4-5	0.5-2	0.5-2	0.5-2					1-3				Bal
Elinvar	33.5			8.4	0.71	2.4	0.33		0.018	0.01		2.98				Bal
	36			12	0.8		1-2									Bal
		54		9												Bal
Stainless Invar		54.2		9.40	0.05	0.37										Bal
	31.5	5														Bal
	31	4-6														Bal
Super Invar	31	7														Bal
Super Nilvar	31	5														Bal
Co-Elinvar		57-60		8-15												Bal
Elinvar Extra	41-43		2.4	5.5	0.6 max	0.5		0.4								Bal
Velinvar		55-63													7-13	Bal
Vibralloy	38-42												9			Bal
Ni-Span Lo 42	40.5-42.5		2.2-2.6		0.06 max	0.3-0.6	0.3-0.8	0.4-0.8	0.04 max	0.04 max						Bal
Ni-Span Lo 45	44.5-46.5		2.2-2.6		0.06 max	0.3-0.6	0.3-0.8	0.4-0.8	0.04 max	0.04 max						Bal
Ni-Span Lo 52	51.0-53		2.2-2.6		0.06 max	0.3-0.6	0.3-0.8	0.4-0.8	0.04 max	0.04 max						Bal
Ni-Span Hi	28.0-30.0		2.2-2.6	8.0-9.0	0.06 max	0.3-0.6	0.3-0.8	0.4-0.8	0.04 max	0.04 max						Bal
Ni-Span C Alloy 902	41.0-43.0		2.2-2.6	5.1-5.7	0.06 max	0.3-0.6	0.3-0.8	0.4-0.8	0.04 max	0.04 max						Bal
Carpenter Low Expansion 42	42															Bal
Carpenter Low Expansion 39	39															Bal
Carpenter No. 37 - 7 FM	37															Bal
Carpenter No. 22-3	22			3												Bal
Iso-Elastic	36			8	0.19	0.46	0.35		0.11	0.10			0.5			Bal

TABLE 2. SUMMARY OF INVAR-TYPE ALLOYS

Trade Name	References
Invar	2, 3, 4, 5, 6, 7, 8, 9, 11, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 36, 39, 42, 71, 72, 73, 74, 75, 76, 79, 81, 84, 90, 91, 95, 96, 97, 98, 99, 100, 101, 102, 103, 104, 105, 106, 107, 110, 115, 122, 125, 127, 128, 129, 137, 139, 141, 142, 145, 146, 152, 156, 157, 160, 164, 165, 166, 167, 169, 170, 171, 176, 180, 181, 184, 190, 191, 196, 199, 200, 201, 202, 203
Elinvar	11, 13, 14, 20, 25, 30, 42, 64, 83, 92, 94, 97, 98, 103, 116, 117, 122, 141, 160, 173, 190, 195
Stainless Invar	34, 38, 40, 41, 61, 64, 92, 120, 159, 197
Super Invar	15, 20, 22, 35, 36, 37, 92, 97, 141, 197
Co-Elinvar	54, 61, 62, 63, 64, 65, 83, 92, 159, 183
Elinvar Extra	190
Velinvar	55, 66, 159
Vibralloy	50, 51, 52, 122
Ni-Spans	11, 12, 22, 28, 42, 43, 44, 45, 47, 48, 49, 122, 141, 158, 189, 190, 196, 203, 204
Carpenter Alloys	13, 21
Iso-Elastic	11, 42, 44, 46, 47, 53, 78, 113, 122, 190

TABLE 3. THERMAL EXPANSION OF IRON-NICKEL ALLOYS[20]

Ni	Mean Coefficient,[a] µin./in./C	Ni	Mean Coefficient, µin./in./C
31.4	3.395+0.00885 t	43.6	7.992-0.00273 t
34.6	1.373+0.00237 t	44.4	8.508-0.00251 t
35.6	0.877+0.00127 t	48.7	9.901-0.00067 t
37.3	3.457-0.00647 t	50.7	9.984+0.00243 t
39.4	5.357-0.00448 t	53.2	10.045+0.00031 t

(a) Between 0 and 38C.

TABLE 4. EFFECT OF HEAT TREATMENT ON THE COEFFICIENT OF EXPANSION OF INVAR[20]

Treatment		Mean Coefficient, µin./in./C
After forging	17 to 100 C	1.66
	17 to 250 C	3.11
Quenched from 830 C	18 to 100 C	0.64
	18 to 250 C	2.53
Quenched from 830 C, tempered	15 to 100 C	1.02
	15 to 250 C	2.43
Cooled from 830 C to room temperature in 19 hr	15 to 100 C	2.01
	15 to 250 C	2.89

TABLE 5. EFFECT OF QUENCHING AND COLD DRAWING ON THE EXPANSIVITY OF INVAR PER DEGREE CENTIGRADE[20]

Direct From Hot Mill	Annealed and Quenched	Quenched and Cold Drawn 0.125 to 0.250 In.
1.4×10^{-6}	0.5×10^{-6}	0.14×10^{-6}
1.4×10^{-6}	0.8×10^{-6}	0.3×10^{-6}

TABLE 6. SOME PHYSICAL AND MECHANICAL PROPERTIES OF INVAR[20]

Solidus Temperature	2600 F (1425 C)
Density	8.0 g/cu cm (500 lb/cu ft)
Tensile Strength	65,000 to 85,000 psi
Yield Point	40,000 to 60,000 psi
Elastic Limit	20,000 to 30,000 psi
Elongation	30 to 45 percent
Reduction in Area	55 to 70 percent
Scleroscope Hardness	19
Brinell Hardness	160
Modulus of Elasticity in Tension	21,400,000 psi
Thermoelastic Coefficient	500×10^{-6}/C
Specific Heat (25 to 100 C)	0.123 cal/g/C
Thermal Conductivity (20 to 100 C)	0.0262 cgs units
Thermoelectric Potential (Against Copper) (-96 C)	9.8 microvolts/C

TABLE 7. ANNEALING[a] INSTRUCTION FOR CARPENTER INVAR "36"[21]

Temperature	Rockwell Hardness
1200 F (650 C), air treat	B-87/88
1500 F (815 C), air treat	B-77/78
1800 F (980 C), air treat	B-70/71
1900 F (1040 C), air treat	B-66/68

(a) Annealing: Heat to 1450 F (790 C) and hold at heat 1/2 hour per inch of thickness, air cool. Heating to temperatures above 1000 F (540 C) relieves the presence of cold-work stresses. The higher the temperature, the lower the annealed hardness as shown here.

Specimen held 5 minutes at heat.

TABLE 8. PROPERTIES OF INVAR AND SOME LOW-EXPANSION IRON-NICKEL ALLOYS(21)

Properties	Invar 36	Free-Cut Invar 36	Low-Expansion 39	Low-Expansion 42	Low-Expansion 49
Type Analysis					
Carbon	0.12	0.12	0.08	0.10	0.10
Manganese	.35	.90	0.40	0.50	0.50
Silicor	0.30	0.35	0.25	0.25	0.40
Chromium	—	—	—	—	—
Nickel	36.00	36.00	39.00	42.00	49.00
Other Elements	Fe bal	Fe bal	Fe bal	Fe bal	Fe bal
Physical Constants					
Specific Gravity	8.05	8.05	8.08	8.12	8.25
Density, lb/cu in.	0.291	0.291	0.292	0.293	0.298
Thermal Conductivity (Range 20/100 C)					
cal/cm^3/sec/C	0.0250	0.0250	0.0253	0.0257	0.030
Btu/hr/sq ft/F/in.	72.6	72.6	73.5	74.5	90.0
Electrical Resistivity:					
µohm-cm	82	82	—	72	48
ohms/cir mil ft	495	495	—	430	290
Curie Temperature, C	280	280	340	380	500
Melting Point, C	1425	1425	1425	1425	1425
Specific Heat	0.123	0.123	0.121	0.120	0.120
Coefficient of Thermal Expansion					
(in./in./C x 10^{-6})					
(in./in./F x 10^{-6})					
(As Annealed)					
Temperature Range:					
25 - 100 C	1.18	1.60	2.20	4.63	8.67
25 - 200	1.72	2.91	2.66	4.76	9.38
25 - 300	4.92	5.99	3.39	4.88	9.30
25 - 350	6.60	7.56	4.68	5.02	9.25
25 - 400	7.82	8.88	6.00	5.65	9.14
25 - 450	8.82	9.30	7.22	6.90	9.65
25 - 500	9.72	10.66	8.17	7.78	9.72
25 - 600	11.35	12.00	9.60	9.90	10.80
25 - 700	12.70	12.90	11.00	11.00	11.71
25 - 800	13.45	13.60	11.95	11.99	12.57
25 - 900	13.85	14.60	12.78	12.78	13.29
25 - 1000	—	—	13.42	—	—
Values in both columns for cold-worked condition					
77 - 212 F	0.655	0.89	1.22	2.57	4.80
77 - 392	0.956	1.62	1.48	2.54	5.20
77 - 572	2.73	3.32	1.88	2.71	5.17
77 - 662	3.67	4.20	[illegible]	2.78	5.14
77 - 752	4.34	4.93	3.34	3.14	5.07
77 - 842	4.90	5.45	4.01	3.83	5.36
77 - 932	5.40	5.92	4.54	4.32	5.40
77 - 1112	6.31	6.67	5.33	5.50	6.00
77 - 1292	7.06	7.17	6.11	6.12	6.51
77 - 1472	7.48	7.56	6.64	6.66	7.06
77 - 1652	7.70	8.12	7.10	7.10	7.38
77 - 1832	—	—	7.45	—	—
Mechanical Properties (As Annealed)					
Tensile Strength, psi	65,000	65,000	75,000	82,000	85,000
Yield Strength, psi	40,000	40,000	38,000	40,000	40,000
Elongation in 2 in., %	35	35	30	30	35
Hardness, Rockwell	B-70	B-70	B-76	B-76	B-70
Elastic Modulus, psi x 10^6	20.5	20.5	21.0	21.0	24.0
Forms Available					
Strip					
Cold Rolled	X	—	X	X	X
Annealed	X	—	X	X	X
Annealed for Deep Drawing	X	—	X	X	X
Wire					
Cold Drawn	X	X	X	X	X
Annealed	X	X	X	X	X
Bars					
Hot Rolled	[illegible]	X	X	X	X
Cold Drawn	X	X	X	X	X
Centerless Ground	X	X	X	X	X
Annealed	X	X	X	X	X
Flats, square	X	X	X	X	X
Billets	X	X	X	X	X

TABLE 9. EXPANSION CHARACTERISTICS[a] OF INVAR[27]

Testing Temperature Range, F	Coefficient of Expansion, in./in./F	Testing Temperature Range, F	Coefficient of Expansion, in./in./F
-200 to 0	1.10×10^{-6}	800 to 1000	9.50×10^{-6}
0 to 200	0.70×10^{-6}	1000 to 1200	9.90×10^{-6}
200 to 400	1.50×10^{-6}	1200 to 1400	10.20×10^{-6}
400 to 600	6.40×10^{-6}	1400 to 1600	10.50×10^{-6}
600 to 800	8.60×10^{-6}		

(a) The above data show the low expansion of Invar up to a temperature of approximately 400 F. Above this, it expands at an increasingly rapid rate, and above 525 F, it expands at a rate more rapid than ordinary steel.

TABLE 10. TYPICAL PROPERTIES OF INVAR[27]

	Condition			
	Annealed	Cold Worked 15%	Cold Worked 25%	Cold Worked 30%
Tensile Strength, psi	71,400	93,000	100,000	106,000
Yield Strength (0.2% Offset), psi	40,000	65,000	89,500	95,000
Elongation in 2 in., %	41	14	9	8
Reduction of Area, %	72	64	62	59
Hardness, Bhn	131	187	207	217
Modulus of Elasticity, psi	21,000,000	—	—	—
Poisson's Ratio	0.290	--	--	--
Density, lb/cu ft	507	--	--	--

TABLE 11. PHYSICAL AND MECHANICAL PROPERTIES OF INVAR[27]

Annealed condition unless noted otherwise.

Average Coefficient of Expansion, in./in./F	Temp, F
1.1×10^{-6}	-200 to 0
$.7 \times 10^{-6}$	0 to 200
1.5×10^{-6}	200 to 400
6.4×10^{-6}	400 to 600
8.6×10^{-6}	600 to 800
9.5×10^{-6}	800 to 1000

Cure Temperature	530 F
Modulus of Elasticity	21×10^6 psi
Temperature Coefficient of the Modulus of Elasticity per F	$+270 \times 10^{-6}$
Modulus of Rigidity	81×10^6 psi
Temperature Coefficient of the Modulus of Rigidity per F	$+300 \times 10^{-6}$
Poisson's Ratio	0.290
Electrical Resistance:	
Ohms/mil ft	490
μohm-cm	81
Temperature Coefficient of Electrical Resistance per F	0.67×10^{-3}
Specific Heat Between 77-212 F:	
Btu/lb/F or cal/g/C	.123
Thermal Conductivity Between 68-212 F:	
Btu/hr/sq ft/in. thickness/F	93
Cal/sec/sq cm/cm thickness/C	0.0323
Melting Point:	
Temp, F	2600
Temp, C	1425
Density:	
Lb/cu ft	508
G/cm^3	8.13

	Tensile Properties			
	Annealed	Cold Worked 15%	Cold Worked 25%	Cold Worked 30%
Tensile Strength, 10^3 psi	71.4	93.0	100.0	106.0
Yield Strength (0.2% Offset), 10^3 psi	52.5	65.0	89.5	95.0
Elongation in 2 in., %	41	14	9	8
Reduction of Area, %	72	64	62	59
Hardness, Brinell	131	187	207	217

Magnetic Properties

Field Strength,* H, oersteds	Normal Induction, B, gauss	Permeability μ
Annealed		
0.1	200	1000
0.4	9500	2200
0.8	3100	3700
1.2	4400	3500
1.3	4450	3400
Hardened		
2	300	175
4	1500	400
6	4000	700
8	5600	710
10	6500	650

Variation of Permeability With Temperature – Field Strength of 5 Oersteds

Temperature, F	Permeability
0	1800
50	1715
100	1630
150	1545
200	1450
240	1360

	Annealed	Hardened
Initial Permeability (approx)	1000	180
Maximum Permeability (approx)	3500	600

* Also known as Magnetizing Force (H).

TABLE 12. SOME PHYSICAL AND MECHANICAL PROPERTIES OF FREE-CUTTING INVAR[25]

Recommended Use: For low coefficient of linear expansion, good elastic limit, and stability.

