

The University of Michigan • Office of Research Administration
Ann Arbor, Michigan

Final Report

to

The International Nickel Company, Inc.

on

THE INFLUENCE OF MAGNESIUM ON THE CREEP-
RUPTURE PROPERTIES OF A Ni-Cr-Ti-Al ALLOY

by

Jay W. Schultz

J. W. Freeman

Project 02947

April, 1965.

INTRODUCTION

Magnesium is commonly added to nickel-base alloys during air melting for the dual purposes of deoxidation and desulfurization. When the alloys are vacuum melted the addition has not been considered necessary because of the availability of rapid carbon deoxidation and the use of higher purity melting stock. Recently it was suggested^{1*} that small amounts of magnesium may have a beneficial effect on the creep-rupture properties of vacuum melted nickel-base alloys. This experimental program was devised to examine such a possibility.

Research was conducted to quantitatively determine the effects of magnesium on the creep-rupture properties of a vacuum-induction melted alloy of the following aim composition:

<u>C (%)</u>	<u>Cr (%)</u>	<u>Al (%)</u>	<u>Ti (%)</u>	<u>Ni (%)</u>
0.06	20.0	1.2	3.8	balance

Magnesium levels up to 0.1 percent were studied. All heats were split with 0.0035 percent boron and 0.045 percent zirconium being added to half of each heat. The split heat procedure was used to provide material with and without boron and zirconium, as was done in previous studies on the effects of lead² and sulfur³.

All ingots were hot rolled to barstock at 2150°F. The barstock was heat treated and machined into creep-rupture specimens. Sufficient creep-rupture tests were run at 1200° and 1500°F to establish the position of the stress-rupture time curves between 10 and 1000 hours. The properties used to evaluate the effects of magnesium were 100-hour rupture strength and average reduction of area (ductility). Microstructural examinations were performed in an effort to establish the relationships between properties and structure as influenced by magnesium.

* Superscripts refer to literature listed under References.

EXPERIMENTAL PROCEDURE

The general procedure was to make, process and evaluate small laboratory heats of an experimental nickel-base alloy having systematically varied magnesium contents.

Experimental Alloy

The alloy studied had the following aim composition in weight percent:

<u>C</u>	<u>Cr</u>	<u>Al</u>	<u>Ti</u>	<u>Ni</u>
0.06	20.0	1.2	3.8	balance

This particular alloy, although relatively simple, has properties representative of successful wrought superalloys and had been used in previous investigations to establish the effects of lead² and sulfur³ on Ni-Cr-Al-Ti alloys. On the basis of this past experience it was a logical choice for the study of magnesium.

All heats were made with and without boron and zirconium additions by splitting each heat, no boron and zirconium being added to the first ingot and 0.0035 percent boron and 0.045 percent zirconium added to the second. As in previous studies^{2, 3}, it was felt that the effects of magnesium could not be successfully clarified unless the alloy was made with and without boron and zirconium since these two elements can have marked beneficial effects on creep-rupture properties.

The initial intent was to evaluate the influence of magnesium at analyzed levels of 0.02, 0.04 and 0.10 percent. However, the apparent recoveries of magnesium were too erratic to accurately evaluate the effects at the lower levels.

Melting Stock and Crucibles

Generally, the purest materials available in the quantities needed for the investigation were utilized.

Nickel

Mond carbonyl nickel pellets were used for all heats. These were furnished in 200-pound lots by The International Nickel Company, Inc. Their chemical analysis of several pellets from one lot was as follows:

<u>C (%)</u>	<u>S (%)</u>	<u>Pb (%)</u>	<u>B (%)</u>	<u>Si (%)</u>	<u>Mn (%)</u>
0.013	0.0030	<0.001	<0.001	<0.005	<0.005
<u>Fe (%)</u>	<u>Co (%)</u>	<u>Cu (%)</u>	<u>P (%)</u>	<u>Mg (%)</u>	<u>Al (%)</u>
0.011	<0.01	<0.005	0.002	<0.005	<0.01
		<u>Ti (%)</u>	<u>Zr (%)</u>		
		<0.01	<0.01		

Chromium

Shieldalloy aluminum-reduced "VMG" chromium was used for all heats. A typical analysis was as follows:

<u>C (%)</u>	<u>S (%)</u>	<u>Si (%)</u>	<u>Fe (%)</u>	<u>Al (%)</u>	<u>Cr (%)</u>
0.01	0.012	0.12	0.21	0.06	99.43

Titanium

Dupont sponge titanium metal was used for the experimental alloys. The only impurity reported for the lot used was 0.06 percent iron. A sulfur analysis performed by The International Nickel Company, Inc. indicated 0.0020 percent of that element.

