NASA TECHNICAL NOTE

NASA TN D-4338

c. 1

NASA TN D-4338

DEVELOPMENT OF A COBALT-TUNGSTEN FERROMAGNETIC, HIGH-TEMPERATURE, STRUCTURAL ALLOY

by Richard L. Ashbrook, Anthony C. Hoffman, Gary D. Sandrock, and Robert L. Dreshfield

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MARCH 1968

DEVELOPMENT OF A COBALT-TUNGSTEN FERROMAGNETIC, HIGH-TEMPERATURE, STRUCTURAL ALLOY

By Richard L. Ashbrook, Anthony C. Hoffman, Gary D. Sandrock, and Robert L. Dreshfield

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

DEVELOPMENT OF A COBALT-TUNGSTEN FERROMAGNETIC, HIGH-TEMPERATURE, STRUCTURAL ALLOY

by Richard L. Ashbrook, Anthony C. Hoffman, Gary D. Sañdrock, and Robert L. Dreshfield

Lewis Research Center

SUMMARY

Rotors for space power generators require a compromise between high-temperature strength and magnetic properties. Rotors must withstand high centrifugal stresses at high temperature and develop high induction for small exciting fields. Alloys considered for rotors include maraging steels, H-11 steel, and a cobalt-base alloy, Nivco. This report discusses work to develop alloys with improved high-temperature strength and good high-temperature magnetic properties. Because cobalt has the highest Curie temperature of any metal and is a good base for high-temperature alloys, a NASA superalloy, cobalt - 25 tungsten - 1 titanium - $\frac{1}{2}$ zirconium - $\frac{1}{2}$ carbon (Co - 25W - 1Ti - $\frac{1}{2}$Zr - $\frac{1}{2}$C), was chosen for further study. Modifications of this alloy were screened for maximum magnetic induction B_{max} at a maximum magnetizing force H_{max} of 100 oersteds (7958 A/m) over a range of temperatures. For increasing tungsten, Curie temperature decreased for the base Co - 1Ti - $\frac{1}{2}$Zr - $\frac{1}{2}$C, and B_{max} above 1000° F (538° C) decreased. Below 1000° F (538° C), low tungsten alloys show inflections in a plot of B_{max} as a function of temperature due to the instability of the face-centered cubic (fcc) phase. Stability of the fcc increased with increasing tungsten and iron. A preferred alloy, Co - 7$\frac{1}{2}$W - 2$\frac{1}{2}$Fe - 1Ti - $\frac{1}{2}$Zr - $\frac{1}{2}$C, was evaluated for magnetic and mechanical properties in cast form and for mechanical properties as sheet. After aging at 1700° F (927° C) for 72 hours, this alloy had a coercive force of 10.5 oersteds (835 A/m) at 75° F (24° C), and a B_{max} of 11.5 and 10.3 kilogauss (1.15 and 1.03 T) at 1200° and 1400° F (649° and 760° C), respectively. The stress-rupture life at 1200° to 1400° F (649° to 760° C) was greater than that of the strongest high-temperature commercially available magnetic-structural alloy.

INTRODUCTION

A feature common to many turboelectric space power conversion systems is the electrical generator or alternator. To reduce system weight, generator components must be small and capable of high-temperature operation. High generator operating temperatures are particularly important in space power conversion systems because they permit reductions in radiator size that can significantly reduce system weight (ref. 1). One of the most critical components of a generator (or of a motor) is the rotor. Choosing a rotor material requires a compromise between high-temperature strength and magnetic characteristics. Rotors must not only withstand high centrifugal stresses at high temperatures but must also develop high magnetic induction for small exciting field strengths.

Materials currently under consideration for generator rotors include maraging steels, H-11 steel, and a cobalt-base alloy Nivco (ref. 2). All these materials can be forged and can also be rolled into sheet. Although forgings are usually used for generator rotors, small rotors for space power alternators might be cast also. Advances in casting technology have made possible the use of cast material for applications previously limited to wrought products (ref. 3).

To meet the requirements of space power systems, a program was initiated to develop materials with improved high-temperature strength as well as high-temperature magnetic properties suitable for use in generator rotors. Because cobalt has the highest Curie temperature of all metals and a number of cobalt-base alloys have good elevated-temperature strength, work was confined to cobalt-base alloys. Earlier NASA research (refs. 4 and 5) had resulted in a series of workable, strong, high-temperature alloys based on the cobalt-tungsten system. An alloy from this series, Co - 25W - 1Ti - $\frac{1}{2}$Zr - $\frac{1}{2}$C was chosen as a base for further study. A number of experimental alloys were screened for their magnetic properties over a range of temperatures in the as-cast condition. A preferred alloy[1], Co - 7$\frac{1}{2}$W - 2$\frac{1}{2}$Fe - 1Ti - $\frac{1}{2}$Zr - $\frac{1}{2}$C, was evaluated more extensively for magnetic and mechanical properties in both the as-cast and heat-treated conditions. Limited mechanical property data were also obtained for the preferred alloy in sheet form. The properties of the preferred NASA alloy are compared with those of Nivco, one of the strongest commercially available magnetic alloys for high-temperature use.

---

[1]The alloy was developed at the NASA Lewis Research Center by John C. Freche, Richard L. Ashbrook, Gary D. Sandrock, and Robert L. Dreshfield; a patent has been applied for.

MATERIALS, APPARATUS, AND PROCEDURE

Alloys Investigated

Systematic alloying modifications were made to alloy Co - 25W - 1Ti - $\frac{1}{2}$Zr - $\frac{1}{2}$C, which had been developed originally for high-temperature service in the high vacuum of space (ref. 4). Two alloying approaches were used. First, the tungsten content was progressively reduced to as low as 5 percent to raise the alloy Curie temperature. Second, additions of iron up to 5 percent were made to increase the stability of the fcc matrix of the as-cast alloy. The zirconium, titanium, and carbon content were held constant. When these alloy modifications were made, a compromise was sought between high-temperature strength and high-temperature magnetic properties. The nominal compositions, expressed in weight percent, of the alloys investigated are as follows:

Cobalt	Tungsten	Titanium	Zirconium	Carbon	Iron
Balance	20	1	$\frac{1}{2}$	$\frac{1}{2}$	--
↓	12	↓	↓	↓	--
	10				--
	$7\frac{1}{2}$				--
	5				--
	$7\frac{1}{2}$				5
	$7\frac{1}{2}$				$2\frac{1}{2}$

The form and purities of the alloying elements used in preparing experimental alloys are given in table I. Table II presents the results of chemical analyses by an independent laboratory of several heats of the $7\frac{1}{2}$W - $2\frac{1}{2}$Fe alloy chosen for the most intensive study. Also shown is the supplier's analysis of the commercial alloy that was used for a comparative evaluation.

Casting Techniques

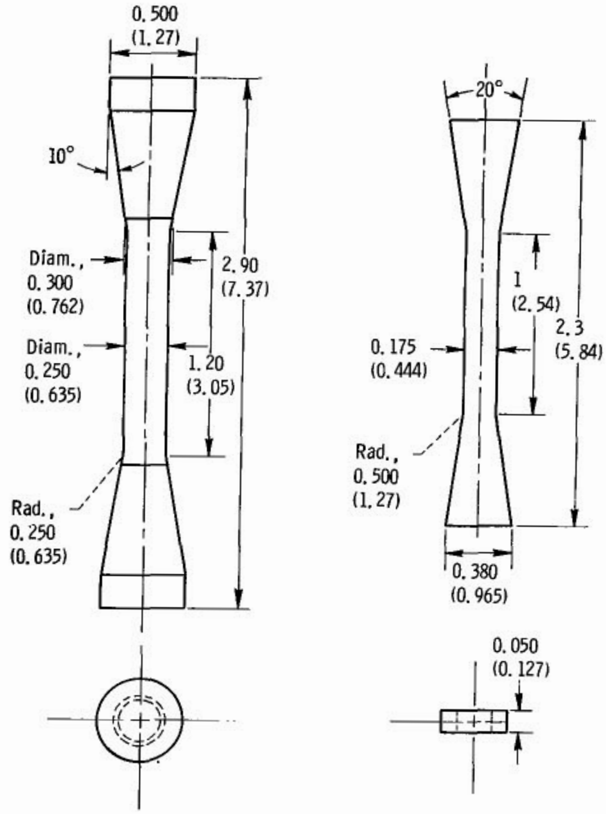
The experimental alloys were melted in a vacuum induction furnace. A new zirconia crucible was used for each melt. The melting procedure was as follows: The tungsten, the carbon, and a portion of the cobalt were charged into the cold crucible. The vacuum chamber pressure was kept below 10^{-2} torr (1.3 N/m^2) during most of the heating and melting cycle; however, during the early stages of melting, the chamber was backfilled with argon to about 40 torr (5.3×10^3 N/m^2) to limit boiling and splashing. After the initial melting the balance of the cobalt and the iron were added, and the chamber was reevacuated to a pressure generally less than 5×10^{-3} torr (6.7×10^{-1} N/m^2). A gentle "carbon boil" (evolution of CO) was maintained for 20 minutes by gradually increasing the temperature to approximately 3050° F (1677° C). Approximately 0.1 percent carbon was lost during the boil. After this refining period, titanium and zirconium were added under vacuum. The melt temperature was then adjusted to the pouring temperature of 2900°±50° F (1593°±28° C) and the chamber was backfilled with argon to a pressure of 15 torr (2×10^3 N/m^2) to prevent the possible formation of gas holes in the castings.

For cast-to-size bars, a 1.5-kilogram melt was poured into a zircon shell mold that was bedded in grog (granular fire clay) and held under vacuum at 1600° F (871° C) in a resistance furnace. Ten minutes after pouring, the casting was removed from the vacuum chamber and allowed to cool overnight before the mold material was removed. Rolling blanks were cast into an unheated copper mold.

Test Specimens

A shell mold and cast cluster of stress-rupture (tensile) bars and a magnetic test specimen are shown in figure 1. For a given alloy, both stress-rupture or tensile

Figure 1. - Ceramic shell mold and cast cluster of test bars and magnetic test ring.



(a) Cast. (b) Rolled.

Figure 2. - Tensile and stress-rupture specimens. (Dimensions in inches (and cm).)

specimens and a toroidal magnetic specimen were cast at the same time. The cast-to-size test bars are illustrated in figure 2(a). They had conical shoulders with a 20° included angle and a gage section 0.250 inch (0.635 cm) in diameter and 1.20 inch (3.05 cm) long. Sheet specimens illustrated in figure 2(b) were machined from rolled strips, approximately 0.060 inch (1.53 mm) thick. The magnetic specimen illustrated in figure 3 was a torus with a 2-inch (5.1-cm) outside diameter and a 0.25-inch-(0.635-cm-) diameter cross section.

Stress-rupture (fig. 2(a)) specimens of the commercial alloy were machined longitudinally from a bar heat-treated by the vendor. Magnetic specimens (fig. 3) were also machined from this bar.

All cast test specimens, as well as rolled sheet, were sandblasted prior to inspection. Cast specimens were inspected by X-ray and with fluorescent-dye penetrant prior to testing.

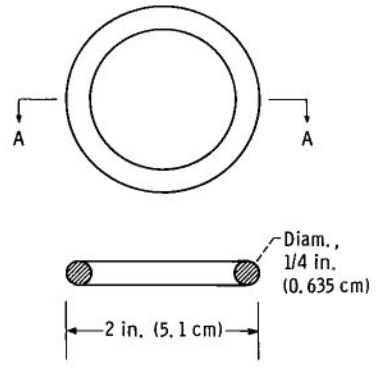


Figure 3. - Toroidal magnetic test specimen.

Rolling Procedure

Cast slabs that were approximately 3 by 3 by $\frac{1}{2}$ inch (7.6 by 7.6 by 1.3 cm) were ground to a 15/32-inch (1.2-cm) thickness to eliminate surface defects before rolling. Rolling was done on a standard 2-high mill. Rolling blanks were heated in air to $2000^{\circ} \pm 50^{\circ}$ F ($1093^{\circ} \pm 28^{\circ}$ C) and were reheated to this range between rolling passes. Reductions of about 0.025 inch (0.635 mm) were taken with each pass except for the last few passes, which were about 0.015 inch (0.38 mm). The final thickness was about 0.060 inch (1.5 mm). The resulting strips (approximately 20 by 3.1 by 0.060 in.; 50.8 cm by 7.9 cm by 1.5 mm) were machined into tensile and stress-rupture specimens after heat treatment.

Heat Treatments

Before it was machined into stress-rupture and tensile specimens, all sheet material was first annealed in argon for $\frac{1}{2}$ hour at 2350° F (1288° C) and air cooled. Some of the sheet material was subsequently aged in argon for 72 hours at 1700° F (927° C) and air cooled. Some of the cast stress-rupture specimens were aged for 72 hours at 1300° F, 1500° F, or 1700° F (704°, 816°, or 927° C). The commercial alloy was purchased in a proprietary solution-treated and aged condition.

Alloy Evaluation

Magnetic measurements. - For a given power output, the size and weight of an alternator rotor are inversely proportional to the maximum induction of the rotor material. Therefore, maximum induction is an important magnetic parameter when materials for rotor applications are evaluated. Since the solid rotors under consideration for space power systems carry a direct-current flux, there are no losses due to flux reversals except at the pole faces, and the material can be operated in a magnetically saturated condition. To evaluate properly a magnetic material for use as a rotor in a high-temperature alternator, its maximum induction should be determined as a function of temperature with the material subjected to a magnetizing force comparable to that encountered in service. A force of 100 oersteds (7958 A/m) was used in this study.