Dimensional Stability

Temperature, F	Time, Months	Dimensional Changes, μ in./in.
RT	6	10
160	6	0
-100 to +200		10[a]

Heat treatment for: Maximum stability

Procedure: Initial Condition: Cold Drawn

(1) 1200 F, 1 hr, furnace cool; 200 F, 20 hr.

(2) 1525 F, 1/2 hr, water quench; 1200 F, 1 hr, air cool; 200 F, 48 hr, air cool.

Physical Properties

Density	8.13 g/cm^3
Thermal Conductivity	0.025 cal/g/cm^2/cm/g/sec
Resistivity	μohm-cm
Specific Heat	cal/g
Permeability (max)	3800
Thermal-Expansion Coefficient	2.0 in./in./C

Mechanical Properties[b]

Hardness	90 Rockwell B
UTS	90 x 10^3 psi
YP (0.2% Offset)	70 x 10^3 psi
Elongation (2 in.)	20%
Modulus of Elasticity	22 x 10^6 psi
Elastic Limit	47 x 10^3 psi
Elastic Limit/density	5.85 x 10^3 psi/g/cm^3
Modulus/density	2.71 x 10^6 psi/g/cm^3

(a) After 10 cycles between -100 and +200 F

(b) Mechanical properties for Heat Treatment 1 (stress relief).

TABLE 13. EFFECT OF STRESS ON EXPANSION COEFFICIENT[29]

Steel	E at 20 C, 10^6 psi	dE/dT, 10^4 psi/C	10^{-11}/psi-C: dα/dσ, $-1/E^2(dE/dT)$, calculated	10^{-11}/psi-C: dα/dσ, experimental
1020[a]	30.5	-1.1	1.2	0.6
	30.4	-0.7	0.8	1.0
1040[b]	29.9	-1.4	1.5	1.5
	29.6	-1.6	1.8	2.2
1080[b]	29.4	-1.2	1.4	1.7
	30.2	-1.3	1.4	2.1
Regular Invar[c]	19.8	1.7	-4.3	-2.9
	20.3	2.3	-5.6	-5.3
Free-Cut Invar[c]	20.3	1.5	-3.7	-4.3
	20.6	1.6	-4.6	-5.8

(a) 1675 F (30 min), water quench; 600 F (1 hr), air cool.

(b) 1550 F (30 min), oil quench; 700 F (1 hr), air cool.

(c) 1200 F (1 hr), furnace cool.

TABLE 14. VARIATION IN SOME PHYSICAL PROPERTIES WITH NICKEL CONTENT OF IRON-NICKEL ALLOYS CONTAINING FROM 20 TO 60 PERCENT NICKEL

Tensile Properties

Nickel, %	Manganese, %	Carbon, %	Treatment	Tensile Strength, 10^3 psi	Elastic Limit, 10^3 psi	Elongation, %	Reduction of Area, %
26.0	1.50	0.20	As rolled	78.5	12.0	50.0	70.7
			Quenched	76.0	15.0	49.5	70.5
30.0	1.50	0.15	As rolled	90.0	27.0	39.5	69.7
			Annealed	84.5	28.0	46.5	68.5
			Quenched	81.5	23.0	44.2	70.5
30.0	2.00	0.40	As rolled	105.0	45.0	47.0	66.6
			Annealed	101.5	35.0	46.5	66.4
			Quenched	91.0	25.0	45.7	69.3
32.3	2.30	0.12	As rolled	82.0	30.0	37.5	65.6
			Annealed	77.5	22.0	43.0	66.2
			Quenched	73.0	18.6	39.5	64.7
35.1	1.50	0.22	As rolled	89.0	30.0	40.6	67.5
			Annealed	85.0	30.0	42.0	67.3
			Quenched	82.0	27.5	41.0	65.0
36.0	0.50	0.08	As rolled	76.5	36.5	36.3	65.6
			Annealed	72.5	24.0	39.2	67.5
			Quenched	70.5	20.0	38.0	58.3
43.0	1.50	0.35	Cold drawn	100.0	52.5	16.2	46.0
45.0	1.50	0.37	As rolled	107.0	40.0	40.0	51.1
			Annealed	94.5	35.0	43.7	51.1
			Quenched	73.0	19.5	38.0	46.3
50.7	1.25	0.17	As rolled	99.0	48.5	38.5	67.7

Steels from The Midvale Company; annealed from above 790 C (1450 F); quenched from above 760 C (1400 F).

Elastic Modulus (Guillaume)

Nickel, %	Modulus of Elasticity, 10^6 psi
24.1	27.5
26.2	26.4
27.9	25.8
30.4	22.8
31.4	22.0
34.6	21.9
35.2	21.2
37.2	20.8
39.4	21.5
44.3	23.2
70.0	28.2

Density

Nickel, %	Density, g/cc: Hegg	Density, g/cc: Guillaume
20.0	8.02	--
24.1	--	8.111
26.2	--	8.096
30.0	8.06	--
30.4	--	8.049
31.4	--	8.008
34.6	--	8.066
37.2	--	8.005
39.4	--	8.076
44.3	--	8.120
50.0	8.05	--
60.0	8.29	--

Electrical and Thermal Properties

Nickel, %	Temperature Coefficient of Resistance, 0 - 100 C	Thermoelectric Power (Against Copper), 0 - 96 C, microvolts/C	Thermal Conductivity 20 - 100 C, cgs units	Specific Heat 25 - 100 C, cal/g
21.0	0.0018	23.5	--	--
22.1	0.0018	21.0	0.0490	0.1163
25.2	--	--	0.0320	0.1181
26.4	0.0016	16.7	--	--
28.4	--	--	0.0278	0.1191
35.1	0.0011	9.8	0.0262	0.1228
40.0	0.0022	22.4	--	--
45.0	--	29.0	--	--
47.1	0.0036	31.9	0.0367	0.1196
75.1	--	--	0.0691	0.1181

TABLE 15. PROPERTIES OF LOW-EXPANSION NICKEL ALLOY[31][a]

Composition, %	Ni 36 Fe-Bal	Ni 42 Fe-Bal	Ni 47-50 Fe-Bal
Physical Properties			
Density, lb/cu in.	0.292	0.292	0.296
Melting Point, F	2600	2606	2600
Thermal Conductivity, Btu/hr/sq ft/ft/F, 68-212 F	6.05	6.21	6.91
Coefficient of Expansion per F:			
-200 to 0 F	1.10×10^{-6}	3.42×10^{-6}	5.37×10^{-6}
0 to 200 F	0.70×10^{-6}	3.18×10^{-6}	5.55×10^{-6}
200 to 400 F	1.50×10^{-6}	2.97×10^{-6}	5.55×10^{-6}
400 to 600 F	6.35×10^{-6}	3.15×10^{-6}	5.55×10^{-6}
600 to 800 F	8.61×10^{-6}	5.50×10^{-6}	5.60×10^{-6}
800 to 1000 F	9.18×10^{-6}	8.55×10^{-6}	7.26×10^{-6}
Specific Heat, Btu/lb/F, 77-212 F	0.123	0.121	0.120
Electrical Resistivity, microhm-cm at 68 F	81	70	48
Mechanical Properties			
Modulus of Elasticity in Tension, psi	21×10^6	22×10^6	24×10^6
Tensile Strength, 10^3 psi:			
Annealed	70	76	82
Cold worked	90	120	140
Yield Point, 10^3 psi:			
Annealed	24	28	31
Cold worked	70	--	--
Elongation in 2 In., %:			
Annealed	36	38	41
Cold worked	20	--	--
Reduction of Area, %:			
Annealed	68	70	72
Cold worked	60	--	--
Hardness:			
Annealed (Bhn)	143	156	170
Cold worked (Rockwell)	--	B100	B103
Modulus of Rigidity, psi	8.1×10^6	8.5×10^6	9.3×10^6
Poisson's Ratio	0.290	0.290	0.290
Thermal Treatment			
Annealing Temperature, F	Soften progressively in range 1000 to 2300 F.		
Fabricating Properties			
Hot-Working Temp Range, F	to 2300 F	to 2300 F	to 2300 F
Machinability Index	Machine best at a hardness of about Rockwell C 20.		
Weldability	Can be welded by acetylene torch, metal arc, carbon arc, resistance methods.		
Corrosion Resistance	Resistant to atmospheric corrosion and to fresh and salt water.		
Available Forms	Bars, plate, sheet, strip, wire, tubing, forgings, castings.		
Uses	Length standards. instruments, hypodermic syringes, textile machining parts, thermostatic bimetal (to 400 F 400 F).		
	Higher temperature thermostatic bimetal, instruments, glass sealing (to 650 F).		
	Higher temperature low-expansion applications (to 1000 F).		

(a) Alloys which have become most widely used are 36% nickel (Invar) for low expansivity up to about 400 F, 42% nickel for temperatures up to 650 F, and 47 to 50% nickel for temperatures up to 1000 F.

TABLE 16. MECHANICAL PROPERTIES OF MINVAR[31]

Tensile Strength, 10^3 psi	20 to 30
Compressive Strength, 10^3 psi	80 to 100
Torsional Strength, 10^3 psi	30 to 35
Torsional Modulus, 10^6 psi	4.5
Modulus of Elasticity (Stiffness) at 25 Percent Tensile Strength, 10^6 psi	10.5
Transverse Strength[a]	
Load, lb	1,800 to 2,000
Deflection, in.	0.6 to 0.9
Resistance to Galling and Wear	High (similar to gray iron)
Vibration Damping Capacity	High (similar to gray iron)
Endurance Limit, 10^3 psi	9.9
Hardness, Brinell	100 to 125
Toughness by Impact, ft-lb[b]	150[c]
Pattern Shrinkage, in./ft	3/16
Machinability	Excellent

(a) Standard ASTM Type B bar.
(b) Arbitration bar unnotched, struck 3 in. above supports.
(c) 25 to 35 ft-lb for gray iron.

TABLE 17. PHYSICAL PROP?R?IES OF MINVAR[31]

Specific Gravit'	7.6
Density, ib/cu in.	0.275
Melting Point	?,250 F

Mean Coefficient of Expan?ion ?f Minvar Having 35 Percent ? ?kel

Temperature Range, F	Mi.?? ths ? ?
50-125	2.18
50-200	2.24
5C-300	2.40
50-400	2.75

Thermal Conductivi?y, cal/cm?/sec/C	0.094
Electrical Resistivity, /cm	1??-170
Magnetic Response	About 70 percent of gray iron

TABLE 18. SOME PROPERTIES OF NILVAR[32]

Composition

Nickel	?5.00-36.00
Carbon	0.10 max
Manganese	0.30 max
Silicon	0.50 max
Iron	Balance

Physical and Electrical Properties (Annealed)

Specific Gravity	8.08
Density, lb/cu in.	0.292
Thermal Emf Copper (0-100 C) microvolts/C	9.72
Specific Resistance, ohms/cir. mil ft	500
Temperature Coefficient of Electrical Resistance, ohms/ohm/C	1.354×10^{-3}
Specific Heat, Btu/lb/F (77-212 F)	0.123
Thermal Conductivity, Btu/ft²/in./F/hr (68-212 F)	72.6
Melting Point, C	1425
Curie Temperature, C	277
Inflection Temperature, C	190
Typical Thermal Coefficient Expansion, in./in./F (Reference 70 F)	
-200 to 0 F	0.0000011
0 to 200 F	0.0000007
200 to 400 F	0.0000015
400 to 600 F	0.0000064
600 to 800 F	0.0000086
800 to 1000 F	0.0000095
Poisson's Ratio	0.290
Modulus of Elasticity, 10^6 psi	21
Modulus of Rigidity, 10^6 psi	8

Total Expansion Versus Temperature

Temperature, F	Expansion, in./in.
-100	0.0000
0	0.0001
100	0.0002
200	0.00025
300	0.00035
400	0.00055
500	0.0015
600	0.0018
700	0.0026
800	0.0035
900	0.0045
1000	0.0055

Typical Tensile Properties

	Annealed	Cold Drawn
Tensile Strength, 10^3 psi	70	90
Yield Point, 10^3 psi	24	70
Elongation, % in 2 in.	36	20
Reduction of Area, %	68	60
Brinell Hardness	143	185

Variation of Permeability with Temperature (for a field strength of 5 oersteds)

Temperature, F	Permeability, μ
0	1800
50	1715
100	1630
150	1545
200	1450
240	1360

Thermomagnetic Properties (Hard Drawn)

Field Strength,* H, oersteds	Normal Induction, B, gauss	Permeability, μ
2	300	1700
4	1600	2900
6	4000	4400
8	5600	4500
10	6500	4300
Thermomagnetic Properties (Annealed)		
0.1	200	1000
0.4	9500	2200
0.8	3100	3700
1.2	4400	3500
1.3	4450	3400

* Also known as Magnetizing Force (H).

TABLE 19. RELATIVE MACHINABILITY OF CARPENTER FREE-CUT INVAR 36(21)

Operation	Regular Invar (Non-Free-Machining) Speed	Regular Invar (Non-Free-Machining) Remarks	Carpenter Free-Cut Invar 36 Speed	Carpenter Free-Cut Invar 36 Remarks
Roughing (Bar 1" round) Cut: 3/32" Feed: 0.0055"	29 sur ft/min	Machining satisfactory		
	49 sur ft/min	Tool failed after cutting about 1" along bar		
	82 sur ft/min	Tool failed after only a few revolutions.	82 sur ft/min	Machining satisfactory; no effect on tool
			137 sur ft/min	Top speed for the lathe used; no indication of failure; at this speed feed was increased from 0.0055" to 0.0125" with results still satisfactory
Finishing Cut: 0.050" Feed: 0.0055"	23 sur ft/min	Indications were that this speed provided the best possible finish	112 sur ft/min	This speed gave a very good finish; with feed increased to 0.0125" the finish was still good
NOTE: This test made to determine highest speed possible for satisfactory finish				
Drilling 7/16" rough high-speed drills, test block 2-3/16" thick. Feed: 0.004" per revolution	665 rpm, 75 fpm	Drill failed completely when hole was only 1-1/16" deep	665 rpm	Drill went through entire 2-3/16" test block with ease; after test, drill still in good condition
Threading Single-point tool. Ten threads per in. Two roughing cuts, 0.04". Two finish cuts, 0.004"	60 rpm	Two rough cuts resulted in "torn" threads; two finish cuts failed to provide satisfactory threads	188 rpm	Same number of rough and finish cuts made; threads greatly superior to those on regular Invar sample
NOTE: This test made to determine highest speed for best possible threads.				

