

A REVIEW OF DIMENSIONAL INSTABILITY IN METALS

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A REVIEW OF DIMENSIONAL INSTABILITY IN METALS

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SUMMARY

Interest in maintaining very close dimensional control in precision parts has led to increased research activity in areas usually associated with the subject of dimensional stability. Included are the related phenomena of elastic-limit determinations, microcreep, microstrain, the mechanisms which cause them, and the practical methods that can be employed to improve dimensional control.

This memorandum discusses some of the problems that arise as a result of dimensional instability, and presents information that has been made available to the Defense Metals Information Center. General recommendations are made for the processing of parts for use in applications where a high degree of dimensional stability is required.

INTRODUCTION

The dimensional stability of a material refers to its ability to maintain its original size and shape over a period of time under specified environmental conditions. Although the term is self-explanatory, it becomes necessary not only to specify the conditions to which the material is exposed, but also the accuracy to which dimensional changes are measured. Because true dimensional stability can be defined as an absolute concept, it may be more realistic to consider the degree of instability that can be measured with suitable accuracy.

Improved techniques of metrology developed during the past decade or two have increased the potential accuracy of such measurements by one or two orders of magnitude. Similarly, the requirements of industry and Government, as exemplified by the needs of missile and space systems, have become increasingly stringent. Manufacturing methods have been improved to the point where tolerances specified in microinches (millionths of an inch) are becoming commonplace; in many instances, it is important not only to manufacture a component with such precision, but also to ensure that its dimensions do not change during service. It may be expected that the standards for producing and maintaining very high degrees of precision in manufactured parts will continue to increase during the next decade, and that these will be extended into broader segments of industry not yet fully affected by the increased requirements for precision.

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In the past, the distortion or dimensional instability of metals was studied mainly for the purpose of eliminating or reducing relatively large changes in dimensions in such parts as castings and die blocks. Most of these applications involved ferrous alloys, and a considerable volume of research was conducted to study the mechanisms leading to distortion, and methods for its reduction. A summary of the information available on this subject was presented in a recent DMIC report, "Control of Dimensions in High-Strength Heat-Treated Steel Parts", DMIC Report No. 163.

Additional information of a somewhat different character is needed to meet material requirements for recent developments in precision devices, such as bearings, gyros, accelerometers, and missile-guidance systems. In these applications, very high degrees of precision and dimensional stability may be needed over long periods of time. The metals involved range from the more conventional alloy steels and aluminum alloys to the newer metals - titanium, beryllium, and the refractory metals. Interest also has been shown in composite structures (sandwich, laminates, etc.) and in nonmetallics - glass, ceramics, and plastics. In general, material selection is limited by factors other than dimensional stability; examples are strength/density, resistance to corrosion, elastic modulus, and magnetic behavior. The necessity for achieving specified physical or mechanical properties in addition to stability of dimensions frequently leads to difficulties, since the processing requirements often are incompatible.

Another problem area is involved with the conditions of service under which dimensional stability is to be maintained. The influence of temperature and stress, both steady and cyclic, combined with the presence of various types of fields are the most important variables. A part of the dimensional change is (in most materials) unavoidable but predictable: thermal expansion and contraction from temperature changes, and elastic strain from stress application, for example. These effects usually can be compensated for by suitable design, and can be minimized by careful selection of material. For example, the thermal expansion can be reduced to essentially zero over a restricted temperature range by selecting a suitable alloy of the Invar type. Elastic strains can be minimized by using a material with a high elastic modulus, and by designing for low stress levels. The thermal-expansion and elastic-strain effects are essentially reversible, and are not ordinarily considered as a form of dimensional instability.

Many of the available data have been obtained on specimens that are not subjected to external loads other than their own weight. This probably is because much of the initial research in this field was done to develop improved methods for making reference standards, such as gage blocks, rather than components subject to external loads. On the other hand, most parts in precision equipment are subjected to stress during service, even though the stress levels usually are relatively low. It has been observed that deformation, both time independent and time dependent, can occur at the microinch-per-inch level at stresses well below the conventional yield stress or proportional limit. As an example, the conventional yield strength (0.2 per cent offset) for wrought 6061 aluminum alloy was reported to be 40,000 psi, whereas the precision elastic limit was about 12,000 psi.

Studies on the mechanisms of microstrain have been carried out rather intensively in recent years. Although terminologies vary, the terms "precision elastic limit" and "microcreep limit" have been used to designate the stresses at which time-independent and time-dependent plastic flow occur. The precision elastic limit is defined as the lowest stress at which a specified residual strain (usually of 1 microinch per inch) is detected. It is ordinarily determined by loading to successively increasing stresses in tension until a residual strain is detected.⁽¹⁾ The microcreep limit, as defined by Hughes⁽²⁾, is the lowest stress sufficient to cause a progressive increase in residual strain on three successive loadings.

As a result of the foregoing, it appears that in a stressed part, the importance of microstrain, as distinguished from true dimensional instability, must be recognized. For convenience, therefore, the total dimensional change is considered to be composed of three parts:

- (1) Recoverable dimensional changes; time independent (these generally are understood and predictable, and include elastic strain, thermal expansion, and magnetostrictive strain) and time dependent (these include stress-induced and magnetically induced ordering).
- (2) Plastic deformation (microstrain); this term includes the irrecoverable plastic strains, time dependent and time independent, that result from an applied stress.
- (3) Dimensional instability; this term is reserved here for changes in dimensions resulting from internal stress systems

or metallurgical instability (such as precipitation or phase change); that is, changes that occur in the absence of external forces.

In the discussions that follow, these three causes of dimensional change are discussed, and available information on how they can be controlled is presented. Emphasis is placed upon the causes and effects of dimensional instability.

RECOVERABLE DIMENSIONAL CHANGES

Certain recoverable dimensional changes result from external changes in stress, temperature, and magnetic fields. Both linear and volume changes are involved; however, here we will be concerned primarily with linear changes. The elastic modulus (E) relates the magnitude of an applied stress to the corresponding elastic strain; the coefficient of linear expansion (α) relates the change of temperature to the resulting thermal strain; and the Joule magnetostriction coefficient (λ) relates the magnitude of an applied magnetic field to the corresponding linear dimensional change. Within restricted ranges of these primary variables, the dimensional changes are essentially reversible, and their magnitudes can be calculated. It remains a design problem to ensure that these changes in dimensions are suitably accounted for in each specific application.

Although these parameters (E , α , λ) are sometimes expressed as constants over restricted ranges of stress, temperature, and field strength, it is well known that these are really average values. Further, there is usually a difference in the strain path which is determined by whether the applied force, temperature, or field is increasing or decreasing. This path dependence is reflected by a hysteresis loop, indicating an absorption of energy. This energy can be related to the mechanisms involved in the strain by suitable theoretical treatment.

As pointed out previously, these reversible effects can be predicted and, to a degree, minimized individually, provided that other considerations do not preclude a free choice of material and condition. The three effects described here frequently are, to a degree, related. For example, alloys of the iron-nickel type designed for low coefficient of expansion depend upon magnetostrictive effects to accomplish this, as do similar alloys with a controlled variation of elastic modulus with temperature. Invar and Ni-Span-C are two examples of such alloys.

For most purposes, the conventional handbook values for the parameters E , α , and λ are sufficiently accurate to provide design information. Where greater accuracy is needed for a specific application, it probably will be necessary to conduct experiments on the particular material and condition to be used, since variations in composition and structure are likely to be significant. A few data on selected materials are included in the Appendix for the values of elastic modulus and expansion coefficient.

PLASTIC DEFORMATION (MICROSTRAIN)

As it is employed here, the term microstrain is defined as the irrecoverable plastic strain resulting from an applied stress. It has been pointed out for many years that the values of the elastic limit and the proportional limit of a metal, as conventionally defined, depend upon the precision of the strain measurement. Advances in measurement techniques now have progressed to the point where residual strains can be measured to a resolution of about 1×10^{-6} with resistance gages, and as great as 1×10^{-7} or 1×10^{-8} by suitable capacitance gages. The elastic limit (or precision elastic limit) usually is defined as the lowest stress for which a measurable residual strain is obtained; this is sometimes arbitrarily set at 1 microinch per inch.* In some recent studies⁽³⁾, the term anelastic limit (σ_A) has been used to denote the same quantity; that is, the lowest stress at which the hysteresis loop on the stress-strain curve is not closed. Again, these values reflect the resolution of strain measurement.

The precision elastic limit is a useful quantity to the designer because it represents a limiting value for the design stress. It is necessary, however, to specify the corresponding residual strain. This ordinarily will be the smallest strain that can be detected by the strain-measuring system, or an arbitrary value such as 1 microinch per inch.

The residual microstrains corresponding to the (precision) elastic limit or the anelastic limit are considered to be essentially time independent. Studies of time-dependent deformation at microstrain levels also have been conducted. The term "microcreep limit" has been defined by Hughes as the stress just sufficient to cause progressive

increase in residual strain on three successive loadings to the same stress level.⁽²⁾ For beryllium, it was found that the microcreep limit was significantly higher than the precision elastic limit. In other work, microcreep in Invar and 356-T6 aluminum at room and slightly elevated temperatures has been observed at stresses near (and in some instances below) the elastic limit.⁽⁴⁾

DIMENSIONAL INSTABILITY

The term "dimensional instability", as it is used here, refers to changes in dimensions that occur over a period of time in a specimen without external loading. Data have been reported for a number of metals and alloys exposed both at constant temperature and to temperature cycling.

Mechanisms Leading to Dimensional Instability in Metals

The two primary mechanisms that cause dimensional instability in metals are reasonably well known. These are (1) metallurgical instability and (2) relaxation of residual stresses. There are, in addition, more subtle metallurgical reactions that are not so well understood. These may include the effects of ordering of interstitial and substitutional atoms, the effects of grain-boundary migration, and movements of magnetic domain walls. The effects of radiation on dimensional changes and on properties of materials, particularly fuel element materials, have been studied extensively; however, these are considered to be beyond the scope of this report. Some of the characteristics of the mechanisms leading to dimensional changes are discussed in the following sections.

Metallurgical Mechanisms

- (1) Metals or alloys that do not undergo a phase change form one of the simplest classes of materials. The only apparent microstructural changes are in grain size, shape, and orientation. One metallurgical change which can cause small dimensional changes is ordering. Individual solute atoms often will tend to occupy specific positions in the solvent lattice relative to like or unlike atoms. Because these reactions are controlled by the diffusivity of the solute in question, the reaction rates are distinguished by a relatively strong temperature dependence. Small dimensional changes will follow changes in

*Elastic limit also has been defined⁽³⁾ as the lowest stress at which a hysteresis loop is observed on the stress-strain curve after unloading.

stress, magnetization, or possibly temperature. Such reactions can be responsible for warm-up times for oscillating devices, hysteresis behavior during the stress cycle, or time dependence after reaching some fixed new temperature.

- (2) An alloy that rejects a second phase from solid solution (typical of the age-hardening alloy systems) will usually undergo a gradual change in volume. The rate of the reaction is dependent upon time and temperature, and upon the degree of departure from phase equilibrium. The reaction also may be sensitive to applied stress, the application of vibrational energy, and the level of impurities in the alloy.
- (3) A metal or alloy that undergoes a transformation from one allotropic form to another will change in volume. The change may be positive or negative, depending upon the relative specific volumes of the two phases. In steel, for example, the transformation from austenite to martensite results in a volume increase, the magnitude of which is dependent upon alloy composition.
- (4) Combinations of the several mechanisms described above may occur concurrently. For example, a steel may exhibit simultaneously a positive volume change from the transformation of retained austenite and a negative volume change from the tempering of martensite. Thus, the net volume change may be positive, negative, or zero; it also may change from one to the other over a period of time as one mechanism becomes dominant over another.

Residual-Stress Mechanisms

Shape distortions introduced by the relaxation of residual stresses are somewhat more difficult to analyze. Residual stresses most frequently are introduced during fabrication or heat treatment, and are characteristically nonuniform. Distortion then takes place through time-dependent plastic flow. The analysis of this problem is complicated by the fact that distortions in the microinch-per-inch range can result from residual-stress changes well below the present limits of experimental stress measurement. Further, present methods for the measurement of residual stresses are quantitatively useful only for sections of simple geometry. The stress distribution and consequent distortion of parts with more complex shapes can be predicted only qualitatively.

As was pointed out previously, both metallurgical and residual-stress mechanisms are operative in most cases; therefore, the gross dimensional change measured will be the sum of the two types of distortions. Under very special conditions, it may be possible to balance the two to obtain satisfactory dimensional stability, as has been done by the National Bureau of Standards in some of its gage-block studies. More usually, it will be necessary to reduce both the metallurgical instability and the residual-stress levels to attain the necessary degree of dimensional stability.

Evaluation of Dimensional Instability

The lack of extensive data on the dimensional instability of metals and alloys reflects the difficulties encountered in making highly precise and accurate measurements. In many instances, changes in dimensions are inferred from the drift observed in a completed instrument or system rather than from actual measurements of dimensions. This frequently leads to the anomalous situation in which changes in the calibration of an instrument can be measured to a precision much greater than that of measuring dimensional changes in the parts that are causing the change.

Perhaps the most advanced metrology techniques in use today are those developed by the National Bureau of Standards for its gage-block program, whereby changes in length approaching 10^{-7} inch per inch (1/10 microinch per inch) can be detected. The basis of measurement is the interferometer, with which the length of the reference gage block is determined. An interference comparator is used to intercompare the reference and specimen gage blocks. To increase the capacity of the measurement system, an electromechanical comparator was used in conjunction with reference gage blocks. With errors minimized by statistical procedures, an accuracy of about 0.2 microinch was obtained in a 2-inch length. It should be pointed out that extremely careful control of environmental and testing conditions is vital to the attainment of this high degree of accuracy.

In studies of dimensional instability in the range of a microinch per inch per year, it is important to note the distinction between accuracy and resolution of measurements. It was pointed out earlier that the resolution of strain measurements can be as high as 1×10^{-8} inch per inch with a device such as the capacitance gage. This means that very small relative changes in length over a reasonably short time period, can be observed with comparatively simple equipment.

Accuracy in the measurement of absolute lengths calls for a highly advanced measurements facility and for careful techniques of standardization.

RESEARCH ON DIMENSIONAL INSTABILITY AND ASSOCIATED PROBLEMS

An examination of the open literature and available Government reports dealing with dimensional instability reveals a comparatively small amount of useful data. This reflects in part the experimental difficulties in obtaining truly significant data, and the consequent high investment involved in such measurements. It also indicates the fact that such information frequently is regarded as highly proprietary by those industrial companies who have developed it.

The most comprehensive published compilations of data on this subject were prepared by the Instrumentation Laboratory of the Massachusetts Institute of Technology.^(5,6) The data presented in these reports were collected over about a 15-year period, and have formed the basis for many of the materials-processing schedules that are in use today for the manufacture of precision devices.

A study has been in progress for a number of years at the National Bureau of Standards to improve the stability of gage-block materials.^(7,8,9,10) It is restricted to those materials that are potentially useful as gage blocks (that is, with surface hardness values of at least $R_C 65$), and it has resulted in several materials and processing methods that produce extremely good dimensional stability.

A current research program, sponsored by the Naval Applied Science Laboratory, is being conducted by Alloyd General Corporation.⁽⁴⁾ It presently is developing data on elastic limits, creep, and dimensional stability for a number of selected alloys including Invar, 356-T6 cast aluminum, and 310 stainless steel.

Only scattered data in addition to those listed above have been found. A number of papers in the open literature have been published, most of which deal with bearing steels, and a report on beryllium was released by the General Motors Laboratory.⁽²⁾ All of the data presented in this report were taken from the sources listed above.

A number of research programs now are in progress which deal with microstrain and the mechanisms that are associated with it. These

studies, which are generally basic in nature, involve the observation of microstrain effects in tension-compression, bending, and torsion, both with static and dynamic (internal friction) loading techniques. The recoverable elastic strains and the associated hysteresis loops are related to mechanisms such as the bowing of dislocation loops between pinning points. Theoretical expressions, based upon dislocation dynamics, have been developed which show promise of providing a rational basis for expressing the energy loss involved with the fundamental dislocation parameters.

The stress at which the dislocation loops break away from their pinning points likewise has been related to the stress at which a measurable residual strain is observed. This effect has been studied in various ways including direct tension and internal-friction experiments.

Much of the most recent information on microstrain was presented at a symposium sponsored by AIME,⁽¹¹⁾ for which the proceedings will serve as a reference. In summary, it appears that an improved understanding of the basic mechanisms that lead to microstrain has already been developed, and that application of these concepts to the over-all dimensional control of metals should be possible in the near future.

PROCEDURES FOR PROCESSING TO REDUCE DIMENSIONAL INSTABILITY

The degree of dimensional instability that is found in a finished metal part is influenced by: (1) material composition and structure, (2) its thermal and mechanical history, and (3) the environmental conditions of exposure and use. The designer has only limited control over these factors. For example, the material selection is frequently based upon physical or mechanical-property requirements other than dimensional control: strength, density, magnetic behavior, corrosion resistance, etc. The thermal and mechanical history is likewise limited by, for example, the necessity for fabricating into a given configuration, or the need to develop a high strength or hardness by heat treatment. The conditions of environment and use likewise are largely factors that cannot be completely controlled by the designer, although he may be able to limit some of their effects; for instance, the stress level in a part may be reduced through an increase in section size.

Of the three factors, the processing treatments which determine the thermal and mechanical history are most under the control of the manu-

factorer. Thus, the attainment of a satisfactory degree of dimensional stability in a finished part will depend strongly upon the selection of suitable processing procedures. These can be related to the mechanisms leading to instability that were discussed previously. It is usual practice to stress relieve between successive machining operations, and to perform stabilizing heat treatments before and after finish machining.

The general procedures recommended in the MIT work⁽⁵⁾ are as follows:

- (1) Stress relieve
- (2) Rough machine
- (3) Stress relieve
- (4) Perform main heat treatment
- (5) Machine slightly oversize
- (6) Stabilize
- (7) Machine to final dimensions
- (8) Stabilize.

Steps (1), (3), and (8) are indicated as optional.

There are certain general observations that can be made concerning the effects of thermal and mechanical treatments on dimensional stability:

(1) Phase equilibrium under service conditions should be approached as closely as possible, since gradual transformation is one cause of instability. In quenched and tempered steels, it is usual practice to eliminate as much retained austenite as possible from the structure by quenching to subzero temperatures before tempering. This is because definite correlations have been found between dimensional instability and the gradual transformation of retained austenite. Although repeated subzero exposures sometimes are recommended to reduce the amount of austenite retained in the structure, there is some question as to the actual effectiveness of such cyclic treatments.