The standard method for determining induction is the ballistic galvanometer system (ref. 6). This method can be used to measure magnetic induction as a function of temperature by the heating of a sample transformer to successive temperature levels and obtaining point-by-point values. However, the Co - W alloys used in this study exhibited humps in their curves of induction against temperature, which were not easily detected by the isolated readings obtained by the ballistic galvanometer method. Therefore, it was decided to use an alternating-current testing method (ref. 7) that gives continuous data as a function of temperature. This system also permitted determination of the Curie temperatures of the alloys.

In the alternating-current testing method, the sample is energized by a sinusoidal alternating current. As a result, hysteresis and eddy current losses occur in the core material. Hysteresis losses have no measurable effect (ref. 7); however, eddy current losses can cause errors in the measurement of induction (ref. 7). By operating at a low frequency (60 Hz in this case), the error due to eddy current loss was made small with respect to the other errors in the system. The probable error in the magnetic measurements was less than 0.3 kilogauss (0.03 T).

The magnetic test specimen (fig. 3) was used as the core of a two-winding transformer that was built up in steps. The core was wrapped with a tape woven of fused silica fibers. A 250-turn primary winding was then distributed uniformly around the core. The wire was 20-gage-stranded-nickel-clad copper insulated with a braid of fused silica fibers. The primary winding was then wrapped with a double layer of silica tape. Then a 50-turn secondary was distributed uniformly around the core. The wire was 26 gage but otherwise was identical to that on the primary.

To obtain magnetic data as a function of temperature, the sample was placed in a resistance-heated furnace and heated at the maximum rate of the furnace to a temperature of 1800° F (982° C) or to the Curie point, if lower, in approximately 2 hours. A chromel-alumel thermocouple welded to the torus was used to sense temperature. Once the furnace was at temperature, the power was removed and the furnace was cooled at its natural rate to about 300° F (166° C) in approximately 8 hours. During both heating and cooling, the sample was energized with a sinusoidal current of 60 hertz to give a constant maximum magnetizing force of 100 oersteds (7958 A/m). An alternating-current power amplifier with constant current output held the maximum magnetizing force constant throughout the run. The induced voltage from the secondary of the sample was amplified, then averaged to make it proportional to maximum induction, and plotted against temperature on an X, Y-recorder. The instrument system used to obtain the magnetic data is shown in the block diagram of figure 4. A detailed description and analysis of this instrument system can be found in reference 7.

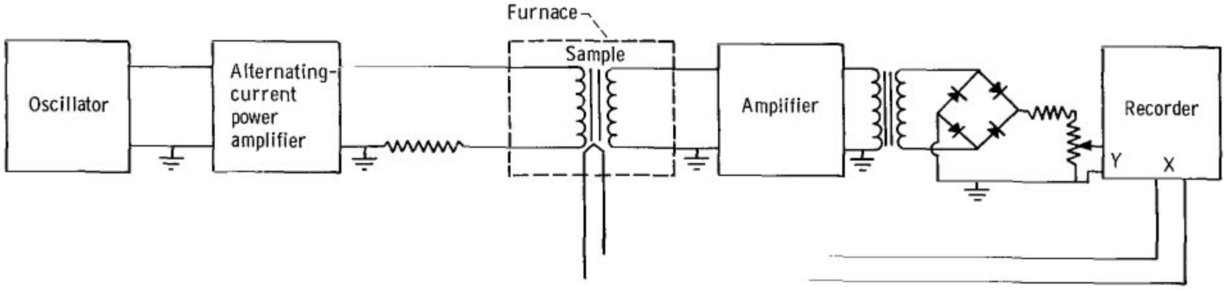


Figure 4. - Diagram of instrument system used to plot maximum induction of magnetic materials as function of temperature (ref. 7).

Coercive-force measurements were made at room temperature with cast toroidal specimens. A fluxmeter was used in accordance with ASTM A341-64 (ref. 6).

Mechanical property determinations. - All tensile and stress-rupture tests for both the cast and rolled specimens were run in air. Table III lists the tensile test conditions.

All tensile tests were run at a constant valve setting on hydraulic testing machines. A rough measure of average plastic-strain rate was determined for each specimen by dividing the percent elongation at fracture by the time of the test. For room-temperature tests, the average plastic strain rates were between 0.2 and 0.9 percent per minute.

For the high-temperature tests, the strain rates were between 1.3 and 4.8 percent per minute.

Table IV presents the stress-rupture test conditions for both as-cast and sheet specimens. During stress-rupture testing, measurements of crosshead travel were recorded which were used to estimate minimum creep rates (table V).

Rockwell A hardness readings were taken of cast specimens at various conditions of heat treatment. Table VI lists the hardness data.

Metallography. - The microstructure of the alloys was examined by both light and electron microscopy. X-ray diffraction was used to identify constituents electrolytically extracted in 25 percent phosphoric acid (H_3PO_4) in water. Debye-Scherer patterns were also obtained from wires electropolished from small sheet specimens.

RESULTS AND DISCUSSION

Magnetic Test Results

Magnetic properties pertinent to high-temperature generator applications of the Co - W alloys are presented in the following sections.

Magnetic induction. - The magnetic properties of an alloy are sensitive to both structure and composition. The effect of tungsten content on magnetic induction of a cobalt-base alloy that contains 1Ti, $\frac{1}{2}$Zr, and $\frac{1}{2}$C is shown in figure 5. The magnetic induction obtained during heating from 200° to 1800° F (93° to 982° C) is plotted in terms of B_{max} for a maximum magnetizing force of 100 oersteds (7958 A/m). Generally, the greater the tungsten content, the lower the Curie temperature. At 20 weight percent tungsten, the Curie temperature is approximately 1500° F (816° C), whereas at 5 weight percent tungsten it is above 1800° F (982° C). The latter test temperature was not exceeded because of electrical insulation limitations. As might be expected, the magnetic induction at elevated temperatures also increases as tungsten content decreases. For example, at 1300° F (704° C), the alloys that contained 20, 12, 10, 7.5, and 5 weight percent tungsten had a B_{max} of 3.6, 9.1, 9.6, 10.2, and 10.6 kilogauss (0.36, 0.91, 0.96, 1.02, and 1.06 T), respectively. However, at lower temperatures the magnetization curves cross, and the alloys with 5 and 7.5 weight percent tungsten have lower magnetic induction at 200° F (93° C) than do the 10- and 12-weight percent tungsten alloys.

We believe the drop in induction at lower temperatures and the double maximums in the curve of B_{max} against temperature are related to a hexagonal close packed $\rightleftharpoons$ face centered cubic transformation of the matrix. These effects are characteristic of the magnetization curves for unalloyed cobalt during the hexagonal close packed $\rightleftharpoons$ face centered cubic transformation (ref. 8).

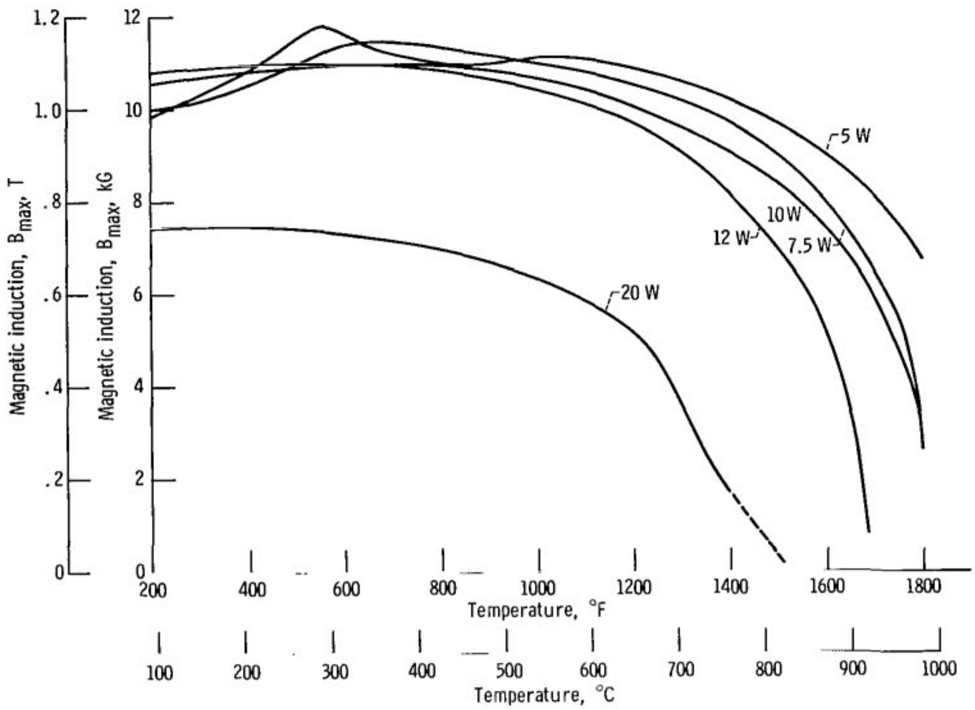
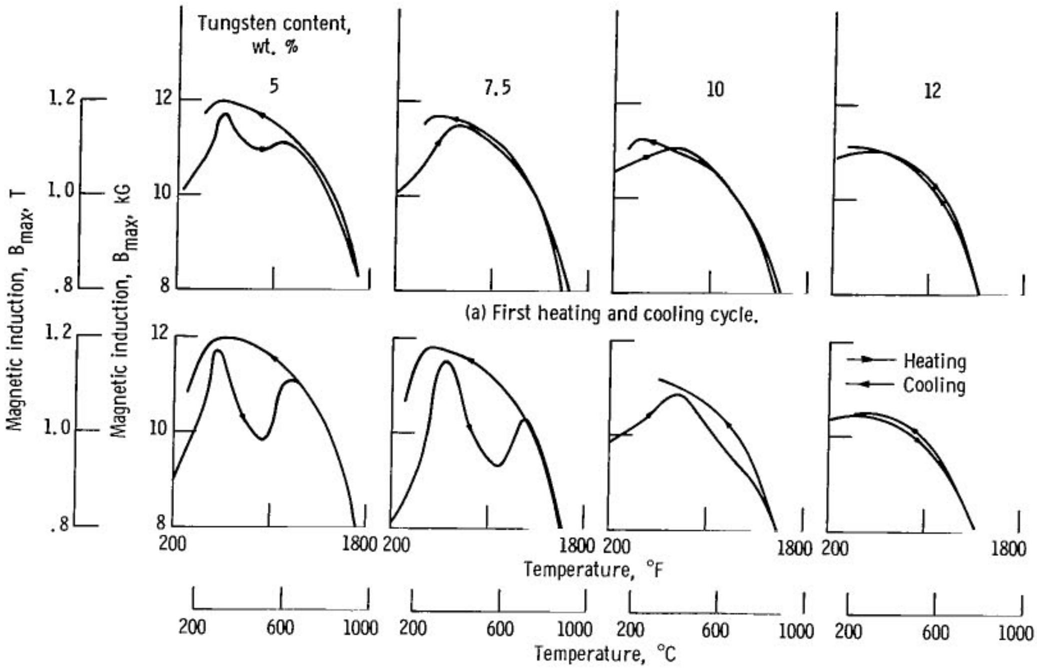


Figure 5. - Effect of temperature and tungsten content (wt. %) on magnetic induction of alloy Co-1Ti-$\frac{1}{2}$Zr-$\frac{1}{2}$C. Maximum magnetizing force, 100 oersteds (7958 A/m). Data recorded during first heating of cast specimens.

Figure 6 shows the effect of a single and a double heating and cooling cycle on the magnetic induction of alloys that contain 5 to 12 weight percent tungsten. There appeared to be no substantial difference between induction values obtained during the first heating and cooling cycle except for the 5-weight percent tungsten alloy. However, during the second heating cycle, the difference was marked for alloys that contained up to 10 percent tungsten.

The curve for the 5-weight percent tungsten alloy showed two maximums at about 580° and 1050° F (304° and 566° C) during the first heating cycle, and the higher tungsten alloys showed only a single maximum. During the second cycle, the 5- and 7.5-weight percent tungsten alloys showed double maximums. Also, the single maximum of the 10-weight percent tungsten alloy became more pronounced. Although not shown, induction data were obtained for some of these alloys during several additional heating cycles, and the trends presented in figure 6 were generally magnified with increasing numbers of cycles.

The 7.5-weight-percent-tungsten alloy had greater high-temperature magnetic induction than the 10- and 12-weight-percent-tungsten alloys; yet, it had greater magnetic stability than the 5-weight-percent-tungsten alloy. However, a sharp drop in magnetic induction occurred on reheating between 600° and 1400° F (316° and 760° C). Because iron stabilizes the face-centered-cubic phase at low temperatures in unalloyed



(b) Second heating and cooling cycle.

Figure 6. - Effect of tungsten content on magnetic stability of alloy Co-1Ti-$\frac{1}{2}$Zr-$\frac{1}{2}$C. Maximum magnetizing force, 100 oersteds (7958 A/m).