Aluminum

The aluminum was supplied by the Aluminum Company of America as 99.99 percent Aluminum Ingot (1-pound notch bars) with the following impurities:

<u>Cu (%)</u>	<u>Fe (%)</u>	<u>Si (%)</u>	<u>Mg (%)</u>
0.001	0.001	0.003	0.002

Boron

Boron was added as a nickel-boron alloy purchased from the Electro-met Division of Union Carbide. The chemical composition furnished for the alloy was:

<u>Ni (%)</u>	<u>B (%)</u>	<u>Al (%)</u>	<u>Fe (%)</u>	<u>C (%)</u>	<u>Si (%)</u>
77.25	16.38	0.11	2.98	0.44	0.01

Zirconium

Reactor grade chunk zirconium was purchased from the Mallory Sharon Metals Company. They reported the following impurity content:

<u>C (%)</u>	<u>Si (%)</u>	<u>Mn (%)</u>	<u>Fe (%)</u>	<u>Pb (%)</u>
0.025	0.006	0.002	0.0309	0.002

Magnesium

Magnesium was added as pure magnesium metal and a nickel-magnesium alloy supplied by The International Nickel Company, Inc. The nickel-magnesium alloy had the following reported composition:

<u>Mg (%)</u>	<u>Ni (%)</u>	<u>Si (%)</u>	<u>Cu (%)</u>
15.21	81.1	0.22	0.05

Carbon

Spectrographically pure graphite rods were turned on a lathe to produce coarse powder which was used for all carbon additions.

Crucibles

All melting was carried out in Norton Alundum 99 percent fused alumina crucibles. The crucibles had an inside diameter of 3.5 inches and were 7.0 inches high. The following typical chemical composition was reported for the refractory:

<u>Al₂O₃ (%)</u>	<u>SiO₂ (%)</u>	<u>Fe₂O₃ (%)</u>	<u>Na₂O₃ (%)</u>	<u>other</u>
99.01	0.58	0.11	0.17	balance

A personal communication from the Norton Company stated that this grade of crucible material is spectrographically free from boron or boron compounds.

Melting Procedure

All melting was done in a vacuum induction melting furnace designed and built at the University of Michigan. The furnace had a 30-cubic foot cylindrical tank and a 6-inch booster-diffusion pump and mechanical

fore pump combination capable of maintaining pressures of less than 10 microns of Hg during the melting of the charge.

The melting procedure established to provide reproducible results was as follows:

- (1) All heats were the same size, 5500 grams (12 lbs.).
- (2) All the Cr and C and as much Ni as possible were charged into the crucible. The remaining nickel and the necessary additions were placed in charging buckets in the vacuum tank. The B and Zr were wrapped in aluminum foil to prevent losses during addition.
- (3) The tank was evacuated to a maximum pressure of 2 microns with a maximum apparent leak-up rate of 4 microns per minute.
- (4) The power was then turned on and the melting of the initial charge and the remainder of the Ni completed in about 45 minutes. Shorter melting times were not possible due to the power limitations of the furnace. In most cases no carbon boil was observed when the melt surface was finally visible, indicating that deoxidation occurred mainly during melt-down. If a boil was observed, the melt was held until it subsided before proceeding with further additions.
- (5) The Al and Ti were added.
- (6) Argon was then bled into the tank until a pressure of about 1/2-atmosphere was attained. The melt was simultaneously cooled to near the melting point of the alloy.
- (7) The Mg was then added (with the power on) and a superheat of 200°F established.
- (8) One half of the heat was poured.
- (9) B and Zr additions were made, superheat re-established, and the second half of the heat was poured. The total elapsed time from the start of melting was about one hour.

The molds used were 4-inch sections of 2-inch I. D. steel pipe. A 2-inch high hot-top, made from insulating brick, was mounted on each mold.