Stabilization treatments generally are designed to accelerate any aging that otherwise would take place at the service temperature. For a part that is to be used at room temperature, a stabilization treatment of 24 hours at 200 F is suggested.⁽⁵⁾ It is pointed out further that the stabilization temperature should not exceed the last temperature of the main heat treatment to avoid the loss of mechanical properties.

(2) Residual stresses leading to distortion can be introduced by drastic heating or cooling during processing. Wherever possible, parts should be heated and cooled slowly to prevent the forming of large temperature gradients. This is, of course, more important where large and complex shapes are involved. Where quenching is needed as part of a heat-treatment process, it may be desirable to reduce the severity of the quench as much as possible. For example, a quench into boiling water rather than cold water may be used after solution annealing certain age-hardening aluminum alloys.

(3) Residual stresses and consequent distortion may be introduced during machining and grinding operations. In addition, the presence of residual stresses in a heat-treated part may lead to distortion during machining due to the unequal removal of metal. This in turn may make it difficult to attain the desired dimensional tolerances, and may require that finish machining be carried out in steps, each followed by an appropriate stress-relieving treatment.

(4) The attainment of a suitable degree of stress relief without a loss of mechanical properties may require that a compromise of time and temperature be made. Newer techniques for increasing the rate of stress relief, notably by the application of ultrasonic energy, are in the development stage and may be of considerable value in the future. Temperature cycling also has been used to relieve residual stresses. This usually is done by cycling between room temperature or a moderately elevated temperature and a subzero temperature. It has been reported⁽⁵⁾ that 10 cycles or less usually are sufficient.

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APPENDIX

COMPILATIONS OF DATA

The data presented in this Appendix have been taken from the sources cited in the preceding section. With few exceptions, no changes have been made except for the correction of a few obvious misprints.

There are some precautions that should be observed in using the information presented in these tables. First, it should be noted that even where a specific processing schedule is recommended, it does not necessarily follow that this procedure develops the optimum degree of dimensional stability for that alloy. Also, treatments leading to a high degree of stability of dimensions in samples exposed without stress do not necessarily produce the highest stability in parts that are subjected to external loads. Finally, it should be pointed out that some of the information presented here has been taken from sources that may not now be considered to be fully authenticated.

With these reservations in mind, the data presented here should provide a useful source of information for the selection and processing of parts for applications in which dimensional stability is needed. Each group of tables taken from a single source is identified, and the pertinent information on experimental techniques is presented briefly.

Data From R-95, Summary Report
No. 1, "Measurement and Control of
the Dimensional Behavior of Metals"

by

B. S. Lement and B. L. Averbach,
Metals Processing Division, Department of Metallurgy, December, 1955.
Instrumentation Laboratory, Massachusetts Institute of Technology,
Cambridge 39, Massachusetts

These data were obtained using test specimens $3/8$ inch in diameter and 4 inches long, with the ends spherically ground to a 2-inch radius. Length measurements were made with a 5000X comparator at 70 F. Changes in length were measured after $1/2$ hour at 70 F following heat treatment for time periods up to 1 year of aging at constant temperature. The precision of the length-change determination was reported to be about 10 per cent for changes greater than about 30 microinches per inch, and about ± 3 microinches for smaller changes. In the tables of data, length changes are reported to the nearest 5 microinches per inch.

Dimensional-stability data are reported for three types of exposure: (1) 70 F, (2) 160 F, and (3) after cycling 10 times between 70 F and -95 F, with a 30-minute holding period at -95 F.

TABLE A-1. DIMENSIONAL STABILITY OF PLAIN-CARBON AND LOW-ALLOY STEELS

Alloy	Spec. No.	Treatment	Rock- well Hard- ness	Microinch per Inch Length Change in Time and Cyclic Stability Tests						Cycled 10X to -95F	Thermal Expan. Coef. 10 ⁻⁶ /°C
				Aged at 70F			Aged at 160F				
				1 mo.	3 mo.	12 Mo.	1 mo.	3 mo.	12 mo.		
1112		cold drawn (as received)	B95	-	-	-	-	-	-	-	
	175-1,2,3	stress relieve 800F, 1 hr., A.C.-(R)	B95	+5	0	-5°	-5	-5	-5°	0	11.0
	175-4,5,6	1200F, 1 hr., A.C.-(R)	B77	-10	-10	-10°	-5	-5	-5°	-5	11.0
1050	1L ^{oo} -1,2,3	anneal 1650F, 1hr., F.C.	B74	-15	-15	-25	-10	-10	-15	-15	11.4
	1T ^{oo} -1,2,3	anneal 1650F, 1hr., F.C.	B74	-5	-5	-10	-20	-25	-40	-15	
X1080	10-1,2,3	cold drawn (as received)	B93	-5	-10	-15	-5	-10	-15	-15	
	10-4,5,6	stress relieve 1200F, 1hr., A.C.	B62	-15	-20	-30	-5	-5	-10	0	
	10-7,8,9	normalize 1600F, 1/2hr., A.C.	B74	-10	-10	-15	-45	-30	-65	-25	
	10-10,11,12	harden 1600F, 1/2hr., B.Q.	C40	+40	+50	+65	+100	+105	+120	+60	
	10-13,14,15	temper 300F, 1/2 hr., A.C.	C40	-5	-5	-5	+15	+20	+30	+10	11.0
1045	5-10,17,18	cold drawn (as received)	B94	-5	-10	-15	0	0	-20	-5	
	5-10,20,21	stress relieve 1200F, 1 hr., F.C.-(R)	B93	-5	-5	-10	0	0	-5	-5	
	5-7,8,9	anneal 1550F, 1/2 hr., F.C.	B90	-5	-5	-	-5	-5	-	-5	11.2
	5-10,11,12	stabilize 300F, 1 hr., A.C.-(R)	B93	0	0	-	-5	-5	-	-5	
	5-23,23,24	normalize 1600F, 1/2 hr., A.C.	B95	-25	-25	-45	-20	-25	-35	-15	
	5-6	draw 800F, 1hr., A.C.	B95	-5	-10	-	-	-	-	-	
	5-25,26,27	harden 1535F, 1/2hr., B.Q.	C56	-30	-50	-70	+55	+55	+55	-205	
	5-28,29,30	temper 300F, 1hr., A.C.	C56	-5	-5	-10	-25	-30	-35	-15	
1144	13-7,8,9	anneal 1550F, 1/2 hr., F.C.	B95	0	0	-	0	0	-	0	
	13-4,5,6	normalize 1600F, 1/2 hr., A.C.	B95	-15	-20	-	-10	-15	-	-	
	13-6	draw 800F, 1 hr., A.C.	B95	-5	-5	-	-	-	-	-	
		harden 1550F, 1/2 hr., O.Q.									
	13-1,2,3	temper 1100F, 1 hr., W.Q.	C23	0	0	0°	0	0	-	-5	11.1
4140	6-9,10,11	anneal 1550F, 1/2hr., F.C.-(R)	B95	0	-5	-	0	-5	-	+5	11.4
	6-6,7	normalize 1600F, 1/2 hr., A.C.	C23	+20	+25	+30	+5	+25	-	-	
	6-8	draw 800F, 1/2 hr., A.C.	C23	-5	-5	-	-	-	-	-	
	6-4	harden 1550F, 1/2 hr., O.Q.	C54	+90	+100	+105°	-	-	-	-	
4140	6-5	subc oil	C54	-10	-10	-10°	-	-	-	-	
		harden 1600F, 1/2hr., O.Q.									
	6-13,14,15	temper 300F, 2hrs., A.C.	C54	-5	0	0°	+5	+15	+20°	0	
	6-16,17,18	1600F, 2hrs., A.C.-(R)	C30	-10	-10	-10°	-5	-5	-5°	-5	
	6-1,2,3	1100F, 1hr., W.Q.	C23	-25	-25	-35	-25	-45	-60	-15	11.1
4340	10-4,5,6	anneal 1550F, 1/2hr., F.C.-(R)	B93	0	0	-	0	0	-	0	11.2
	10-7,8,9	harden 1600F, 1/2hr., O.Q.	C55	+90	+90	+90°	-25	-30	-	+200	
	10-15,16,17	temper 300F, 2hrs., A.C.	C56	-5	-5	+5°	+15	+25	+40°	+10	
	10-1,2,3	1100F, 1hr., W.Q.	C25	-5	-5	-10°	-15	-20	-20	-20	10.0
		normalize 1550F, 1/2hr.									
	10-10,10,20	martemper H.Q. to 800F, A.C.	C40	+5	+5	+10°	+25	+25	+60	+70	
1070	3-7,8,9	anneal 1650, 1/2hr., F.C.	B75	-15	-20	-20	-5	-5	-10	-20	
		normalize 1600F, 1/2 hr., A.C.									
	3-4,5,6	draw 1200F, 1 hr., A.C.	B94	-15	-15	-20	-5	-5	-5	-5	
		harden 1500F, 1/2 hr., W.Q.									
	3-1,2,3	temper 300F, 1hr., A.C.	C66	-20	-20	-20	-25	-25	-20	-15	

96 months of aging
^{oo}L - longitudinal direction
^{oo}T - transverse direction
 (R) - recommended treatment

F.C. - furnace cool
 A.C. - air cool
 O.Q. - oil quench
 W.Q. - water quench
 B.Q. - brine quench
 H.Q. - hot quench
 A.H. - air heat

TABLE A-2. DIMENSIONAL STABILITY OF TOOL STEELS

Alloy	Spec. No.	Treatment	Rock well Hard- ness	Microinch per Inch Length Change in Time and Cyclic Stability Tests								Thermal Expans. Coeff. 10 ⁻⁶ /°C
				Aged at 70F			Aged at 160F			Cycled 10X to -95F		
				1mo.	3mo.	12mo.	1mo.	3mo.	12mo.			
10100	8-7, 8, 9	anneal	1450F, 1hr., F.C.	B87	-10	-15	-15	-15	-20	-20	-20	
		normalize	1550F, 1/2hr., A.C.									
	8-4, 5, 6	draw	1100F, 1hr., A.C.	B97	-10	-10	-15 ⁰	-5	+5	+5	-15	
		harden	1450F, 1/2hr., W.Q.									
	8-1, 2, 3	temper	300F, 1hr., A.C.	C65	-5	-10	-15	10	-5	-	+30	
10100	K-57, 62	harden	1450F, 1/2hr, W.Q.	C66	-175	-265	-405	-	-	-	-	11.8
	K-58, 63	temper	300F, 1hr., A.C.	C65	-5	-5	-10	-	-	-	-	
	K-70, 85		350F, 1hr., A.C.-(R)	C64	-5	-5	-10	-	-	-	-	
	K-115		400F, 1hr., A.C.	C63	0	-5	-5	-	-	-	-	
	K-116		500F, 1hr., A.C.	C62	0	-5	-5	-	-	-	-	
		harden	1450F, 1/2hr., W.Q.									
	K-80	subcool	-320F, 1hr., A.H.	C67	-240	-350	-525	-	-	-	-	
	K-81	temper	300F, 1hr., A.C.	C68	-5	-10	-15	-	-	-	-	
	K-164		400F, 1hr., A.C.-(R)	C64	-5	-5	-5	-	-	-	-	
	K-155		500F, 1hr., A.C.-(R)	C60	-5	-5	-5	-	-	-	-	
		harden	1450F, 1/2hr., W.Q.									
		temper	300F, 1hr., A.C.									
	K-82	subcool	-320F, 1hr., A.H.	C66	-10	-10	-15	-	-	-	-	
	K-84	temper	300F, 1hr., A.C.	C66	-10	-10	-15	-	-	-	-	
		austenitize	1450F, 1/2hr.									
		quench	oil at 125F, A.C.									
	K-167	temper	300F, 1hr., A.C.	C66	-5	-5	-	-	-	-	-	
	K-156		400F, 1hr., A.C.	C63	-10	-15	-	-	-	-	-	
Mangan-												
ese Die	H-44, 46	harden	1450F, 1/2hr., O.Q.	C64	-30	-50	-90	-	-	-	-	11.8
	H-45, 47	temper	300F, 1hr., A.C.-(R)	C65	0	0	0	-	-	-	-	
	H-56	subcool	-320F, 1hr., A.H.	C63	-10	-10	-15	-	-	-	-	
		temper	300F, 1hr., A.C.	C62	-5	-5	-10	-	-	-	-	
		harden	1450F, 1/2hr., O.Q.									
	H-54	subcool	-320F, 1hr., A.H.	C65	-90	-130	-185	-	-	-	-	
	H-55	temper	300F, 1hr., A.C.	C68	-5	-5	-10	-	-	-	-	
		austenitize	1450F, 1/2hr.									
		quench	oil at 125F, A.C.									
	H-57, 62, 65, 67, 72, 75											
		temper	300F, 1hr., A.C.	C62	+15	+20	-	-	-	-	-	
	H-76		400F, 1hr., A.C.	C61	+5	+5	-	-	-	-	-	
		austenitize	1450F, 1/2hr.									
		Marquench	H.Q. to 450F, A.C.									
	H-70	temper	300F, 1hr., A.C.	C63	+10	+15	-	-	-	-	-	
	H-71		400F, 1hr., A.C.	C60	0	-5	-	-	-	-	-	
Tungsten												
Die	G-22, 25	harden	1600F, 1/2hr., O.Q.	C66	-100	-155	-260	-	-	-	-	11.6
	G-24, 26	temper	300F, 1hr., A.C.-(R)	C65	0	0	0	-	-	-	-	
	G-35	subcool	-320F, 1hr., A.H.	C65	-10	-10	-15	-	-	-	-	
	G-36	temper	300F, 1hr., A.C.	C65	-5	-5	-10	-	-	-	-	
		harden	1600F, 1/2hr., O.Q.									
	G-32	subcool	-320F, 1hr., A.H.	C64	-175	-250	-360	-	-	-	-	
	G-33	temper	300F, 1hr., A.C.	C66	-5	-5	-10	-	-	-	-	

TABLE A-2. (Continued)

Microinch per inch Length Change in												
Alloy	Spec. No.	Treatment	Rock- well Hard- ness	Time and Cyclic Stability Tests								Thermal Expan. Coef. 10 ⁻⁶ /°C
				Aged at 70F			Aged at 100F			Cycled 10X -95F		
				1mo.	3mo.	12mo.	1mo.	3mo.	12mo.			
91100		harden	1550F, 1/2hr., O.Q.									
		subcool	-75F, 1hr., A.H.									
	170-1,2,3	double temper	300F, 1hr., A.C. (2)	C66	-5	-10	-10 ⁰	-10	-15	-25 ⁰	-5	11.0
93100		harden	1550 F, 1/2hr., O.Q.									
	2L ⁰⁰ -1,2,3	temper	300F, 1hr., A.C.	C64	-5	0	0	+10	+15	-	+10	
	2T ⁰⁰⁰ -1,2,3	temper	300F, 1hr., A.C.	C64	-5	-5	0	+10	+20	-	+15	
93100	T-11	harden	1550F, 1/2hr., O.Q.	C64	-40	-80	-110	-	-	-	-	
	T-20, 60	temper	250F, 10hrs., A.C. - (R)	C65	0	0	-	-	-	-	-	
	T-40, 60		300F, 1hr., A.C.	C64	0	0	0	-	-	-	-	
	T-84		400F, 1hr., A.C. - (R)	C62	0	0	0	-	-	-	-	11.0
			300F, 1hr., A.C.	C60	0	0	0	-	-	-	-	
		harden	1550F, 1/2hr., O.Q.									
	T-20, 42	subcool	-320F, 1hr., A.H.	C95	-90	-35	-105	-	-	-	-	
	T-56	temper	250F, 10hrs., A.C.	C66	0	0	-	-	-	-	-	11.0
	T-60		300F, 1hr., A.C.	C64	-5	-5	-5	-	-	-	-	
			400F, 1hr., A.C.	C61	-5	-5	-5	-	-	-	-	
			500F, 1hr., A.C.	C60	0	0	0	-	-	-	-	
		harden	1550F, 1/2hr., O.Q.									
		temper	300F, 1hr., A.C.									
	T-72	subcool	-320F, 1hr., A.H.	C64	-5	-5	-10	-	-	-	-	
	T-73	temper	300F, 1hr., A.C.	C65	0	-5	-5	-	-	-	-	
		austenitize	1550F, 1/2 hr.,									
		quench	oil to 125F, A.C.									
	T-22, 65	temper	300F, 1hr., A.C.	C65	+15	+25	-	-	-	-	-	
	T-81		400F, 1hr., A.C.	C62	0	-5	-	-	-	-	-	
93100		austenitize	1550F, 1/2 hr.									
		marquench	H.Q. to 250F, A.C.									
	T-55, 53	temper	300F, 1hr., A.C.	C64	0	0	-	-	-	-	-	
	T-50		400F, 1hr., A.C.	C63	-5	-5	-	-	-	-	-	
		austenitize	1550F, 1/2hr									
		marquench	H.Q. To 400F, A.C.									
		subcool	-320F, 1hr., A.H.									
	T-60	temper	250F, 10 hrs., A.C.	C66	-5	-5	-	-	-	-	-	
	T-70		300F, 1hr., A.C.	C64	-5	-5	-	-	-	-	-	
	T-71		400F, 1hr., A.C.	C63	-5	-5	-	-	-	-	-	
93100	53-1	harden	1550F, 1/2hr., O.Q.		-80	+7 ⁰	-	-	-	-	-	
	53-2	subcool	-320 F, 1hr., A.H.		-110	-140	-	-	-	-	-	
		harden	1550F, 1hr., O.Q.									
	53-3	temper	200F, 1hr., A.C.		+45	+30	-	-	-	-	-	
	53-4		300F, 1hr., A.C.		-5	-10	-	-	-	-	-	12.5
1C-5Cr	63-2	harden	1800F, 1/2hr., A.C.	C96	+290	+225	+220 ⁰	-	-	-	-	
	63-3, 4, 5	temper	300F, 2hrs., A.C.	C94	-5	-5	-5 ⁰	-10	-10	-10 ⁰	+65	12.3
	63-6, 7, 8		950F, 2hrs., A.C.	C60	+440	+470	+490	+425	+430	+440 ⁰	+600	10.0
High C, P-53		harden	1900F, 1/2hr., A.C.	C65	+15	+5	-10	-	-	-	-	
High Cr P-46		temper	300F, 2hrs., A.C. - (R)	C61	0	-5	-10	-	-	-	-	
			900F, 2hrs., O.Q.	C63	+30	+25	+20	-	-	-	-	
		harden	1900F, 1/2hr., A.C.									
		triple temper	900F, 1hr., O.Q. (3)	C65	+310	+270	-	-	-	-	-	
P-57		stress relieve	650F, 1hr., A.C.	C61	+150	+105	-	-	-	-	-	