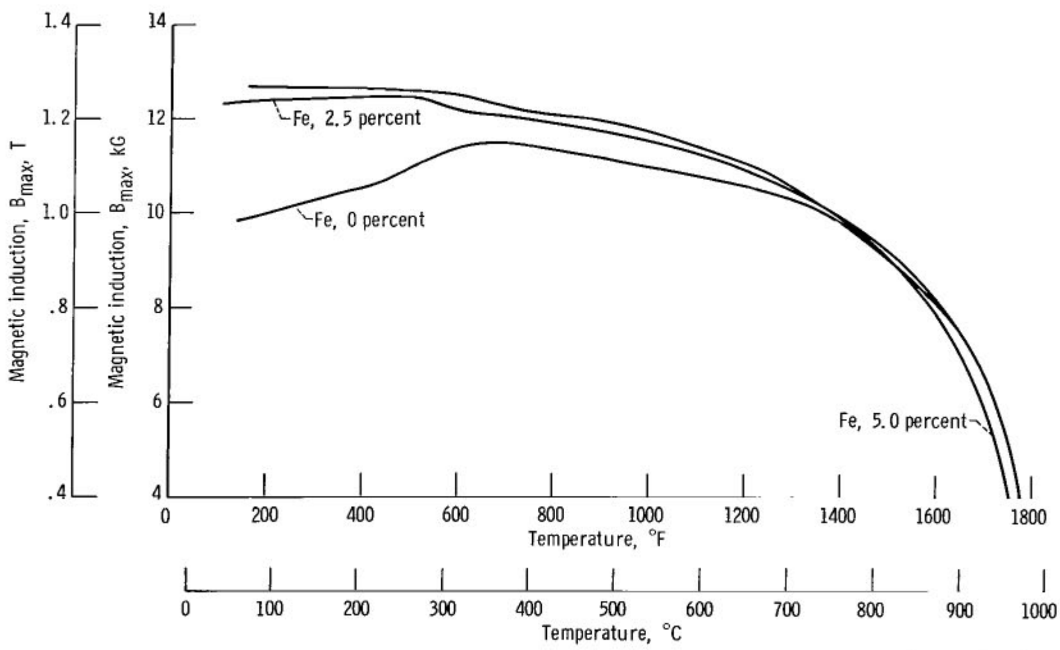


Figure 7. - Effect of temperature and iron content on magnetic induction of alloy Co-7$\frac{1}{2}$W-1Ti-$\frac{1}{2}$Zr-$\frac{1}{2}$C. Maximum magnetizing force, 100 oersteds (7958 A/m). Data obtained during first heating of cast specimens.

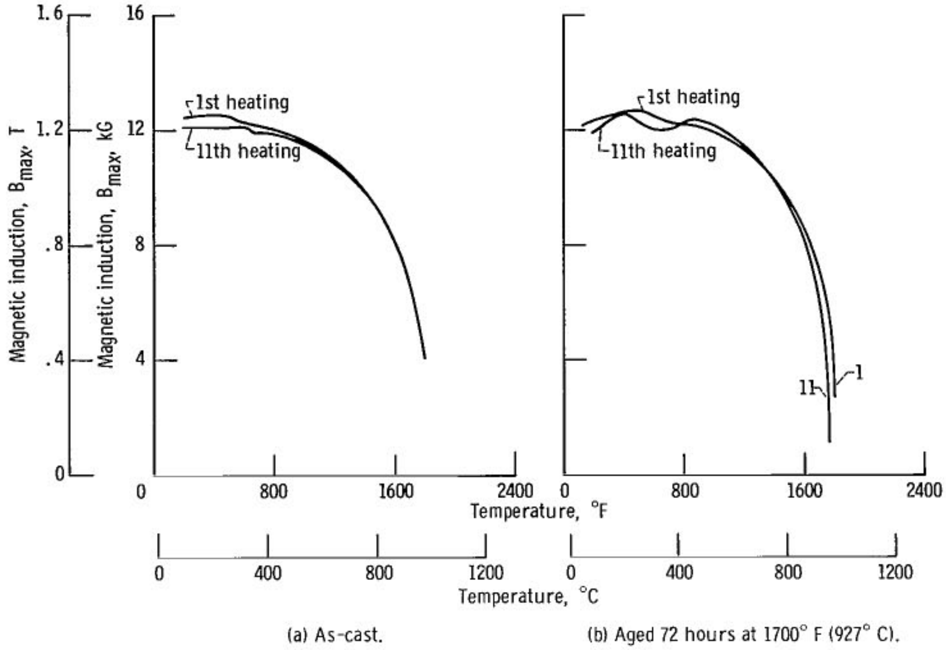


Figure 8. - Effect of heat treatment on magnetic stability of alloy Co-$7\frac{1}{2}$W-$2\frac{1}{2}$Fe-1Ti-$\frac{1}{2}$Zr-$\frac{1}{2}$C after repeated heating cycles. Maximum magnetizing force, 100 oersteds (7958 A/m).

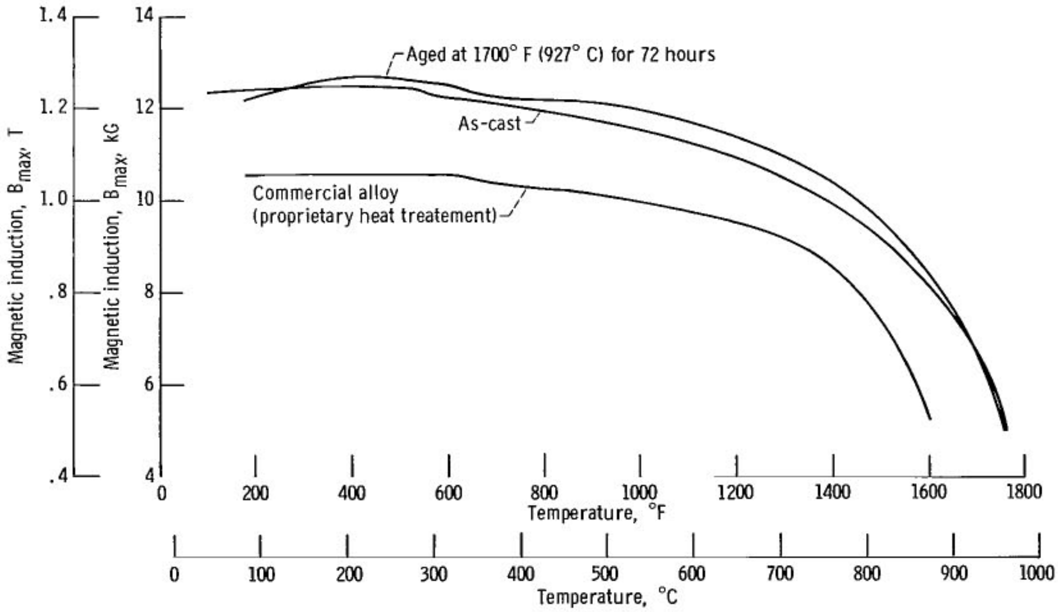


Figure 9. - Comparison of effect of temperature during first heating on magnetic induction of alloy Co-$7\frac{1}{2}$W-$2\frac{1}{2}$Fe-1Ti-$\frac{1}{2}$Zr-$\frac{1}{2}$C and commercial alloy. Maximum magnetizing force, 100 oersteds (7958 A/m).

cobalt (ref. 9), iron additions were made to stabilize the face-centered-cubic structure in the alloy matrix. The effect of these additions on the magnetic induction of a 7.5-weight percent tungsten alloy are shown in figure 7. Both the 2.5- and the 5.0-weight-percent-iron alloy had improved magnetic induction at low and intermediate temperatures. Only a slight decrease in Curie temperature was noted as a result of adding 5-weight percent iron. The 2.5-weight-percent-iron alloy was selected for further study because it had greater magnetic induction and greater magnetic stability than the alloy without iron. Moreover, limited screening tests indicated that this amount of iron would not seriously degrade mechanical properties. As discussed in the section Mechanical Test Results, this alloy was aged at 1700° F (927° C) for 72 hours to improve stress-rupture properties. Figure 8 shows that the aged alloy was slightly less stable magnetically in cyclic heating than the as-cast material, as indicated by the more pronounced inflections in the magnetization curves of the aged alloy. These inflections suggest that a greater degree of transformation from the face-centered cubic to the hexagonal close-packed phase occurred in the aged alloy. Also evident from figure 8 is the very little difference in the level of magnetization curves obtained during the first and the eleventh heating cycles.

To establish a frame of reference, the magnetic and mechanical properties of the Co - W alloy were compared with those of Nivco, a cobalt-base precipitation-hardening alloy. This alloy is one of the strongest high-temperature magnetic alloys commercially available (ref. 2) and has been widely considered for application to generator components of space power systems.

Figure 9 shows magnetization curves for the aged and unaged $7\frac{1}{2}$W - $2\frac{1}{2}$Fe alloy as well as for the commercial magnetic alloy in a proprietary solution-treated and aged condition. At all temperatures, the magnetic induction of the commercial alloy is approximately 2 kilogauss (0.2 T) less than that of the $7\frac{1}{2}$W - $2\frac{1}{2}$Fe alloy. For example, at 1300° F (704° C), the magnetic induction of the $7\frac{1}{2}$W - $2\frac{1}{2}$Fe alloy was 11 kilogauss (1.1 T) in the heat-treated condition, while that of the commercial alloy was 9.2 kilogauss (0.92 T). The effect of prolonged exposure at an elevated temperature on magnetic properties was also determined. Figure 10 shows the effect of 1000 hours exposure at 1300° F (704° C) on the curves of B_{max} against temperature. The maximum temperature during the heating cycle was 1300° F (704° C). The relative positions of the magnetization curves for the two alloys are now reversed, with the commercial alloy having about 1.5 kilogauss (0.15 T) greater induction than the $7\frac{1}{2}$W - $2\frac{1}{2}$Fe alloy over the entire range of temperatures. The rather large decrease in magnetic induction in the $7\frac{1}{2}$W - $2\frac{1}{2}$Fe alloy is believed to be associated with the formation of an additional precipitate.

Coercive force. - To reduce hysteresis losses in the pole faces of a generator rotor and to allow the use of a moderate exciting field, it is important to minimize the coercive

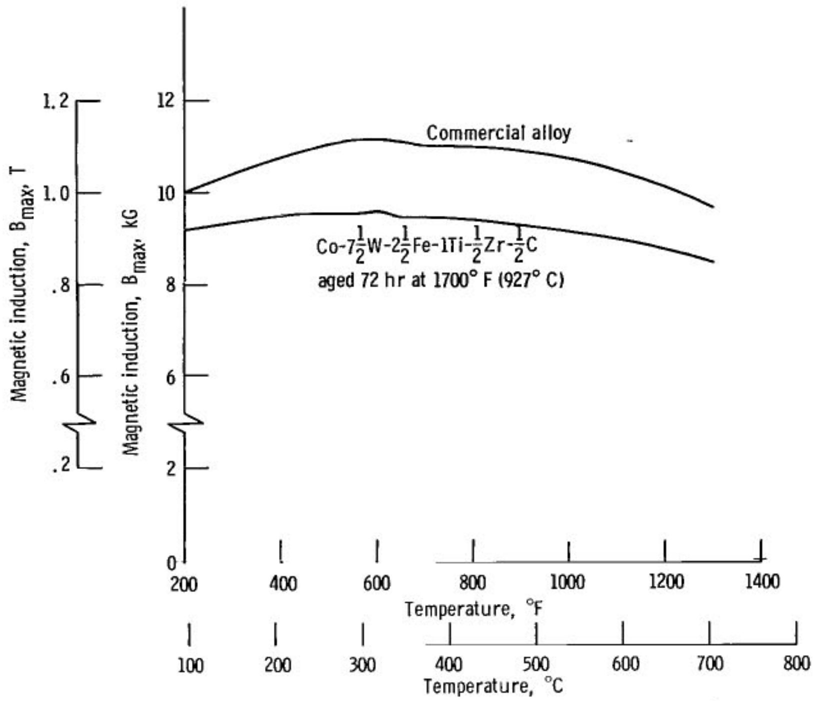


Figure 10. - Comparison of magnetic induction of alloy Co-7$\frac{1}{2}$W-2$\frac{1}{2}$Fe-1Ti-$\frac{1}{2}$Zr-$\frac{1}{2}$C and commercial alloy after 1000 hours exposure at 1300° F (704° C). Maximum magnetizing force, 100 oersteds (7958 A/m).

force. A target room-temperature coercive force of less than 25 oersteds (1980 A/m) has been set (ref. 10) to assure that candidate rotor materials were sufficiently soft magnetically. For a given microstructure, a larger coercive force would be found at room temperature than at a higher testing temperature. In the as-cast condition, the 7$\frac{1}{2}$W - 2$\frac{1}{2}$Fe alloy had a coercive force of 7.3 oersteds (582 A/m) at room temperature; in the aged condition (1700° F or 927° C for 72 hours), it was 10.5 oersteds (835 A/m). By comparison, the coercive force of the commercial alloy is 11.46 oersteds (915 A/m) at room temperature (ref. 2).

Mechanical Test Results

The Co - 7$\frac{1}{2}$W - 2$\frac{1}{2}$Fe - 1Ti - $\frac{1}{2}$Zr - $\frac{1}{2}$C alloy was selected for extensive mechanical property determinations.