TABLE 20. SOME PROPERTIES OF INVAR(21)

Physical Constants

Thermal Conductivity:

In British thermal units = 72.6
(Btu hr/sq ft/in. thickness/F from +70 F to 212 F)

In CGS Units = 0.025
(Cal/sec/sq cm/cm thickness/C from 21 C to 100 C)

Specific Heat (77 F to 212 F) = 0.123

Thermoelastic Coefficient:

60 F to 122 F = +27 x 10^{-5}/F
16 C to 50 C = +50 x 10^{-5}/C

Specific Electrical Resistance:

Carpenter Invar 36 --
Annealed: 530 ohms/cir. mil ft (88 Microhms per cc)
Cold drawn: 490 ohms/cir. mil ft (81 microhms per cc)

Carpenter Free-Cut Invar 36 --
Annealed: 570 ohms/cir. mil ft (95 microhms per cc)
Cold draw : 510 ohms/cir. mil ft (85 microhms per cc)

Tensile Properties, Hardness, etc., for 1" Round Specimen

Tensile Strength 10^3 psi	Elastic Limit--Yield Point, 10^3 psi	Reduction of Area, %	Elongation in 2", %	Hardness Brinell	Hardness Rockwell	Elastic Modulus, 10^6 psi
(Annealed)						
65	40	65	35	125	B-70	20.
(Cold Drawn)						
90	70	60	20	185	B-90	21.

Izod Impact at B-90 Rockwell = 90 ft-lbs
Shearing Strength at B-90 Rockwell = 45 x 10^3 psi
Torsional Modulus = 7,100,000
Endurance Ratio $\frac{\text{(endurance limit)}}{\text{(tensile strength)}}$ = approximately 0.4

TABLE 21. DIMENSIONAL STABILITY OF VARIOUS INVAR-TYPE ALLOYS AFTER HEAT TREATMENT[33]

Alloy	Specimen	Treatment[a]		Rockwell Hardness	Length Change in Time and Cyclic Stability Tests, µ in./in. Aged at 70 F 1 mo	3 mo	12 mo	Aged at 160 F 1 mo	3 mo	12 mo to	Cycled 10X, -95 F	Thermal Expansion Coefficient, 10^{-6}/C
Ni-Span Lo 45	60-1A	Cold rolled	(as received)	A63	5	-10	-10[b]	-	-	-	-	-
		Solutionize	1800 F, 1-1/4 hr, WQ	-	-	-	-	-	-	-	-	-
	60-1,2,3	Age	1250 F, 21 hr, AC	C34	-10	-15	-15[b]	-15	-15	-20[b]	-10	
42Ni-	77-1A	Quench-Anneal	1525 F, 1/2 hr, WQ	B72	0	0	0	-10	-	-	-	1.5
58 Fe	77-2,3			-	-	-	-	-	-	-	-	-
Ni-Span-C	61-1	Cold drawn	(as received)	A60	- 5	- 5	- 5[b]	-	-	-	-	-
		Solutionize	1800 F, 1-1/4 hr, WQ	-	-	-	-	-	-	-	-	-
	61-1,2,3	Age	1250 F, 21 hr, AC	C29	-10	-10	-10[b]	-15	-15	-15[b]	-30	7.2
Super		Cold drawn	(as received)	B98	-	-	-	-	-	-	-	-
Nilvar	9-1,2,3	Anneal	1525 F, 1 hr, FC	B97	-10	-	-	- 5	-	-	+25	-
		Stress Relieve	1200 F, 1 hr, FC	-	-	-	-	-	-	-	-	-
	9-3	Stabilize	200 F, 24 hr, AC	-	-	-	-	-	-	-	-	0.8
32 Ni-	75-1,2,3	Quench-Anneal	1525 F, 1/2 hr, WQ	B93	0	+ 5	+ 5	+ 5	-	-	-55	3.4
68 Fe				-	-	-	-	-	-	-	-	-
Ni-Span-	62-1	Cold drawn	(as received)	A62	0	-10	-15[b]	-	-	-	-	-
Hi		Solutionize	1800 F, 1-1/4 hr, WQ	-	-	-	-	-	-	-	-	-
	62-1,2,3	Age	1250 F, 20 hr, AC-(R)	C30	- 5	- 5	- 5[b]	-10	-10	-10[b]	-10	15.5

(a) (R)-recommended treatment; WQ - water quenched; FC - furnace cooled; AC - air cooled.

(b) 6 months of aging

TABLE 22. COMPOSITIONS OF ALLOYS REFERRED TO IN TABLE 19[33]

Specimen No.	Nickel Alloy	Composition C	Mn	Si	S	P	Ni	Fe	Cr	Cu	Al	Ti
60	Ni-Span-Lo 45	0.02	0.55	0.39	0.007	-	44.88	51.03	0.31	0.05	0.65	2.11
77	42Ni-50Fe	0.08	0.52	0.21	0.008	0.009	40.87	Bal	-	-	-	-
61	Ni-Span C	0.04	0.57	0.55	0.007	-	41.60	48.11	6.01	0.05	0.61	2.10
51	Reg. Invar	0.07	[illegible]	0.39	0.018	0.010	35.80	Bal	-	-	-	-
50	Reg. Invar	0.10	0.16	0.28	0.013	0.008	35.13	Bal	-	-	-	-
52	Free-Cut Invar	0.07	0.88	0.32	0.005	0.009	35.37	Bal	Mo 0.08	Se 0.16	-	0.44
65	Free-Cut Invar	0.03	0.85	0.34	0.016	0.006	36.37	Bal	Mo 0.00	Se 0.13	-	0.40
9	Super Nilvar	0.08	0.15	0.12	0.013	0.008	31.20	Bal	-	Co 5.37	-	-
76	32Ni-68Fe	0.10	0.76	0.27	0.008	0.006	32.56	Bal	-	-	-	-
62	Ni-Span-Hi	0.04	0.58	0.53	0.007	-	28.82	58.39	8.62	0.04	0.72	2.23

TABLE 23. DIMENSIONAL STABILITY OF INVAR AFTER VARIOUS HEAT TREATMENTS(33)

Alloy	Specimen No.	Treatment(a)	Rockwell Hardness	Length Change in Time and Cyclic Stability Tests, µin./in.: Aged at 70 F, 1 Mo.	Aged at 70 F, 3 Mo.	Aged at 70 F, 12 Mo.	Aged at 160 F, 1 Mo.	Aged at 160 F, 3 Mo.	Aged at 160 F, 12 Mo.	Cycled 10X, to -95 F	Thermal Expansion Coefficient, 10^{-6}/C
Free-Cut Invar	52-1,2,3	Cold drawn, as received	B98	0	0	0	+15	0	+50(b)	-20	--
	52-42,42	Stabilize, 200 F, 20 hr, AC	B98	- 5	- 5	-	- 5	- 5	--	--	--
		Cold drawn, as received	B95	--	--	--	--	--	--	--	--
	52-4,5,6	Stress relieve, 1200 F, 1 hr, FC	B95	-15	-20	-25	0	--	-10(b)	- 5	--
	52-31	Stress relieve, 200 F, 1 hr, AC	B95	-15	-20	-20(b)	--	--	--	--	--
	52-32,33,34	Stress relieve, 200 F, 20 hr, AC-(R)	B95	- 5	- 5	- 5(b)	0	5	- 5(b)	-10	1.5
	52-7,8,9	Stress relieve, 300 F, 1 hr, FC	B95	-15	-20	-30	-20	-20	-35	-15	--
	52-30	Stress relieve, 400 F, 1 hr, AC	B95	- 5	- 5	- 5(b)	--	--	--	--	--
	52-10,19,20	Quench-anneal, 1525 F, 1/2 hr, WQ	B78	- 5	-10	-10	-40	--	--	-10	--
	52-19	Stabilize, 158 F, 1 mo, WQ	B78	0	0	0	--	--	--	--	--
	53-36,37,38	Stabilize, 200 F, 20 hr, AC	B78	-35	-35	-30(b)	- 5	- 5	--	0	--
	52-15	Stabilize, 200 F, 1 mo, WQ	B78	0	0	- 5	--	--	--	--	--
	52-11	Stabilize, 250 F, 1 hr, FC	B78	- 5	-10	-10	--	--	--	--	--
	52-18C	Stabilize, 300 F, 1 mo, WQ	B78	-10	-10	-15	--	--	--	--	--
	52-17	Stabilize, 400 F, 1 mo, WQ	B78	0	- 5	- 5	--	--	--	--	--
	52-21	Stabilize, 600 F, 1 mo, WQ	B78	- 5	- 5	-10	--	--	--	--	--
	52-27,28,29	Anneal, 1525 F, 1/2 hr, FC	B78	-10	- 5	-20(b)	- 5	- 5	- 5(b)	-15	--
	52-39,40	Stabilize, 200 F, 20 hr, AC	B77	- 5	- 5	--	- 5	- 5	--	--	--
Free-Cut Invar	66-10,11,12	Cold drawn, as received	B87	--	--	--	--	--	--	--	--
		Stress relieve, 1200 F, 1 hr, FC									
		Stabilize, 200 F, 48 hr, AC-(R)	B69	-10	-10	-10(b)	- 5	- 5	0(b)	-35	2.0
	66-7,8,9	Quench-anneal, 1525 F, 1/2 hr, WQ		--	--	--	--	--	--	--	--
		Stress relieve, 1200 F, 1 hr, AC		--	--	--	--	--	--	--	--
		Stabilize, 200 F, 48 hr, AC(R)	B79	- 5	- 5	-10(b)	- 5	0	0(b)	-10	--
	66-1,2,3	Quench-anneal, 1525 F, 1/2 hr, WQ	B78	-20	-20	-25(b)	-20	-20	-20(b)	-25	--
	66-4,5,6	Stress relieve, 600 F, 1 hr, AC		--	--	--	--	--	--	--	--
		Stabilize, 200 F, 48 hr, AC	B78	-10	-10	-15(b)	-10	-10	-15(b)	-10	--
Regular Invar	50L-1,2,3	Quench-anneal, 1525 F, 1/2 hr, WQ	B77	-15	-20	-20	+40	+ 5	-70	-75	--
	50T-1,2,3	Quench-anneal, 1525 F, 1/2 hr, WQ	B77	-45	-40	-35(b)	-10	-20	-30(b)	+20	--
Regular Invar	51-17,18,19	Anneal, 1525 F, 1 hr, FC	B77	-25	-25	--	+ 5	+ 5	--	-15	--
	51-1,2,3	Quench-anneal, 1525 F, 1/2 hr, WQ	B77	- 5	- 5	--	+25	+25	--	-15	--
	51-2C,D	Stress relieve, 158 F, 1 mo, WQ	B77	0	- 5	- 5	--	--	--	--	--
	51-4,5,6	Stress relieve, 250 F, 1 hr, FC	B77	-10	- 5	0	-10	0	--	-10	--
	51-10	Stress relieve, 300 F, 1 mo, WQ	B77	+ 5	+ 5	+ 5	--	--	--	--	--
	51-9	Stress relieve, 400 F, 1 mo, WQ	B77	+10	+10	+10	--	--	--	--	--
	51-8	Stress relieve, 600 F, 1 mo, WQ	B77	+ 5	+ 5	--	--	+30	--	--	--
	51-20	Stress relieve, 600 F, 1 hr, WQ	B77	--	--	--	+25	+25	+25(b)	--	--
		Stress relieve, 1200 F, 1 hr, AC									
	51-22,23,24	Stabilize, 200 F, 48 hr, AC		- 5	- 5	- 5(b)	- 5	0	0(b)	-10	--
Minover Cast Iron	49-1,2,3	As cast, as received	B59	0	+ 5	+20	+25	+25	+30(b)	- 5	4.2

(a) (R) - recommended treatment; WQ - water quenched; FC - furnace cooled; AC - air cooled.
(b) 6 months of aging.

TABLE 24. SOME OF THE ALLOYS STUDIED BY HIDNERT AND KIRBY(38)

Sample	Chemical Composition, %						Treatment	Test	Phase
	Co[b]	Fe	Cr	C	Mn	Si			
1762	53.8_8	36.9_8	8.5_6	0.13	0.01	0.44	Hydrogen-annealed at 1000 C for 1 hr and furnace-cooled in 20 hr	1H	γ
								1C	γ
								2C	
								2H	α+γ
								3H	α+γ
								3C	α+γ
17[illegible]1	54.2_4	36.5_6	9.0_6	-	-	0.14	Hydrogen-annealed at 1000 C for 1 hr and furnace-cooled in 20 hr	1H	γ
								1C	γ
								2C	γ
								2H	γ
								3H	γ
								3C	γ
								4H	γ
17[illegible]3	53.8_1	36.6_5	9.0_9	0.07	0.07	0.31	"	1H	γ
								2H	γ
								2C	γ
								3C	γ
								3H	γ
								4H	γ
								4C	γ
								5H	γ
								6H	[illegible]
1783	54.0_9	36.6_1	9.1_5	-	-	0.15	"	1H	γ
								1C	[illegible]
								2C	γ
								2H	γ
								3H	γ
								3C	γ
								4H	γ
1782	54.3_2	3[illegible].3_3	9.2_0	-	-	0.15	"	1H	γ
								1C	γ
								[illegible]	γ
								2H	γ
								3H	γ
								3C	γ
								4H	γ
1767	53.4_0	36.9_2	9.3_0	0.06	0.08	0.24	Hydrogen-annealed at 1000 C for 1 hr and furnace-cooled in 20 hr	1H	γ
								1C	γ
								2C	γ
								2H	γ
								3H	γ
								3C	γ
								4H	γ
1770	53.5[illegible]	36.7_0	9.3_6	0.03	0.07	0.29	"	1H	γ
1772	53.5_3	36.6_1	9.4_3	0.08	0.07	0.28	"	1H	γ
								1C	γ
								2C	γ
								2H	γ
								3H	γ
								3C	γ
								4H	γ
1769	53.5_6	[illegible]	9.5_6	0.06	0.07	0.22	"	1H	γ
								1C	γ
								2C	γ
								2H	γ
								3H	γ
								3C	γ
								4H	γ

TABLE 24. (Continued)

Sample	Chemical Composition, % Co[b]	Fe	Cr	C	Mn	Si	Treatment	Test	Phase
1764	53.3_0	36.6_3	9.5_7	.09	.08	.33	"	1H	γ
								2H	γ
1765A	53.1_7	36.7_8	9.5_7	-	-	-	"	1H	γ
								1C	α+γ
								2C	γ
								2H	γ
								3H	γ
								3C	γ
								4H	γ
1773	53.9_2	36.2_2	9.6_7	.07	.07	.05	"	1H	γ
								1C	γ
								2C	γ
								2H	γ
								3H	γ
								3C	γ
								4H	γ
1765	53.1_4	36.5_1	9.8_7	.11	.10	.27	"	1H	γ
								1C	γ
								2C	γ
								2H	γ
								3H	γ
								3C	γ
								4H	γ