TABLE A-2. (Continued)

				Microinch per Inch Length Change in							Thermal Expans. Coeff. 10 ⁻⁶ /°C
Alloy	Spec. No.	Treatment	Rock- well Hard- ness	Time and Cyclic Stability Tests							
				Aged at 70F			Aged at 160F			Cycled 10X 10-93F	
				1mo.	3mo.	12mo.	1mo.	3mo.	12mo.		
High C,		harden	1800F, 1/2hr., A.C.								
High Cr	F-46	subcool	-125F, 1hr., A.H.	C66	-90	-90	-120	-	-	-	-
		temper	850F, 1hr., O.Q.	C63	-5	-10	-	-	-	-	-
	F-47		910F, 2hrs., A.C.	C61	+45	+55	+80	-	-	-	-
		harden	1900F, 1/2hr., A.C.								
		subcool	-320F, 1hr., A.H.								
		triple temper	950F, 1 hr., O.Q. (3)								
	F-60		450F, 1hr., A.C.	C62	+85	+135	-	-	-	-	-
		harden	1900F, 1/2hr., A.C.								
		subcool	a. -320F, 1hr., A.H.								
		temper	b. 950F, 1 hr., O.Q.								
		cycle	c. Repeat steps a and b four times								
	F-62		d. 450F, 1 hr., A.C. -(R)	C60	0	0	-	-	-	-	10.2
High C,	F4-8, 9, 10	anneal	1600F, 2 hrs., F.C.	B66	-5	-5	-50	0	0	0	+5
High Cr	64-1	harden	1800F, 1/2 hr., O.Q.	C65	+100	+90	+70	-	-	-	-
	64-2, 3, 4	temper	300F, 2 hrs., A.C. -(R)	C63	0	0	0	-10	-10	-10	-5
	64-5, 6, 7		900F, 2 hrs., A.C.	C58	+260	+300	+340	+380	+395	+410	+435
M-2 High Speed	E-9	air harden	2220F, 3 mins., A.C.	C60	-5	-25	-50	-	-	-	-
	E-8, 10	harden	2220F, 3 mins., O.Q.	C65	-70	-100	-150	-	-	-	-
		temper	1050F, 2 1/2 hrs., O.Q.								
	E-10	stress relieve	800F, 1 hr., A.C.	C64	-5	0	+5	-	-	-	-
		harden	2220F, 3 min., O.Q.								
	E-11	temper	1050F, 2 1/2 hrs., A.C.	C65	+25	+35	+50	-	-	-	-
	E-13	stress relieve	800F, 1hr., A.C.	C65	+10	+15	+20	-	-	-	-
	E-12		900F, 1hr., A.C.	C65	+20	+30	+45	-	-	-	-
M-2 High Speed		harden	2220F, 3min., O.Q.								
		double temper	1050F, 2 1/2 hrs., A.C. (2)								
	E-14	stress relieve	800F, 1hr., A.C.	C64	+10	+10	+15	-	-	-	-
		harden	2220F, 3min., O.Q.								
	E-15	triple temper	1050F, 2 1/2 hrs., A.C. (3)								
		stress relieve	800F, 1hr., A.C.	C65	+10	+10	-	-	-	-	-
		harden	2220F, 3mins. O.Q.								
		triple temper	1050F, 2 1/2 hrs., O.Q. (3)								
	E-26	stress relieve	800F, 1hr., A.C.	C65	5	5	-	-	-	-	-
	E-26		900F, 1hr., A.C. -(R)	C65	0	0	-	-	-	-	-
		harden	2220F, 3mins., O.Q.								
	E-24	subcool	-320F, 1hr., A.H.	C66	-190	-235	-	-	-	-	-
		temper	1050F, 2 1/2hr., A.C.								
	E-17	stress relieve	800F, 1hr., A.C.	C64	+25	+35	-	-	-	-	-
		harden	2220F, 3min., O.Q.								
		subcool	-320F, 1hr., A.H.								
		triple temper	1050F, 2 1/2hrs., O.Q. (3)								
	E-18	stress relieve	800F, 1hr., A.C.	C64	0	0	-	-	-	-	-
	E-19		900F, 1hr., A.C. -(R)	C64	0	0	-	-	-	-	10.5

* 6 months of aging

F.C. - furnace cool

** L - longitudinal direction

A.C. - air cool

*** T - transverse direction

O.Q. - oil quench

(R) - recommended treatment

W.Q. - water quench

H.Q. - hot quench

A.H. - air harden

TABLE A-3. DIMENSIONAL STABILITY OF STAINLESS STEELS

Alloy	Spec. No	Treatment	Rock- well Hard- ness	Microinch per Inch Length Change in Time and Cyclic Stability Tests							Thermal Expans. Coef. 10 ⁻⁶ /°C	
				Aged at 70F			Aged at 160F			Cycled 10X to -95F		
				1mo.	3mo.	12mo.	1mo.	3mo.	12mo.			
302	15-11, 12, 13	quench anneal	1950F, 1/2hr., W.Q.	B79	-5	-5	-10	-10	-15	-20	-80	16.3
	15-8, 9, 10	stress relieve	600F, 1hr., A.C.	B79	0	-	-	C	-	-	+5	
	15-14, 15, 16		750F, 1hr., A.C.	B79	0	0	-5	-5	-10	-15	-10	
303		cold drawn	(as received)									16.1
	7-28, 29, 30	stress relieve	750F, 1hr., A.C.	B98	-10	-15	-20	-5	-10	-20	-5	
	7-4, 2, 3	quench anneal	1950F, 1/2hr., W.Q.	B82	-5	-5	-10	-20	-30	-45	-50	
	7-13, 14, 15	stabilize	200F, 20hrs., A.C.	B83	0	-	-	-5	-5	-	-25	
	7-22, 23, 24	quench anneal	1950F, 1/2hr., W.Q.	B83	-10	-	-10 ⁰	-10	-10	-10 ⁰	-40	
	7-8, 7, 8	stress relieve	600F, 1hr., A.C.	B82	-5	-5	-	-5	-5	-	-10	
	7-25, 26, 27		750F, 1hr., A.C.	B82	0	0	0	-10	-10	-15	-15	
		quench anneal	1950F, 1/2hr., W.Q.									
		stress relieve	600F, 1hr., A.C.									
	7-19, 20, 21	stabilize	200F, 20hrs., A.C.-(R)	B82	-5	-5	0 ⁰	-5	-5	-	-5	
310	25-4, 5, 6	quench anneal	1950F, 1/2hr., W.Q.	B84	-10	-10	-10	-5	-5	-5	-20	14.6
	25, 7, 8, 9	stress relieve	750F, 1hr., A.C.	B84	-5	-5	-5	-5	-5	-10	-20	
410	24, 11, 12, 13	anneal	1600F, 2 hrs., F.C.									10.2
			to 1100F, A.C.	B78	-5	-5	-10 ⁰	-10	-10	-10 ⁰	-15	
	24-4	harden	1800F, 1/2 hr., O.Q.	C47	+15	+10	+5 ⁰	-	-	-	-	
	24-1, 2, 3	temper	450F, 1hr., A.C.-(R)	C46	-5	-5	-10	-5	-5	-5	-10	
	24-5, 6, 7, 14		600F, 1hr., A.C.-(R)	C41	0	0	-5	-5	-5	-10	-5	
	24-8-9, 10		1200F, 4hrs., A.C.	C22	-10	-10	-15 ⁰	-5	-5	-10 ⁰	-15	
440C	39-6, 7, 8	anneal	1650F, 2hrs., F.C.	B94	-5	-5	-5 ⁰	0	0	0 ⁰	0	10.2
		harden	1900F, 1/2hr., O.Q.	C63								
	39-2, 4, 5	temper	300F, 1hr., A.C.-(R)	C61	0	-5	-10 ⁰	0	0	-5 ⁰	-5	

*6 months of aging

W.Q. - water quench

F.C. - furnace cool

(R) recommended treatment

A.C. - air cool

O.Q. - oil quench

TABLE A-4. DIMENSIONAL STABILITY OF NICKEL ALLOYS

Alloy	Spec. No.	Treatment	Rockwell Hardness	Microinch per Inch Length Change in Time and Cyclic Stability Tests							Thermal Expans. Coef. $10^{-6}/^{\circ}\text{C}$	
				Aged at 70F			Aged at 160F			Cycled 10X to -85F		
				1mo.	3mo.	12mo.	1mo.	3mo.	12mo.			
A-Nickel	55-1	cold drawn	(as received)	B83	0	-5	-5 ^o	-	-	-	-	
	55-2,3,4	quench anneal	1525F, 1/2 hr., W.Q.	B36	-65	-70	-70	-30	-	-	+15	12.3
Z-Nickel		cold drawn	(as received)	C29								
	54-1,2,3	age harden	1000F, 9hrs., F.C. to 900F, A.C.	C40	0	0	-	-	-	-	-5	12.4
Inconel	57-1	cold drawn	(as received)	C20	-5	-10	-10 ^o	-	-	-	-	
Inconel	173-1,2,3	anneal	1700F, 1hr., F.C.	B71	0	0	0	0	0	0	+3	12.5
	173-4,5,6	stabilize	200F, 24hrs., A.C. -(R)	B71	0	0	-5	0	0	-5	0	12.7
Inconel		anneal	1700F, 1hr., F.C.									
	185-1,2,2,4	stabilize	200F, 24hrs., A.C. -(R)	B79	-5	-5	-	0	0	-	-5	12.6
Inconel X	58-1	cold drawn	(as received)	C27	0	-10	-10 ^o	-	-	-	-	
Monel	59-1	cold drawn	(as received)	B96	0	-10	-15 ^o	-	-	-	-	13.6
K-Monel	56-1A	cold drawn	(as received)	A64	0	-5	-5 ^o					
		age harden	1000F, 9hrs., F.C. to 900F, A.C.	C37	-5	-5	-	0	-5	-	0	13.4
	56-1,2,3											
Hastalloy B		quench anneal	2100F, 1hr., W.Q.									
	179-1,2,3	quench anneal	1950F, 1hr., W.Q.	B95	-10	-15	-15 ^o	-35	-40	-40 ^o	-15	
	179-4,5,6	stress relieve	600F, 1hr., A.C. -(R)	B95	0	0	0	0	0	0 ^o	0	10.4
Ni-Span Lo 45	60-1A	cold rolled	(as received)	A63	-5	-10	-10 ^o	-	-	-	-	
		solutionize	1800F, 1 1/4 hr., W.Q.									
	60-1,2,3	age	1250F, 21hrs., A.C.	C34	-10	-15	-15 ^o	-15	-15	-20 ^o	-10	
42Ni-59Fe	77-1A	quench-anneal	1525F, 1/2 hr., W.Q.	B72	0	0	0	-10	-	-	-	4.5
	77-2,3											
Ni-Span-C	61-1	cold drawn	(as received)	A60	-5	-5	-5 ^o	-	-	-	-	
		solutionize	1800F, 1 1/4 hr., W.Q.									
	61-1,2,3	age	1250F, 21hrs., A.C.	C29	-10	-10	-10 ^o	-15	-15	-15 ^o	-20	7.2
Regular Invar	50L-1,2,3	quench-anneal	1525F, 1/2hr., W.Q.	B77	-15	-20	-20	+40	+5	-70	-75	
	50T-1,2,3	quench-anneal	1525F, 1/2hr., W.Q.	B77	-45	-40	-25 ^o	-10	-20	-30 ^o	+20	
Regular Invar	51-17,18,19	anneal	1525F, 1hr., F.C.	B77	-25	-25	-	+5	+5	-	-15	
	51-1,2,3	quench-anneal	1525F, 1/2hr., W.Q.	B77	-5	-5	-	+25	+25	-	-15	
	51-2C,D	stress relieve	150F, 1 mo., W.Q.	B77	0	-5	-5	-	-	-	-	
	51-4,5,6		250F, 1hr., F.C.	B77	-10	-5	0	-10	0	-	-10	
	51-10		300F, 1 mo., W.Q.	B77	+5	+5	+5	-	-	-	-	
	51-9		400F, 1 mo., W.Q.	B77	+10	+10	+10	-	-	-	-	
	51-8		600F, 1 mo., W.Q.	B77	+5	+5	-	-	+30	-	-	
	51-20		600F, 1 hr., W.Q.	B77	-	-	-	+25	+25	+25 ^o	-	
		stress relieve	1200F, 1 hr., A.C.									
	51-22,23	stabilize	200F, 48hrs. A.C.		-5	-5	-5 ^o	-5	0	0 ^o	-10	

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TABLE A-4. (Continued)

Alloy	Spec. No.	Treatment	Rock- well Hard- ness	Microinch per Inch Length Change in Time and Cyclic Stability Tests									Thermal Expans. Coef. 10 ⁻⁶ /°C
				Aged at 70F			Aged at 160F			Cycled 10X to -85F			
				1mo.	3mo.	12mo.	1mo.	3mo.	12mo.				
Free Cut Invar	52-1,2,3	cold drawn	(as received)	B98	0	0	0	+15	0	+50°	-20		
	52-42,42	stabilize	200F, 20 hrs., A.C.	B98	-5	-5	-	-5	-5	-	-		
		cold drawn	(as received)	B95									
	52-4,5,6	stress relieve	1200F, 1 hr., F.C.	B95	-15	-20	-25	0	-5	-10°	-5		
	52-31		200F, 1 hr., A.C.	B95	-15	-20	-20°	-	-	-	-		
	52-32,33,34		200F, 20hrs., A.C.-(R)	B95	-5	-5	-5°	0	-5	-5°	-10	1.5	
	52-7-8,9		300F, 1 hr., F.C.	B95	-15	-20	-30	-20	-20	-35	-15		
	52-30		400F, 1 hr., A.C.	B95	-5	-5	-5°	-	-	-	-		
	52-10,19,20	quench anneal	1525F, 1/2 hr., W.Q.	H78	-5	-10	-10	-40	-	-	-10		
	52-19	stabilize	158F, 1mo., W.Q.	H78	0	0	0	-	-	-	-		
	52-36,37,38		200F, 20 hrs., A.C.	H78	-35	-35	-30°	-5	-5	-	0		
	52-15		200F, 1 mo., W.Q.	H78	0	0	-5	-	-	-	-		
	52-11		250F, 1 hr., F.C.	H78	-5	-10	-10	-	-	-	-		
	52-18C		300F, 1 mo., W.Q.	H78	-10	-10	-15	-	-	-	-		
52-17		400F, 1 mo., W.Q.	H78	0	-5	-5	-	-	-	-			
52-21		600F, 1mo., W.Q.	H78	-5	-5	-10	-	-	-	-			
52-27,28,29	anneal	1525F, 1/2 hr., F.C.	H78	-10	-5	-20°	-5	-5	-5°	-15			
52-39,40	stabilize	200F, 20hrs., A.C.	H77	-5	5	-	-5	-5	-	-			
Free Cut Invar	66-10,11,12	cold drawn	(as received)	H87									
		stress relieve	1200F, 1hr., F.C.										
		stabilize	200F, 48hrs., A.C.-(R)	B89	-10	-10	-10°	-5	-5	0°	-35	2.0	
	66-7,8,9	quench-anneal	1525F, 1/2 hr. W.Q.										
		stress relieve	1200F, 1 hr., A.C.										
		stabilize	200F, 48hrs., A.C.-(R)	B79	-5	-5	-10°	-5	6	0°	-10		
	66-1,2,3 4,5,6	quench-anneal	1525F, 1/2 hr., W.Q.	H78	-20	-20	-25°	-20	-20	-20°	-25		
	stress relieve	600F, 1 hr., A.C.											
		stabilize	200F, 48 hrs., A.C.	B78	-10	-10	-15°	-10	-10	-15°	-10		
Super Invar		cold drawn	(as received)	B98									
	9-1,2,3	anneal	1525F, 1hr., F.C.	B97	-10	-	-	-5	-	-	+25		
	9-5	stress relieve	1200F, 1hr., F.C.										
		stabilize	200F, 24hrs., A.C.								0.8		
52Ni- 68Fe	72-1,2,3	quench-anneal	1525F, 1/2hr., W.Q.	B95	0	+5	+5	+5	-	-	-55	2.4	
Ni-Span- Ni	62-1	cold drawn	(as received)	A63	0	-10	-15°	-	-	-	-		
		solutionize	1800F, 1 1/4 hrs., W.Q.										
	62-1,2,3	age	1250F, 20hrs., A.C.-(R)	C90	-5	-5	-5°	-10	-10	-10°	-10	15.8	

* 6 months of aging
(R)- Recommended Treatment

W.Q. - water quenched
F.C. - furnace cooled
A.C. - air cooled

TABLE A-6. DIMENSIONAL STABILITY OF COPPER ALLOYS

Alloy	Spec. No.	Treatment	Rock- well Hard- ness	Microinch per Inch Length Change in Time and Cyclic Stability Tests						Cycled 10X to -95F	Thermal Expans. Coef. 10 ⁻⁶ /°C	
				Aged at 70F			Aged at 160F					
				1mo.	3mo.	12mo.	1mo.	3mo.	12mo.			
85Cu-5Zn	29-1,2,3	cast	(as received)	F46-71	-10	-45	-45	-10	-5	-5 ^b	-15	17.2
-55Sn-5Pb												
Beryllium		solutinize	1450F, 2 hrs., W.Q.									
Copper	31-4,5,6	age	800F, 2 hrs., A.C.	C37	0	0	-	0	-5	-	-5	15.9
		solutionize	1400F, 1/2 hr., W.Q.									
	31-1,2,3	age	825F, 3hrs., A.C.	C38	-15	-15	-20	0	0	-	-10	
Beryllium	47-1,2,3	cast	(as received)	B72	-15	-20	-	-10	-10	-10 ^b	-10	15.3
Copper		solutionize	1450F, 2 hrs., W.Q.									
	47-4,5,6	age	800F, 2hrs., A.C.	C36	-	-	-	-	-	-	-	16.0
70Cu - 30Zn	41-1,2,3	cast	(as received)	F30-50	-30	-30	-30	-35	-45	-50 ^b	-30	18.1
Aluminum	43-1,2,3	cast	(as received)	F65-90	-10	-15	-15 ^b	-10	-15	-	-5	
Bronze		harden	1625F, 1hr., W.Q.									
	43-4,5,6	temper	1000F, 1hr., W.Q.	B74	-10	-10	-	-10	-15	-	-5	16.2
Nickel	46-1,2,3	cast	(as received)	F80	-30	-30	-35 ^b	-10	-15	-	-20	15.5
Silver												