Tensile properties. - All tensile data are shown in table III. The effect of test temperature on the tensile properties of this alloy in both the as-cast and heat-treated conditions is shown in figure 11. There is no significant difference in tensile strength between the as-cast and heat-treated material. For comparison, the tensile properties of the commercial alloy are also shown (ref. 2). The tensile strength of the commercial

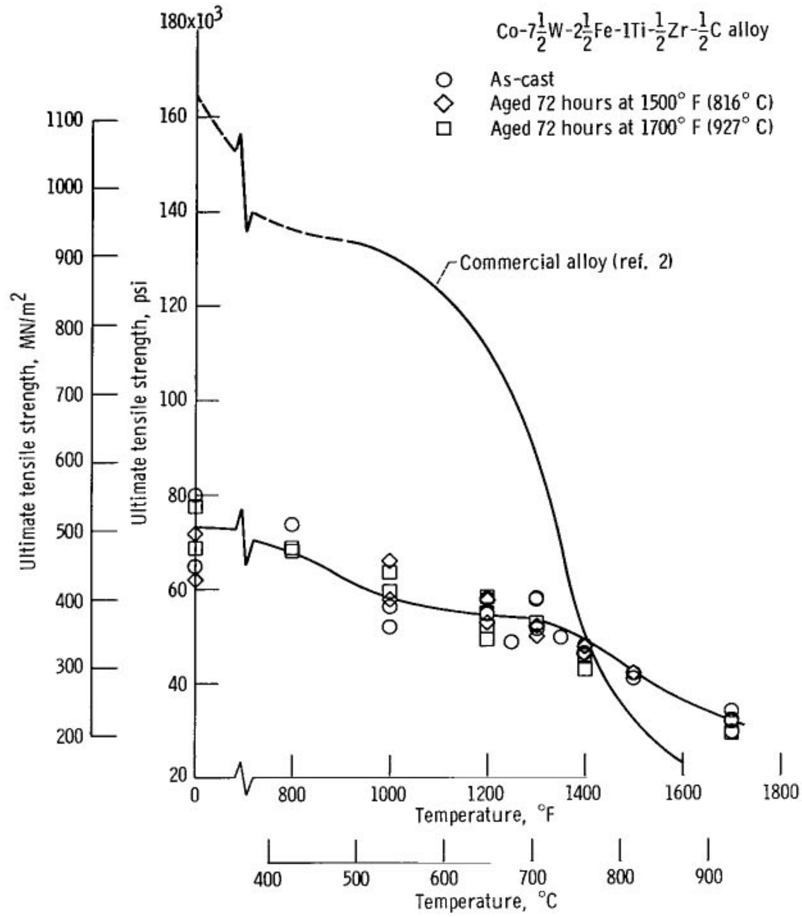


Figure 11. - Effect of temperature on ultimate tensile strength of alloy Co-7$\frac{1}{2}$W-2$\frac{1}{2}$Fe-1Ti-$\frac{1}{2}$Zr-$\frac{1}{2}$C and of commercial magnetic alloy.

alloy is much greater than that of the Co - W alloy up to 1400° F (760° C). At room temperature and 1300° F (704° C), the ultimate tensile strength values for the commercial alloy are 165 000 and 88 000 psi (1140 and 606 MN/m^2), respectively. For the Co - W alloy, the average values at these temperatures are 73 000 and 54 000 psi (505 and 373 MN/m^2), respectively. However, the curves cross at 1400° F (760° C) and above this temperature, the Co - W alloy has the greater tensile strength. An increase in room-temperature tensile strength (table III) of the Co - W alloy from the average value of 73 000 to 104 000 psi (505 to 717 MN/m^2) after exposure for 1000 hours at 1300° F (704° C) is evidence of aging in this alloy system.

The percentage elongation of the Co - W alloy is plotted against test temperature in figure 12. The heat treatment at 1700° F (927° C) generally increased elongation over the as-cast values and provided the highest tensile elongations. Average elongations ranged from 2.4 percent at room temperature to 29 percent at 1700° F (927° C) for the material heat treated at 1700° F (927° C). There was no substantial difference

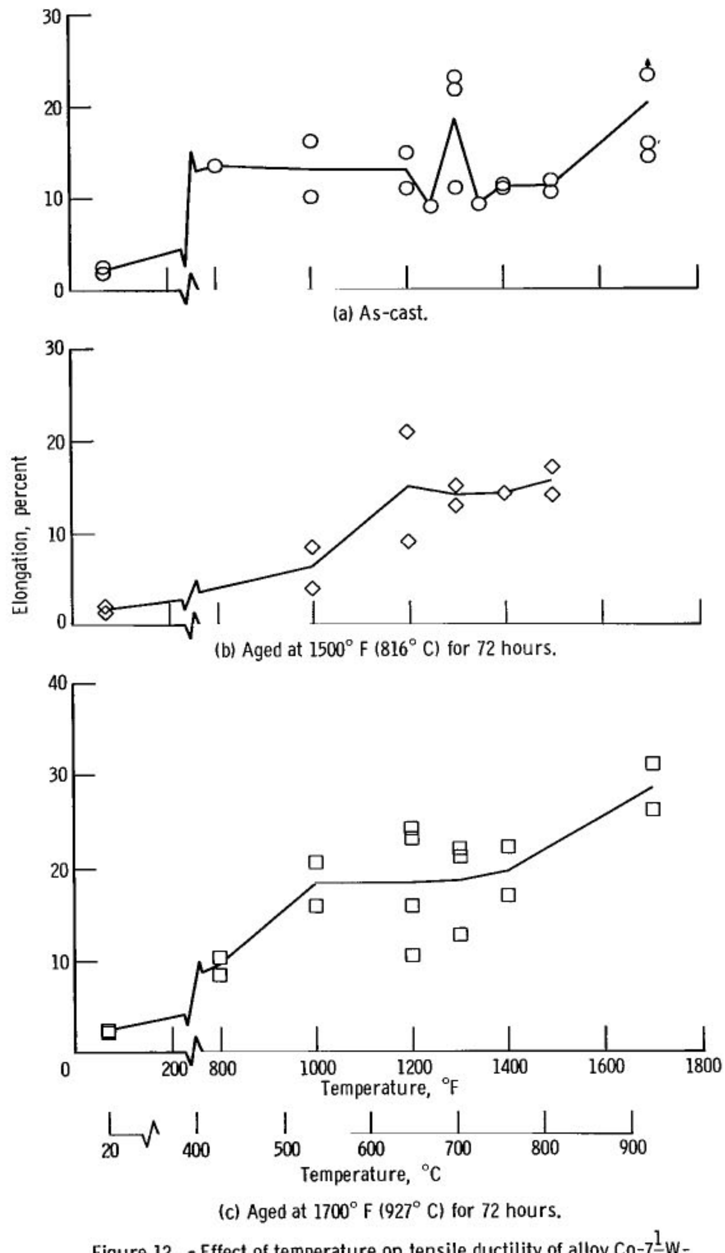


Figure 12. - Effect of temperature on tensile ductility of alloy Co-$7\frac{1}{2}$W-$2\frac{1}{2}$Fe-1Ti-$\frac{1}{2}$Zr-$\frac{1}{2}$C.

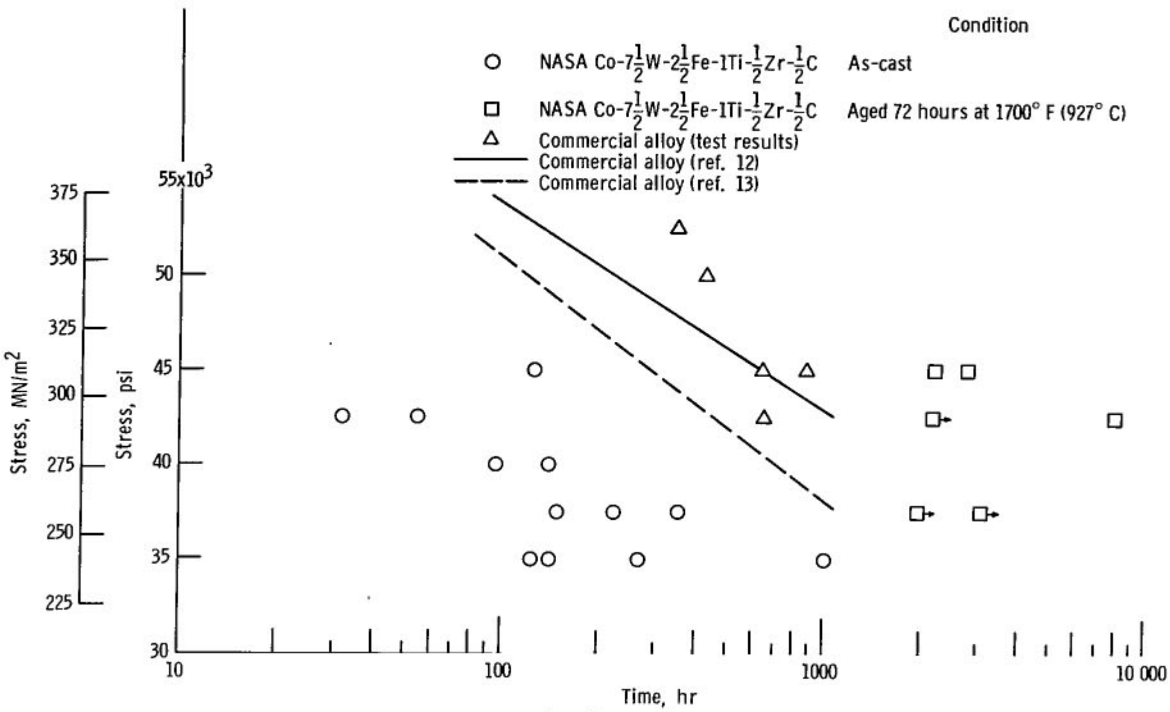


Figure 13. - Stress-rupture data for Co-$7\frac{1}{2}$W-$2\frac{1}{2}$Fe-1Ti-$\frac{1}{2}$Zr-$\frac{1}{2}$C alloy and commerical alloy at 1200° F (649° C).

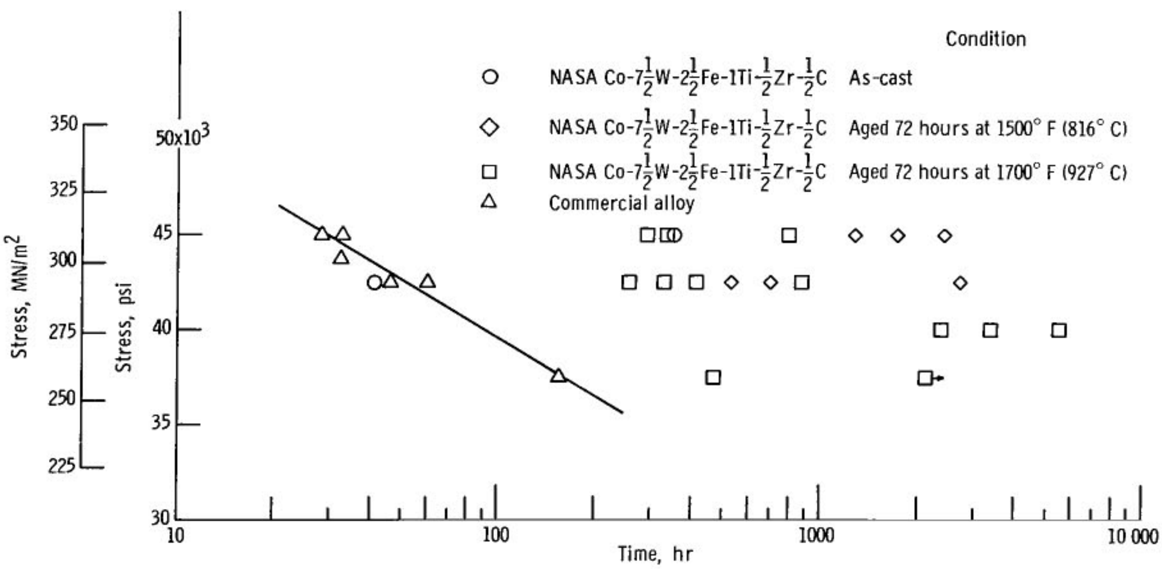


Figure 14. - Stress-rupture data for alloy Co-$7\frac{1}{2}$W-$2\frac{1}{2}$Fe-1Ti-$\frac{1}{2}$Zr-$\frac{1}{2}$C and commercial alloy at 1300° F (704° C).

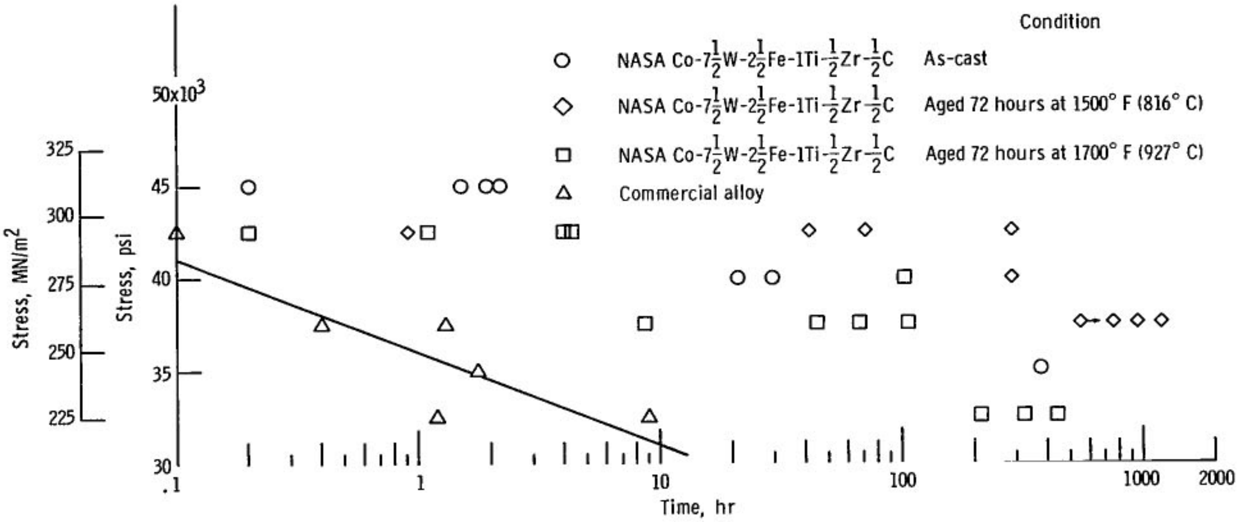


Figure 15. - Stress-rupture data for alloy Co-$7\frac{1}{2}$W-$2\frac{1}{2}$Fe-1Ti-$\frac{1}{2}$Zr-$\frac{1}{2}$C and commercial alloy at 1400° F (760° C).