TABLE 25. PHYSICAL AND MECHANICAL PROPERTIES OF ELINVAR ALLOYS[42]

Chemical Composition (Varies With Different "Elinvars")	
Nickel	33 to 35 percent
Iron	61 to 53 percent
Chromium	21 to 5 percent
Tungsten	1 to 3 percent
Manganese	0.5 to 2 percent
Silicon	0.5 to 2 percent
Carbon	0.5 to 2 percent
Mechanical Properties (Elinvar)	
Elastic Limit, psi	45,000
Coefficient of Modulus of Elasticity (-50 to +50 C)	-6.6×10^{-5}
Coefficient of Modulus of Ridigity (-50 to +50 C)	-7.2×10^{-5}
Mechanical Properties (Modelvar)	
Coefficient of Modulus of Elasticity (-50 to +50 C)	$+46.2 \times 10^{-5}$
Thermal Properties (Elinvar)	
Coefficient of Thermal Expansion	$0.6 \times 10^{-6}/C$
Thermal Properties (Modelvar)	
Coefficient of Thermal Expansion	$0.0 \times 10^{-6}/C$

TABLE 26. NOMINAL MECHANICAL PROPERTIES OF Ni-SPAN ALLOYS

	Condition			Mechanical Properties						
Alloy	Solution Treated	Cold Working, %	Aging	Proportional Limit, 10^3 psi	Yield Strength 0.2% Offset, psi	Tensile Strength, 10^3 psi	Elongation in 2 in., %	Hardness Brinell, (3000 Kg)	Tensile Modulus of Elasticity, 10^{-6} psi	Torsional Modulus of Elasticity, 10^{-6} psi
Ni-Span Lo 42	Yes	No	No	20	40	90	32.0	140	21.0	—
	Yes	No	Yes	65	120	165	14.0	330	22.0	—
	Yes	50	No	70	115	130	3.0	240	22.5	—
	Yes	50	Yes	110	165	195	5.0	385	23.0	—
Ni-Span Lo 45	Yes	No	No	Slightly lower than Ni-Span Lo 42.						
	Yes	No	Yes							
	Yes	50	No							
	Yes	50	Yes							
Ni-Span Lo 52	Yes	No	No	15	35	85	27.0	125	—	—
	Yes	No	Yes	55	95	120	17.0	305	22.0	—
Ni-Span Hi	Yes	No	No	20	35	80	30.0	140	—	—
	Yes	No	Yes	60	95	150	20.0	305	25.0	—
	Yes	50	No	60	120	140	4.0	250	24.5	—
	Yes	50	Yes	80	130	180	8.0	370	26.0	—
Ni-Span C	Yes	No	No	15	35	90	40.0	145	24.0	—
	Yes	No	Yes	65	115	180	18.0	345	26.5	10.0
	Yes	50	No	55	130	135	6.0	275	25.5	—
	Yes	50	Yes	105	180	200	7.0	395	27.0	10.0

TABLE 27. EFFECT OF NICKEL CONTENT ON AGING TEMPERATURE FOR MAXIMUM HARDNESS IN Ni-SPAN Lo ALLOYS

Alloy	Nickel, %	Optimum Aging Temp, F	Hardness, Brinell (3000 Kg)
Ni-Span Lo 42	42	1225	330
Ni-Span Lo 45	45	1250	320
Ni-Span Lo 52	52	1300	305

TABLE 28. RECOMMENDED AGING CONDITIONS FOR MAXIMUM HARDNESS

	Hours at Temperature for	
Temp, F	Solution-Treated Material	Solution-Treated and Cold-Worked Material
1100	48	3 to 4
1200	24	3 to 4
1250	24	3 to 4
1300	9 to 12	1
1350	3	1

TABLE 29. COMPOSITION AND PROPERTIES OF Ni-SPAN C(44)

Composition Specification	
Nickel	41 to 43 percent
Chromium	4.9 to 5.5 percent
Titanium	2.2 to 2.6 percent
Carbon	0.06 max
Manganese	0.80 max
Silicon	1.00 max
Aluminum	0.30 to 0.80 percent
Sulfur	0.04 max
Phosphorus	0.04 max
Iron	Balance

Physical Properties of Constant-Modulus Alloy	
Melting Range	2650 to 2700 F
Density	0.294 lb/cu in.
Specific Gravity	8.15 g/cc
Specific Heat, 32 to 212 F	0.12 Btu/lb/F
Thermal-Expansion Coefficient -50 to +150 F	4.5 x 10^{-6} F
Thermal Conductivity, 32 to 212 F	90 Btu/sq ft/F/in./hr

	Soft Annealed	Fully Aged(a)
Thermal Coefficient of Resistivity, per F	0.00025	0.00031
Electrical Resistivity, ohms/sq mil/ft at 68 F	580	480
Electrical Conductivity, % IACS at 68 F	1.4	1.7
Modulus of Elasticity, 10^6 psi	24	27.5
Modulus of Rigidity, 10^6 psi	9.4	9.8
Thermoelastic Coefficient, x 10^{-6}/F	-35 to -15	-10 to +10
Tensile Strength, 10^3 psi	90	200
Yield Strength (0.2% offset), 10^3 psi	35	180
Proportional Limit, 10^3 psi	15	110
Elongation, % in 2 in.	40	7
Brinell Hardness	125	395
Rockwell Hardness	70B	42C

	With No Cold Work				With 50 Percent Cold Work			
	Before Hardening	After Heat Treatment at Temperature 1100 F	1250 F	1350 F	Before Hardening	After Heat Treatment at Temperature 1100 F	1250 F	1350 F
Typical Mechanical Properties								
Tensile Strength, 10^3 psi	90	150	180	175	135	185	200	200
Yield Strength (0.2% Offset), 10^3 psi	35	95	115	115	130	160	180	180
Proportional Limit, 10^3 psi	15	70	65	65	55	105	110	105
Elongation, % in 2 in.	40	30	18	17	6	8	7	7
Rockwell Hardness	70B	23C	33C	32C	28C	39C	42C	42C
Brinell Hardness	125	245	305	300	270	360	395	395
Modulus of Elasticity, x 10^6 psi	24	27	26.5	26.5	25.5	27.5	27	27

(a) For strip 50 percent cold worked before aging. Values for wire are higher.

TABLE 30. PROPERTIES OF Ni-SPAN C[45]

(Nominal Composition: 42 Percent Nickel, 2.5 Titanium, 5.5 Chromium, 0.06 Carbon)

	Solution Annealed	Heat-Treating Temperature 1100 F	1250 F	1350 F	Solution Annealed Plus 50 Percent Cold Worked	Heat-Treating Temperature 1100 F	1250 F	1350 F
Tensile Strength, 10^3 psi	90	150	180	175	135	185	200	200
Yield Strength (0.2% Offset), 10^3 psi	35	95	115	115	130	160	180	180
Proportional Limit, 10^3 psi	15	70	65	65	55	105	110	105
Elongation in 2 Inches, %	40	30	18	17	6	8	7	7
Rockwell Hardness	78B	32C	37C	37C	29C	39C	42C	42C
Brinell Hardness	145	300	345	340	275	365	395	395
Modulus of Elasticity, 10^6 psi	24	27	26.5	26.5	25.5	27	27.5	27
Modulus of Rigidity, 10^6 psi	10	10	10	10	10	10	10	10
Approximate Thermoelastic Coefficient x 10^6/F	-15	-10	- 5	0	-10	- 5	0	+10
Thermal-Expansion Coefficient x 10^{-6}/F (-50 to 150 F)	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
Thermal Conductivity, Btu/sq ft/F/in.	90	90	90	90	90	90	90	90
Electrical Resistivity, ohms/sq mil ft at 68 F	480 to 580[a]							
Electrical Conductivity (at 68 F)	1.4 to 1.7 percent[a]							

(a) Depending on amount of cold working and precipitation heat treatment.

TABLE 31. MECHANICAL PROPERTIES OF LOW-EXPANSION ALLOYS[45]

	Ni-Span Lo 42			Ni-Span Lo 45			Ni-Span Lo 52		
Composition:	Ni-42% Ti-2.4%	C-0.06% Bal - Fe		Ni-45% Ti-2.4%	C-0.06% Bal - Fe		Ni-52% Ti-2.4%	C-0.6% Bal - Fe	
Condition:	Annealed	Hardened	50% Cold Worked and Hardened	Annealed	Hardened	50% Cold Worked and Hardened	Annealed	Hardened	50% Cold Worked and Hardened
Proportional Limit, 10^3 psi	20	65	110	19	61	103	15	55	100
Yield Strength, Offset, 10^3 psi	40	120	165	37	113	155	35	95	140
Tensile Strength, 10^3 psi	90	165	195	85	155	183	85	120	175
Elongation, %	32	14	5	30	13	5	27	17	5
Rockwell Hardness	78B	34C	40C	74B	33C	37C	71B	32C	36C
Modulus of Elasticity, 10^6 psi	21.0	22.0	22.5	21.0	22.0	22.5	21.0	22.0	22.3

TABLE 32. CHEMICAL COMPOSITION AND PROPERTIES OF Ni-SPAN C SPRING MATERIAL[42]

Chemical Composition

Nickel	41 to 45 percent
Chromium	4.9 to 5.5 percent
Titanium	2.2 to 2.6 percent
Carbon	0.06 max
Manganese	0.80 max
Silicon	1.00 max
Aluminum	0.30 to 0.80 percent
Sulfur	0.04 max
Phosphorus	0.04 max
Iron	Balance

Physical Properties

Density, lb/cu in.	0.294
Specific Gravity, g/cc	8.[illegible]

Mechanical Properties

Modulus of Elasticity at Room Temperature, psi Solution Annealed	24×10^6

Modulus of Elasticity at Room Temperature, 10^6 psi

	Unaged	After Heat Treatment at Temperature 1100 F	1250 F	1350 F
Solution Annealed	24	27	26.5	26.5
Solution Annealed +[illegible]% Cold Worked	25.5	27.5	27	27

Temperature Coefficient of Modulus of Elasticity, psi F	-10 to $+10 \times 10^{-6}$
Thermoelastic Coefficient, ($\times 10^{-6}$/F)	
Solution Annealed	-35 to -15
Fully Aged	-10 to +10
Modulus of Rigidity at Room Temperature, psi $\times 10^{-6}$	
Solution Annealed	9.4
Fully Aged	9.8

(values are for strip 50% cold worked, values for wire are higher)

Tensile Strength (Typical) at Room Temperature, psi

	Unaged	After Heat Treatment at Temperature 1100 F	1250 F	1350 F
Solution Annealed	90,000	150,000	180,000	175,000
Solution Annealed +50% Cold Work	135,000	185,000	200,000	200,000

Tensile Strength at Elevated Tmperatures (for 1/8" diam wire, 50% cold work, heat treated 1250 F for 4-1/2 hr, fast cool in vacuum):

500 F	177,000 psi
600 F	171,000 psi

Yield Strength (Typical) at Room Temperature, psi

	Unaged	After Heat Treatment at Temperature 1100 F	1250 F	1350 F
Solution Annealed	35,000	95,000	115,000	115,000
Solution Annealed +50% Cold Work	130,000	160,000	180,000	180,000

Yield Strength at Elevated Temperatures (for 1/8" diam wire, 50% cold work, heat treated 1250 F for 4-1/2 hr, fast cool in vacuum):

500 F	140,000 psi
600 F	135,000 psi

Proportional Limit (Typical) at Room Temperature, psi

	Unaged	After Heat Treatment at Temperature 1100 F	1250 F	1350 F
Solution Annealed	15,000	70,000	65,000	65,000
Solution Annealed + 50% Cold Work	55,000	105,000	110,000	105,000

TABLE 32 (CONTINUED)

Proportional Limit at Elevated Temperatures (for 1/8" diam wire, 50% cold worked, heat treated 1250 F for 4-1/2 hr, fast cool in vacuum):

500 F	71,000 psi
600 F	44,000 psi

Hardness (Typical) at Room Temperature, Rockwell

		After Heat Treatment at Temperature		
	Unaged	1100 F	1250 F	1350 F
Solution Annealed	70 B	23C	33C	32C
Solution Annealed +50% Cold Work	28C	39C	42C	42C

Safe Working Stresses for Cold-Coiled Compression Springs

Light Service	62,000 psi
Average Service	54,000 psi
Severe Service	44,000 psi

Relaxation at Elevated Temperatures (Load Loss) (Under Steady Load of 50,000 psi)

600 F	2.0%
700 F	3.0%
800 F	9%

Hysteresia Error (percent of deflection)	0.05 max
Creep Error (percent of deflection in 5 min)	0.02 max

Thermal Treatment

Hardening Temperature, (in nonoxidizing atmosphere depends on degrees of cold work)	1100-1350

Thermal Properties

Linear Coefficient of Thermal Expansion (-50 to +150 F), in./in./F	4.5×10^{-6}
Specific Heat (32-212 F), Btu/lb/F	0.12
Thermal Conductivity (32-212 F), Btu/sq ft/F/in./hr	90

Electrical Properties

Electrical Resistivity, 68 F, ohms/sq mil/ft

Soft Annealed Condition	580
Fully Aged, 50% cold work before aging (wire values are higher)	480

Thermal Coefficient of Resistivity/F

Soft Annealed Condition	0.00025
Fully Aged, 50% cold work before aging (wire values are higher)	0.00031

Electrical Conductivity, 68 F (Copper = 100%)

Soft Annealed Condition	1.4
Fully Aged Condition	1.7

TABLE 33. TENSILE PROPERTIES OF Ni-SPAN C (1/8-In.-Diameter Wire)[42]