* 6 months of aging

W.Q. - water quench

(R)- recommended treatment

A.C. - air cool

TABLE A-6. DIMENSIONAL STABILITY OF ALUMINUM ALLOYS

Alloy	Spec. No.	Treatment	Rockwell Hardness	Microinch per Inch Length Change in Time and Cyclic Stability Tests							Thermal Expans. Coef. 10 ⁻⁶ /°C	
				1mo.	Aged at 70F		Aged at 160F		Cycled 10X to -85F			
					3mo.	12mo.	1mo.	3mo.		12mo.		
2017 (17 S)												
	163-1,2,3	solutionize	940F, 2hrs., B.W.Q.									
		age	72F, 96 hrs., A.C.	B40	0	-10	-15	-10	-15	-20	-5	
		solutionize	940F, 1/2 hr., W.Q.									
	163-7,8,9	age	250F, 11hrs., A.C.	B37	-5	-5	-	-5	-5	-	6	21.5
2024 (24 S)	21-15	anneal	775F, 1 hr., F.C.	F41	-10	-10	-15	-	-	-	-	
	21-1,2,3	solutionize	920F, 1/2 hr., W.Q.	B52-79	+95	+80	+65	+25	+25	+20 ^o	+85	
	21-16,17,18,22	age	375F, 12hrs., A.C.-(R)	B71	-5	-5	-5	+5	+10	+10	-5	21.3
	21-19,20,21		400F, 1hr., A.C.	B70	+5	+10	+20	+5	+10	+15	+15	
	21-25,26,27		400F, 2 hrs., A.C.	B72	+5	+5	-	-5	-5	-	0	
		solutionize	950F, 1/2 hr., W.Q.									
	21-7,8,9	age	200F, 20 hrs., A.C.	B72	-10	-	-20 ^o	-10	-	-10 ^o	-45	
40 E	140-1,2,3	age	380F, 10 hrs., A.C.	B50	-20	-	-	-30	-	-	+5	
40 H	141-19,20,21	age	280F, 52 hrs., A.C.	B79	-5	-10	-	-30	-35	-	-10	
		solutionize	920F, 10 hrs., W.Q.									
	141-1,2,3	age	300F, 4hrs., A.C.	B45	-20	-	-	-45	-	-	-10	-1.8
	141-10,11,12		300F, 7 hrs., A.C.	B43	-5	-5	-	-15	-35	-	0	
4043 (43)	26-1,2,3	cast	(as received)	F70	-	-40	-55 ^o	-	-15	-20 ^o	-85	
	26-4,5,6		650F, 2hrs., F.C.	B73	-15	-20	-25	-25	-30	-35	-15	21.3
	26-7,8,9		650F, 2hrs., W.Q.	B72	-10	-15	-20 ^o	-30	-35	-40 ^o	-100	
6061 (61 S)	18-4	anneal	750F, 2 hrs., F.C.	F17	-10	-10	-15	-	-	-	-	
	18-5,6,7	solutionize	970F, 1/2 hr., W.Q.	B36	+20	+30	+35 ^o	+70	+80	-	-25	20.0
	18-14,15,16	age	300F, 22 hrs., A.C.	B40	-10	-10	-	-25	-30	-	-40	
	18-17,18,19		350F, 6 hrs., A.C.	B55	-15	-15	-	+5	+5	-	-20	
7075 (75 S)	19-4	anneal	775F, 1 hr., F.C.	F30	-5	-5	-10	-	-	-	-	
	19-5,6,7	solutionize	900F, 1/2 hr., W.Q.	B43-60	-10	-30	-55	-150	-200	-275	-50	
		age	315F, 8 hrs., A.C.									
	19-8,9,10	stabilize	210F, 4 hrs., A.C.	B91	-25	-20	-20	-	-	-	-30	22.1
195	27-1,2,3	cas.	(as received)	F66	-20	-25	35	-	-25	-30 ^o	+10	
	27-5,6,7	solutionize	960F, 2 hrs., B.W.Q.					-50	-80	-80	-30	
	27-14,15,16	age	310F, 4 hrs., A.C.	B49	-15	-20	-	-35	-45	-	-15	
	27-11,12,13		310F, 22 hrs., A.C.	F70	-10	-10	-	-15	-5	-	-15	22.1
	27-4	anneal	650F, 2 hrs., F.C.	F26	-55	-60	-60 ^o	-	-	-	-	
505	28-1,2,3	cast	(as received)	F70	-	-	-	-	+25	-	+15	
	28-4,5,6	stress relieve	440F, 8hrs., F.C.	F76	-5	-5	-	0	+15	-	-15	
		solutionize	1000F, 12 hrs., W.Q.									
	28-10,21,22	age	440F, 8hrs., F.C.	B30	-5	-5	-	+5	+5	-	-10	
		solutionize	1000F, 2hrs., W.Q.									
	28-17,18,19	age	440F, 8 hrs., A.C.	B30	-5	-10	-	-5	0	-	-20	
		solutionize	1000F, 3 hrs., B.W.Q.									
	28-8,9,10	age	310F, 4hrs., A.C.-(R)	B58	0	0	-	-5	0	-	-5	20.8
Alcoa Tern. alloy 6 152-1,2,3,4		stress relieve	400F, 8hrs., A.C.	F81	0	-5	-5	-10	-10	-20 ^o	+5	21.2

* 6 months of aging

(R) - recommended heat treatment

B.W.Q. - boiling water quench

A.C. - air cool

W.Q. - water quench

F.C. - furnace cool

TABLE A-7. DIMENSIONAL STABILITY OF MAGNESIUM ALLOYS

Alloy	Spec. No.	Treatment	Rock well Hard- ness	Microinch per Inch Length Change in Time and Cyclic Stability Tests							Cycled 10K 100 F -95 F	Thermal Expan- sion Coef. 10 ⁻⁶ /°C
				1mo.	Aged at 70F		Aged at 160F			1mo. to -95 F		
					3mo.	12mo.	1mo.	3mo.	12mo.			
Dow H	30-1,2,3	as cast	(as received)	F67								
	30-19,20,21	stress relieve	300F, 4 hrs., A.C.	E37	-20	-20	-25°	-20	-20	-15°	-10	25.2
		solutionize	750F, 8 hrs., A.C.									
	30-13,14,15	age	375F, 18 hrs., A.C.	E71	-15	-15	-15°	-20	-20	-20°	0	25.0
	30-16,17,18		300F, 4 hrs., A.C.	E75	-10	-20	-25°	-25	-25	-25°	-10	25.1
Dow G-1		wrought	(as received)									
	32-24,25,26	stress relieve	400F, 4hrs., A.C.	E74	-20	-25	-25°	-5	+15	+20°	+10	24.0
		solutionize	750F, 4hrs., A.C.									
	32-18,19,20	age	350F, 20 hrs., A.C.	E61-64	-15	-15	-15°	-15	-15	-10°	+10	
	32-21,22,23		300F, 4 hrs., A.C.	E61-64	-15	-15	-20°	-20	-25	-25°	0	24.1
Dow M		extruded	(as received)									
	33-16,17,18	stress relieve	300F, 1/4 hr., A.C.-(R)	E36	-5	-10	-10°	+5	+10	+10°	-10	24.2
Dow J-1		wrought	(as received)									
	34-10,11,12	stress relieve	300F, 1/4 hr., A.C.	E66	-10	-20	-20°	-15	-15	-15°	-5	25.0
Dow C		cast	(as received)									
	100-7,8,9	stress relieve	300F, 4 hrs., A.C.	E74	-5	-10	-15°	-15	-20	-20°	-5	
		solutionize	750F, 20hrs., A.C.									
	100-1,2,3	age	420F, 14 hrs., A.C.	E32	-10	-10	-15°	-40	-40	-40°	-15	24.4
	100-4,5,6		300F, 4 hrs., A.C.	E40	-10	-15	-20°	-15	-15	-10°	-5	24.4
Dow AZ 91C		cast	(as received)									
	170-1,2,3	stress relieve	400F, 4 hrs., A.C.	E34	-20	-20	-40°	-20	-20	-20°	-10	24.3
Dow F8-1	171-1,2,3	extruded	(as received)									
		stress relieve	300F, 1/4 hr., A.C.	E34	-5	-5	-10°	-10	-10	-15°	0	24.7

* 6 months of aging

(R) - recommended treatment

A.C. - air cool

TABLE A-8. DIMENSIONAL STABILITY OF TITANEUM ALLOYS

Alloy	Spec. No.	Treatment	Rock- well Hard- ness	Microinch per Inch Length Change in Time and Cyclic Stability Tests								Thermal Expan. Coef. 10 ⁻⁶ /°C
				Aged at 70F			Aged at 160F			Cycled 10X to -95F		
				1mo.	3mo.	12mo.	1mo.	3mo.	12mo.			
Ti 75A	132-1,3,3	hot rolled	(as received)	B99	-10	-15	-	-20	-25	-	+10	8.6
	132-10,11,12	stress relieve	400F, 1 hr., A.C.	B93	0	0	- 5	0	0	+ 5	+20	
	132-4,5,6		600F, 1hr., A.C.	B90	0	- 5	-	0	0	-	+15	
	132-7,8,9		1000F, 1hr., A.C.	B86	+ 5	-	-	+ 5	-	-	+20	
Ti 150A	139-1,2,3	normalize	1550F, 1/2 hr., A.C.	C38	- 5	- 5	-	-10	-10	-	- 5	8.2
	139-4,5,6	harden	1550F, 1/2 hr., O.Q.	C52	0	0	-	-15	-30	-	- 5	
	139-10,11,12	stress relieve	350F, 4hrs., A.C.	C53	0	0	0	- 5	-15	-15	0	
	139-7,8,9		950F, 1hr., A.C.-(R)	C53	0	0	0	0	0	0	- 5	
92Ti-90Zr	116-4,5,6	cold drawn	(as received)	C31	0	0	0	+ 5	+ 5	+ 5	- 5	8.6
- 2Al	1,2,3	anneal	1500F, 3 hrs., F.C.	C34	-10	-15	-	-10	-15	-	-15	
	7,8,9	stabilize	200F, 1hr., A.C.-(R)	C34	-10	-10	-10 ⁰	0	0	0 ⁰	- 5	

* 6 months of aging
(R) - recommended treatment

A.C. - air cool
O.Q. - oil quench
F.C. - furnace cool

TABLE A-9. DIMENSIONAL STABILITY OF MISCELLANEOUS ALLOYS

Alloy	Spec. No.	Treatment	Rock- well Hard- ness	Microinch per Inch Length Change in Time and Cyclic Stability Tests						Cycled 10X to -95F	Thermal Expan. Coef. 10 ⁻⁶ /°C	
				1mo.	Aged at 70F		Aged at 160F					
					3mo.	12mo.	1mo.	3mo.	12mo.			
Gray Cast Iron	48-1,2,3	as cast	(as received)	B62	-15	-10	+5	-5	-5	-10	-20	10.3
Manganese Cast Iron	49-1,2,3	as cast	(as received)	B68	0	+5	+20	+25	+25	+30*	-5	4.2
Koniametal K10	70-1,2,3	sintered	(as received)	-	0	-5	-	0	-5	-	-5	4.4
Koniametal K11	69-1,2,3	sintered	(as received)	-	0	-5	-	0	0	-	-5	4.8
Koniametal K12	71-1,2,3	sintered	(as received)	-	0	0	-	0	0	-	+5	4.2
Grey Mol	178-1,2,3	sintered	(as received)	C25	-5	-5	-5	-10	-10	-10	-5	8.0
Nitrided	14-1	nitrided	975F, 48 hrs., F.C.	54**	-10	-10	-15	-10	-10	-10	-10	12.3
Nitralloy	14-2	stress relieve	1000F, 1hr., A.C. -(R)	54**	0	0	0	0	0	0	-5	12.1

* 6 months of aging
** case hardness 15N scale
(R) - recommended treatment

TABLE A-10. RECOMMENDED HEAT TREATMENT FOR OBTAINING HIGH DIMENSIONAL STABILITY IN SELECTED ALLOYS

Alloy	Initial Condition	Desired Condition	Heat Treatment	Rockwell Hardness	Thermal Expansion Coef. $10^{-6}/^{\circ}\text{C}$	Elastic Modulus 10^4 psi	Elastic Limit 10^4 psi
1112 steel	cold drawn	stress relieved	800F, 1 hr., A.C. or 1200F, 1 hr., A.C.	B93 B77	11.8 11.8	28.5 28.4	76. 63.0
1045 steel	cold drawn	stress relieved annealed	1200F, 1 hr., F.C. a) 1550F, 1/2 hr., F.C. b) 300F, 1 hr., A.C.	B92 B90	- 11.2	- -	- -
1144 steel	hot rolled	annealed hardened and tempered	1550F, 1/2 hr., F.C. a) 1850F, 1/2 hr., O.Q. b) 1100F, 1 hr., W.Q.	B85 C23	- 11.1	- -	- -
4140 steel	hot rolled	annealed hardened and tempered	1550F, 1/2 hr., F.C. a) 1550F, 1/2 hr., O.Q. b) 1000F, 2 hrs., A.C.	B93 C38	11.4 -	- -	- -
10100 steel	annealed	hardened and tempered	a) 1450F, 1/2 hr., W.Q. b) 350F, 1 hr., A.C.	C64	11.0	-	-
Manganese Die Steel	annealed	hardened and tempered	a) 1450F, 1/2 hr., O.Q. b) 300F, 1 hr., A.C.	C63	11.9	-	-
Tungsten Die steel	annealed	hardened and tempered	a) 1800F, 1/2 hr., O.Q. b) 300F, 1 hr., A.C.	C85	11.6	-	-
52100 steel	annealed	hardened and tempered	a) 1550F, 1/2 hr., O.Q. b) 250F, 10 hrs., A.C. or 400F, 1 hr., A.C.	C65 C82	- 11.9	- -	- -
High C High Cr Die steel	annealed	hardened and tempered hardened and tempered	a) 1850F, 1/2 hr., A.C. b) 300F, 2 hrs., A.C. or 500F, 2 hrs., A.C. a) 1900F, 1/2 hr., A.C. b) 320F, 1 hr., A.M. c) 950F, 1 hr., O.Q. d) Repeat b) and c) four times e) 450F, 1 hr., A.C.	C63 C61 C60	10.3 - 10.2	- - -	- - -
M-2 High Speed steel	annealed	hardened and tempered	a) 2220F, 3 min., O.Q. b) 1050F, 2 1/2 hrs., O.Q. c) repeat b) three times d) 900F, 1 hr., A.C.	C85	-	-	-
303 Stainless steel	cold drawn	quench-annealed and stress relieved	a) 1950F, 1/2 hr., W.Q. b) 600F, 1 hr., A.C. c) 200F, 20 hrs., A.C.	B82	16.1	27.9	10.0
310 Stainless steel		quench-annealed and stress relieved	a) 1950F, 1/2 hr., W.Q. b) 750F, 1 hr., A.C.	B84	14.8	-	-
410 Stainless steel		hardened and tempered	a) 1800F, 1/2 hr., O.Q. b) 450F, 1 hr., A.C. or 600F, 1 hr., A.C.	C66 C41	- 10.2	- 31.4	- 10.8
440C stainless Steel	annealed	hardened and tempered	a) 1900F, 1/2 hr., O.Q. b) 500F, 1 hr., A.C.	C81	10.3	-	-
Z-Ni-Ni	cold drawn	age hardened	1060F, 8 hrs., F.C. to 900F, A.C.	C40	12.4	32.1	114
Inconel	cold drawn	annealed	a) 1700F, 1 hr., F.C. b) 200F, 24 hrs., A.C.	B71-79	12.7	30.1	10.0
K-Monel	cold drawn	age hardened	1000F, 8 hrs., F.C. to 900F, A.C.	C37	13.4	28.2	110
Hastalloy B	cast	quench-annealed and stress relieved	a) 2100F, 1 hr., W.Q. b) 1950F, 1 hr., W.Q. c) 600F, 1 hr., A.C.	B93	10.4	-	-
Regular Invar	cold drawn	stress relieved	a) 1200F, 1 hr., A.C. b) 200F, 48 hrs., A.C.	-	-	-	-

TABLE A-10. (Continued)

Alloy	Initial Condition	Desired Condition	Heat Treatment	Rockwell Hardness	Thermal Expansion Coef. $10^{-6}/^{\circ}\text{C}$	Elastic Modulus 10^4 psi	Elastic Limit 10^4 psi
Free Cut Invar	cold drawn	stress relieved	a) 1200F, 1 hr., F.C.	B99-95 B79	1.5	22.0	47.5
			b) 200F, 20 hrs., A.C.				
	cold drawn	quench-tempered	a) 1825F, 1/2 hr., W.Q.				
			b) 1200F, 1 hr., A.C.				
Ni-Span-Ni	cold drawn	solutionized	c) 200F, 48 hrs., A.C.	C39	15.5	-	-
		and aged	a) 1000F, 1 1/4 hrs., W.Q.				
	cold drawn	solutionized	b) 1250F, 20 hrs., A.C.				
		and aged	a) 1450F, 7 hrs., W.Q.				
Beryllium-Copper	cold drawn	solutionized	b) 600F, 2 hrs., A.C.	C37	15.9	19.0	56.5
		and aged	a) 900F, 1/2 hr., W.Q.				
	solutionized	solutionized	b) 250F, 11 hrs., A.C.				
		and aged	a) 820F, 1/2 hr., W.Q.				
2017 (17 S) Aluminum alloy	solutionized	solutionized	b) 375F, 12 hrs., A.C.	B71 B72	21.6	10.8	32.0
		and aged	or 400F, 2 hrs., A.C.				
	solutionized	solutionized	a) 1000F, 2 hrs., B.W.Q.				
		and aged	b) 310F, 4 hrs., A.C.				
266 Aluminum alloy	cast	solutionized	a) 500F, 1/6 hr., A.C.	E36	24.2	-	-
		and aged	b) 1550F, 1/2 hr., A.C.				
	cold drawn	hardened and stress relieved	a) 1850F, 1/2 hr., O.Q.				
		and stress relieved	b) 600F, 1 hr., A.C.				
92Ti-8Cr-2Al Titanium alloy	cold drawn	annealed	a) 1380F, 3 hrs., F.C.	C34	8.6	-	-
		and stress relieved	b) 600F, 1 hr., A.C.				
	nitrided	stress relieved	1000F, 1 hr., A.C.				

* Treatment recommended if service temperature is maintained at about 70F.