Hot Rolling Procedure

All ingots were hot rolled directly to barstock on a 2-Hi Reversing Bar Mill. The procedure used was to soak the ingots for two hours at the rolling temperature, 2150°F, and then roll them to 1/2-inch square bars. The rolling schedule included 21 passes with a 10-minute reheat between each pass to maintain the temperature at 2150°F. The reduction of area per pass, as calculated from roll geometry, was as follows:

	Pass Number		
	<u>1 through 4</u>	<u>5 through 10</u>	<u>11 through 21</u>
Reduction of Area	13% total	10% each	12 to 14% each

Initial square-up of an ingot took place in passes 1 through 4, resulting in a low true reduction of area per pass. Total contact of the material with the rolls occurred during passes 4 or 5. Passes 16 and 17 were diamond-shaped as opposed to square and, although the reduction per pass was not varied at this point, the overall shape of a bar was severely changed on going through these passes. The last pass was followed by air cooling.

Chemical Analyses

All chemical analyses were performed by the Research Laboratory of The International Nickel Company, Inc.

The sampling procedure consisted of taking a 1.5-inch section from the center of each piece of barstock and machining chips from this section. This provided a 1.5-inch by 0.5-inch by 0.25-inch sample for spectrographic analysis and sufficient chips for other methods.

Heat Treatment

The following heat treatment was used on the hot-rolled material before machining creep-rupture specimens:

8 hours at 1975°F, air cool,
plus 16 hours at 1300°F, air cool.

Creep-Rupture Tests

Creep-rupture properties were evaluated at 1200°F and 1500°F to determine if the effects of magnesium were the same at temperatures near the upper and lower limits of the range where creep governs the strength of wrought nickel-base alloys with amounts of Ti and Al comparable to the alloy studied.

Creep-rupture properties were established at each temperature by conducting tests over a range of stresses so as to define stress-rupture time curves from about 10 to 1000 hours. The deviations of the test points from smooth curves on a log stress versus log rupture time plot gave an indication of the reproducibility of test results. More important, the variations in slope within a single curve and between the different curves enabled the determination of effects produced by stress variations. This insured that erroneous conclusions from comparative tests at a single stress, a widely used procedure for studies of this nature, would be avoided if compositional effects should prove to be stress dependent.

Elongation and reduction of area were measured for the fractured specimens. Ductility comparisons were made using reduction of area, as the values were more consistent and more accurately measurable than elongation values.

All of the creep-rupture tests were conducted in conventional beam loaded creep-rupture units in accordance with ASTM Recommended Procedures. The specimens were placed in the furnaces, which were at temperature, and allowed a maximum of four hours to attain proper test temperature and temperature distribution prior to application of the load. Temperature variation along the gage length was limited to $\pm 3^\circ\text{F}$. Rupture times were recorded by automatic timers. Creep (time-elongation) measurements were made on tests expected

to last more than 10 hours with modified Martens-type extensometers having sensitivities of 10^{-5} inches. These measurements are available as a matter of record.

Structural Studies

Optical metallographic techniques were used for the microstructural studies carried out in this investigation. As-cast and as-heat treated samples were surveyed as to general structure and the relationships between magnesium content and micro-constituents.

Metallographic samples were mechanically polished on wet silicon carbide papers through 600 grit; then on cloths impregnated with 6 and 1 micron diamond paste; the final polish was obtained on either a Syntron vibratory polishing unit or cloth wheel using a mixture of Linde B alumina powder and distilled water. Microstructures were delineated with an electrolytic etch using an etchant composed of 12 parts phosphoric acid (85 percent), 47 parts sulfuric acid (96 percent) and 41 parts nitric acid (70 percent) at current densities of 0.1 to 0.3 amps per square inch.

RESULTS

Chemical Composition

The chemical analyses of the heats used in this investigation are presented in Table I.

Heat 1314 was selected from previous studies for a base heat (no magnesium) because it had a carbon content similar to the heats with magnesium added. It had previously³ been demonstrated that, of the major alloying elements, carbon had the most influence on the creep-rupture properties of the 20Cr-1.2Al-3.8Ti alloy.