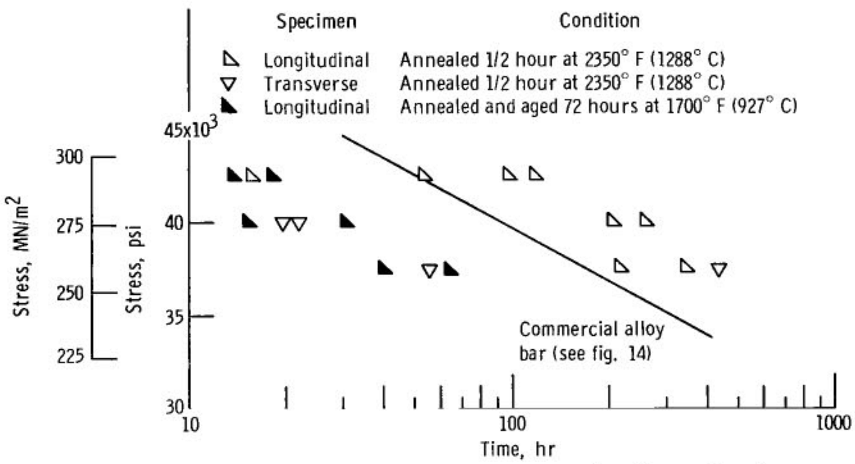


Figure 16. - Stress-rupture data for alloy Co-$7\frac{1}{2}$W-$2\frac{1}{2}$Fe-1Ti-$\frac{1}{2}$Zr-$\frac{1}{2}$C sheet at 1300° F (704° C).

between the elongations observed for the material heat treated at 1500° F (816° C) and for the as-cast alloy.

Stress-rupture and creep properties. - All stress-rupture data are summarized in table IV. The stress-rupture properties at 1200°, 1300°, and 1400° F (649°, 704°, and 760° C) of the $7\frac{1}{2}$W - $2\frac{1}{2}$Fe alloy in the as-cast and heat-treated conditions compared with those of the commercial alloy are shown in figures 13 to 15. Although the effect of heat treatment on the tensile properties of the Co - W alloy was small, it had a pronounced effect on rupture life. An increase of about 1 to 2 orders of magnitude over as-cast life values was obtained at 1200° F (649° C). At 1300° and 1400° F (704° and 760° C), where only limited as-cast data were obtained, rupture life was generally greater in the heat-treated condition, although the degree of increase was not as marked as that at 1200° F (649° C). At all three test temperatures, the rupture lives of the aged Co - W alloy were an order of magnitude or more greater than those of the commercial alloy. Although the heat treatment at 1500° F (816° C) generally resulted in longer lives than that at 1700° F (927° C), the higher temperature treatment would be preferred because of the greater tensile ductility obtained (fig. 12). In the as-cast condition, the Co - W alloy showed lower stress-rupture lives than the commercial alloy at 1200° F (649° C). Limited data at 1300° F (704° C) showed that rupture lives of the two alloys were about equal. However, at 1400° F (760° C), the as-cast Co - W alloy had substantially greater life, which may be attributed to aging effects in these alloys during testing. In the Co - W alloy, aging is distinctly beneficial at the higher test temperatures, whereas overaging, which tends to reduce the high-temperature life of an alloy, may occur in the commercial alloy at these same temperatures.

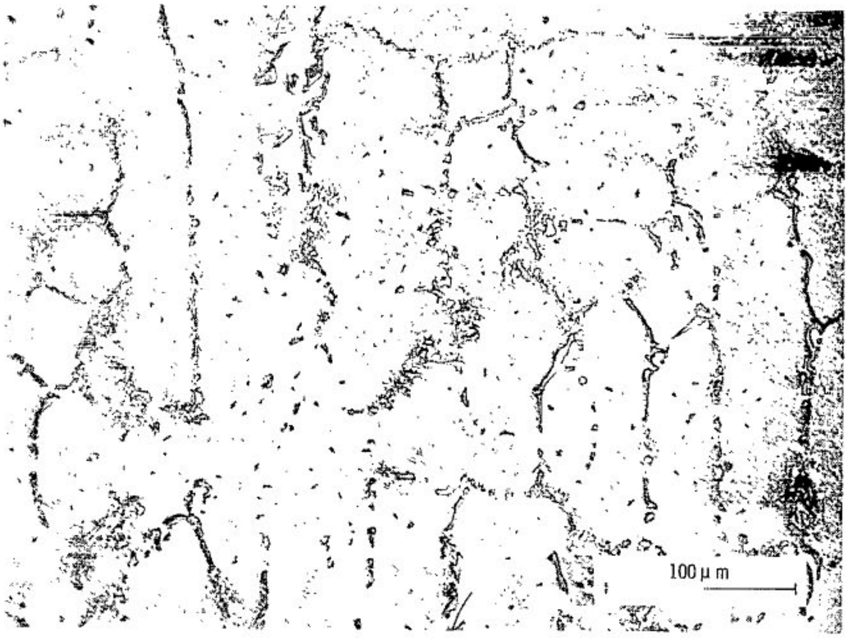
To reduce eddy current losses in certain types of alternating current motors, a laminated construction is used in the rotor. If the Co - W alloy were to be considered for this type of application as well, it would require good stress-rupture properties in sheet form. A limited number of 1300° F (704° C) rupture tests were made with sheet specimens of the Co - W alloy. The sheet was tested in the annealed (2350° F or 1288° C) condition and after annealing and aging at 1700° F (927° C). Figure 16 presents a comparison of the rupture properties at 1300° F (704° C) of the Co - W alloy sheet and the commercial magnetic alloy bar.

Annealed specimens of the Co - W alloy machined parallel to the rolling direction had greater lives than those of the commercial alloy. The annealed and aged sheet, on the other hand, had lower rupture lives than those of the commercial alloy. As might be expected, specimens machined transverse to the rolling direction had considerably lower lives than those of the longitudinal specimens.

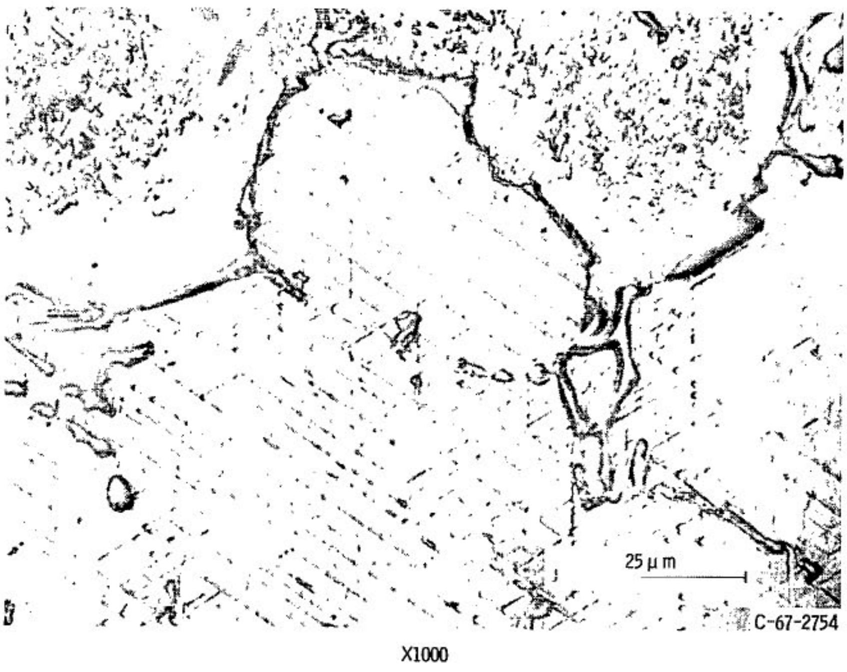
Measurements of crosshead travel were recorded during stress-rupture testing. Since the origin of the creep curves was not established, only the slopes of the curves were significant. A comparison of minimum creep rates for the cast and aged Co - W alloy and the commercial alloy obtained at several test conditions is shown in table V. At both 1200° and 1300° F (649° and 704° C), the Co - W alloy has a minimum creep rate of less than one-tenth that of the commercial alloy.

Metallography

The microstructure of the Co - $7\frac{1}{2}$W - $2\frac{1}{2}$Fe - 1Ti - $\frac{1}{2}$Zr - $\frac{1}{2}$C alloy in the as-cast condition is shown in figure 17. A significant feature of the structure is the massive carbides (probably monocarbide (MC) type) at grain boundaries and in the interdendritic regions. The matrix consists of face-centered cubic, β cobalt, some of which has



X250



X1000

Figure 17. - Microstructure of Co - $7\frac{1}{2}$W - $2\frac{1}{2}$Fe - 1Ti - $\frac{1}{2}$Zr - $\frac{1}{2}$C alloy in as-cast condition.

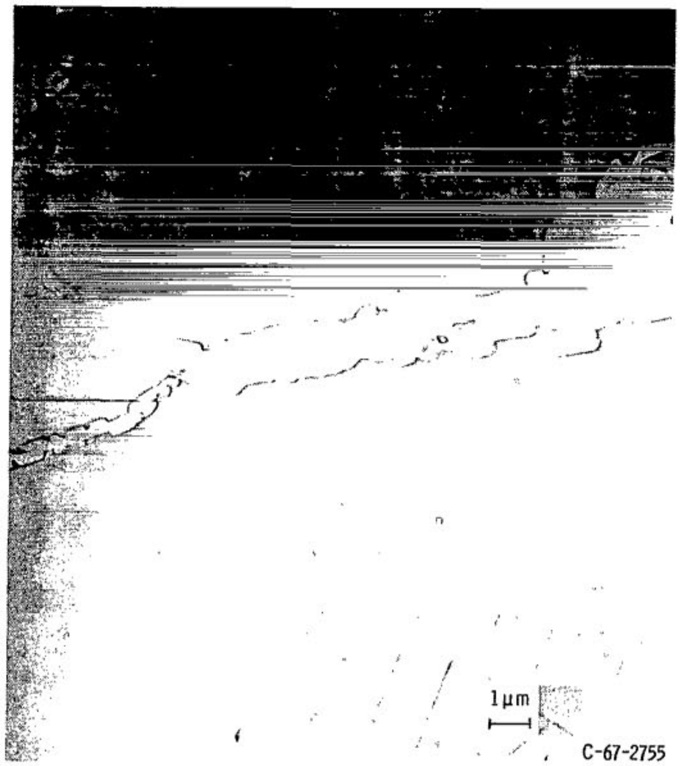
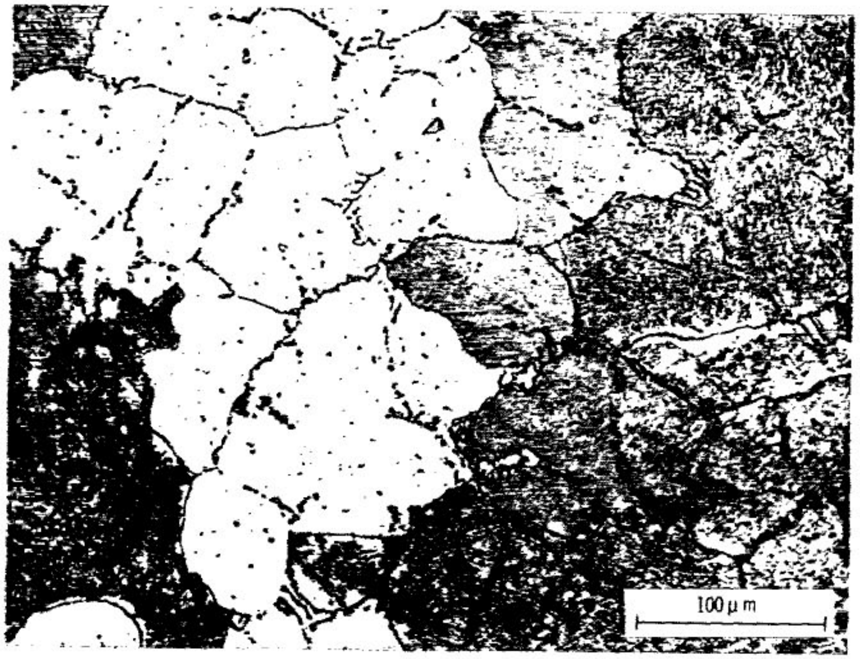


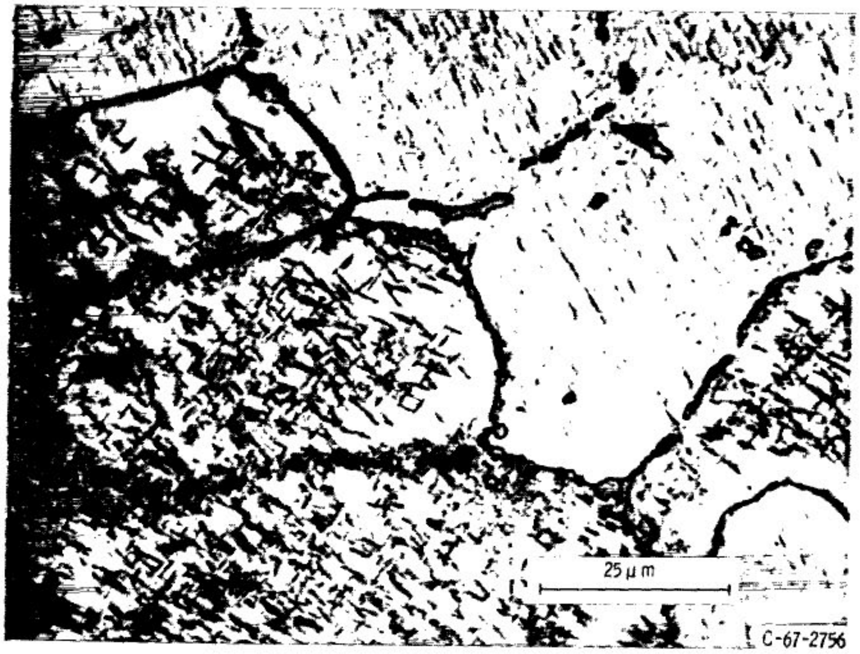
Figure 18. - Electron micrograph of alloy Co-$7\frac{1}{2}$W-$2\frac{1}{2}$Fe-1Ti-$\frac{1}{2}$Zr-$\frac{1}{2}$C in as-cast condition. X10 500.

apparently transformed to hexagonal-close-packed α cobalt on cooling.