A.C. - air cool
F.C. - furnace cool
O.Q. - oil quench

W.Q. - water quench
A.H. - air heat
B.W.Q. - boiling water quench

TABLE A-11. CHEMICAL COMPOSITION OF ALLOYS LISTED IN TABLES A-1 THROUGH A-10

I. Plain Carbon and Low Alloy Steels

No.	Alloy	C	Mn	Si	S	P	Cr	Ni	Mo
175	1113	0.11	0.30	0.01	0.004	0.003	-	-	-
1	1020	0.10	0.40	0.01	0.013	0.010	-	-	-
10	X1020	0.17	0.30	0.00	0.004	0.011	-	-	-
5	1045	0.47	0.34	0.31	0.001	0.013	-	-	-
10	1144	0.41	1.30	0.00	0.000	0.003	-	-	-
5	4140	0.30	0.80	0.20	0.010	0.000	1.00	0.10	0.10
10	4040	0.40	0.80	0.23	0.014	0.000	0.00	0.20	1.07
3	1070	0.70	0.30	0.20	0.000	0.001	-	-	-

II. Tool Steels

No.	Alloy	C	Mn	Si	S	P	Cr	Mo	V	W	Co
0	10100	1.00	0.30	0.30	0.014	0.014	-	-	-	-	-
X	10100	1.37	0.30	0.30	0.014	0.011	-	-	-	-	-
H	Manganese Die	0.94	1.17	0.31	0.010	0.000	0.50	-	0.04	0.00	-
G	Tungsten Die	1.34	0.30	0.30	0.007	0.000	0.70	0.20	0.00	1.00	-
170	01100	0.80	0.37	0.10	0.011	0.000	1.00	-	-	-	-
3	02100	1.00	0.30	0.20	0.010	0.000	1.04	-	0.01	-	-
T	02100	1.04	0.30	0.34	0.013	0.014	1.04	-	0.20	-	-
00	03100	1.00	0.30	0.20	0.014	0.010	1.20	0.00	-	-	-
00	1C-SCr	1.00	0.01	0.17	0.013	0.014	0.51	1.10	0.07	-	-
P	High C, High Cr	1.04	0.30	0.40	0.007	0.010	12.0	0.20	0.77	-	0.00
04	High C, High Cr	1.00	0.30	0.20	0.010	0.010	11.00	0.70	0.20	-	-
B	M-2 High Speed	0.70	0.37	0.34	0.010	0.000	4.10	4.00	1.00	0.70	-

III. Stainless Steels

No.	Alloy	C	Mn	Si	S	P	Cr	Ni
10	300	0.00	0.71	0.01	0.013	0.000	10.20	0.40
7	300	0.13	0.04	0.20	0.100	0.000	17.00	0.00
20	310	0.10	1.07	0.20	0.000	0.010	24.10	10.70
24	410	0.13	0.40	0.07	0.013	0.010	13.00	-
20	440C	1.00	0.30	0.07	0.000	0.010	17.10	-

IV. Nickel Alloys

No.	Alloy	C	Mn	Si	S	P	Ni	Fe	Cr	Cu	Al	Ti
55	A-Nickel	0.00	0.21	0.20	0.000	-	90.00	0.10	-	0.00	-	-
54	Z-Nickel	0.10	0.27	0.00	0.000	-	94.14	0.10	-	0.00	4.00	0.20
173	Inconel	0.01	0.30	0.10	0.007	0.000	73.10	0.10	10.04	0.10	-	-
57	Inconel	0.07	0.27	0.20	0.007	-	77.00	7.10	14.00	0.10	-	-
100	Inconel	0.00	0.20	0.10	0.007	-	70.04	7.01	10.00	0.10	-	-
						Co						
50	Inconel X	0.04	0.40	0.20	0.007	0.00	73.40	0.00	14.00	0.00	0.77	0.04
50	Monel	0.10	1.00	0.10	0.000	-	60.20	1.20	-	20.00	-	-
54	K-Monel	0.14	0.04	0.10	0.000	-	60.10	0.00	-	20.04	0.10	0.00
									V	Mo		
170	Hastelloy B	0.04	0.41	0.20	-	-	60.70	0.07	0.00	0.00	20.00	-
00	Ni-Span-Le 40	0.00	0.50	0.20	0.007	-	44.00	51.00	0.21	0.00	0.00	0.11
77	42Ni-50Fe	0.00	0.30	0.21	0.000	0.000	40.07	bal.	-	-	-	-
01	Ni-Span C	0.04	0.27	0.00	0.007	-	41.00	40.11	0.01	0.00	0.01	0.10
51	Reg. Invar	0.07	0.10	0.20	0.010	0.010	30.00	bal.	-	-	-	-
50	Reg. Invar	0.10	0.10	0.20	0.010	0.000	30.10	bal.	-	-	-	-
									Mo	Si		
52	Free Cut Invar	0.07	0.00	0.20	0.000	0.000	30.37	bal.	0.00	0.10	-	0.04
									Mo	Si		
00	Free Cut Invar	0.04	0.00	0.20	0.010	0.000	30.37	bal.	0.00	0.10	-	0.00
									Co			
0	Super Invar	0.00	0.10	0.10	0.010	0.000	31.20	bal.	-	0.27	-	-
70	33Ni-60Fe	0.10	0.70	0.27	0.000	0.000	33.00	bal.	-	-	-	-
03	Ni-Span-Ni	0.04	0.00	0.20	0.007	-	20.00	60.00	0.00	0.04	0.70	0.20

TABLE A-11. (Continued)

V. Copper Alloys

No.	Alloy	Cu	Sn	Zn	Pb	Fe	P	Mn	Si	Al
30	86-5-5-5	86.46	5.23	4.46	4.85	0.06	0.04	Tr	-	-
31	Beryl. Copper	97.04	-	-	-	0.07	-	0.22	2.06	-
47	Beryl. Copper	97.01	-	-	-	0.06	0.06	0.03	1.02	Tr
41	70Cu-30Sn	69.47	Tr	31.53	Tr	Tr	-	-	-	Tr
43	Alum. Bronze	89.41	-	-	-	0.76	-	-	-	0.63
										<u>Mn</u>
48	Nichel Silver	68.06	-	16.04	-	-	0.02	17.82	-	<u>0.07</u>

VI. Aluminum Alloys

No.	Alloy	Al	Si	Fe	Cu	Mn	Cr	Zn	Mg	Ti
143	2017 (17 S)	bal.	-	-	-	-	-	-	-	-
31	2004 (34 S)	bal.	0.14	0.33	4.41	0.73	-	-	1.55	-
140	40E	bal.	-	-	-	-	0.5 ^o	5.5 ^o	0.6 ^o	0.3 ^o
141	40N	bal.	-	-	-	-	0.5 ^o	5.5 ^o	2.3 ^o	0.3 ^o
36	4043 (43 S)	bal.	5.54	0.33	0.015	0.01	-	0.02	0.01	0.10
18	6061 (61 S)	bal.	0.36	0.33	0.34	0.06	0.27	-	1.10	-
19	7075 (75 S)	bal.	0.18	0.31	1.03	0.08	0.25	5.00	2.50	-
37	105	bal.	1.00	0.00	4.56	0.00	-	0.00	0.01	0.00
38	304	bal.	7.36	0.31	0.09	0.00	-	0.00	0.35	0.13
152	Apex Ternalloy	bal.	-	-	-	-	-	3.7 ^o	1.8 ^o	-

VII. Magnesium Alloys

No.	Alloy	Mg	Al	Zn	Mn	Si	Mn	Cu
30	Dow M	bal.	0.0 ^o	3.0 ^o	0.30(max) ^o	-	-	-
32	Dow 9-1	bal.	0.5 ^o	0.5 ^o	0.15 ^o	-	-	-
33	Dow M	bal.	-	-	1.50 ^o	-	-	-
34	Dow J-1	bal.	0.5 ^o	1.0 ^o	0.30 ^o	-	-	-
100	Dow C	bal.	0.0	2.1	0.30	0.05	0.001	0.01
170	Dow AZ 91C	bal.	0.8	0.00	0.23	0.024	0.002	0.01
171	Dow PS-1	bal.	3.0 ^o	1.0 ^o	0.3 ^o	-	-	-

VIII. Titanium Alloys

No.	Alloys	Ti	Al	Cr	Fe	N
132	Ti 75A	bal.	-	-	0.10 ^o max.	0.03 ^o
139	Ti 150A	bal.	-	2.5 ^o	1.3 ^o	0.08 ^o
118	92Ti-8Cr-3Al	bal.	3 ^o	5 ^o	-	-

IX. Miscellaneous Alloys

No.	Alloy	T. C.	Mn	Si	P	S	Mn	Cr	Cu	Mo
66	Gray Cast Iron	3.07	0.67	1.78	0.106	0.007	0.01	-	-	0.44
68	Miner Cast Iron	3.16	0.61	1.60	0.010	0.007	34.9	0.13	0.08	-
		<u>W</u>	<u>Al</u>	<u>C</u>	<u>Ca</u>					
70	KM Kennametal	67.5 ^o	17.6 ^o	6.6 ^o	11 ^o					
69	KM Kennametal	66 ^o	16.7 ^o	6.3 ^o	6 ^o					
71	K13 Kennametal	70.5 ^o	17.6 ^o	-	13 ^o					
		<u>W</u>	<u>Ca</u>	<u>Mn</u>						
178	Heavy-Met	70-80 ^o	3-30 ^o	1-10 ^o						
		<u>C</u>	<u>Mn</u>	<u>Si</u>	<u>P</u>	<u>S</u>	<u>Cr</u>	<u>Mo</u>	<u>Al</u>	
14	Harsco 135 mod.	0.41	0.61	0.30	0.016	0.017	1.00	0.34	1.10	

^o Nominal Composition

Data From R-137, "The Properties of Metals and Alloys of Particular Interest in Precision Instrument Construction;

Compilation of data from various handbooks and other sources, by L. M. Schetky, January, 1957. Instrumentation Laboratory, Massachusetts Institute of Technology, Cambridge 39, Massachusetts.

The compilations in this report were taken from various published sources. The data on elastic limits and dimensional stability were taken from Report R-95(6), although in some cases differences in results or treatments can be noted. The units for the various parameters included are given as follows:

Density	Grams per cubic centimeter
Thermal Conductivity	Calories per square centimeter per centimeter per degree centigrade per second
Resistivity	Microhm-centimeter
Specific Heat	Calories per gram
Magnetic Properties	Either indicates permeability or whether material is or is not magnetic
Linear Coefficient of Expansion	Inch per inch per degree centigrade
Hardness	Rockwell scale as indicated or Brinell scale as indicated
UTS (Ultimate Tensile Strength)	1000 pounds per square inch
YP (0.2 Per Cent Offset Yield Strength)	Stress in 1000 pounds per square inch to produce 0.2 per cent offset
Elongation (in 2 in.)	Per cent
Modulus of Elasticity	1,000,000 pounds per square inch
Elastic Limit	1000 pounds per square inch
Elastic Limit/Density	(Pounds per square inch per gram per cubic centimeter) $\times 10^{-3}$
Modulus of Elasticity/Density	(Pounds per square inch per gram per cubic centimeter) $\times 10^{-6}$

The data for dimensional stability are presented in abbreviated form to show (1) the exposure condition: RT, 160, and cycle, meaning, respectively, exposure at 70 F, 160 F, or cycled ten times between -100 F and +200 F (note difference in cyclic exposure from that reported in R-95), (2) the dimensional change in microinches, and (3) the exposure time in months or years.

TABLE A-12. PROPERTIES OF METALS AND ALLOYS OF PARTICULAR INTEREST IN PRECISION INSTRUMENT CONSTRUCTION

4140 STEEL			
Recommended Use		A deep hardening, hard, tough steel. May be copper treated and hardened without excessive distortion.	
RT - 10 - 1 yr			
160 - 5 - 1 yr			
Cycle - 5			
Heat Treatment for		Maximum dimensional stability	
Procedure		Initial condition: hot rolled Anneal 1750°F, 1/2 hr, furnace cool, 1500°F, 1/2 hr, oil quench 1000°F, 2 hr, air cool	
Physical Properties		Mechanical Properties	
Density	7.85	Hardness	25C
Thermal conductivity	8.107	UTS	145
Resistivity	22.3	YP (0.2% offset)	140
Specific heat	0.114	Elongation (2 in.)	18
Magnetic properties	yes	Modulus of elasticity	29
Coefficient of expansion	11.1	Elastic limit	-160
		Elastic limit/dens.	12.7
		Mod/dens.	5.7

1040 STEEL			
Recommended Use		A water hardening steel; have high hardness, high strength as desired. Stability fair	
RT - 10 - 1 yr			
Heat Treatment for		Maximum dimensional stability and high hardness	
Procedure		Initial condition: annealed stock 1470°F, 1/2 hr, water quench 770°F, 1 hr, air cool	
Physical Properties		Mechanical Properties	
Density	7.85	Hardness	64C
Thermal conductivity	8.107	UTS	- 90
Resistivity	21.2	YP (0.2% offset)	- 250
Specific heat	0.116	Elongation (2 in.)	- 10
Magnetic properties	yes	Modulus of elasticity	- 29
Coefficient of expansion	11.8	Elastic limit	- 90
		Elastic limit/dens.	11.5
		Mod/dens.	5.71

NITRALLOY - 178 BISMUTH			
Recommended Use		For use where extreme wear resistance is desired. Excellent stability.	
RT - 5 - 1 yr			
160 - 5 - 1 yr			
Cycle - 5			
Heat Treatment for		Maximum dimensional stability combined with a case hardened, tough core structure	
Procedure		Initial condition: annealed Stress relieved 1000°F, air cool	
Physical Properties		Mechanical Properties	
Density	7.24	Hardness	44C (case)
Thermal conductivity	8.124	UTS	205
Resistivity	27-29	YP (0.2% offset)	181.5
Specific heat	0.11-0.12	Elongation (2 in.)	15.2
Magnetic properties	yes	Modulus of elasticity	26-30
Coefficient of expansion	12.1	Elastic limit	-120
		Elastic limit/dens.	15.5
		Mod/dens.	3.82

TABLE A-12. (Continued)

1008 STEEL

Recommended Use: ST - 0 - 6 mo Fine machining, hardenable plain carbon general purpose steel SB - 0 - 3 mo Cycle - 0	
Heat Treatment for: Maximum dimensional stability with medium mechanical properties.	
Procedure: Initial condition: hot rolled 1550°F, 1/2 hr, oil quench 1000°F, 1 hr, air cool	
Physical Properties:	Mechanical Properties:
Density 7.82	Hardness 23C
Thermal conductivity 0.121	UTS 100
Resistivity 15.9	YP (0.2% offset) 70
Specific heat 0.116	Elongation (2 in.) 16
Magnetic properties $\mu = 1000$ approx	Modulus of elasticity 30
Coefficient of expansion -11.1	Elastic limit -40
	Elastic limit/dens. 5.11
	Mod./dens. 5.04

SILICON STEEL M15

Recommended Use: Motors, generators, transformers	
Heat Treatment for: Maximum magnetic properties	
Procedure: Anneal 1500°F, 1 hr, furnace cool	
Physical Properties:	Mechanical Properties:
Density 7.55	Hardness 75B
Thermal conductivity 0.096	UTS 61-79
Resistivity 61	YP (0.2% offset) 60-66
Specific heat 0.12	Elongation (2 in.) 4.5-7.8
Magnetic properties $\mu = 1000$ approx	Modulus of elasticity -29
Coefficient of expansion -11.5	Elastic limit -50
	Elastic limit/dens. 6.62
	Mod./dens. 5.04

1008 STEEL

Recommended Use: ST - 0 - 3 mo As a hardenable plain carbon steel SB - 1 - 3 mo Cycle - 3	
Heat Treatment for: Maximum dimensional stability	
Procedure: Initial condition: cold drawn 1550°F, 1/2 hr, furnace cool 1000°F, 1 hr, air cool	
Physical Properties:	Mechanical Properties:
Density 7.85	Hardness 92B
Thermal conductivity 0.121	UTS 72
Resistivity 15.9	YP (0.2% offset) 70
Specific heat 0.116	Elongation (2 in.) 16
Magnetic properties $\mu = 1000$ approx	Modulus of elasticity 30
Coefficient of expansion -11.2	Elastic limit -17
	Elastic limit/dens. 2.16
	Mod./dens. 5.02

* Annealed properties, considerably higher in hardened condition.