Specimen	Test Temp, F	Ftu, 10^3 psi	Fty, 10^3 psi (0.2% Offset)	Elongation, in 6 In., %	Modulus of Elasticity, 10^6 psi	Approximate Tensile Proportional Limit, 10^3 psi	Approximate Torsional Proportional Limit, 10^3 psi	Approximate Modulus of Rigidity, 10^6 psi
1A-12	-40	196.8	157.6	3.3	24.2	75.7	41.6	9.3-9.7
1B-23	-40	--	--	--	26.1	70.8	38.9	10.0-10.4
1B-24	-40	--	--	--	24.7	71.6	39.4	9.5-9.9
1C-12A	-40	--	--	--	24.3	--	--	9.3-9.7
1C-12B	-40	--	--	--	24.7	--	--	9.5-9.9
1A-13	RT	200.0	153.9	10.0	28.0	53.8	29.6	10.8-11.2
1B-25	RT	--	--	--	25.0	55.4	30.5	9.6-10.0
1B-26	RT	--	--	--	24.9	54.6	30.0	9.6-10.0
1C-13A	RT	--	--	--	24.8	--	--	9.5-9.9
1A-14	165	195.4	150.4	9.2	26.3	71.6	39.4	10.1-10.5
1B-27	165	--	--	--	25.7	64.1	35.3	9.9-10.3
1B-28	165	--	--	--	23.5	54.7	30.1	9.0-9.4
1C-14A	165	--	--	--	24.0	--	--	9.2-9.8
1A-15	300	192.9	146.5	7.0	26.7	62.0	34.1	10.3-10.7
1B-29	300	--	--	--	25.6	53.5	29.4	9.8-10.2
1B-30	300	--	--	--	25.1	50.5	27.8	9.7-10.0
1C-15A	300	--	--	--	24.4	--	--	9.4-9.8
1A-16	800	178.0	132.1	1.3	24.2	60.0	33.0	9.3-9.7
1B-31	800	--	--	--	24.0	58.0	31.9	9.2-9.6
1B-32	800	--	--	--	24.0	56.6	31.1	9.2-9.6
1C-16A	800	--	--	--	22.9	--	--	8.8-9.2

TABLE 34. PROPERTIES OF Ni-SPAN C[28]

Recommended Use

High physical properties; age hardenable, can replace BeCu particularly where brazing is necessary; zero temperature coefficient of modulus

Dimensional Stability

Temperature, F	Time, months	Dimensional Changes, μin./in.
160	6	10
-100 to +200		30(a)

Procedure

Initial Condition: Cold drawn, 1800 F, 1-1/4 hr water quench, age 1250 F, 21 hr, air cool

Physical Properties

Density	8.15 g/cm^3
Thermal Conductivity	0.0202 cal/g/cm^2/cm/C/sec
Resistivity	79.7 ohm/cm
Specific Heat	0.12 cal/g
Magnetic Properties	Ferro magnetic
Thermal-Expansion Coefficient	7.2 in./in./C

Mechanical Properties

Hardness	29 Rockwell C
UTS	100 x 10^3 psi
YP (0.2% offset)	115 x 10^3 psi
Elongation (2 in.)	18%
Modulus of Elasticity	26.5 x 10^6 psi
Elastic Limit	57 x 10^3 x psi
Elastic Limit/Density	7.06 x 10^3 psi/g/cm^3
Modulus/Density	3.25 x 10^6 psi/g/cm^3

(a) After 10 cycles between -100 and +200 F.

TABLE 35. MECHANICAL PROPERTIES OF WILCO Ni-SPAN C CONSTANT-MODULUS ALLOY[a](49)

(Nominal Composition: 42.2% Nickel, 2.5% Titanium, 5.3% Chromium, 0.03% Carbon)

	Solution Annealed	After Heat Treatment at Temperature			Solution Annealed Plus 50% Cold Worked	After Heat Treatment at Temperature		
		1100 F	1250 F	1350 F		1100 F	1250 F	1350 F
Tensile Strength, 10^3 psi	90	150	180	175	135	185	200	200
Yield Strength (0.2% Offset), 10^3 psi	35	95	115	115	130	160	180	180
Proportional Limit, 10^3 psi	15	70	65	65	55	105	110	105
Elongation in 2 In., %	40	30	18	17	6	8	7	7
Rockwell Hardness	70B	23C	33C	32C	28C	39C	42C	42C
Brinell Hardness	125	245	305	300	270	360	395	395
Modulus of Elasticity, 10^6 lb/sq in.	24	27	26.5	26.5	25.5	27.5	27	27

(a) The values listed are typical and are for general engineering use. They should not be used for specification purposes.

TABLE 36. SUMMARY OF PHYSICAL AND MECHANICAL PROPERTIES OF WILCO Ni-SPAN C CONSTANT-MODULUS ALLOY[a](49)

Melting Range	2650 to 2700 F	
Density	.294 lb/cu in.	
Specific Gravity	8.15 g/cc	
Specific Heat (32 to 212 F)	.12 Btu/lb/F	
Thermal Expansion Coefficient (-50 to +150 F)	4.5×10^{-6}/F	
Thermal Conductivity (32 to 212 F)	90 Btu/sq ft/F/in./hr	
	Solution Annealed	Fully Aged
Thermal Coefficient of Resistivity (/F)	.00025	.00031
Electrical Resistivity (ohms/sq mil ft at 68 F)	580	480
Electrical Conductivity (% IACS at 68 F)	1.4	1.7
Modulus of Elasticity, psi	24×10^6	27.5×10^6
Modulus of Rigidity, psi	9.4×10^6	9.8×10^6
Thermoelastic Coefficient (x 10^{-6}/F)	-35 to -15	-10 to +10
Tensile Strength, 10^3 psi	90	200(a)
Yield Strength (0.2% Offset), 10^3 psi	35	180(a)
Proportional Limit, 10^3 psi	15	110(a)
Elongation in 2 In., %	40	7
Brinell Hardness	125	395
Rockwell Hardness	70B	42C

(a) These properties are for strip 50% cold worked before aging. Values for wire are somewhat higher.

TABLE 37. YOUNG'S MODULUS AND HARDNESS FOR VARIOUS COMPOSITIONS AND AMOUNTS OF COLD REDUCTION(52)

Nickel Content, percent	Cold Reduction, percent	Young's Modulus dynes/cm²	Hardness, R_B
38	30.6	1.72×10^{12}	92
38	49.0	1.74×10^{12}	94
38	60.9	1.26×10^{12}	96
41.5	30.6	1.72×10^{12}	92
41.5	49.0	1.77×10^{12}	95
41.5	60.9	1.54×10^{12}	98

TABLE 38. PHYSICAL AND MECHANICAL PROPERTIES OF ISO-ELASTIC ALLOY(53)

Composition	36% nickel, 8% chromium, 0.5% molybdenum, balance iron and other small constituents
Thermal Coefficient of the Modulus	-20×10^{-6}/F to $+15 \times 10^{-6}$/F (spring steel is -190×10^{-6}/F)
Hysteresis Error	Less than 0.05% of deflection
Creep Error	Not more than .02 % of deflection in 5 minutes
Tensile Strength	170,000 psi
Young's Modulus	26×10^6
Torsion Modulus	9.2×10^6 psi
Practical Working Stress in Bending	90,000 to 100,000 psi
Practical Working Stress in Torsion	40,000 to 60,000 psi
Hardness	Rockwell C 30 to C 36
Electrical Resistance	Approximately 528 ohms/mil ft (at 20C)
Coefficient of Linear Expansion	Approximately $+4 \times 10^6$

TABLE 39. PHYSICAL AND MECHANICAL PROPERTIES OF ISO-ELASTIC ALLOY(42)

Chemical Composition	
Chromium	8 percent
Nickel	36 percent
Molybdenum	0.5 percent
Iron	Balance
Physical Properties	
Density, lb/in.^{3}	0.292
Mechanical Properties	
Modulus of Elasticity, psi	26×10^6
Temperature Coefficient of Modulus of Elasticity	-20×10^{-6} to $+15 \times 10^{-6}$/F
Modulus of Rigidity, psi	9.2×10^6
Tensile Strength, Maximum, 10^3 psi	170
Elastic Limit in Tension	60 percent of tensile strength
Elastic Limit in Torsion	35 percent of tensile strength
Maximum Working Stress (Torsion), 10^3 psi	40 to 60
Maximum Working Stress (Bending), 10^3 psi	90 to 100
Rockwell Hardness	C-30 to 36
Hysteresis Error (percent of deflection)	0.05 maximum
Creep Error (percent of deflection in 5 minutes)	0.02 maximum
Thermal Properties	
Linear Coefficient of Expansion, in./in./F	4×10^{-6}
Thermal Treatment	
Internal Stress Relief Temperature, F	750 (for 0.5 hour)
Electrical Properties	
Electrical Resistivity, μohm/in.	0.8 (?)
Electrical Resistance, ohms/mil ft (68 F)	~528
Magnetic Properties	
Slightly magnetic	

TABLE 40. RIGIDITY MODULUS (G), THERMAL-EXPANSION COEFFICIENT (α), AND THERMOELASTIC COEFFICIENT (g), FOR Co-Fe-Cr-Ni ALLOYS (Ni is 10% of Gross Composition)(63)

Composition, % Co	Fe	Cr	+Ni	G, kg/cm^2 (20)	α (10~50 C)	g (20~50 C)	Composition, % Co	Fe	Cr	+Ni	G kg/cm^2 (20)	α (10~50 C)	g (20~50 C)
				$\times 10^5$	$\times 10^{-6}$	$\times 10^{-5}$					$\times 10^5$	$\times 10^{-6}$	$\times 10^{-5}$
32	63	0	10	8.70	10.53	-25.3	45	45	10	10	6.80	3.24	+29.7
42	58	0	10	8.20	10.51	-20.8	46.5	43.5	10	10	6.91	4.39	+14.3
48	52	0	10	7.98	11.05	-21.6	48	42	10	10	6.83	4.95	+13.8
56	44	0	10	7.58	11.06	-25.4	52	38	10	10	6.74	7.78	+ 0.2
60	40	0	10	7.02	10.92	-27.9	56	34	10	10	6.83	8.78	-12.9
64	36	0	10	7.02	9.91	-24.7	60	30	10	10	7.39	9.96	-22.4
70	30	0	10	6.35	11.78	-33.6	65	25	10	10	6.88	10.61	-26.2
75	25	0	10	6.28	12.55	-33.4	70	20	10	10	6.76	11.78	-29.2
32	64	4	10	8.37	11.07	-34.3	43.5	45.5	11	10	7.05	3.71	+22.9
36	60	4	10	8.19	10.71	-34.1	--	--	--	--	--	--	--
39	57	4	10	8.07	1[illegible].42	-26.6	36	51	13	10	7.71	17.01	-41.2
42	54	4	10	7.76	10.75	-25.8	39	48	13	10	8.08	16.01	-27.7
45	51	4	10	7.91	10.83	-25.4	42	45	13	10	7.89	10.51	- 8.1
48	48	4	10	8.07	10.76	-29.0	45	42	13	10	7.76	8.08	+ 4.4
52	44	4	10	6.79	11.02	-27.8	48	39	13	10	7.14	6.37	+ 5.3
56	40	4	10	--	11.16	--	50	37	13	10	6.96	6.78	+ 1.1
60	36	4	10	6.48	10.76	-19.6	52	35	13	10	7.00	7.27	- 4.7
66	30	4	10	6.58	11.58	-30.3	56	31	13	10	7.25	8.36	-18.8
71	25	4	10	6.00	12.22	-26.4	60	27	13	10	7.23	9.84	-18.9

TABLE 40. (Continued)

Composition, %				G, kg/cm²	α	g
Co	Fe	Cr	+Ni	(20)	(10~50 C)	(20~50 C)
48	46.5	5.5	10	7.22	10.95	-32.7
36	57	7	10	7.06	10.89	-34.0
39	54	7	10	7 60	10.69	-31.1
42	51	7	10	6.97	10.89	-31.6
45	48	7	10	6.59	11.07	-33.5
48	45	7	10	6.06	10.92	+ 7.4
52	41	7	10	6.57	8.16	- 0.3
56	37	7	10	6.89	9.24	-13.4
63	30	7	10	6.50	11.10	-25.1
68	25	7	10	6.47	11.74	-28.5
42.5	48.5	9	10	6.70	4.06	+32.3
44.5	46.5	9	10	6.48	3.66	+18.5
43.5	47	9.5	10	6.89	2.20	+46.7
44	46.5	9.5	10	6.71	2.36	+29.9
44.5	46	9.5	10	6.58	2.65	+35.5
45	45.5	9.5	10	6.83	2.90	+29.7
32	58	10	10	6.81	12.40	-44.2
36	54	10	10	7.03	12.05	-39.2
39	51	10	10	7.76	8.86	- 5.8
42	48	10	10	7.21	3.03	+28.2
43	47	10	10	6.83	2.42	+40.6
43.5	46.5	10	10	6.83	2.47	+34.9

Composition, %				G, kg/cm²	α	g
Co	Fe	Cr	+Ni	(20)	(10~50 C)	(20~50 C)
65	22	13	10	8.09	14.39	-30.0
48	38	14	10	7.08	7.35	0
32	52	16	10	7.90	16.95	-47.9
36	48	16	10	8.05	17.73	-41.7
39	45	16	10	8.00	16.91	-39.2
42	42	16	10	8.16	15.64	-29.8
48	36	16	10	7.87	13.64	-27.9
52	32	16	10	7.47	9.07	- 6.0
54	30	16	10	7.36	9.46	- 6.2
59	25	16	10	7.74	10.37	- 2.3
67	17	16	10	8.33	14.63	- 9.0
58	25	17	10	7.44	10.90	- 9.5
52	30	18	10	7.86	13.52	-29.4
32	48	20	10	7.54	17.25	-43.1
36	44	20	10	7.76	16.89	-35.1
42	38	20	10	7.98	16.54	-42.1
48	32	20	10	7.90	16.01	-43.2
52	28	20	10	8.57	13.81	-29.7
57.5	22.5	20	10	8.74	18.06	-36.7
65	15	20	10	9.10	17.84	-30.2

TABLE 41. RIGIDITY MODULUS (G), THERMAL-EXPANSION COEFFICIENT (α), AND THERMOELASTIC COEFFICIENT (g) FOR Co-Fe-Cr-Ni ALLOY (Ni IS 30 PERCENT OF GROSS COMPOSITION)[62]

Composition, %				G, kg/cm²	α	g
Co	Fe	Cr	+Ni	(20)	(10~50 C)	(20~50 C)
				$\times 10^5$	$\times 10^{-6}$	$\times 10^{-5}$
10	90	0	30	6.16	10.58	-22.2
20	80	0	30	6.06	10.93	-28.0
24	76	0	30	6.16	11.12	-19.9
30	70	0	30	6.16	11.82	-24.6
35	65	0	30	5.93	11.92	-25.3
40	60	0	30	4.79	12.38	+10.0
44	56	0	30	5.37	10.54	+ 8.7
50	50	0	30	6.14	11.64	-19.5
55	45	0	30	5.83	11.90	-21.3
15	82	3	30	5.75	10.83	-25.3
20	77	3	30	5.72	10.59	-25.3
25	72	3	30	5.55	10.08	-22.1
32	65	3	30	5.40	8.25	+18.1
37	60	3	30	4.55	9.12	+10.2
41	56	3	30	5.20	9.78	+12.1
44	53	3	30	5.48	10.65	- 3.2
10	84	6	30	6.98	15.52	-32.5
13	81	6	30	6.67	12.56	-10.6
17	77	6	30	6.57	3.83	+39.8
20	74	6	30	6.28	2.54	+62.7
21	73	6	30	5.88	1.87	+76.4
25	69	6	30	5.26	3.63	+61.7
29	65	6	30	5.39	4.75	+46.6
34	60	6	30	5.65	6.14	+28.4
38	56	6	30	5.84	8.77	+10.5
44	50	6	30	6.08	10.40	- 6.8
49	45	6	30	6.52	11.02	-22.8
18	74	8	30	6.37	4.18	+39.9