The platelets that form the Widmanstätten pattern in figure 17 (×1000) are believed to be the α phase. There is also a fine precipitate in the central portion of some grains. The electron micrograph (fig. 18) shows that a zone adjacent to the massive carbides is denuded of the fine precipitate and that the fine precipitate also forms a Widmanstätten pattern. The effect of aging the alloy 72 hours at temperatures of 1300°, 1500°, and 1700° F (704°, 816°, and 927° C) is shown in figure 19. The most striking feature in this series of photomicrographs is the increase in the quantity of α cobalt at the higher aging temperature. The α regions have changed from platelets, evident in the as-cast condition and after aging at 1300° F (704° C), to broad bands that resemble twins after aging at 1700° F (927° C). An examination of electron micrographs of the alloy after exposure at 1700° F (927° C) for 72 hours revealed that, in addition to the bands of α cobalt, a fine precipitate had formed in the matrix. Figure 20 is an electron micrograph of a replica prepared from a sample aged at 1700° F (927° C) for 72 hours, and figure 21 is an electron micrograph of an extraction replica from the same sample. The latter figure clearly shows the precipitate to be platelike. No change in the carbide network due to aging could be observed with the light microscope. Figure 22 shows the



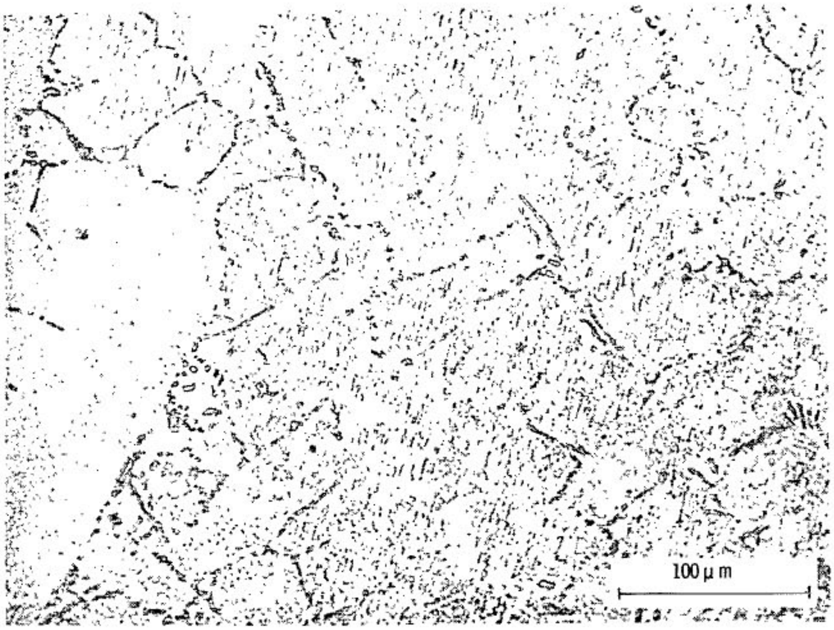
X250



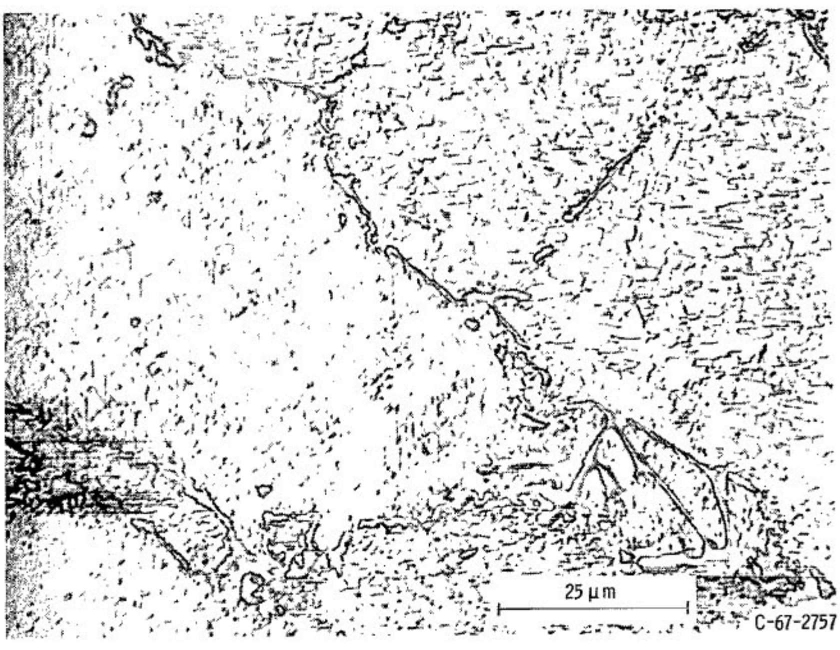
X1000

(a) Aging condition, 72 hours at 1300° F (704° C).

Figure 19. - Microstructure of alloy Co - $7\frac{1}{2}$W - $2\frac{1}{2}$Fe - 1Ti - $\frac{1}{2}$Zr - $\frac{1}{2}$C after aging at several different temperatures.



X250



X1000

(b) Aging condition, 72 hours at 1500° F (816° C).

Figure 19. - Continued.

X250

X1000

(c) Aging condition, 72 hours at 1700° F (927° C).

Figure 19. - Concluded.

Figure 20. - Electron micrograph of cast alloy Co - $7\frac{1}{2}$W - $2\frac{1}{2}$ Fe - 1Ti - $\frac{1}{2}$Zr - $\frac{1}{2}$C aged 72 hours at 1700° F (927° C). X27 000.

Figure 21. - Electron micrograph of extraction replica of cast alloy Co - $7\frac{1}{2}$W - $2\frac{1}{2}$ Fe - 1Ti - $\frac{1}{2}$Zr - $\frac{1}{2}$C aged 72 hours at 1700° F (927° C). X27 000.

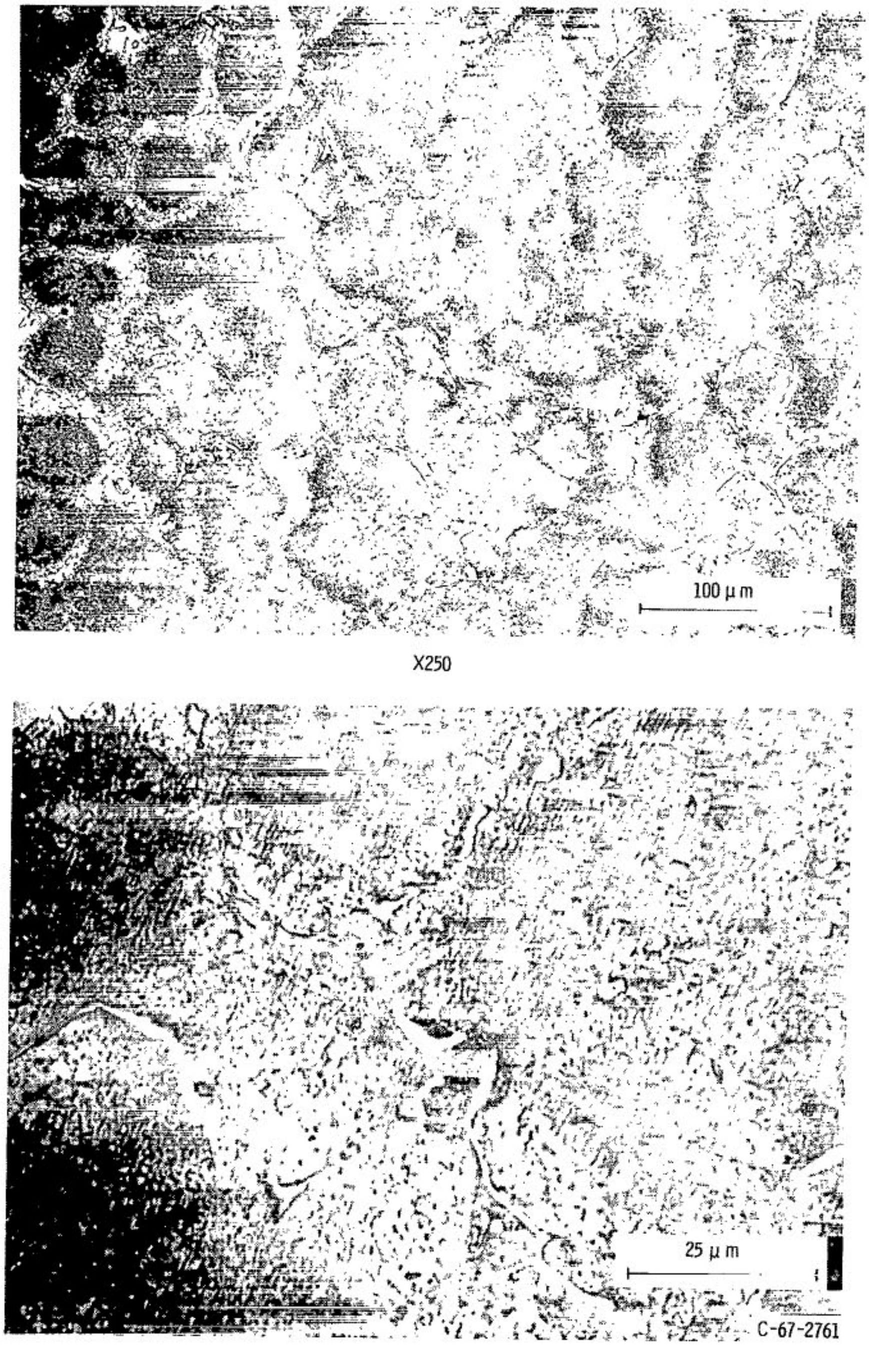


Figure 22. - Microstructure of alloy Co - $7\frac{1}{2}$W - $2\frac{1}{2}$Fe - 1Ti - $\frac{1}{2}$Zr - $\frac{1}{2}$C after aging 72 hours at 1700° F (927° C) and subsequent exposure for 1000 hours at 1300° F (704° C).

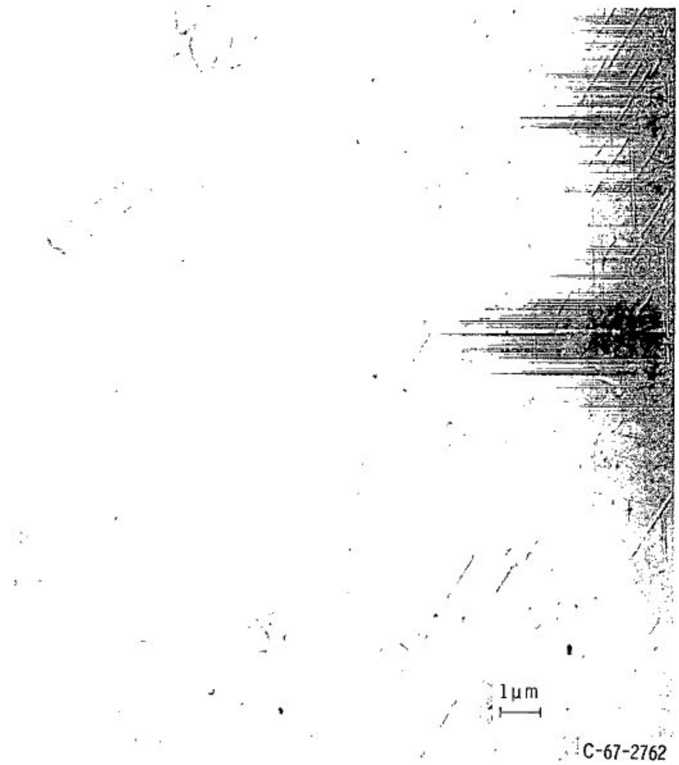


Figure 23. - Electron micrograph of cast alloy Co - $7\frac{1}{2}$ W - $2\frac{1}{2}$ Fe - 1Ti-$\frac{1}{2}$ Zr - $\frac{1}{2}$ C aged 72 hours at 1700° F (927° C) and exposed for 1000 hours at 1300° F (704° C). X10 500.

structure of the alloy after aging for 72 hours at 1700° F (927° C) and then soaking for 1000 hours at 1300° F (704° C). Segregation effects are apparent in the region near the carbide network. The morphology of the α cobalt has reverted from the broad bands observed after the alloy was aged at 1700° F (927° C) to a fine structure similar to that observed after the 1300° F (704° C) aging treatment alone; however, the α phase after the subsequent exposure for 1000 hours at 1300° F (704° C) appears to be finer and more uniformly distributed in the matrix. Figure 23 is an electron micrograph of the alloy after aging and soaking. The fine precipitate observed after the 1700° F (927° C) aging persists, and a Widmanstätten precipitate is also present. The results of X-ray diffraction patterns are summarized in table VII. The patterns obtained from wires from an annealed sheet indicate the presence of titanium carbo-nitride (Ti(CN)), zirconium carbo-nitride (Zr(CN)), and β cobalt. In addition to these phases, the sheet sample aged at 1700° F (927° C) showed the presence of α cobalt. The residues from as-cast material contained primarily Zr(CN), up to three resolvable Ti(CN) phases with slightly different lattice parameters, and possibly traces of a complex-carbide phase (M_6C). The residue from material aged for 72 hours at 1500° F (816° C) contained Ti(CN) and Zr(CN). Indications of traces of an M_6C phase were also observed in a few patterns. Patterns of the residue extracted after the material was aged at 1700° F (927° C) for 72 hours showed Ti(CN) and two Zr(CN) phases of slightly different lattice parameters as well as a trace of a phase believed to be M_6C. Residues obtained from the sample aged first at 1700° F (927° C) for 72 hours and then soaked at 1300° F (704° C) for 1000 hours contained two Ti(CN) phases of slightly different lattice parameters, Zr(CN), and a trace of M_6C.