1112 STEEL

Recommended Use: ST - 0 - 1 yr A low carbon, free machining steel of moderate strength and good stability SB - 0 - 1 yr Cycle - 0	
Heat Treatment for: Maximum dimensional stability	
Procedure: Initial condition: cold rolled Stress relief 800°F, 1 hr, air cool	
Physical Properties:	Mechanical Properties:
Density 7.85	Hardness 77B
Thermal conductivity 0.124	UTS 87
Resistivity 12.6	YP (0.2% offset) 74
Specific heat 0.115	Elongation (2 in.) 17
Magnetic properties $\mu = 1000$ approx	Modulus of elasticity 28.4
Coefficient of expansion -11.8	Elastic limit 65
	Elastic limit/dens. 8.05
	Mod./dens. 5.62

SILICON STEEL

Recommended Use: ST - 10 A magnetic steel, typically for transformers requiring low loss.	
Heat Treatment for: Maximum magnetic properties	
Procedure: Anneal 1500°F, 1 hr, furnace cool	
Physical Properties:	Mechanical Properties:
Density 7.55	Hardness 70B
Thermal conductivity 0.099	UTS 65-75
Resistivity 56	YP (0.2% offset) 54-62
Specific heat 0.12	Elongation (2 in.) 7.3-6.3
Magnetic properties $\mu = 1000$ approx	Modulus of elasticity -29
Coefficient of expansion -11.1	Elastic limit -45
	Elastic limit/dens. 5.91
	Mod./dens. 5.04

1008 STEEL

Recommended Use: General structural, but particularly stable.	
Heat Treatment for: None	
Procedure: Cold rolled. If annealed use 1600°F, 1 hr.	
Physical Properties:	Mechanical Properties:
Density 7.85	Hardness 80B
Thermal conductivity 0.122	UTS 75
Resistivity 15.9	YP (0.2% offset) 61.7
Specific heat 0.116	Elongation (2 in.) 20
Magnetic properties $\mu = 1000$ approx	Modulus of elasticity 30.1
Coefficient of expansion -12.2	Elastic limit -50
	Elastic limit/dens. 6.54
	Mod./dens. 5.04

TABLE A-12. (Continued)

S2100 STEEL

Recommended Use RT - 3 - 1 yr. Bearing use. 150°F - 0 - 1 yr. Cycle - 3	
Heat Treatment for Maximum dimensional stability with high strength and hardness	
Procedure Initial condition - annealed 1550°F, 1/2 hr, oil quench 600°F, 1 hr, air cool	
Physical Properties	Mechanical Properties
Density 7.85	Hardness 61.5C
Thermal conductivity 0.108	UTS - 900
Resistivity - 22	YP (0.2% offset) - 250
Specific heat 0.122	Elongation (2 in.) - 10
Magnetic properties yes	Modulus of elasticity 29.2
Coefficient of expansion 11.9	Elastic limit 89
	Elastic limit down 11.4
	Mod. down 5.75

DIE STEEL - A2

Recommended Use RT - 0 - 1 yr. Oil hardening for non-forming characteristics. Excessive warpage in heat treatment is to be avoided	
Heat Treatment for Maximum dimensional stability	
Procedure Initial condition - annealed 1450°F, 1/2 hr, oil quench 500°F, 1 hr, air cool	
Physical Properties	Mechanical Properties
Density 7.85	Hardness 65C
Thermal conductivity 0.108	UTS
Resistivity - 22	YP (0.2% offset)
Specific heat 0.122	Elongation (2 in.)
Magnetic properties yes	Modulus of elasticity
Coefficient of expansion 11.9	Elastic limit
	Elastic limit down
	Mod. down

DIE STEEL - A2

Recommended Use RT - 0 - 1 mo. General purpose high speed steel. Typical care required to maximizing distortion on heat treatment	
Heat Treatment for Maximum dimensional stability	
Procedure Initial condition - annealed a. 2220°F - 3 min, oil quench c. Repeat b 3 times b. 1050°F - 2 1/2 hr, oil quench d. 900°F, 1 hr, air cool	
Physical Properties	Mechanical Properties
Density 7.85	Hardness 65C
Thermal conductivity 0.108	UTS
Resistivity - 22	YP (0.2% offset)
Specific heat 0.122	Elongation (2 in.)
Magnetic properties yes	Modulus of elasticity
Coefficient of expansion 10.5	Elastic limit
	Elastic limit down
	Mod. down

DIE STEEL - HIGH C, HIGH C

Recommended Use RT - 0 - 6 mo. Used for die purposes requiring air hardening and extreme wear resistance. 160 - 10 - 6 mo. Cycle - 10	
Heat Treatment for Maximum dimensional stability with die properties	
Procedure Initial condition - annealed *1850°F, 1/2 hr, air cool 100°F, 2 hr, air cool 500°F, 2 hr, air cool for maximum warpage	
Physical Properties	Mechanical Properties
Density 7.85	Hardness 65K (100°F) 61C (500°F)
Thermal conductivity 0.108	UTS
Resistivity - 22	YP (0.2% offset)
Specific heat 0.122	Elongation (2 in.)
Magnetic properties yes	Modulus of elasticity
Coefficient of expansion 10.5	Elastic limit
	Elastic limit down
	Mod. down

* Note: This quench gives better stability. 1800°F, 1/2 hr, oil quench
temper 100°F, 2 hr, air cool

DIE STEEL - TUNGSTEN

Recommended Use RT - 0 - 1 yr. For high wear resistance, non-gritting	
Heat Treatment for Maximum dimensional stability	
Procedure Initial condition - annealed 1800°F, 1/2 hr, oil quench 500°F, air cool	
Physical Properties	Mechanical Properties
Density 19.3	Hardness 64K
Thermal conductivity 0.113	UTS
Resistivity 75	YP (0.2% offset)
Specific heat 0.12	Elongation (2 in.)
Magnetic properties none	Modulus of elasticity
Coefficient of expansion 11.6	Elastic limit
	Elastic limit down
	Mod. down

STAINLESS STEEL 316

Recommended Use RT - 5 - 1 yr. Non-staining in annealed or cold work state. High heat and corrosion resistance. Good general purpose stainless steel. 160 - 10 - 1 yr. Cycle - 20	
Heat Treatment for Maximum dimensional stability	
Procedure Quench anneal, 1950°F, 1/2 hr Water quench, stress relieve 750°F, 20 hr, air cool	
Physical Properties	Mechanical Properties
Density 7.98	Hardness 27D
Thermal conductivity 0.113	UTS 100
Resistivity 75	YP (0.2% offset) 45
Specific heat 0.12	Elongation (2 in.) 50
Magnetic properties none	Modulus of elasticity 29
Coefficient of expansion 14.4	Elastic limit 10
	Elastic limit down 1.81
	Mod. down 1.88

TABLE A-12. (Continued)

STAINLESS STEEL 400C

Recommended Use: RT - 0 - 6 mo Non-critical stainless 100 - 1 - 6 mo Highest grades of the stainless steels. Cycle - 1			
Heat Treatment for: Maximum dimensional stability			
Procedure: Initial condition annealed 1000°F, 1/2 hr, air quench 100°F, 1 hr, air cool			
Physical Properties:		Mechanical Properties:	
Density	7.75	Hardness	61C
Thermal conductivity	8.17	UTS	285,000
Resistivity	59	YP (0.2% offset)	275,000
Specific heat	0.11	Elongation (2 in.)	1
Magnetic properties	yes	Modulus of elasticity	29
Coefficient of expansion	10.2	Elastic limit	~190,000
		Elastic limit/dens.	24.5
		Mod. dens.	5.74

STAINLESS STEEL 303

Recommended Use: RT - 0 - 6 mo For corrosion resistance; nonmagnetic, though can be slightly magnetic upon cold work. Low yield and elastic limits. 100 - 1 - 5 mo Cycle - 5			
Heat Treatment for: Maximum dimensional stability			
Procedure: 1950°F, 1/2 hr, water quench Stress relief 600°F, 1 hr, air cool 200°F, 20 hr, air cool			
Physical Properties:		Mechanical Properties:	
Density	7.9	Hardness	80S
Thermal conductivity	8.090	UTS	90
Resistivity	60	YP (0.2% offset)	50
Specific heat	0.122	Elongation (2 in.)	50
Magnetic properties	none	Modulus of elasticity	28
Coefficient of expansion	16.1	Elastic limit	10.4
		Elastic limit/dens.	1.3
		Mod. dens.	3.65

STAINLESS STEEL 403

Recommended Use: RT - 1 - 1 yr General purpose chrome stainless. 100 - 10 - 1 yr Hardenable by heat treatment. Corrosion and heat resistance. Cycle - 5			
Heat Treatment for: Maximum dimensional stability			
Procedure: 1000°F, 1/2 hr, oil quench 600°F, 1 hr, air cool (R _h 41) or 650°F, 1 hr, air cool (R _h 40)			
Physical Properties:		Mechanical Properties:	
Density	7.75	Hardness	41C
Thermal conductivity	8.099	UTS	195
Resistivity	56	YP (0.2% offset)	152
Specific heat	0.115	Elongation (2 in.)	15
Magnetic properties	yes	Modulus of elasticity	31.4
Coefficient of expansion	10.2	Elastic limit	108
		Elastic limit/dens.	14.0
		Mod. dens.	4.7

NICKEL

Recommended Use: RT - 1 - 1 yr As an alloying addition for electronic devices. As a protective coating for chemical or heat resistance			
Heat Treatment for: Normal properties			
Procedure: Anneal - 1500°F, 3 to 6 min, air cool Stress relief 600°F for 1 hr (Note: Reasonably stable in the as-received cold-drawn condition)			
Physical Properties:		Mechanical Properties:	
Density	8.9	Hardness	76B
Thermal conductivity	0.21	UTS	8.5
Resistivity	6.84	YP (0.2% offset)	46
Specific heat	0.108	Elongation (2 in.)	50
Magnetic properties	$\mu < 3000$	Modulus of elasticity	22
Coefficient of expansion	12.5	Elastic limit	4.5
		Elastic limit/dens.	0.505
		Mod. dens.	2.47

STAINLESS STEEL 303 COLD DRAWN

Recommended Use: Higher strength to weight. Slight magnetic. Better elastic limit than annealed 303.			
Heat Treatment for: Stress relief with maximum decrease in mechanical properties.			
Procedure: Cold drawn (approximately 50% red.) Stress relieve furnace heat 750°F, 1 hr, air cool 200°F, 20 hr, air cool			
Physical Properties:		Mechanical Properties:	
Density	7.9	Hardness	80T
Thermal conductivity	8.090	UTS	215
Resistivity	60	YP (0.2% offset)	170
Specific heat	0.122	Elongation (2 in.)	5
Magnetic properties	slight	Modulus of elasticity	28
Coefficient of expansion	16.1	Elastic limit	41
		Elastic limit/dens.	5.30
		Mod. dens.	3.55

HASTALLOY B

Recommended Use: RT - 0 - 1 yr Very high strength, high corrosion resistance, excellent stability. 100 - 0 - 1 yr Cycle - 0			
Heat Treatment for: Maximum dimensional stability			
Procedure: Quench anneal 2100°F, 1 hr, water quench Quench anneal 1950°F, 1 hr, water quench Stress relieve 600°F, 1 hr, air cool			
Physical Properties:		Mechanical Properties:	
Density	8.34	Hardness	94B
Thermal conductivity	6.827	UTS	160-200
Resistivity	115	YP (0.2% offset)	125-150
Specific heat	4.000	Elongation (2 in.)	50-75
Magnetic properties	Param, $\mu = 1$	Modulus of elasticity	32.1
Coefficient of expansion	10.4	Elastic limit	114
		Elastic limit/dens.	12.5
		Mod. dens.	3.48

TABLE A-12. (Continued)

INCONEL

Recommended Use RT - 2 - 1 yr For excellent high temperature oxidation resistance, high creep strength. 150 - 0 - 1 yr good strength Cycle - 5	
Heat Treatment for Maximum stability	
Procedure Initial condition: cold drawn 1700°F, 1 hr, furnace cool 200°F, 60 hr, air cool	
Physical Properties	Mechanical Properties
Density 8.51	Hardness 15-21B
Thermal conductivity 0.036	UTS 90-100
Reactivity 90.1	YP (0.2% offset) 75-90
Specific heat 0.109	Elongation (2 in.) 50-55
Magnetic properties none	Modulus of elasticity 30.1
Coefficient of expansion 12.8	Elastic limit 15
	Elastic limit/dens 1.76
	Mod./dens 3.54

IN SPAN C

Recommended Use RT - 10 - 6 mo High physical properties, age hardenable. Can replace Be-Cu particularly where brazing is necessary. Zero T-coefficient of modulus. 160 - 15 - 6 mo Cycle - 30	
Heat Treatment for Optimum strength and zero T-coefficient of modulus of elasticity.	
Procedure Initial condition: cold drawn 1800°F, 1½ hr, water quench age 1250°F, 21 hr, air cool	
Physical Properties	Mechanical Properties
Density 8.15	Hardness 29C
Thermal conductivity 0.0302	UTS 100
Reactivity 79.7	YP (0.2% offset) 115
Specific heat 0.12	Elongation (2 in.) 18
Magnetic properties yes	Modulus of elasticity 26.5*
Coefficient of expansion 7.2	Elastic limit 57.5
	Elastic limit/dens 7.06
	Mod./dens 3.25

* Near zero T-coefficient.

Z NICKEL

Recommended Use RT - 0 - 1 mo High strength with good corrosion resistance, especially in large sections	
Heat Treatment for Maximum stability after cycling	
Procedure Initial condition: cold drawn 1000°F, 9 hr, furnace cool to 900°F, air cool Cycle - 100 to 200°F maximum 10 times	
Physical Properties	Mechanical Properties
Density 8.26	Hardness 40C
Thermal conductivity 0.04	UTS 160-200
Reactivity 43.1	YP (0.2% offset) 120-150
Specific heat 0.104	Elongation (2 in.) 50-55
Magnetic properties none	Modulus of elasticity 52.1
Coefficient of expansion 17.4	Elastic limit 114
	Elastic limit/dens 19.8
	Mod./dens 3.80

GYROLLOY

Recommended Use No data* Experimental alloy for use as gyro wheel. Elastic limit a function of heat treatment. Coefficient of linear expansion to match 52100.	
Heat Treatment for Maximum stability and elastic properties	
Procedure 1600°F, 1hr/in., furnace cool	
Physical Properties	Mechanical Properties
Density 8.26	Hardness
Thermal conductivity	UTS
Reactivity	YP (0.2% offset)
Specific heat	Elongation (2 in.)
Magnetic properties none**	Modulus of elasticity
Coefficient of expansion 11.5-11.9	Elastic limit
	Elastic limit/dens
	Mod./dens

* Dimensional stability expected to be comparable to Invar.

** Nonmagnetic at T slightly above room temperature.

HYPERNOL

Recommended Use No data For magnetic circuits. Stress sensitive and low creep strength	
Heat Treatment for Maximum magnetic permeability	
Procedure 1200°C, 20 hr, furnace cool (Hydrogen atmosphere)	
Physical Properties	Mechanical Properties
Density 8.25	Hardness 50-60B
Thermal conductivity 0.01	UTS 61
Reactivity 45	YP (0.2% offset) 22
Specific heat 0.115	Elongation (2 in.) 20
Magnetic properties, max μ = 60,000 to 100,000	Modulus of elasticity 24
Coefficient of expansion 8.4	Elastic limit
	Elastic limit/dens
	Mod./dens 2.91

IN SPAN H

Recommended Use RT - 1 - 6 mo. For reasonably corrosion resistant and a specific coefficient of linear expansion. Good elastic limit. 160 - 10 - 6 mo. Cycle 10	
Heat Treatment for Maximum dimensional stability	
Procedure Initial condition: cold drawn 1800°F, 1½ hr, water quench Age at 1250°F, 20 hr, air cool	
Physical Properties	Mechanical Properties
Density 8.1	Hardness 50C
Thermal conductivity - 0.02	UTS 140
Reactivity - 80	YP (0.2% offset) 90
Specific heat - 0.12	Elongation (2 in.) 20
Magnetic properties yes	Modulus of elasticity 29
Coefficient of expansion 15.5	Elastic limit 47
	Elastic limit/dens 5.8
	Mod./dens 5.58

TABLE A-12. (Continued)

MUMETAL

Recommended Use			
No data For magnetic properties, high permeability. Has low creep strength, and is stress sensitive.			
Heat Treatment for			
Maximum magnetic permeability			
Procedure			
1175°C in hydrogen, 10 hr, slow cool.			
Physical Properties		Mechanical Properties	
Density	7.50	Hardness	
Thermal conductivity		UTS	64
Resistivity	~2	YP (0.2% offset)	10.5
Specific heat		Elongation (2 in.)	27
Magnetic properties	high μ	Modulus of elasticity	~ 50
Coefficient of expansion	17.5	Elastic limit	
		Elastic limit stress	
		Mod. stress	~ 3.49

R MONEL

Recommended Use			
No data Same properties as Monel but with greater machinability, dimensional stability should be about the same.			
Heat Treatment for			
None			
Procedure			
Initial condition: cold drawn			
Physical Properties		Mechanical Properties	
Density	8.34	Hardness	60-100B
Thermal conductivity	0.062	UTS	75-115
Resistivity	48.7	YP (0.2% offset)	30-100
Specific heat	0.127	Elongation (2 in.)	50-70
Magnetic properties	$\mu = 2000$ to 10,000	Modulus of elasticity	26
Coefficient of expansion	14.0	Elastic limit	42
		Elastic limit stress	4.75
		Mod. stress	2.94

POLY CUTTING INVAR

Recommended Use			
RT - 10 - 6 mo For low coefficients of linear expansion, good elastic limit and stability.			
60 - 0 - 6 mo			
ycle - 10 (Stability based on heat treatment No. 2. Approximately same for heat treatment No. 1)			
Heat Treatment for			
Maximum stability			
Procedure			
Initial condition: cold drawn			
1. 1200°F, 1 hr, furnace cool			
2. 1525°F, 1/2 hr, water quench			
1200°F, 1 hr, air cool			
200°F, 30 hr			
200°F, 40 hr, air cool			
Physical Properties		Mechanical Properties	
Density	8.15	Hardness	200
Thermal conductivity	0.025	UTS	90
Resistivity	81	YP (0.2% offset)	70
Specific heat	0.125	Elongation (2 in.)	26
Magnetic properties	max μ 5000	Modulus of elasticity	22
Coefficient of expansion	2.0	Elastic limit	47.5
		Elastic limit stress	5.85
		Mod. stress	2.71

Mechanical properties for heat treatment No. 1 (stress relief)

MONEL

Recommended Use			
RT - 15 - 1 yr Strength coupled with excellent resistance to corrosion.			
Heat Treatment for			
None - used in cold drawn condition for maximum strength.			
Procedure			
Initial condition: cold drawn			
Physical Properties		Mechanical Properties	
Density	8.64	Hardness	85B-21C
Thermal conductivity	0.062	UTS	85-125
Resistivity	48.7	YP (0.2% offset)	15-120
Specific heat	0.127	Elongation (2 in.)	35-10
Magnetic properties	$\mu = 2000$ to 10,000	Modulus of elasticity	26
Coefficient of expansion	14	Elastic limit	54
		Elastic limit stress	6.1
		Mod. stress	2.94

R MONEL

Recommended Use			
T - 5 - 3 mo. Good elastic properties and age hardenable. Good corrosion resistance.			
40 - 5 - 3 mo.			
ycle - 0			
Heat Treatment for			
Maximum dimensional stability			
Procedure			
Initial condition: cold drawn			
1. 1000°F for 9 hr, furnace cool to 900°F, air cool			
Physical Properties		Mechanical Properties	
Density	8.47	Hardness	7-11C
Thermal conductivity	0.045	UTS	140-170
Resistivity	58.5	YP (0.2% offset)	100-150
Specific heat	0.127	Elongation (2 in.)	50-15
Magnetic properties	none	Modulus of elasticity	28.7
Coefficient of expansion	13.4	Elastic limit	110
		Elastic limit stress	13.0
		Mod. stress	3.33

COPPER (ELECTROLYTIC TROUGH PITCH)

Recommended Use			
High conductivity use			
Heat Treatment for			
None			
Procedure			
As received			
Physical Properties		Mechanical Properties	
Density	8.94	Hardness	40F
Thermal conductivity	0.934	UTS	52
Resistivity	1.71	YP (0.2% offset)	10
Specific heat	0.92	Elongation (2 in.)	45
Magnetic properties	none	Modulus of elasticity	17
Coefficient of expansion	17.7	Elastic limit	
		Elastic limit stress	
		Mod. stress	1.9

TABLE A-12. (Continued)

BERYLLIUM COPPER NO. 25

Recommended Use RT - 0 - 5 ms High strength; high elastic limit; arc notch sensitive; easy to heat treat 160 - 5 - 5 ms with minimum distortion Cycle - 5	
Heat Treatment for * Maximum dimensional stability and maximum physical properties	
Procedure Initial condition: cold drawn * 1450°F, 7 hr, water quench 600°F, 2 hr, air cool	
Physical Properties	Mechanical Properties
Density 8.25	Hardness 37C
Thermal conductivity 0.25	UTS 175
Resistivity 6.8-9.3	YP (0.2% offset) 80 (0.01%)
Specific heat 0.1	Elongation (2 in.) 5
Magnetic properties none	Modulus of elasticity 19
Coefficient of expansion 15.9	Elastic limit 58.5
	Elastic limit/dens. 7.11
	Mod./dens. 2.3

* Note: a slightly higher elastic limit is obtained by 625°F for 2 hr. This has not yet been checked for stability.