Composition, %				G, kg/cm²	α	g
Co	Fe	Cr	+Ni	(20)	(10~50 C)	(20~50 C)
				$\times 10^5$	$\times 10^{-6}$	$\times 10^{-5}$
11	79	10	30	6.88	15.15	-23.2
15	75	10	30	6.64	10.65	- 9.8
19	71	10	30	6.69	5.31	+22.6
25	65	10	30	6.37	4.90	+27.4
30	60	10	30	6.41	6.47	+16.1
34	56	10	30	6.14	7.50	+ 5.8
40	50	10	30	6.32	9.26	- 6.3
45	45	10	30	6.35	9.96	-14.1
50	40	10	30	6.59	11.39	-21.6
36	51	13	30	6.61	8.10	- 0.3
13	73	14	30	6.98	13.70	-29.8
17	69	14	30	6.94	11.12	-14.0
21	65	14	30	7.12	8.20	+ 5.9
26	60	14	30	6.97	6.40	+14.5
30	56	14	30	6.59	7.19	+ 4.8
41	45	14	30	6.37	9.04	- 3.5
45	41	14	30	6.89	9.08	-13.0
48	38	14	30	6.81	9.11	-16.8
33	50	17	30	7.11	9.33	- 5.0
38	45	17	30	6.94	9.10	- 6.9
10	70	20	30	7.23	16.60	-38.6
14	66	20	30	7.39	15.39	-36.9
20	60	20	30	7.84	15.20	-37.6
24	56	20	30	7.36	14.01	-34.4
30	50	20	30	7.48	11.57	-21.0
35	45	20	30	7.19	10.32	- 8.0
45	35	20	30	7.44	10.52	- 6.7

TABLE 42. RIGIDITY MODULUS (G), THERMAL-EXPANSION COEFFICIENT (α), THERMOELASTIC COEFFICIENT (g) FOR Co-Fe-Cr-Ni ALLOYS[62]

Composition, %				G, kg/cm²	α	g
Co	Fe	Cr	+Ni	(20 C)	(10~50 C)	(20~50 C)
				x 10⁵	x 10⁻⁶	x 10⁻⁵
0	100	0	40	6.32	13.61	-20.8
4	96	0	40	6.40	9.11	- 4.6
11	89	0	40	5.83	8.02	+10.8
15	85	0	40	5.62	8.36	+14.9
20	80	0	40	4.82	4.47	+50.3
25	75	0	40	4.69	6.60	+28.8
30	70	0	40	5.05	8.74	+ 5.4
35	65	0	40	5.08	9.97	- 6.5
40	60	0	40	5.52	10.84	- 8.1
45	55	0	40	5.83	12.22	-14.3
65	35	0	40	6.11	12.07	-27.6
0	98	2	40	7.97	14.55	-23.3
2	96	2	40	8.09	9.32	+14.9
7	91	2	40	6.72	3.05	+55.6
9	89	2	40	5.98	1.56	+63.7
11	87	2	40	5.92	0.54	+78.3
13	85	2	40	5.01	1.04	+81.0
15	83	2	40	5.03	1.37	+77.4
17	81	2	40	4.82	2.53	+55.4
0	95	4	40	8.96	13.77	-18.3
3	93	4	40	7.93	9.70	+ 7.3
7	89	4	40	7.26	4.00	+4[illegible]
11	85	4	40	6.78	1.84	+51.4
13	83	4	40	6.77	1.58	+56.6
15	81	4	40	5.92	2.26	+62.3
17	79	4	40	5.74	2.92	+59.4
20	76	4	40	5.50	4.29	+39.8
23	73	4	40	5.39	5.98	+24.1
26	70	4	40	5.32	7.53	+ 7.5
31	65	4	40	5.75	8.91	- 0.9
36	60	4	40	5.92	10.09	- 7.6
43	53	4	40	5.74	11.34	-17.2
5	89	6	40	6.34	7.18	+ 4.9
8	86	6	40	6.49	5.22	+31.7
11	83	6	40	6.96	2.79	+41.5
13	81	6	40	6.78	2.98	+39.1
15	79	6	40	6.54	3.08	+49.1
17	77	6	40	6.18	3.49	+45.4
0	93	7	40	7.41	14.23	-27.0

Composition, %				G, kg/cm2	α	g
Co	Fe	Cr	+Ni	(20 C)	(10~50 C)	(20~50 C)
				x 10⁵	x 10⁻⁶	x 10⁻⁵
3	89	8	40	7.81	11.32	-14.6
9	83	8	40	6.49	6.14	+25.9
11	81	8	40	6.60	4.69	+29.2
13	79	8	40	6.28	4.03	+29.4
15	77	8	40	6 29	4.21	+32.3
17	75	8	40	6.29	4.12	+36.9
20	72	8	40	5.48	5.50	+28.5
0	90	10	40	8.22	14.88	-30.3
3	87	10	40	7.00	12.81	+ 2.5
7	83	10	40	6.68	7.55	+16.2
9	81	10	40	7.15	6.09	+23.5
11	79	10	40	6.02	4.97	+26.8
13	77	10	40	7.19	5.47	+25.0
15	75	10	40	7.07	4.58	+23.3
20	70	10	40	6.18	5.35	+21.3
25	65	10	40	6.40	7.01	+ 9.7
30	60	10	40	6.26	9.00	- 2.9
40	50	10	40	6.14	10.83	-16.9
4	85	11	40	7.39	9.67	+ 9.6
0	87	13	40	8.20	15.21	-33.9
7	80	13	40	7.54	9.53	+ 5.4
10	77	13	40	7.80	8.86	+ 7.5
12	75	13	40	7.80	7.64	+ 9.3
2	83	15	40	8.19	14.30	-34.2
4	81	15	40	7.99	13.12	-27.4
8	77	15	40	8.14	12.94	-21.6
15	70	15	40	7.03	7.62	+10.0
20	65	15	40	6.77	8.09	+ 4.3
25	60	15	40	6.87	8.31	+ 0.9
30	55	15	40	6.69	8.97	- 6.6
35	50	15	40	6.59	10.44	- 8.7
0	80	20	40	7.60	16.57	-40.0
5	75	20	40	7.29	15.75	-35.9
10	70	20	40	7.37	13.19	-29.3
15	65	20	40	6.82	11.78	-19.5
20	60	20	40	6.82	10.66	- 9.7
25	55	20	40	6.76	9.96	- 8.3
30	50	20	40	6.52	10.08	- 6.9
35	45	20	40	6.76	9.63	- 5.9

TABLE 43. RIGIDITY MODULUS (G), THERMAL-EXPANSION COEFFICIENT (α), AND THERMOELASTIC COEFFICIENT (g) FOR Co-Fe-Cr-Ni ALLOYS(62)

Specimen	Composition, % Co	Fe	Cr	+Ni	G, kg/cm² (20 C)	α (10~50 C)	g (20~50 C)
					x 10^5	x 10^{-6}	x 10^{-5}
316	44(33.8)[a]	53(40.8)	3(2.3)	30(23.1)	5.48	10.65	- 3.2
338	36(27.7)	51(39.2)	13(10.0)	30(23.1)	6.61	8.10	- 0.3
343	30(23.0)	56(43.1)	14(10.8)	30(23.1)	6.59	7.19	+ 4.8
344	41(31.5)	45(34.6)	14(10.8)	30(23.1)	6.37	9.04	- 3.5
347	33(25.3)	50(38.5)	17(13.1)	30(23.1)	7.11	9.33	- 5.0
321	21(16.1)	73(56.2)	6(4.6)	30(23.1)	5.88	1.6[illegible]	+76.4
402	4(2.8)	96(68.6)	0(0.0)	40(28.6)	6.40	9.11	- 4.6
430	31(22.1)	65(46.4)	4(2.9)	40(28.6)	5.75	8.91	- 0.9
433	5(3.6)	89(63.5)	6(4.3)	40(28.6)	6.34	7.18	+ 4.9
448	3(2.1)	87(62.2)	10(7.1)	40(28.6)	7.00	12.81	+ 2.5
456	30(21.5)	60(42.8)	10(7.1)	40(28.6)	6.26	9.00	- 2.9
467	20(14.3)	65(46.4)	15(10.7)	40(28.6)	6.77	8.09	+ 4.3
468	25(17.9)	60(42.8)	15(10.7)	40(28.6)	6.87	8.31	+ 0.9
416	11(7.9)	87(62.1)	2(1.4)	40(28.6)	5.92	0.54	+78.3

(a) The compositions in parentheses show those in the quaternary system.

TABLE 44. RIGIDITY MODULUS (G), THERMAL-EXPANSION COEFFICIENT (α), AND THERMOELASTIC COEFFICIENT (g) OF SOME Co-Fe-Cr-Cu ALLOYS(62)

Composition, % Co	Fe	Cr	Cu	G, kg/cm² (20 C)	α (10~50 C)	g (20~50 C)
				x 10^5	x 10^{-6}	x 10^{-5}
50	45	0	5	6.82	10.49	- 7.5
52.5	42.5	0	5	—	10.18	—
55	40	0	5	—	10.17	—
70	25	0	5	6.77	11.59	-35.6
40	53	2	5	—	10.09	—
45	48	2	5	—	9.71	—
47.5	45.5	2	5	—	10.00	—
50	43	2	5	—	10.12	—
52.5	40.5	2	5	—	10.30	—
55	38	2	5	—	10.19	—
[illegible]	33	2	5	7.82	10.51	-22.0
45	45	5	5	8.88	10.32	-24.5
50	40	5	5	7.36	10.30	-25.4
55	35	5	5	7.21	10.86	-32.9
65	25	5	5	6.97	11.62	-25.5
52.5	35	7.5	5	7.18	9.93	-42.3

Composition, % Co	Fe	Cr	Cu	G, kg/cm² (20 C)	(10~50 C)	g (20~50 C)
				x 10^5	x 10^{-6}	x 10^{-5}
52.5	33	9.5	5	6.24	5.87	+ 4.2
40	45	10	5	7.72	10.50	-35.8
45	40	10	5	7.48	10.60	-45.2
50	35	10	5	6.91	6.40	+ 3.0
52.5	32.5	10	5	6.57	5.55	+10.0
55	30	10	5	6.5[illegible]	6.38	+ 3.8
56	29	10	5	6.82	7.60	- 6.8
60	25	10	5	5.97	10.23	-23.0
52.5	31.5	11	5	8.26	7.23	[illegible] 1.4
45	37.5	12.5	5	8.[illegible]	16.72	-40.5
50	32.5	12.5	5	9.20	12.27	-18.3
55	27.5	12.5	5	7.76	9.15	-10.0
40	40	15	5	8.33	17.18	-46.9
45		15	5	8.69	16.72	-37.9
50		15	5	8.29	15.76	-39.3
55		15	5	8.43	14.42	-3[illegible].3

TABLE 45. RIGIDITY MODULUS (G), THERMAL-EXPANSION COEFFICIENT (α), AND THERMOELASTIC COEFFICIENT (g) FOR SOME Co-Fe-Cr-Cu ALLOYS(65)

Composition, %				G, kg/cm² (20 C)	α (10~50 C)	g (20~50 C)
Co	Fe	Cr	Cu			
				x 10^5	x 10^{-6}	x 10^{-5}
52.5	33	9.5	5	6.24	5.87	+ 4.2
50	35	10	5	6.91	6.40	+ 3.0
55	30	10	5	6.58	6.38	+ 3.8
52.5	31.5	11	5	8.26	7.23	- 1.4
52.5	32.5	10	5	6.57	5.55	+10.0

TABLE 46. RIGIDITY MODULUS (G), THERMAL-EXPANSION COEFFICIENT (α), AND THERMOELASTIC COEFFICIENT (g) OF SOME Co-Fe-V-Ni ALLOYS(65)

Composition, %				G, kg/cm² (20 C)	α (10~50 C)	g (20~50 C)
Co	Fe	V	Ni			
				x 10^5	x 10^{-6}	x 10^{-5}
30.0	48.0	2	20	4.62	13.69	-35.5
32.5	45.5	2	20	5.43	13.09	+16.1
35.0	43.0	2	20	5.13	12.11	+14.5
20.0	56.0	4	20	6.15	13.81	-34.5
25.0	51.0	4	20	5.84	13.58	-20.6
27.5	48.5	4	20	5.24	6.99	+44.2
30.0	46.0	4	20	4.99	8.28	+46.6
35.0	41.0	4	20	5.34	11.56	+ 4.0
40.0	36.0	4	20	5.28	13.08	-11.2
45.0	31.0	4	20	6.07	13.64	-31.9
51.0	25.0	4	20	7.04	13.57	-40.5
15.0	60.0	5	20	6.39	13.61	-31.1
22.5	52.5	5	20	7.64	12.04	+ 6.4
27.5	46.5	6	20	5.48	5.44	+33.1
32.5	41.5	6	20	5.75	9.70	+26.4
37.5	36.5	6	20	5.00	11.60	- 3.8
42.5	31.5	6	20	6.62	13.90	-20.3
47.5	26.5	6	20	7.57	14.63	-29.7
15.0	58.0	7	20	6.80	20.13	-38.7
20.0	53.0	7	20	6.25	7.17	+28.5
22.5	50.5	7	20	6.01	5.02	+50.5
25.0	48.0	7	20	6.11	6.24	+31.8
30.0	43.0	7	20	6.10	7.52	+23.8
32.5	40.5	7	20	6.12	9.15	+ 6.4
35.0	38.0	7	20	6.39	10.73	+ 2.9
37.5	35.5	7	20	6.58	11.05	- 0.6
40.0	33.0	7	20	6.70	11.78	- 8.9
45.0	28.0	7	20	7.40	13.11	-17.4
48.0	25.0	7	20	7.24	11.14	-25.3