An electron microprobe analysis was conducted on the as-cast alloy and on the alloy after it was aged for 72 hours at 1500° F (816° C). The chemistry of the matrix and the monocarbide particles is shown in table VIII. Cobalt concentrations in the matrix changed from approximately 86 percent in the as-cast condition to 93 percent after aging. The tungsten content was lowered from about $6\frac{1}{2}$ percent to 6 percent by the aging treatment. Although not shown, it was further observed that the degree of tungsten depletion near the carbide was reduced by the 1500° F (816° C) aging treatment.

The metallographic, microprobe, and X-ray diffraction analyses of the alloy system suggest the following aging reaction:

$$M(CN) \rightarrow Ti(CN) + Zr(CN) + (M_6C)$$

where M in the M(CN) = Ti, W, Co, Zr. It appears that the MC carbides are unstable between 1300° and 1700° F (704° and 927° C). The limited electron probe analysis of these phases indicated that the M in MC may contain approximately 50 atomic percent Co and 17 atomic percent W, the balance being Ti and Zr. It is possible that these carbides decompose to form more stoichiometric monocarbides plus M_6C while they liberate cobalt to the matrix. Cobalt liberated to the matrix could allow the formation of greater amounts of α cobalt when the alloy is cooled to room temperature. This structural change was reflected in the inflections (humps) in the curve of magnetic induction against temperature for the aged material.

The improvement in stress-rupture properties observed in the heat-treated material is believed to be related to the disassociation of the monocarbide and the subsequent precipitation of fine particles in the matrix. It appears that the strengthening reactions are capable of continuing during use at 1300° F (704° C).

CONCLUDING REMARKS

The Co - W system has a combination of high-temperature magnetic and mechanical properties needed for generator rotors. In the temperature range from 1200° to 1400° F (649° to 760° C), the alloy Co - $7\frac{1}{2}$W - $2\frac{1}{2}$Fe - 1Ti - $\frac{1}{2}$Zr - $\frac{1}{2}$C has stress-rupture properties and magnetic induction that compare well with Nivco, which is currently being considered for space power generators and is one of the strongest high-temperature magnetic alloys commercially available. After an aging heat treatment of 72 hours at 1700° F (927° C), the Co - W alloy has higher magnetic induction than the commercial alloy over the entire temperature range up to the Curie temperature. However, exposure at 1300° F (704° C) for 1000 hours lowered the induction of the heat-treated Co - W alloy while slightly increasing the induction of the commercial alloy. As a result, the commercial alloy had an induction of about 1.5 kilogauss (0.15 T) greater than that of the Co - W alloy in the range tested, 200° to 1300° F (93° to 704° C). The rupture strength of the Co - W alloy is substantially greater than that of the commercial alloy at the higher temperatures from 1200° to 1400° F (649° to 760° C). Although the Co - W alloy was developed with cast specimens, the alloy can be rolled and has demonstrated reasonably good properties as sheet. In the solution-treated condition, sheet specimens exhibited rupture lives at 1300° F (704° C) comparable to those of the commercial alloy in bar form. No attempt was made to optimize heat treatment for the Co - W alloy sheet.

The data obtained in the present investigation of the Co - W alloy suggest that further changes in chemistry could be made to increase ductility and stability. Additions of iron greater than $2\frac{1}{2}$ percent, or possibly nickel additions, might reduce the instability of the face-centered cubic structure that becomes more evident after the heat treatment at 1700° F (927° C). Reductions in carbon content might improve the ductility of the cast alloy by decreasing the continuity of the interdendritic carbide network. Finally, other heat treatments might be devised to improve properties further. Such improvement would be expected particularly for the sheet material.

Finally, it should be noted that other work is being done to develop improved magnetic materials for use in the 800° to 1600° F (427° to 871° C) range under NASA contract (NAS3-6465). Modifications in composition and heat treatment of Nivco have been made to improve creep resistance. Dispersion-strengthened alloys are being investigated. Precipitation-hardening alloys with improved high-temperature creep and magnetic properties have been developed also. One of these alloys, (1-B-S-1), with a composition of Co - 15Ni - 5Fe - 1.3Al - 5Ta - 0.2Zr is expected to have use temperatures as high as 1382° F (750° C). The lack of published stress-rupture data for these materials prevents detailed comparison with the Co - W alloy of this investigation.

SUMMARY OF RESULTS

The following results were obtained from a program to develop improved high-temperature, high-strength magnetic cobalt-base alloys for generator rotor applications.

1. For the alloy base of Co - 1Ti - $\frac{1}{2}$Zr - $\frac{1}{2}$C, the Curie temperature decreased as

tungsten was added. The maximum induction B_{max} for a maximum magnetizing force H_{max} of 100 oersteds (7958 A/m) at temperatures above 1000° F (537° C) also decreased. Below about 1000° F (537° C), low-tungsten-content alloys (5 and $7\frac{1}{2}$ percent) exhibited inflections in the curve of maximum induction against temperature and marked decreases in magnetic induction. We attributed this result to the instability of the face-centered cubic phase.

2. Additions of iron up to 5 percent to an alloy containing $7\frac{1}{2}$ percent tungsten increased the stability of the face-centered cubic structure.

3. The composition Co - $7\frac{1}{2}$W - $2\frac{1}{2}$Fe - 1Ti - $\frac{1}{2}$Zr - $\frac{1}{2}$C was chosen as a preferred composition that represented a compromise between magnetic and mechanical properties.

4. The maximum induction for a maximum magnetizing force of 100 oersteds (7958 A/m) of this alloy aged at 1700° F (927° C) for 72 hours was approximately 2 kilogauss (0.2 T) higher at all temperatures than that of one of the strongest commercially available high-temperature magnetic alloys. However, exposure for 1000 hours at a possible use temperature of 1300° F (704° C) reduced the maximum induction of the aged preferred alloy below that of the commercial alloy when it was similarly exposed. After this exposure, the maximum induction (field strength of 100 Oe or 7958 A/m) of the aged preferred alloy was 8.4 kilogauss (0.84 T) and that of the commercial alloy was 9.6 kilogauss (0.96 T) at 1300° F (704° C).

5. At projected use temperatures of 1200°, 1300°, and 1400° F (649°, 704°, and 760° C) and at a stress level of 42 500 pounds per square inch (293 MN/m^2), the preferred cobalt-tungsten alloy had rupture lives up to 8000, 850, and 4 hours, respectively in the aged condition (1700° F or 927° C). These rupture lives compare with approximately 1200, 50, and less than 1 hour for the commercial alloy.

6. The preferred alloy was rollable into sheet. The stress-rupture life of annealed sheet of the preferred alloy was substantially reduced from that of the as-cast and aged material. At 1300° F (704° C) and 42 500 pounds per square inch (293 MN/m^2), the stress-rupture life of the annealed sheet was about the same as that of the commercial alloy bar.

7. X-ray diffraction and microprobe analyses revealed the presençe of monocarbides (MC) and possibly complex carbides (M_6C) in the preferred alloy. The alloy matrix was a solid solution cobalt that was primarily face-centered cubic. Varying amounts of hexagonal close-packed cobalt were present at room temperature, depending on the heat treatment used.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 3, 1967,
129-03-01-04-22.

REFERENCES

1. Lieblein, Seymour: Heat-Transfer Aspects of Space Radiators. Paper presented at the Sixth National Heat Transfer Conference, AIChE and ASME, Boston, Aug. 11-14, 1963.
2. Kueser, P. E., et al.: Magnetic Materials Topical Report: Research and Development Program on Magnetic, Electrical Conductor, Electrical Insulation, and Bore Seal Materials. Rep. No. WAED-64-52E (NASA CR-54091), Westinghouse Electric Corp., Sept. 1964.
3. Harris, R. F.; and Chandley, G. D.: Application of Fundamental Research to Production of Superior Steel Castings. Trans. Am. Foundryman's Soc., vol. 70, 1962, pp. 1287-1294.
4. Freche, John C.; Ashbrook, Richard L.; and Klima, Stanley J.: Cobalt-Base Alloys for Space-Power Systems. J. Metals, vol. 15, no. 12, Dec. 1963, pp. 928-934.
5. Freche, J. C.; Ashbrook, R. L.; and Sandrock, G. D.: High-Temperature, Cobalt-Tungsten Alloys for Aerospace Applications. J. Eng. Ind., Trans. ASME, vol. 87, no. 1, Feb. 1965, pp. 9-20.
6. Anon.: Standard Methods of Test for Normal Induction and Hysteresis of Magnetic Materials. ASTM Designation: A341-64, ASTM Standards, Part 8, 1964.
7. Hoffman, Anthony C.: Instrument System for Determining Temperature Effects on Maximum Induction of Magnetic Materials. NASA TN D-3568, 1966.
8. Bozorth, Richard M.: Ferromagnetism. D. Van Nostrand Co., Inc., 1951.
9. Hansen, Max; and Anderko, Kurt: Constitution of Binary Alloys. Second ed., McGraw-Hill Book Co., Inc., 1958.
10. Kueser, P. E., et al.: Development and Evaluation of Magnetic and Electrical Materials Capable of Operating in the 800° to 1600° F Temperature Range. Rep. No. WAED 66.39 (NASA CR-54359), Westinghouse Electric Corp., June 1966.
11. Kueser, P. E., et al.: Research and Development Program on Magnetic, Electrical Conductor, Electrical Insulation, and Bore Seal Materials. Rep. No. WAED 64.30E (NASA CR-54089), Westinghouse Electric Corp., June 1964.
12. Anon.: High Temperature Alloy Data Sheet. Cobalt Information Center, 1962.
13. Anon.: Alloy Digest, NIVCO 10 Filing Code-37, Cobalt Alloy, June 1964.

14. Parrish, W.; Ekstein, M. G.; and Irwin, B. W.: Data for X-ray Diffraction. Vol. II, North American Phillips Co., Inc., 1953. (Tables for Computing the Lattice Constant of Cubic Crystals. Vol. 2 of Data for X-ray Analysis. N. V. Phillips' Gloeilampenfabrieken (Eindhoven), 1953.)

TABLE I. - FORM AND PURITY OF ALLOYING ELEMENTS

Element	Form	Minimum purity,[a] wt. %
Cobalt	Electrolytic	99.5^+
Tungsten	Powder	99.9^+
Titanium	Sponge	99.3^+
Zirconium	Sponge	99.9^+
Iron	Electrolytic	99.8^+
Carbon	Granular graphite	98^+

[a]As reported by suppliers.

TABLE II. - CHEMICAL ANALYSIS OF REPRESENTATIVE HEATS OF COBALT - $7\frac{1}{2}$ TUNGSTEN - $2\frac{1}{2}$ IRON - 1 TITANIUM - $\frac{1}{2}$ ZIRCONIUM - $\frac{1}{2}$ CARBON AND HEAT OF COMMERCIAL MAGNETIC ALLOY

[Concentrations given as weight percentages.]

Cobalt	Tungsten	Iron	Titanium	Zirconium	Carbon	Nickel	Sulfur	Phosphorus	Silicon	Manganese	Aluminum
Cobalt-tungsten alloy											
Balance	7.15	2.75	0.97	0.55	0.56	---	---	---	---	---	---
	7.11	2.70	.94	.55	.51	---	---	---	---	---	---
	7.02	2.70	.96	.56	.53	---	---	---	---	---	---
	7.03	2.57	.95	.57	.53	---	---	---	---	---	---
	7.08	2.73	.97	.57	.49	---	---	---	---	---	---
	7.08	2.74	.93	.55	.46	---	---	---	---	---	---
	7.05	2.70	.95	.57	.49	---	---	---	---	---	---
Commercial alloy NIVCO[a]											
Balance	----	<0.25	1.79	0.69	0.003	23.8	0.004	0.001	0.18	0.31	0.21

[a]Heat 8030.