PHOSPHOR BRONZE 75

Recommended Use For springs, bellows, lock washers, readily formed cold; general purpose spring material	
Heat Treatment for	
Procedure Cold rolled	
Physical Properties	Mechanical Properties
Density 8.16	Hardness 90B
Thermal conductivity 0.19	UTS 92
Resistivity 9.6	YP (0.2% offset) 82
Specific heat 0.09	Elongation (2 in.) 5.1
Magnetic properties none	Modulus of elasticity 16
Coefficient of expansion 17.8	Elastic limit 72
	Elastic limit/dens. 8.15
	Mod./dens. 1.81

BRASS 60-40

Recommended Use General purpose for fits and noncritical parts. Good machining	
Heat Treatment for None	
Procedure Initial condition: 1/2 hard	
Physical Properties	Mechanical Properties
Density 8.19	Hardness 80B
Thermal conductivity 0.29	UTS 70
Resistivity 6.2	YP (0.2% offset) 50 (0.1%)
Specific heat 0.09	Elongation (2 in.) 5
Magnetic properties none	Modulus of elasticity 15
Coefficient of expansion 20.8	Elastic limit 24
	Elastic limit/dens. 2.86
	Mod./dens. 1.79

ALUMINUM 2024

Recommended Use RT - 0 - 5 ms Best casting alloy for high strength dimensionally stable parts. 160 - 0 - 5 ms Cycle - 5	
Heat Treatment for Maximum dimensional stability	
Procedure Initial condition: as cast 1000°F, 2 hr, boiling water quench 310°F, 4 hr, air cool	
Physical Properties	Mechanical Properties
Density 2.68	Hardness 54B
Thermal conductivity 0.36	UTS 53
Resistivity 4.42	YP (0.2% offset) 24
Specific heat 0.23	Elongation (2 in.) 4
Magnetic properties none	Modulus of elasticity 10.5
Coefficient of expansion 20.8	Elastic limit 12
	Elastic limit/dens. 3.92
	Mod./dens. 4.47

BRASS 70-30

Recommended Use RT - 10 - 1 yr Deep drawing characteristics; not stable 160 - 5 - 1 yr Cycle - 10	
Heat Treatment for None	
Procedure Initial condition: hard (50% cold reduction)	
Physical Properties	Mechanical Properties
Density 8.13	Hardness 81B
Thermal conductivity 0.29	UTS 60
Resistivity 6.2	YP (0.2% offset) 49 (0.1%)
Specific heat 0.09	Elongation (2 in.) 19.5
Magnetic properties none	Modulus of elasticity 15
Coefficient of expansion 19.4	Elastic limit 27
	Elastic limit/dens. 3.17
	Mod./dens. 1.76

ALUMINUM 6061 (WROUGHT)

Recommended Use RT - 15 - 4 ms Very good corrosion resistance; good strength and machinability. 160 - 5 - 1 ms Cycle - 20	
Heat Treatment for Optimum mechanical properties	
Procedure 970°F, 1/2 hr, water quench 550°F, 6 hr, air cool	
Physical Properties	Mechanical Properties
Density 2.7	Hardness 15B
Thermal conductivity 0.37	UTS 45
Resistivity 4.3	YP (0.2% offset) 40
Specific heat 0.21	Elongation (2 in.) 15
Magnetic properties none	Modulus of elasticity 10
Coefficient of expansion 20.0	Elastic limit 12
	Elastic limit/dens. 4.44
	Mod./dens. 1.7

TABLE A-12. (Continued)

ALUMINUM 2017 (UNSOLUNT)

Recommended Use: Good formability; good corrosion resistance; may be readily modified.	
Heat Treatment for: Maximum mechanical properties.	
Procedure: 900°F, 1 hr, water quench 500°F, 0-12 hr, air cool	
Physical Properties:	Mechanical Properties:
Density 2.80	Hardness 93B
Thermal conductivity 6.41	UTS 67
Resistivity 3.60	YP (0.2% offset) 40
Specific heat 0.25	Elongation (2 in.) 20
Magnetic properties none	Modulus of elasticity 10.2
Coefficient of expansion 23.5	Elastic limit -30
	Elastic limit/dens. 7.94
	Mod./dens. 9.79

ALUMINUM 2024

Recommended Use: RT - 5 - 1 yr 150 - 10 - 1 yr Cycle - 5 Stress strengths higher than 2017 are required.	
Heat Treatment for: Maximum dimensional stability	
Procedure: 900°F, 1/2 hr, water quench 375°F, 12 hr, air cool	
Physical Properties:	Mechanical Properties:
Density 2.77	Hardness 69B
Thermal conductivity 6.32	UTS 60
Resistivity 3.75	YP (0.2% offset) 46
Specific heat 0.25	Elongation (2 in.) 22
Magnetic properties none	Modulus of elasticity 10.4
Coefficient of expansion 21.6	Elastic limit 22
	Elastic limit/dens. 7.94
	Mod./dens. 5.75

ALUMINUM 7075 (UNSOLUNT)

Recommended Use: RT - approx 20 - 1 yr Highest strength of the aluminum alloys. Not particularly suitable.	
Heat Treatment for: Maximum mechanical properties	
Procedure: 900°F, 1 hr, water quench 750°F, 24 to 36 hr, air cool	
Physical Properties:	Mechanical Properties:
Density 2.8	Hardness 69B
Thermal conductivity 6.25	UTS 80
Resistivity 3.75	YP (0.2% offset) 60
Specific heat 0.25	Elongation (2 in.) 10
Magnetic properties none	Modulus of elasticity 10.4
Coefficient of expansion 23.6	Elastic limit -40
	Elastic limit/dens. 14.5
	Mod./dens. 3.72

ALUMINUM - 8

Recommended Use: RT - 10 - 6 mo. 100 - 10 - 6 mo. Cycle - 10 Strength; may be used cast. For light structures of moderate strength.	
Heat Treatment for: Maximum dimensional stability	
Procedure: As received - extruded Stress relieve - 500°F, 1/4 hr, air cool	
Physical Properties:	Mechanical Properties:
Density 1.76	Hardness 83B
Thermal conductivity 6.30	UTS 30
Resistivity 5.0	YP (0.2% offset) 20
Specific heat 0.21	Elongation (2 in.) 10
Magnetic properties none	Modulus of elasticity 6.5
Coefficient of expansion 24.2	Elastic limit -9
	Elastic limit/dens. 3.1
	Mod./dens. 3.7

ALUMINUM 2017

Recommended Use: RT - 5 - 5 mo 100 - 5 - 5 mo Cycle - 0 Relatively one of the higher strength alloys; good forming; good resistance to corrosion. Obsolete in larger sizes than 2024.	
Heat Treatment for: Maximum dimensional stability	
Procedure: 900°F, 1/2 hr, water quench 350°F, 11 hr, air cool	
Physical Properties:	Mechanical Properties:
Density 2.79	Hardness 66B
Thermal conductivity 6.39	UTS 62
Resistivity 3.75	YP (0.2% offset) 40
Specific heat 0.25	Elongation (2 in.) 22
Magnetic properties none	Modulus of elasticity 10.5
Coefficient of expansion 21.5	Elastic limit 30
	Elastic limit/dens. 10.8
	Mod./dens. 3.75

ALUMINUM - 4340A

Recommended Use: No dimensional change	
Heat Treatment for: Maximum mechanical properties	
Procedure: As received - cast 750°F, 20 hr, air/cool 500°F, 6 hr, air cool	
Physical Properties:	Mechanical Properties:
Density 1.8	Hardness 40B
Thermal conductivity 6.17	UTS 60
Resistivity 14	YP (0.2% offset) 22
Specific heat 0.25	Elongation (2 in.) 5
Magnetic properties none	Modulus of elasticity 6.5
Coefficient of expansion 26	Elastic limit -12
	Elastic limit/dens. 6.7
	Mod./dens. 3.6

TABLE A-12. (Continued)

DUCTILE TITANIUM (PURE)

Recommended Use: Strength to weight typical of the 70A alloy. Good corrosion resistance. Readily joined.			
Heat Treatment for: Stress relief			
Procedure: Anneal 1600°F			
Physical Properties:		Mechanical Properties:	
Density	4.5	Hardness	90-100A
Thermal conductivity	0.056	UTS	90
Resistivity	55	YP (0.2% offset)	80
Specific heat	0.126	Elongation (2 in.)	20
Magnetic properties	none	Modulus of elasticity	16.6
Coefficient of expansion	8.8	Elastic limit	52
		Elastic limit/dens.	11.6
		Mod./dens.	5.55

TITANIUM 3M S C

Recommended Use: RT - 10 - 6 mo 100 - 0 - 6 mo Cycle - 5			
For strength to weight ratio material. Good corrosion resistance. Machinable by cold work.			
Heat Treatment for: Maximum stability			
Procedure: Initial condition: cold drawn Anneal 1300°F, 5 hr, furnace cool Stabilize 600°F, 1 hr, air cool			
Physical Properties:		Mechanical Properties:	
Dens.	4.59	Hardness	34C
Thermal conductivity	0.056	UTS	155
Resistivity	145	YP (0.2% offset)	145
Specific heat	0.120	Elongation (2 in.)	15.5
Magnetic properties	none	Modulus of elasticity	16.7
Coefficient of expansion	8.6	Elastic limit	115
		Elastic limit/dens.	25
		Mod./dens.	5.65

TITANIUM 70A

Recommended Use: RT - 5 - 1 yr 160 - 5 - 1 yr Cycle 20			
Machinable by cold work only. Ductile; weldable; good corrosion resistance.			
Heat Treatment for: Maximum dimensional stability			
Procedure: Initial condition: hot rolled Stress relieve 600°F, 1 hr, air cool or 600°F, 1 hr, air cool			
Physical Properties:		Mechanical Properties:	
Density	4.51	Hardness	90B
Thermal conductivity	0.022	UTS	80
Resistivity	54.8	YP (0.2% offset)	70
Specific heat	0.125	Elongation (2 in.)	15
Magnetic properties	none	Modulus of elasticity	15.5
Coefficient of expansion	8.6	Elastic limit	
		Elastic limit/dens.	
		Mod./dens.	3.52

ELILOY

Recommended Use: Very high elastic limit. Very high fatigue strength. Springs and suspensions.			
Heat Treatment for: Maximum physical properties			
Procedure: As received wire or strip Flare - 900°F - 5 hr, air cool wire - 900°F - 5 hr, air cool			
Physical Properties:		Mechanical Properties:	
Density	8.3	Hardness	19C
Thermal conductivity		UTS	540
Resistivity	160	YP (0.2% offset)	380
Specific heat		Elongation (2 in.)	
Magnetic properties	none	Modulus of elasticity	29.5
Coefficient of expansion	12.7	Elastic limit	~230
		Elastic limit/dens.	27.7
		Mod./dens.	5.55

TITANIUM 70B

Recommended Use: RT - 0 - 1 yr 160 - 0 - 1 yr Cycle - 5			
Good corrosion resistance; high strength to weight. Machinable by heat treatment.			
Heat Treatment for: Maximum dimensional stability			
Procedure: 1550°F, 1/2 hr, air cool (normal) 1550°F, 1/2 hr, air quench Stress relieve 600°F, 1 hr, air cool			
Physical Properties:		Mechanical Properties:	
Density	4.61	Hardness	15C
Thermal conductivity	0.097	UTS	160-175
Resistivity	60	YP (0.2% offset)	120
Specific heat	0.129	Elongation (2 in.)	15
Magnetic properties	none	Modulus of elasticity	16
Coefficient of expansion	8.2	Elastic limit	~100-110
		Elastic limit/dens.	16.5
		Mod./dens.	5.67

TANTALUM

Recommended Use: Ductile, high corrosion resistance, no recrystall. phase.			
Heat Treatment for: Annealed			
Procedure: Annealed in vacuum 1920°F			
Physical Properties:		Mechanical Properties:	
Density	16.6	Hardness	60B
Thermal conductivity	0.130	UTS	50
Resistivity	13.5	YP (0.2% offset)	
Specific heat	0.094	Elongation (2 in.)	60
Magnetic properties	none	Modulus of elasticity	27
Coefficient of expansion	6.5	Elastic limit	
		Elastic limit/dens.	
		Mod./dens.	1.65

TABLE A-13. (Continued)

TIN

Recommended Use: None			
Heat Treatment for: None			
Procedure: None - annealed			
Physical Properties:		Mechanical Properties:	
Density	7.3	Hardness	30-35 (60°C)
Thermal conductivity	0.175	UTS	100 (60°C)
Resistivity	12.0	YP (0.2% offset)	all
Specific heat	0.094	Elongation (2 in.)	6.0
Magnetic properties	none	Modulus of elasticity	all
Coefficient of expansion	25.1	Elastic limit	all
		Elastic limit/dens.	all
		Mod./dens.	9.3

OVER NET (GALLERY)

Recommended Use: High density. None of these types is mechanical properties.			
Heat Treatment for: None			
Procedure: None			
Physical Properties:		Mechanical Properties:	
Density	16.7-17.05	Hardness	30-35
Thermal conductivity	0.235	UTS	195
Resistivity	12.45	YP (0.2% offset)	154
Specific heat	0.092	Elongation (2 in.)	3
Magnetic properties	none	Modulus of elasticity	44
Coeff. of expansion	1.80	Elastic limit	62
		Elastic limit/dens.	4.04
		Mod./dens.	2.6

SILVER (PURE)

Recommended Use: Electrical; optical film			
Heat Treatment for: Roll of working anneal			
Procedure: 1774° anneal			
Physical Properties:		Mechanical Properties:	
Density	10.5	Hardness	27-28
Thermal conductivity	1.00	UTS	22.9
Resistivity	1.6	YP (0.2% offset)	700
Specific heat	0.096	Elongation (2 in.)	54
Magnetic properties	none	Modulus of elasticity	11
Coefficient of expansion	19.1	Elastic limit	670
		Elastic limit/dens.	0.0635
		Mod./dens.	1.05

CRYSTALLINE (GIV BROWN)

Recommended Use: RT - 0 - 5 m High modulus to density ratio. Moderate elastic limit/density. 100 - 4 - 5 m Cycle - 20			
Heat Treatment for: Dimensional stability on established. No heat treatment.			
Procedure: None present			
Physical Properties:		Mechanical Properties:	
Density	1.85	Hardness	50-55
Thermal conductivity	0.40	UTS	91
Resistivity	0.4	YP (0.2% offset)	~44
Specific heat	0.30-0.41	Elongation (2 in.)	10"
Magnetic properties	none	Modulus of elasticity	44.5
Coefficient of expansion	11.3	Elastic limit	12.0
		Elastic limit/dens.	10.0
		Mod./dens.	23.2

GALLERY 100

Recommended Use: High density material			
Heat Treatment for: None			
Procedure: None			
Physical Properties:		Mechanical Properties:	
Density	16.7	Hardness	30-35
Thermal conductivity	0.225	UTS	94-112
Resistivity	12.45	YP (0.2% offset)	75
Specific heat	0.092	Elongation (2 in.)	2.5
Magnetic properties	none	Modulus of elasticity	40
Coefficient of expansion	1.4	Elastic limit	25
		Elastic limit/dens.	1.1
		Mod./dens.	2.4

GOLD

Recommended Use: Electrical properties; density.			
Heat Treatment for: None			
Procedure: None - wrought, annealed			
Physical Properties:		Mechanical Properties:	
Density	19.3	Hardness	25 BHN 100 kg. load
Thermal conductivity	0.3	UTS	39
Resistivity	2.25	YP (0.2% offset)	all
Specific heat	0.031	Elongation (2 in.)	45
Magnetic properties	none	Modulus of elasticity	11.4
Coefficient of expansion	14.1	Elastic limit	all
		Elastic limit/dens.	all
		Mod./dens.	0.6

TABLE A-12. (Continued)

GE METAL

Recommended Use: BT - 8 - 1 yr 10 - 9 - 1 yr Circle - 5		High density. Tungsten powder, metal binder.	
Heat Treatment for:		Maximum stability as received.	
Procedure:		As received.	
Physical Properties:		Mechanical Properties:	
Density	16.9-17.2	Hardness	20-30C
Thermal conductivity	0.325	UTS	95
Resistivity	6.0	YP (R. 25 offset)	75
Specific heat	0.052	Elongation (2 in.)	2
Magnetic properties	none	Modulus of elasticity	10
Coefficient of expansion	3.6	Elastic limit	27
		Elastic limit/dens.	1.79
		Mod./dens.	2.94

PANEVEL NO. 77

Recommended Use:		As a high density material. Stability as established.	
Heat Treatment for:		Maximum dimensional stability	
Procedure:		As received - as heat treatment	
Physical Properties:		Mechanical Properties:	
Density	17	Hardness	20C
Thermal conductivity	0.326	UTS	105
Resistivity	12.5	YP (R. 25 offset)	85
Specific heat	0.052	Elongation (2 in.)	2.5
Magnetic properties	none	Modulus of elasticity	40
Coefficient of expansion	6.5	Elastic limit	30
		Elastic limit/dens.	1.766
		Mod./dens.	2.97

OSIN SILVER

Recommended Use:		Precipitation hardening alloy for good strength and conductivity.	
Heat Treatment for:		Maximum electrical and strength	
Procedure:		Quench and age	
Physical Properties:		Mechanical Properties:	
Density	- 10	Hardness	65B
Thermal conductivity	- 1	UTS	55
Resistivity	1.0	YP (R. 25 offset)	0
Specific heat	- 0.056	Elongation (2 in.)	11
Magnetic properties	none	Modulus of elasticity	11
Coefficient of expansion	- 19	Elastic limit	1.1
		Elastic limit/dens.	
		Mod./dens.	

TUNGSTEN CARBIDE (WMC-4C)

Recommended Use:		Very high hardness. Tools, pins, bearing surfaces.	
Heat Treatment for:		None	
Procedure:		None	
Physical Properties:		Mechanical Properties:	
Density	14.8	Hardness	90-92A
Thermal conductivity	6.79	UTS	Compression 690-750
Resistivity	20	YP (R. 25 offset)	
Specific heat	0.05	Elongation (2 in.)	00
Magnetic properties	none	Modulus of elasticity	Compression 625
Coefficient of expansion	5	Elastic limit	Compression 42.5
		Elastic limit/dens.	Mod./dens. 5.95
		Mod./dens.	