Composition, %				G, kg/cm² (20 C)	α (10~50 C)	g (20~50 C)
Co	Fe	V	Ni			
				x 10^5	x 10^{-6}	x 10^{-6}
27.5	44.5	8	20	6.29	6.74	+28.1
32.5	39.5	8	20	6.72	8.64	+13.0
35.0	37.0	8	20	6.92	10.01	+ 5.6
37.5	34.5	8	20	6.96	11.07	- 3.5
42.5	29.5	8	20	7.11	12.41	-15.0
22.5	48.5	9	20	5.77	6.76	+22.6
30.0	41.0	9	20	6.99	8.33	+20.3
35.0	36.0	9	20	7.04	10.18	+ 2.8
40.0	31.0	9	20	7.22	11.79	- 9.7
45.0	26.0	9	20	7.69	13.55	-21.0
15.0	55.0	10	20	7.20	20.37	-42.9
20.0	50.0	10	20	7.50	14.32	-11.8
25.0	45.0	10	20	7.39	15.76	-16.4
32.5	37.5	10	20	7.32	10.85	- 0.9
37.5	32.5	10	20	7.34	11.34	- 9.1
42.5	27.5	10	20	7.73	12.94	-18.2
45.0	25.0	10	20	7.83	13.20	-30.3
27.5	40.5	12	20	8.19	14.41	-14.7
30.0	38.0	12	20	7.32	10.09	- 1.1
35.0	33.0	12	20	7.88	11.97	- 9.4
20.0	47.0	13	20	7.64	19.61	-43.2
25.0	42.0	13	20	7.62	19.75	-29.0
30.0	37.0	13	20	7.80	18.63	-30.6
35.0	32.0	13	20	8.16	13.50	-16.4
40.0	27.0	13	20	7.95	14.07	-23.8
15.0	50.0	15	20	7.74	18.41	-46.6

TABLE 47. RIGIDITY MODULUS (G), THERMAL-EXPANSION COEFFICIENT (α), AND THERMOELASTIC COEFFICIENT (g) OF SOME Co-Fe-V-Ni ALLOYS[66]

Composition, %				G, kg/cm^2 (20 C)	α (10~50 C)	g (20~50 C)	Composition, %				G, kg/cm^2 (20 C)	α (10~50 C)	g (20~50 C)
Co	Fe	V	Ni				Co	Fe	V	Ni			
				x 10^5	x 10^{-6}	x 10^{-5}					x 10^5	x 10^{-6}	x 10^{-5}
0	68.0	2	30	6.89	17.56	-16.5	34.0	30.0	6	30	6.83	15.93	-22.9
2.5	65.5	2	30	6.54	9.25	+25.3							
5.0	63.0	2	30	5.97	5.11	+50.6	2.5	59.5	8	30	6.82	18.70	-29.7
7.5	60.5	2	30	5.46	1.86	+78.2	7.5	54.5	8	30	7.04	16.69	-10.5
10.0	58.0	2	30	5.32	2.57	+71.7	12.5	49.5	8	30	6.50	9.98	+ 5.6
15.0	53.0	2	30	5.20	7.30	+36.5	15.0	47.0	8	30	6.21	9.75	+13.3
17.5	50.5	2	30	5.38	9.98	+17.6	17.5	44.5	8	30	6.67	11.08	+12.2
22.5	45.5	2	30	5.50	12.38	+ 1.1	20.0	42.0	8	30	6.79	9.61	+ 8.6
25.0	43.0	2	30	5.73	13.47	- 5.6	22.5	39.5	8	30	6.84	11.29	- 1.4
30.0	38.0	2	30	6.08	13.94	-15.1	25.0	37.0	8	30	6.86	12.02	- 1.7
35.0	33.0	2	30	6.22	15.54	-19.5	27.5	34.5	8	30	6.10	11.92	+ 0.7
							32.0	30.0	8	30	6.11	15.25	- 9.3
2.5	63.5	4	30	5.24	2.11	+72.5							
5.0	61.0	4	30	6.14	6.44	+27.2	0	60.0	10	30	7.37	22.63	-34.0
7.5	58.5	4	30	5.68	5.57	+41.5	5.0	55.0	10	30	8.00	18.60	-23.6
10.0	56.0	4	30	5.69	4.36	+53.5	15.0	45.0	10	30	6.85	12.43	+ 1.4
12.5	53.5	4	30	5.84	6.17	+56.9	20.0	40.0	10	30	7.08	11.63	- 0.7
17.5	48.5	4	30	5.65	8.61	+25.5	25.0	35.0	10	30	7.25	12.28	- 6.7
20.0	46.0	4	30	5.84	12.03	+ 2.8	30.0	30.0	10	30	7.36	16.84	-22.5
22.5	43.5	4	30	5.77	12.27	- 0.3							
25.0	41.0	4	30	6.00	12.01	- 4.4	2.5	55.5	12	30	7.18	20.22	-30.6
27.5	38.5	4	30	6.12	12.05	-13.7	7.5	50.5	12	30	7.38	18.45	-23.3
30.0	36.0	4	30	6.44	13.26	-17.6	12.5	45.5	12	30	7.70	13.25	-17.6
							17.5	40.5	12	30	7.37	16.77	-18.6
0	64.0	6	30	7.04	23.20	-35.8	22.5	35.5	12	30	7.88	13.22	-10.1
5.0	59.0	6	30	6.60	14.82	-24.3	28.0	30.0	12	30	7.97	12.94	-18.1
7.5	56.5	6	30	6.54	9.06	+ 4.3	35.0	23.0	12	30	—	10.95	—
12.5	51.5	6	30	5.87	7.13	+33.0							
15.0	49.0	6	30	6.20	7.50	+ 8.9	0	55.0	15	30	—	21.03	—
17.5	46.5	6	30	6.12	9.58	+17.6	5.0	50.0	15	30	7.11	20.70	-32.2
20.0	44.0	6	30	6.24	9.82	+ 8.0							
25.0	39.0	6	30	6.60	11.86	- 7.8							

TABLE 48. RIGIDITY MODULUS (G), THERMAL-EXPANSION COEFFICIENT (α), AND THERMOELASTIC COEFFICIENT (g) OF "MOELINVARS", Co-Fe-Mo-Ni ALLOYS[55]

Composition, %				G, kg/cm^2 (20 C)	α (20~50 C)	g (20~50 C)
Co	Fe	Mo	Ni			
				x 10^5	x 10^{-6}	x 10^{-5}
57.5	27.5	15.0	0.0	6.99	+7.54	-2.3
50.0	32.5	17.5	0.0	7.50	+9.57	-0.2
45.0	35.0	10.0	10.0	6.27	+8.47	+0.7
40.0	35.0	15.0	10.0	8.14[a]	+7.06	+3.3
20.0	55.0	5.0	20.0	7.75	+7.00	+4.2
35.0	35.0	10.0	20.0	6.81	+9.58	-3.7
25.0	40.0	15.0	20.0	7.53	+7.49	+4.7
30.0	35.0	15.0	20.0	7.34	+8.74	+3.0
20.0	40.0	20.0	20.0	7.85	+8.40	+0.9
20.0	45.0	5.0	30.0	5.98	+8.68	+0.9
5.0	50.0	15.0	30.0	7.59	+8.88	-1.2
10.0	45.0	15.0	30.0	8.00[a]	+9.78	-0.4
15.0	40.0	15.0	30.0	7.20	+8.55	-2.6
5.0	45.0	20.0	30.0	7.41	+9.11	-2.7

(a) Small temperature coefficients of modulus and large rigidity modulus.

TABLE 49. RIGIDITY MODULUS (G), THERMAL-EXPANSION COEFFICIENT (α), AND THERMOELASTIC COEFFICIENT (g) OF Co-Fe-Cr ALLOYS WITH AN ADDITION OF 20 PERCENT OF NICKEL[63]

Composition, %				G, kg/cm² (20 C)	α (10~50 C)	g (20~50 C)	Composition, %				G, kg/cm² (20 C)	α (10~50 C)	g (20~50 C)
Co	Fe	Cr	+Ni	x 10⁵	x 10⁻⁶	x 10⁻⁵	Co	Fe	Cr	+Ni	x 10⁵	x 10⁻⁶	x 10⁻⁵
20	80	0	20	6.86	10.46	-27.1	43	47	10	20	7.39	7.81	+ 3.5
30	70	0	20	7.86	10.87	-26.9	45.5	44.5	10	20	7.53	7.77	- 6.2
43	57	0	20	6.09	11.08	-24.7	50	40	10	20	6.44	9.41	-13.6
55	45	0	20	5.51	11.52	-16.5	55	35	10	20	6.48	10.57	-18.8
60	40	0	20	5.99	12.05	-24.7	60	30	10	20	6.60	12.00	-24.9
65	35	0	20	6.14	12.37	-26.9							
							20	67	13	20	7.64	17.62	-43.7
28	68	4	20	6.84	11.66	-29.0	23.5	63.5	13	20	7.44	16.23	-37.1
33.5	62.5	4	20	6.85	11.35	-31.0	26.5	60.5	13	20	7.00	13.40	-22.6
36	60	4	20	6.20	10.65	-23.3	29	58	13	20	6.82	10.47	+ 4.1
41	55	4	20	6.36	9.22	-25.4	31.5	55.5	13	20	6.96	7.66	+11.6
43.5	52.5	4	20	5.94	8.61	+15.1	34	53	13	20	7.26	6.88	+ 8.3
46	50	4	20	6.04	8.21	+ 7.8	36.5	50.5	13	20	6.90	5.95	+20.4
48.5	47.5	4	20	5.88	8.87	- 4.1	39	48	13	20	7.42	6.17	+ 9.7
53	43	4	20	6.27	11.21	-18.8	41.5	45.5	13	20	7.78	7.72	+ 0.8
58	38	4	20	6.29	11.95	-22.1	44	43	13	20	6.82	7.79	- 2.8
60.5	35.5	4	20	6.11	11.75	-25.4	46.5	40.5	13	20	6.89	8.34	- 8.7
							52	35	13	20	7.02	9.64	-16.6
24	69	7	20	6.04	11.02	-33.1	56	31	13	20	7.06	10.80	-23.0
29.5	63.5	7	20	5.15	9.25	-10.4							
32	61	7	20	5.09	7.75	+ 0.3	25	59	16	20	8.09	16.40	-38.4
34.5	58.5	7	20	5.80	3.23	+66.0	27.5	56.5	16	20	7.85	16.20	-36.5
37	56	7	20	6.15	5.79	+37.4	30	54	16	20	7.86	14.68	-35.0
39.5	53.5	7	20	6.69	6.82	+25.1	32.5	51.5	16	20	7.96	13.41	-23.6
44.5	48.5	7	20	6.79	9.48	+ 2.9	35	49	16	20	7.91	9.64	- 3.6
47	46	7	20	6.76	9.18	- 9.3	37.5	46.5	16	20	7.42	9.61	- 7.1
49.5	43.5	7	20	7.04	9.76	- 9.4	40	44	16	20	7.12	9.39	- 4.7
53	40	7	20	6.02	10.77	-11.5	42.5	41.5	16	20	7.36	8.92	- 0.6
59	34	7	20	6.29	11.03	-24.8	45	39	16	20	7.44	8.93	+ 1.3
							47	37	16	20	7.03	9.09	- 4.2
30	61.5	8.5	20	6.16	2.04	+34.0	49	35	16	20	7.33	9.68	-11.2
31.3	60.2	8.5	20	6.09	1.69	+35.3	54.5	29.5	16	20	7.36	10.54	-14.5
31	60	9	20	6.24	2.88	+39.0	20	61	19	20	8.04	16.84	-50.8
							26	55	19	20	8.32	15.98	-44.2
20	70	10	20	7.39	17.91	-43.4	28.5	52.5	19	20	8.18	15.70	-40.7
22.5	67.5	10	20	7.20	16.18	-26.0	31	50	19	20	7.88	15.31	-35.6
25	65	10	20	7.30	12.01	-19.6	36	45	19	20	7.87	14.61	-39.5
28	62	10	20	7.03	5.57	+19.6	41	40	19	20	8.36	14.09	-41.8
30.5	59.5	10	20	6.70	3.73	+36.2	43.5	37.5	19	20	7.58	12.22	-22.6
33	57	10	20	7.02	3.88	+31.6	46	35	19	20	7.62	12.33	-21.1
35.5	54.5	10	20	6.70	4.91	+24.0	50.5	30.5	19	20	7.16	10.86	- 4.7
38	52	10	20	6.98	5.98	+ 9.3	55.5	25.5	19	20	7.73	12.39	-14.4
40.5	49.5	10	20	6.81	6.41	+ 9.9							

TABLE 50. RIGIDITY MODULUS (G), THERMAL-EXPANSION COEFFICIENT (α), AND THERMOELASTIC COEFFICIENT (g) OF TERNARY Co-Fe-Cr ALLOYS[61]

Composition, %			G, kg/cm2 (20 C)	α (20~60 C)	g (20~60 C)
Co	Fe	Cr			
			$\times 10^{-5}$	$\times 10^{-5}$	$\times 10^{-5}$
60	40	0	7.00	9.6	-18.9
65	35	0	7.66	9.6	-23.0
75	25	0	7.19	10.5	-34.3
80	20	0	6.71	11.7	-37.0
90	10	0	6.52	11.7	-22.2
50	45	5	9.34	9.3	-22.1
55	40	5	9.09	9.5	-25.7
65	30	5	7.01	9.6	-29.8
70	25	5	6.48	9.7	-33.7
75	20	5	6.67	10.7	-33.4
80	15	5	6.77	10.5	-39.3
85	10	5	7.58	11.4	-39.2
55	37	8	7.28	6.0	+23.4
57	35	8	7.20	3.1	+17.9
60	32	8	6.55	6.6	- 2.5
65	27	8	5.92	8.0	-17.5
54	36.5	9.5	7.35	0.1	+35.9
50	40	10	7.03	12.0	-44.8
51.5	38.5	10	7.70	8.7	-31.5
53	37	10	7.66	0.2	+11.4
55	35	10	7.24	1.4	+28.9
57	33	10	6.98	3.8	+17.6
57.5	32.5	10	6.94	3.5	+10.1
58.5	31.5	10	7.11	5.4	+ 5.1
60	30	10	7.04	5.1	- 0.2
65	25	10	6.97	7.5	-17.2
70	20	10	7.14	8.8	-26.1
75	15	10	7.34	9.5	-28.9
80	10	10	7.53	13.5	-31.9
51	37	12	8.41	13.1	-42.9
55	33	12	8.30	12.0	-23.0
57	31	12	8.09	6.0	+ 6.5
58.5	29.5	12	7.74	6.0	+ 1.0
60	28	12	7.44	7.6	- 4.3
63	25	12	7.39	7.8	-12.3
65	23	12	7.78	8.0	-16.0
50	35	15	8.57	16.0	-49.8
52.5	32.5	15	8.31	15.6	-42.7
55	30	15	8.42	15.4	-34.8
60	25	15	8.16	14.0	- 0.9
65	20	15	8.09	9.5	-30.1
70	15	15	8.21	10.2	-37.0
50	30	20	9.12	16.3	-45.4
60	20	20	8.75	14.8	-44.7