TABLE III. - TENSILE DATA FOR COBALT - $7\frac{1}{2}$ TUNGSTEN - $2\frac{1}{2}$ IRON - 1 TITANIUM - $\frac{1}{2}$ ZIRCONIUM - $\frac{1}{2}$ CARBON ALLOY

Condition	Test temperature		Yield strength, 0.2 percent offset		Ultimate tensile strength		Elongation percent
	°F	°C	psi	MN/m²	psi	MN/m²	
Cast-to-size specimens							
As-cast	Room temperature	Room temperature	62.0×10^3	427	79.6×10^3	549	2.3
	Room temperature	Room temperature	48.2×10^3	332	64.9	447	1.9
	800	427	--------	---	73.1	504	13.5
	1000	538	--------	---	51.5	355	10.0
	1000	538	--------	---	55.9	386	16.0
	1200	649	--------	---	54.2	374	10.8
	1200	649	--------	---	57.5	396	14.6
	1250	677	--------	---	48.7	336	9.0
	1300	704	--------	---	57.0	393	23.1
	1300	704	--------	---	57.3	395	21.5
	1300	704	--------	---	51.0	352	11.0
	1350	732	--------	---	49.5	341	9.0
	1400	760	--------	---	47.3	326	10.8
	1400	760	--------	---	45.4	313	11.2
	1500	816	--------	---	41.9	289	10.4
	1500	816	--------	---	40.4	279	11.9
	1700	927	--------	---	33.6×10^3	232	15.5
			--------	---	31.4	217	15.8
			--------	---	31.7	219	14.2
			--------	---	29.3	202	31.0
Aged at 1300° F (704° C) for 89 hr	Room temperature	Room temperature	--------	---	93.4×10^3	644	<1
Aged at 1300° F (704° C) for 72 hr	1200	649	--------	---	68.2×10^3	470	<1
Aged at 1500° F (816° C) for 72 hr	Room temperature	Room temperature	49.5×10^3	341	62.2×10^3	429	1.1
	Room temperature	Room temperature	52.4×10^3	361	71.8	495	2.1
	1000	538	--------	---	66.4	458	8.5
	1000	538	--------	---	57.7	398	4.0
	1200	649	--------	---	53.3	367	9.0
	1200	649	--------	---	57.4	396	21.0

Aged at 1500° F (816° C) for 72 hr	1300	704	--------	---	51.1×10³	352	15.0
	1300	704	--------	---	50.0	345	13.0
	1400	760	--------	---	46.4	320	14.0
	1400	760	--------	---	47.1	325	14.0
	1500	816	--------	---	41.8	288	14.0
Aged at 1500° F (816° C) for 78 hr	1500	816	--------	---	46.0×10³	317	17.0
Aged at 1500° F (816° C) for 78 hr	1700	927	--------	---	35.0×10³	241	21.0
Aged at 1700° F (927° C) for 72 hr	Room temperature	Room temperature	40.8×10³	281	68.7×10³	474	2.4
	Room temperature	Room temperature	40.4×10³	279	78.2	539	2.4
	800	427	--------	---	67.9	468	10.2
	800	427	--------	---	67.5	465	8.5
	1000	538	--------	---	63.7	439	20.5
	1000	538	--------	---	59.3	409	15.8
	1200	649	--------	---	55.0×10³	379	15.7
					49.3	340	23.0
					51.4	354	10.4
					58.1	401	24.0
	1300	704	--------	---	51.5×10³	355	21.0
					51.7	356	12.5
					52.1	359	21.7
	1400	760	--------	---	46.0×10³	317	22.0
	1400	760	--------	---	42.3	292	16.8
	1700	927	--------	---	29.3	202	31.0
	1700	927	--------	---	29.5	203	26.4
Aged at 1700° F (927° C) for 72 hr plus exposed at 1300° F (704° C) for 1000 hr	Room temperature	Room temperature	--------	---	104.6×10³	721	<1
Sheet specimens							
Annealed at 2350° F (1288° C) for 1/2 hr	1300	704	--------	---	63.5×10³	438	[a]38.0
	1300	704	--------	---	64.1	442	[b]34.0

[a]Longitudinal.
[b]Transverse.

TABLE IV. - STRESS-RUPTURE DATA

(a) Cobalt - $7\frac{1}{2}$ tungsten - $2\frac{1}{2}$ iron - 1 titanium - $\frac{1}{2}$ zirconium - $\frac{1}{2}$ carbon alloy

Condition	Test temperature		Stress		Life, hr	Elongation, percent
	°F	°C	psi	MN/m²		
Cast-to-size specimens						
As-cast	1200	649	35.0×10^3	241	1007.9	----
					142.2	----
					267.7	----
					124.7	----
			37.5×10^3	259	151.8	----
					227.8	----
					356.7	----
					238.1	4
			40.0×10^3	276	95.7	----
			40.0	276	141.2	----
			42.5	293	55.2	----
			42.5	293	31.9	7.2
			45.0×10^3	310	125.8	----
					3.9	----
					.2	----
			50.0×10^3	345	(a)	----
Aged at 1700° F (927° C) for 72 hr	1200	649	37.5×10^3	259	[b]3103	[b]1
			37.5	259	[b]1984	----
			42.5	293	[b]2170	[b]2
			42.5	293	8062.4	7.0
			45.0	310	2207.6	5.5
			45.0	310	2803.7	10.0
As-cast	1300	704	42.5×10^3	293	40.5	----
			45.0	310	346.7	----
			47.5	327	15.8	----
Aged at 1500° F (816° C) for 72 hr	1300	704	42.5×10^3	293	691.4	11
					2687.7	9.5
					526.7	7
			45.0×10^3	310	1281.9	6
					1716.5	6
					2411.1	5.5

[a]Broke on loading.

[b]Discontinued before rupture.

TABLE IV. - Continued. STRESS RUPTURE DATA

(a) Continued. - Cobalt - $7\frac{1}{2}$ tungsten - $2\frac{1}{2}$ iron - 1 titanium - $\frac{1}{2}$ zirconium - $\frac{1}{2}$ carbon alloy

Condition	Test temperature		Stress		Life, hr	Elongation, percent
	°F	°C	psi	MN/m²		
Cast-to-size specimens						
Aged at 1700° F (927° C) for 72 hr	1300	704	37.5×10³	259	[b]2105	[b]3
			37.5×10³	259	472.6	8
			40.0×10³	276	2354.3	5
					3366.9	6.4
					5488.9	4
			42.5×10³	293	255.9	10
					415.9	5
					871.9	8
					328	5
			45.0×10³	310	334.6	9
					784.1	11
					289.6	8
As-cast	1400	760	35.0×10³	241	372.2	----
			40.0	276	29.2	----
			40.0	276	21.0	----
			45.0×10³	310	1.5	----
					1.9	----
					2.2	----
					.2	----
Aged at 1500° F (816° C) for 72 hr	1400	760	37.5×10³	259	942.3	5.0
					1225.9	8
					759.8	5.0
					[b]559.1	
			40.0×10³	276	291.2	7.0
			42.5×10³	293	71.5	10.0
					42.5	13
					290.2	6.0
					0.9	14

[b]Discontinued before rupture.

TABLE IV. - Continued. STRESS RUPTURE DATA

(a) Concluded. - Cobalt - $7\frac{1}{2}$ tungsten - $2\frac{1}{2}$ iron - 1 titanium - $\frac{1}{2}$ zirconium - $\frac{1}{2}$ carbon alloy

Condition	Test temperature, °F	Test temperature, °C	Stress, psi	Stress, MN/m^2	Life, hr	Elongation, percent
Cast-to-size specimens						
Aged at 1700° F (927° C) for 72 hr	1400	760	32.5×10^3	224	430.7	9
					311.5	12
					212.0	11
			37.5×10^3	259	8.6	13
					104.9	13
					67.9	14
					44.0	23
			40.0×10^3	276	101.1	9
			42.5×10^3	293	0.3	14
					4.0	16
					1.1	19
					4.4	10
Annealed, longitudinal	1300	704	80.0×10^3	552	<0.1	34.0
			42.5×10^3	293	15.3	5.0
					97.0	[c]1.5
					119.2	----
					53.6	5.0
			40.0×10^3	276	258.0	3.0
			40.0	276	208.3	3.0
			37.5	259	217.5	2.5+
			37.5	259	344.2	1.5
Annealed, transverse	1300	704	40.0×10^3	276	21.5	5.0
			40.0	276	19.4	6.5
			37.5	259	435.9	3.0
			37.5	259	55.7	2.5
Annealed and aged 72 hr at 1700° F (927° C), Longitudinal	1300	704	42.5×10^3	293	13.9	9.0
			42.5	293	17.8	10.5
			40.0	276	15.3	6.5
			40.0	276	30.7	7.5
			37.5	259	39.7	6.5
			37.5	259	63.1	5.5

[c]Broke outside gage length.

TABLE IV. - Concluded. STRESS-RUPTURE DATA

(b) Commercial magnetic alloy

Condition	Test temperature		Stress		Life, hr	Elongation, percent
	°F	°C	psi	MN/m^2		
Proprietary heat treatment	1200	649	42.5×10^3	293	654.4	31
			45.0	310	643.4	15.5
			45.0	310	892.3	33
			50.0	345	426.4	11
			55.0	379	345.1	21
	1300	704	37.5×10^3	259	154.0	19.0
			37.5	259	157.0	24
			42.5	293	60.1	17
			42.5	293	45.7	18
			43.8	302	32.0	23
			45.0	310	27.7	34
			45.0	310	32.3	13
	1400	760	32.5×10^3	224	1.2	38
			32.5	224	9.1	32
			35.0	241	1.7	33
			37.5	259	1.3	40
			37.5	259	.4	35
			42.5	293	.1	29

TABLE V. - TYPICAL MINIMUM CREEP RATES OF PREFERRED

COBALT-TUNGSTEN ALLOY AND COMMERCIAL ALLOY

Stress		$Co - 7\frac{1}{2} W - 2\frac{1}{2} Fe - 1 Ti - \frac{1}{2} Zr - \frac{1}{2} C$	Commercial alloy
psi	MN/m^2	Minimum creep rate, (in./in.)/hr (or (cm/cm)/hr)	
Temperature, 1200° F (649° C)			
42.5×10^3	293	0.00088×10^{-3}	0.0214×10^{-3}
45.0	310	.0053	.093
45.0	310	.0095	.093
Temperature, 1300° F (704° C)			
37.5×10^3	259	0.017×10^{-3}	0.33×10^{-3}
37.5	259	.067	.33
45.0	310	.033	1.17

TABLE VI. - EFFECT OF AGING ON HARDNESS OF CAST

COBALT - $7\frac{1}{2}$ TUNGSTEN - $2\frac{1}{2}$ IRON - 1 TITANIUM -

$\frac{1}{2}$ ZIRCONIUM - $\frac{1}{2}$ CARBON ALLOY

Condition			Rockwell A - hardness[a]
As-cast			64.3
Aged			
Temperature		Time, hr	
°F	°C		
1300	704	24	66.9
		72	66.6
1500	816	24	65.2
		72	66.1
1700	927	24	64.2
		72	64.5

[a]Average of six readings, three from each of two samples.

TABLE VII. - SUMMARY OF X-RAY DIFFRACTION FOR COBALT - $7\frac{1}{2}$ TUNGSTEN - $2\frac{1}{2}$ IRON - 1 TITANIUM - $\frac{1}{2}$ ZIRCONIUM - $\frac{1}{2}$ CARBON ALLOY

(a) Extractions (castings)

Condition			Residue size	Phases					
				Zr(CN)		Ti(CN)		Other	
				Lattice constant, a_0, [a]10^{-10} m	Relative amount[b]	Lattice constant, a_0, [a]10^{-10} m	Relative amount[b]	Type	Relative amount[b]
As cast			Coarse	4.58	M	4.34 to 4.40	A	-----	--
			Fine	4.59	A	4.33 to 4.38	A	[c]M_6C	--
Heat treated									
Temperature, °F	Temperature, °C	Time, hr							
1500	816	72	Coarse	4.59	M	4.29 to 4.36	A	-----	--
			Fine	4.60	M	4.30 to 4.33	A	[c]M_6C	--
1700	927	72	Coarse	4.58 to 4.63	R	4.31 to 4.37	A	-----	--
			Fine	4.58 to 4.62	R	4.30 to 4.33	M	[c]M_6C	--
{1700	927	72}	Coarse	4.60	M	4.30 to 4.39	A	-----	--
{1300	704	1000}	Fine	4.59	R	4.30 to 4.33	M	[c]M_6C	R

(b) Bulk samples (sheet)

Condition	Phases		
Heat treated			
2350° F (1288° C) 1/2 hr	[d]βCo	----	Ti(CN), Zr(CN)
2350° F (1288° C) 1/2 hr 1700° F (927° C) 72 hr	βCo	[e]αCo	Ti(CN), Zr(CN)

(c) Lattice parameters of stoichiometric compounds[f]

Compound	Lattice constant, a_0, [a]10^{-10} m
ZrC	4.69
ZrN	4.62
TiC	4.315
TiN	4.225

[a]10^{-10} m is equal to 1 Å.

[b]A, abundant; M, moderate, R, rare.

[c]Identification based on less than three lines.

[d]Face-centered cubic.

[e]Hexagonal close-packed.

[f]Ref. 14.

TABLE VIII. - MICROPROBE ANALYSIS OF CAST ALLOY

COBALT - $7\frac{1}{2}$ TUNGSTEN - $2\frac{1}{2}$ IRON - 1 TITANIUM - $\frac{1}{2}$ ZIRCONIUM - $\frac{1}{2}$ CARBON ALLOY

Region measured	Condition	Element				
		Cobalt	Tungsten	Iron	Titanium	Zirconium
		Weight percent				
Matrix	As-cast	86.2	6.7	3.9	0.3	0.2
	Aged at 1500° F (816° C) for 72 hr	92.6	6.1	3.8	0.5	0.05
Grain (or cell) boundary carbides of MC type	As-cast	25.1	31.0	2.5	11.6	8.9
	Aged at 1500° F (816° C) for 72 hr	34.0	30.5	2.8	13.2	5.2
		Atomic percent for M portion of MC				
	As-cast	43.5	17.2	4.6	24.7	10.0
	Aged at 1500° F (816° C) for 72 hr	51.3	14.7	4.5	24.5	5.0

NASA-Langley, 1968 —— 17 E-3910

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Notes, and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546