MAGNESIUM NICKEL SILVER ALLOY

Recommended Use:		Corrosion and electrical. Good conductivity, wear resistance and strength. Better creep strength than pure silver.	
Heat Treatment for:		Maximum stability and electrical	
Procedure:		Annealed - hardened by air heating at 1200-1475 for a time and as a temperature which is a function of thickness.	
Physical Properties:		Mechanical Properties:	
Density	10.5	Hardness	40 (WT)
Thermal conductivity	6.75	UTS	65-80
Resistivity	2.52	YP (R. 25 offset)	15-56
Specific heat	0.05	Elongation (2 in.)	1-5
Magnetic properties	none	Modulus of elasticity	12
Coefficient of expansion	19	Elastic limit	4-66
		Elastic limit/dens.	4.39
		Mod./dens.	1.14

**Data From "An Investigation of the
Precision Mechanical Properties of
Several Types of Beryllium",**

by T. J. Haghel, Research Staff Report,
General Motors Laboratory,
Report No. MR-120, April 4, 1960

This report discusses the mechanical properties of beryllium of importance to gyro applications, and presents data on precision elastic limit, microcreep limit, and the dimensional stability* under stress for several grades of commercial beryllium.

TABLE A-13. AVERAGE PRECISION ELASTIC-LIMIT DATA FOR VARIOUS GRADES OF COMMERCIAL BERYLLIUM

Mesh	Composition	Average Precision Elastic Limit, psi
-200	100% virgin	2200
-200	Standard production grade	2663
-200	60% recycle + 40% virgin	4100
-200	100% recycle	4300
Subsieve	100% virgin	4333
-325	100% virgin	6500
-200	Dispersed iron alloy	6833
Subsieve	100% recycle	11167

TABLE A-14. DATA ON PRECISION ELASTIC LIMIT, ELASTIC MODULUS, AND MICROCREEP LIMIT FOR SPECIMENS OF COMMERCIAL BERYLLIUM

Mesh	Composition	%BeO (GMR)	%BeO (Brush)	Grain Size, microns (GMR)	Grain Size, microns (Brush)	Density, g/cc (GMR)	Density, g/cc (Brush)	PEL, psi	Elastic Modulus, million psi	MCL, psi
-200	100% recycle	2.67	2.19	11.3	19	1.866	1.858	4,000	44	7,500
-200	Ditto	2.67	2.19	11.3	19	1.866	1.858	3,500	45.2	10,500
-200	"	2.93	2.24	8.7	20	1.861	1.854	5,500	43.6	6,000-13,000
-200	"	2.93	2.28	8.7	20	1.861	1.854	5,000	46	7,900
-110	"	2.92	2.60	13.6	21	1.867	1.855	4,500	43.4	5,000
-110	"	2.92	2.60	13.6	21	1.867	1.855	3,300	40.3	7,500
-110	100% virgin	1.39	1.03	15.1	21	1.859	1.856	4,500	45.3	4,700
-110	Ditto	1.39	1.03	15.1	21	1.859	1.856	1,200	36	1,600
-110	"	1.55	1.28	16.6	21	1.849	1.846	2,100	42.4	4,500
-110	"	1.55	1.28	16.6	21	1.849	1.846	1,500	36	4,500
-110	"	1.28	1.06	--	21	1.860	1.851	2,500	44	7,000
-110	"	1.28	1.06	--	21	1.860	1.851	1,750	39.6	4,500
-110	60% recycle	2.18	2.48	10.97	22	1.860	1.855	7,500	39.6	8,000
-110	40% virgin	2.18	2.48	10.97	22	1.860	1.855	800	--	12,500
-110	Ditto	2.41	3.31	--	20	1.862	1.863	4,500	49.5	9,500
-110	"	2.41	3.31	--	20	1.862	1.863	3,000	42.1	9,250
-110	"	2.37	2.31	11.55	19	1.845	1.851	6,700	43.5	6,700
-110	"	2.37	2.31	11.55	19	1.845	1.851	2,500	37.1	9,000
-110	"	2.37	2.31	11.55	19	1.845	1.851	7,000	44	7,000
-325	100% virgin	2.80	2.35	--	20	1.861	1.858	5,000	43.1	11,500
-325	Ditto	2.80	2.35	--	20	1.861	1.858	5,000	43.1	11,500
-325	"	1.80	2.11	11.05	16	1.854	1.853	6,500	46.4	9,000
-325	"	1.80	2.11	11.05	16	1.854	1.853	7,000	44.9	11,500
-325	"	1.92	2.29	9.3	17	1.860	1.849	6,500	45	7,000
-325	"	1.92	2.29	9.3	17	1.860	1.849	7,000	44.3	7,500
-325	"	1.92	2.29	9.3	17	1.860	1.849	7,000	44.3	7,500
S. S.	100% recycle	6.01	5.89	--	10	1.879	1.855	16,000	44	17,700
S. S.	Ditto	6.01	5.89	--	10	1.879	1.855	9,500	47.8	25,800
S. S.	"	6.38	5.50	5.86	10	1.877	1.876	11,000	47.2	23,500
P. S.	"	6.38	5.50	5.86	10	1.877	1.876	8,500	43.04	29,500
S.	"	6.06	5.79	--	10	1.881	1.876	10,000	45.4	21,500
S. S.	"	6.06	5.79	--	10	1.881	1.876	12,000	44.5	19,500
-200	Dispersed-Phase Fe Alloy	1.84	1.73	--	17	1.872	1.855	5,000	41.7	8,700
-200	Ditto	1.86	1.73	--	17	1.872	1.855	9,000	43.4	13,700
-200	"	2.15	2.01	--	21	1.803	1.870	7,500	43.7	14,000
-200	"	2.15	2.01	--	21	1.803	1.870	7,500	44.6	12,500
-200	"	1.77	1.66	--	25	1.878	1.861	6,000	40.3	12,500
-200	"	1.77	1.66	--	25	1.878	1.861	6,000	42.3	9,500
S. S.	100% virgin	4.48	3.60	--	18	1.881	1.876	6,500	45.7	16,000
S. S.	Ditto	4.48	3.60	--	18	1.881	1.876	4,500	41.2	5,300-11,500
S. S.	"	3.38	2.79	--	16	1.874	1.859	6,000	44.4	14,000
S. S.	"	3.38	2.79	--	16	1.874	1.859	2,500	46.5	11,500
S. S.	"	2.91	3.17	--	15	1.859	1.858	4,000	50.3	6,000
S. S.	"	2.91	3.17	--	15	1.859	1.858	2,500	40.6	15,500

*The term "dimensional stability" as used here denotes slow plastic strain at stress levels below the precision elastic limit. This strain is more commonly denoted as creep.

TABLE A-15. DATA ON DIMENSIONAL STABILITY UNDER STRESS (CREEP) FOR COMMERCIAL BERYLLIUM

Mesh Size and Grade	Oxide Content, %		Grain Size, μ		Density, g/cc		Test Stress, psi	Total Test Time, hrs	Total Strain, μ -in. in.	Remarks
	GMR	Brush	GMR	Brush	GMR	Brush				
-100, 100% recycle	2.07	2.12	11.5	19	1.866	1.858	3,600	508.5	+ 6.9	
Ditto	2.93	2.28	8.7	20	1.861	1.854	5,200	468.5	+ 6.6	
"	2.92	2.04	13.6	21	1.867	1.855	3,400	470.5	+97.5	Specimen stress relieved and retested
-100, 100% virgin	1.39	1.03	15.1	21	1.859	1.856	3,800	803	+41.4	Ditto
Ditto	1.55	1.28	16.6	21	1.849	1.846	1,700	347	+ 7.2	
"	8.93*	1.06		21	1.860	1.851	1,665	420	- 2.9	*% BeO redetermined to be 1.28%
-100, 60% recycle	2.18	2.48	10.97	22	1.860	1.855	3,940	97	+20.6	Specimen stress relieved and retested
-100, 40% virgin	2.44	1.91*		20	1.862	1.863	2,800	556.5	+ 3.0	*Reported to be higher because of proximity to surface of pressing
"	2.37	2.11	11.55	19	1.845	1.851	2,400	560	+ 6.8	
-100, 100% virgin	2.80	2.35		20	1.861	1.858	4,800	555	+10.8	
Ditto	1.80	2.11	11.65	16	1.854	1.853	6,200	137.5	+14.6	
"	1.92	2.29	7.3	17	1.860	1.849	6,400	489	+10.1	
Subsieve 100% recycle	6.01	5.89		10	1.879	1.855	12,100	490.5	+87.2	Specimen stress relieved and retested
Ditto	6.38	5.50	5.66	10	1.877	1.876	9,260	420	+ 2.9	
"	6.04	5.70		10	1.881	1.876	10,450	418	+ 4.7	
-100 (see above)	1.68	1.73		17	1.872	1.855	6,750	420	+ 6.8	Dispersed phase Fe alloy
Ditto	5.69*	2.01		21	1.803	1.870	7,125	357	+12.3	Ditto *% BeO redetermined to be 2.15%
"	1.77	1.66		25	1.878	1.861	5,700	359	+12.6	
Subsieve 100% virgin	4.48	3.60		18	1.881	1.876	5,340	431.5	+10.3	
Ditto	5.38	2.79		16	1.874	1.859	4,040	359	+13.8	
"	2.91	1.17		15	1.859	1.858	3,090	359	+ 0.3	
Commercial		1.73	15.1	22	1.861	1.856	500	384	+ 2.0	
Ditto		1.75		22	1.866	1.858	1,900	384	+ 3.7	
"		1.70	12.8	22	1.855	1.858	1,440	525.5	+ 8.2	
"	1.57	1.45	9.25	21	1.842	1.842	4,500	829	+ 9.9	
"	1.44	1.47	10.1	21	1.844	1.842	4,300	466	+ 9.3	
"	1.39		11.5	21	1.842	1.842	950	359	+ 0.2	
"	1.44	1.47	10.1	21	1.844	1.842	4,280	431.5	+ 8.0	
-100, 100% recycle	2.92	2.68	13.6	25	1.867	1.855	3,140	529	+ 3.7	2nd test
-100, 100% virgin	1.39	1.03	15.1	21	1.859	1.856	1,140	695	+26.3	Ditto
-100, 60% recycle	2.18	2.48	10.97	22	1.804	1.855	3,940	383	+ 5.3	"
-100, 40% virgin										
Subsieve 100% recycle	6.01	5.89		10	1.809	1.855	12,100	383	+11.1	"

**Data From "Gage Blocks of Superior
Stability III: The Attainment of Ultrastability"**

by

M. R. Meyerson and M. C. Sola,
Trans. ASM, 57, 164 (1964)

This paper discusses the procedures used in the gage-block program at the National Bureau of Standards for the attainment of a very high degree of dimensional stability. It summarizes the data for a number of materials considered suitable for use as gage blocks; as the results show, several of these are very stable indeed. The test specimens used all have a 2-inch gage length, and a cross section 1-3/8 by 3/8 inch.

TABLE A-16. SUMMARY OF STABILITY CHARACTERISTICS OF ALL GAGE

Type ^a	Symbol	Surface hardness, b RC	Material and identifying treatment	Max period observed, months
3	P	>70	17-4 PH, hardened, aged, nitrided	22
4 ^c	KA	72	Titanium carbide, 25% Ni, stress relieved	20
2	F	68	410, annealed core, nitrided	45
4	S	65	Titanium carbide, steel binder, hardened and tempered	19
2	L	66	1010, pack carburized, case hardened	30
1 ^{d,e}	T	62	52100, directly quenched or martempered, stabilized, R _C 62	49
3	N	68	Nitralloy 135 mod, hardened, tempered, nitrided	34
2	L	65	1010, carbonitrided, case hardened	20
3	N	68	Nitralloy 135 mod, hardened, tempered, nitrided	34
1 ^{d,e}	T	60	52100, directly quenched or martempered, stabilized, R _C 60	50
2	F	67	410, annealed core, nitrided 2-step	45
3	N	57-69	Nitralloy 135 mod, hardened, tempered, liquid nitrided	17
2 ^f	T	68	52100, annealed, chromium plated	48
2	L	62	1010, annealed core, thermal sprayed	17
1 ^d	V	62	T15, hardened, tempered to R _C 62	19
3	E	66	8620, carbonitrided, case hardened	30
1 ^d	T	65	52100, directly quenched or martempered, stabilized, R _C 65	49
4	AL & NBS	>68	Chromium carbide, Ni binder, as received	20
2 ^c	L	68	1010, annealed core, chromium plated	25
4	Q	>70	Aluminum oxide, no binder	29
3	E	65	8620, liquid carburized, case hardened	32
2	N	68	Nitralloy 135 mod, annealed core, nitrided	17
2 ^f	T	72	52100, annealed, flame plated	30
3	E	64	8620, gas carburized, case hardened	20
2	F	68	410, annealed core, nitrided	30
1 ^d	V	65	T15, hardened, tempered to R _C 65	20
2 ^c	L	68	1010, annealed core, chromium plated	36
1 ^d	W	65	W4, hardened, stabilized	16
1 ^d	.	65	Commercial through-hardened steel gage blocks, AA grade	25
4	KB	68	Titanium carbide, 40% Ni, stress relieved	19
3 ^e	C	65 ^g	420, hardened, tempered, nitrided	16
2	D	65	D2, annealed core, nitrided	16
2	F	68	410, annealed, chromium plated	24
1 ^d	D	58	D2, hardened, stabilized	16
2	D	72	D2, annealed, flame plated	24
2	F	72	410, annealed, flame plated	23
1 ^d	T	66	52100, hardened, deliberately unstable	7

a Type 1 is through-hardened; Type 2 has annealed cores and hardened surfaces; Type 3 has partially hard or cermet.

b This value represents hardness of the case or coating where applicable. Where appropriate, hardness converted to R_C.

c Only one specimen of this type tested.

d Results reported were obtained previously and reported in a prior reference (9). They are included for

e Contained short-term periods of greater instability.

f Average of two blocks with widely different values. One block was very stable.

g Estimated.

CHARACTERISTICS OF ALL GAGE BLOCKS, IN ORDER OF MERIT

Type	Max period observed, months	Fabrication of case on nongaging faces			Average change in length, μ -in./in./yr
		Intact	Partially removed	Completely removed	Not applicable
Type 1	22			X	+ 0.05
	20				- 0.07
	45		X		+ 0.10
	19				- 0.10
	30		X		+ 0.11
Type 2	49				- 0.13
	34		X		+ 0.17
	20			X	+ 0.17
Type 3	34			X	+ 0.19
	50				+ 0.20
	45	X			+ 0.20
	17			X	+ 0.21
	48		X		+ 0.21
Type 4	17			X	+ 0.25
	19				+ 0.27
	30			X	+ 0.29
	49				- 0.30
	20				- 0.34
	25		X		+ 0.35
	29				+ 0.38
	32			X	+ 0.38
	17			X	+ 0.40
	30			X	+ 0.41
Type 5	20			X	+ 0.42
	30			X	+ 0.44
	20				+ 0.49
	36			X	+ 0.58
	16				+ 0.59
	25				- 0.67
	19				- 0.78
	16			X	+ 0.80
	16		X		+ 0.81
	24			X	+ 0.85
Type 6	16				+ 0.86
	24			X	+ 0.89
	23			X	+ 0.96
	7				-25.0

A-30

aces; Type 3 has partially hardened cores and hardened cases; Type 4 is a ceramic

Where appropriate, hardness was measured with a micro-tester such as the Vickers and

ice (9). They are included for comparison.

table.

LIST OF DMIC MEMORANDA ISSUED
(Continued)

A list of DMIC Memoranda 1-164 may be obtained from DMIC, or see previously issued memoranda.

<u>DMIC Memorandum Number</u>	<u>Title</u>
165	Review of Uses for Depleted Uranium and Nonenergy Uses for Natural Uranium, February 1, 1963
166	Literature Survey on the Effect of Sonic and Ultrasonic Vibrations in Controlling Grain Size During Solidification of Steel Ingots and Weldments, May 15, 1963
167	Notes on Large-Size Furnaces for Heat Treating Metal Assemblies, May 24, 1963 (A Revision of DMIC Memo 63)
168	Some Observations on the Arc Melting of Tungsten, May 31, 1963
169	Weldability Studies of Three Commercial Columbium-Base Alloys, June 17, 1963
170	Creep of Columbium Alloys, June 24, 1963
171	A Tabulation of Designations, Properties, and Treatments of Titanium and Titanium Alloys, July 15, 1963
172	Production Problems Associated with Coating Refractory Metal Hardware for Aerospace Vehicles, July 26, 1963
173	Reactivity of Titanium with Gaseous N_2O_4 Under Conditions of Tensile Rupture, August 1, 1963
174	Some Design Aspects of Fracture in Flat Sheet Specimens and Cylindrical Pressure Vessels, August 9, 1963
175	Consideration of Steels with Over 150,000 psi Yield Strength for Deep-Submergence Hulls, August 16, 1963
176	Preparation and Properties of Fiber-Reinforced Structural Materials, August 22, 1963
177	Designations of Alloys for Aircraft and Missiles, September 4, 1963
178	Some Observations on the Distribution of Stress in the Vicinity of a Crack in the Center of a Plate, September 18, 1963
179	Short-Time Tensile Properties of the Co-20Cr-15W-10Ni Cobalt-Base Alloy, September 27, 1963
180	The Problem of Hydrogen in Steel, October 1, 1963
181	Report on the Third Maraging Steel Project Review, October 7, 1963
182	The Current Status of the Welding of Maraging Steels, October 16, 1963
183	The Current Status and 1970 Potential for Selected Defense Metals, October 31, 1963
184	A Review and Comparison of Alloys for Future Solid-Propellant Rocket-Motor Cases, November 15, 1963
185	Classification of DMIC Reports and Memoranda by Major Subject, January 15, 1964
186	A Review of Some Electron-Microscopic Fractographic Studies of Aluminum Alloys, February 5, 1964
187	Some Observations on the Electron-Microscopic Fractography of Embrittled Steels, February 19, 1964
188	A Review of Available Information on the Welding of Thick Titanium Plate in the USSR, March 6, 1964

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13. ABSTRACT This memorandum discusses briefly the mechanisms leading to the dimensional instability of metals and alloys, together with some related phenomena; precision elastic limit, microcreep, and microstrain. Information of this type is needed in the design and manufacture of precision devices, such as bearings, gage blocks, gyros, accelerometers, and components of missile guidance systems. Tables of data from available reports and papers are presented for a number of metals and alloys. These should provide a useful source of information for the selection and processing of metals for applications where a high degree of dimensional stability is required. (Author)			

14. KEY WORDS	LINK A		LINK B		LINK C	
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