TABLE 51. RIGIDITY MODULUS (G), THERMAL-EXPANSION COEFFICIENT (α), AND THERMOELASTIC COEFFICIENT (g) FOR Co-Fe-V-Ni ALLOYS CONTAINING 9.1 PERCENT OF NICKEL[66]

Composition, %				G, kg/cm² (20 C)	α (10~50 C)	g (20~50 C)	Composition, %				G, kg/cm² (20 C)	α (10~50 C)	g (20~50 C)
Co	Fe	V	Ni				Co	Fe	V	Ni			
				$\times 10^5$	$\times 10^{-6}$	$\times 10^{-5}$					$\times 10^5$	$\times 10^{-6}$	$\times 10^{-5}$
29.1	61.8	0	9.1	8.70	10.53	-25.3	40.9	42.7	7.3	9.1	5.84	4.38	+42.9
38.2	52.7	0	9.1	8.2[illegible]	10.57	-20.8	42.7	40.9	7.3	9.1	5.72	7.59	+30.3
43.6	47.3	0	9.1	7.98	11.05	-21.6	45.4	38.2	7.3	9.1	5.61	8.59	+20.5
50.9	40.0	0	9.1	7.58	11.06	-25.4	47.3	36.3	7.3	9.1	5.84	8.55	+16.0
54.6	36.3	0	9.1	7.02	10.92	-27.9	50.0	33.6	7.3	9.1	6.20	10.80	+ 4.8
58.2	32.7	0	9.1	7.02	9.91	-24.7	54.5	29.1	7.3	9.1	7.13	12.61	-22.1
63.6	27.3	0	9.1	6.35	11.78	-33.6							
68.2	22.7	0	9.1	6.28	12.55	-33.4	40.9	41.8	8.2	9.1	6.63	7.72	+15.3
							43.6	39.1	8.2	9.1	6.49	6.89	+19.1
52.7	35.5	2.7	9.1	7.00	13.16	-35.6	45.5	37.2	8.2	9.1	6.21	7.48	+22.0
							47.3	35.4	8.2	9.1	6.22	8.50	+16.5
31.8	54.6	4.5	9.1	7.50	10.94	-30.4	49.1	33.6	8.2	9.1	6.02	9.88	+ 8.1
36.4	50.0	4.5	9.1	7.32	10.87	-33.3	50.9	31.8	8.2	9.1	6.83	10.98	+ 1.0
40.9	45.5	4.5	9.1	7.10	13.60	-36.4							
45.5	40.9	4.5	9.1	6.80	14.00	-37.7	31.8	50.0	9.1	9.1	6.63	19.79	-48.6
50.0	36.4	4.5	9.1	5.29	12.19	- 2.1	36.3	45.5	9.1	9.1	6.85	19.27	-41.0
51.8	34.6	4.5	9.1	5.50	11.92	-10.1	40.9	40.9	9.1	9.1	6.85	14.30	-15.0
54.6	31.8	4.5	9.1	5.80	11.49	-10.3	43.6	38.2	9.1	9.1	6.89	7.81	+16.3
59.1	27.3	4.9	9.1	6.61	14.07	-26.1	45.5	36.3	9.1	9.1	7.21	10.27	+13.0
							50.0	31.8	9.1	9.1	7.08	10.57	- 4.4
36.3	48.2	6.4	9.1	7.00	14.28	-38.3	54.5	27.3	9.1	9.1	7.60	13.45	-15.6
39.1	45.4	6.4	9.1	6.79	13.97	-36.9							
40.9	43.6	6.4	9.1	6.66	10.48	-33.3	45.5	34.5	10.9	9.1	8.37	17.33	-27.3
43.6	40.9	6.4	9.1	5.74	4.23	+36.4							
45.4	39.1	6.4	9.1	5.62	7.38	+22.9	31.8	46.4	12.7	9.1	7.93	20.43	-36.3
48.2	36.3	6.4	9.1	6.04	7.48	+11.4	36.4	41.8	12.7	9.1	8.44	19.05	-43.4
50.0	34.5	6.4	911	5.91	10.93	+ 2.5	40.9	37.3	12.7	9.1	8.40	20.25	-39.3
52.7	31.8	6.4	9.1	6.25	10.85	- 9.3							
							45.5	31.8	13.6	9.1	7.96	19.78	-39.4
38.2	45.4	7.3	9.1	6.03	13.88	-36.9	50.0	27.3	13.6	9.1	8.35	11.60	-25.1

TABLE 52. RIGIDITY MODULUS (G), THERMAL-EXPANSION COEFFICIENT (α), AND THERMOELASTIC COEFFICIENT (g) OF Fe-Co-V ALLOYS[5]

Composition(a) %		G, kg/cm² (20 C)	α (10~50 C)	g (20~50 C)	Composition, %		G, kg/cm² (20 C)	α (10~50 C)	g (20~50 C)
Co	V				Co	V			
		$\times 10^5$	$\times 10^{-6}$	$\times 10^{-5}$			$\times 10^5$	$\times 10^{-6}$	$\times 10^{-5}$
60	0	7.00	9.57	-18.9	65	8(7.9)	6.81	9.95	-12.3
65	0	7.66	9.72	-23.0	70	8(7.7)	7.05	11.36	-24.8
75	0	7.19	10.72	-34.3					
80	0	6.71	11.75	-37.0	54	9(9.2)	6.53	9.98	-11.4
					56	9(8.7)	6.32	3.94	+31.5
55	5(5.0)	8.08	9.81	-27.1	58	9(8.7)	6.22	3.96	+26.9
60	5(5.1)	7.63	10.18	-28.6	60	9(8.8)	6.14	6.12	+11.5
65	5(4.7)	7.03	10.48	-38.2	62	9(8.7)	6.46	8.74	- 4.3
70	5(5.1)	5.76	10.64	-24.4					
75	5(5.0)	6.71	11.02	-32.3	50	10(9.9)	6.96	11.86	-37.4
					55	10(10.0)	7.06	13.06	-27.1
55	7(6.8)	7.18	10.06	-34.1	56	10(10.1)	7.27	14.29	-35.9
58	7(6.9)	6.94	10.30	-36.5	58	10(10.0)	6.42	5.34	+15.8
60	7(7.0)	6.77	10.10	-38.8	60	10(10.2)	6.66	8.07	- 0.0
62	7(6.4)	5.94	9.39	- [illegible].1	65	10(9.9)	6.72	9.84	-14.9
63	7(7.0)	5.40	8.52	- 6.7	70	10(10.1)	7.70	11.63	-25.8
65	7(7.0)	6.06	9.24	-13.8					
68	7(7.1)	6.09	9.96	-20.4	56	11(11.3)	6.64	15.60	-45.4
					58	11(11.3)	7.26	12.55	-21.0
52	8(8.1)	7.51	9.98	-34.2	60	11(11.1)	7.77	10.70	-15.8
55	8(7.9)	6.94	9.82	-33.1					
57	8(7.8)	5.93	9.11	-32.7	65	12(12.2)	7.99	11.20	-28.9
59	8(8.0)	5.94	6.06	+15.1					
61	8(7.9)	5.78	7.77	+ 0.5	55	13(13.1)	8.46	14.62	-43.4
63	8(7.9)	6.77	8.56	- 1.6	60	13(13.2)	7.68	12.80	-30.0

(a) Balance iron.

TABLE 53. YOUNG'S MODULUS (E), THERMAL-EXPANSION COEFFICIENT (α), AND THERMOELASTIC COEFFICIENT (e) OF SOME Co-Fe-Cr ALLOYS(54)

Speci-men	Composition, % Co	Fe	Cr	E, kg/cm^2	α 20~60 C	g 0~50 C
				$\times 10^5$	$\times 10^{-6}$	$\times 10^{-5}$
1	60	40	0	—	9.6	-22.5
2	65	35	0	19.5	9.6	-19.5
3	75	25	0	18.3	10.5	-22.2
4	80	20	0	16.7	11.7	-29.5
5	90	10	0	19.9	11.7	-35.1
6	50	45	5	21.6	9.3	-21.0
7	55	40	5	23.1	9.5	-23.1
8	65	30	5	19.6	9.6	-26.7
9	70	25	5	17.4	9.7	-28.7
10	75	20	5	18.3	10.7	-33.0
11	80	15	5	19.7	10.5	-33.4
12	85	10	5	19.7	11.4	-34.6
13	55	37	8	18.0	6.0	+ 5.5
14	57	35	8	16.0	3.1	+ 1.7
15	60	32	8	14.9	6.6	-12.4
16	65	27	8	17.4	8.0	-21.7
17	54	36.5	9.5	16.4	0.1	+28.3
18	50	40	10	22.4	12.0	-31.8
19	51.5	38.5	10	19.2	8.7	- 1.0
20	53	37	10	17.1	0.2	+32.0
21	55	35	10	—	1.4	+29.2
22	57	33	10	17.5	3.8	+ 9.6
23	57.5	32.5	10	16.7	3.5	+ 1.2
24	58.5	31.5	10	17.6	5.4	+ 4.1
25	60	30	10	17.4	5.1	-15.5
26	65	25	10	18.5	7.5	-19.8
27	70	20	10	18.1	8.8	-26.4
28	75	15	10	18.4	9.5	-27.9
29	80	10	10	--	13.5	-31.9
30	51	37	12	--	13.1	- 5.1
31	51.5	36.5	12	20.8	12.0	+60.4
32	55	33	12	18.6	12.0	+37.0
33	57	31	12	19.5	6.0	+25.8
34	58.5	29.5	12	19.6	6.0	+ 4.4
35	60	28	12	--	7.6	- 2.4
36	63	25	12	19.4	7.8	- 9.9
37	65	23	12	19.8	8.0	-16.2
38	52.5	35	12.5	18.7	13.0	+30.3
39	50	35	15	21.3	16.0	-36.4
40	52.5	32.5	15	--	15.6	-34.1
41	55	30	15	19.9	15.4	-29.9
42	60	25	15	22.3	14.0	-19.6
43	65	20	15	22.2	9.5	- 8.5
44	70	15	15	22.6	10.2	-17.7
45	75	10	15	24.4	10.3	-21.5
46	50	30	20	18.5	16.3	-53.2
47	60	20	20	16.7	14.8	-36.8
48	70	0	20	16.7	10.5	-33.4

TABLE 54. RIGIDITY MODULUS (G), THERMAL-EXPANSION COEFFICIENT (α), AND THERMOELASTIC COEFFICIENT (g) FOR VELINVARS(55)

Speci-men	Co, %	V, %	G, kg/cm^2 (20 C)	α 10~50 C	g 20~50 C
			$\times 10^5$	$\times 10^{-6}$	$\times 10^{-5}$
14	63	7(7.0)	5.40	8.52	- 6.7
21	61	8(7.9)	5.78	7.77	+ 0.5
22	63	8(7.9)	6.77	8.56	- 1.6
29	62	9(8.7)	6.46	8.74	- 4.3
34	60	10(10.2)	6.66	8.07	- 0.03
26	56	9(8.7)	6.32	3.94	+31.5

TABLE 55. COEFFICIENTS OF LINEAR(α) THERMAL EXPANSION OF CHEMICAL ELEMENTS (CRYSTALS)[80]

Element	Temperature or Temperature Range, C	Coefficient of Linear Thermal Expansion per C: Parallel to Axis	Coefficient of Linear Thermal Expansion per C: Perpendicular to Axis
		Thermal Expansion	
Osmium	+ 50	$\times 10^{-6}$	$\times 10^{-6}$
	250	5.8	4.0
	500	6.6	4.6
Rhenium	20 to 1917	8.3	5.8
Ruthenium	50	12.4	4.7
	250	8.8	5.9
	550	9.8	6.4
Selenium	15 to 55	11.7	7.6
	20 to 60	-17.9	—
Tellurium	20	—	74.1
	20 to 60	- 1.6	27.2
Thallium	32 to 91	- 1.7	27.0
Tin	-195 to 20	+72	9
	0 to 20	25.9	14.1
	+ 14 to 25	29.0	15.8
	34 to 194	32.2	16.8
Zinc	-190 to 18	45.8	25.7
	+ 20 to 100	49.5	11.3
	0 to 250	64.0	14.1
	20 to 400	56	15
Zirconium	0 to 100	59	16
		4	13
Antimony	-215 to +20	16.0	7.0
	+ 15 to 25	15.6	—
	0 to 100	16.8	—
	20 to 200	—	8.4
	20 to 400	—	8.1
Arsenic	30 to 75	3.2 to 6.8	—
Beryllium	-150	1.6	2.8
	+ 10	8.6	11.7
	18 to 220	10.4	15.0
	18 to 454	13.1	15.7
Bismuth	-140	15.9	10.5
	+ 30	16.2	11.6
	20 to 260	16.5	—
	20 to 240	—	12.0
Cadmium	-190 to 18	48.2	18.5
	+ 20 to 100	50.4	18.9
[illegible] Graphite	-195 to 0	—	4.8
	0 to 40	—	6.6
	0 to 500	17.2	1.3
	0 to 1000	18.8	1.8
	0 [illegible] 1500	20.7	2.0
	[illegible] to [illegible]300	23.1	2.4
	20 to [illegible]	26.7	—
Cobalt	3[illegible] to 100	16.1	12.6
Indium	[illegible]	56	13
	+ 23 [illegible]	45.0	11.7
Magnesium	[illegible] to 100	26.4	25.6
	20 to [illegible]	27.7	26.6
Mercury	[illegible]90 to -1[illegible]	42.6	33.4
	[illegible] to -79	47.0	37.5
	-1[illegible]	49.6	37.5

[illegible] If there is rando[illegible]ation of [illegible]crystals in a polycrystalline element such as antimony or cadmium, the [illegible]cient of linear expansion of the polycrystalline element may be computed from the [illegible]wing equation: $\alpha = 1/3(\alpha_{\parallel} + 2\alpha_{\perp})$, where $\alpha_{\parallel}$ is the coefficient of linear expansion of the cryst[illegible] paral[illegible] to its axis, and $\alpha_{\perp}$ is the coefficient of linear expansion of the crystal in the dir[illegible]tion perpendicular to its axis.

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Number	Title
203	Recent Information on Long-Time Creep Data for Columbium Alloys, April 26, 1965
204	Summary of the Tenth Meeting of the Refractory Composites Working Group, May 5, 1965 (AD 465260)
205	Corrosion Protection of Magnesium and Magnesium Alloys, June 1, 1965
206	Beryllium Ingot Sheet, August 10, 1965