Magnesium analyses were a problem because of discrepancies between

amounts added and recovered. The analyzed magnesium content of Heat 1388 indicated recovery well in excess of 100 percent, yet past experience with over 30 heats suggested that there should have been no significant residual magnesium in the melting stock or crucible material. On the other hand, Heat 1330 had 0.02 percent magnesium added and analysis indicated a final magnesium content of less than 0.01 percent; yet this material seemed to exhibit an effect from the addition. Because of these difficulties it was not possible to define the effects of magnesium below about 0.04 percent. Heat 1330 was treated as though it had a magnesium content of 0.0075 percent and Heat 1388 as though it had 0.04 percent magnesium (100 percent recovery).

Although there were minor variations in reported aluminum and titanium contents, past experience^{2, 3} indicates these should not have significantly influenced creep-rupture properties. The variations in boron and zirconium in the halves of heats to which they were added (B halves) were not considered real. Levels over 0.0035 percent boron and 0.045 percent zirconium represented recoveries in excess of 100 percent, but the other halves of the heats (A halves) consistently had less than detectable amounts of boron and zirconium. Thus, boron and zirconium levels were assumed to be consistent from heat to heat and the creep-rupture properties were evaluated on this basis.

Influence of Magnesium on Creep-Rupture Properties

The addition of magnesium to the 20Cr-1.2Al-3.8Ti alloy influenced creep-rupture properties, but only under a limited set of conditions. Small amounts of magnesium when added to the alloy together with boron and zirconium had a beneficial effect on rupture ductility at 1200°F but not at 1500°F. The level of magnesium for a maximum beneficial effect appeared to be about 0.02-0.04 percent. Magnesium contents above this range caused the rupture ductility to be reduced.

With the exception of the influence of magnesium on rupture ductility,

this element had no significant influence on the rupture properties of this alloy.

The creep-rupture data are summarized in Table II and Figures 1 and 2 as average rupture ductility (reduction of area) and as 100-hour rupture strength. The individual test results are reported in Table III and are displayed in Figure 3 as stress-rupture time curves. The 100-hour rupture strengths were obtained from the stress-rupture time curves in Figure 3 and the average reduction of area values from the individual test results in Table III.

Magnesium without Boron and Zirconium

In the absence of boron and zirconium, magnesium additions up to 0.1 percent to the 20Cr-1.2Al-3.8Ti alloy did not cause significant changes in either rupture ductility or 100-hour rupture strength. The behavior of the alloy as a function of magnesium content is shown graphically in Figures 1 and 2. The ductility curves of Figure 1 were drawn so as to best fit smoothly through the data. The slight decrease in rupture ductility indicated by these curves with increasing magnesium content is not considered to be significant based on the limited amount of data.

The curves of 100-hour rupture strength versus magnesium content (Figure 2) also exhibited a slight drop at low magnesium levels. The limited data coupled with the slight decrease in strength suggests that further verification is needed before an effect of magnesium on rupture strength can be claimed.

Magnesium with Boron and Zirconium

The addition of magnesium to the 20Cr-1.2Al-3.8Ti alloy containing boron and zirconium had an indicated beneficial influence on rupture ductility at 1200°F. As can be seen in Figure 1 the reduction in area at fracture was increased from 10 percent to 18 percent by the presence of approximately 0.04 percent magnesium. If this increased rupture ductility also occurred at 1500°F the magnitude of the effect was greatly reduced. At both temperatures, however, magnesium contents above 0.04 percent were associated with reduced ductility, as can be seen in Figure 1.

Figure 2 shows that magnesium contents up to 0.1 percent did not have any appreciable influence on 100-hour rupture strength at either 1200° or 1500°F.

The addition of magnesium to heats of the alloy containing boron and zirconium may well have reduced the heat-to-heat variation in creep-rupture properties and, if so, this may prove to be its most beneficial effect. The stress-rupture time data from these heats are shown in Figure 3. The data were unusually consistent, as is evidenced by the single rupture curve drawn through the 1200°F rupture data.

Hot Rolling the Heats with Magnesium Added

The quality of the finished barstock of the heats with magnesium added is illustrated in Figure 4. All ingots were rolled without evidence of cracking with the exception of the two from Heat 1386, which exhibited moderate corner cracks. Heat 1386 had the highest level of magnesium investigated, about 0.1 percent. The heat without magnesium added, Heat 1314, was hot rolled to barstock without cracking. Thus no beneficial effect of magnesium on hot-workability was observed and excessive amounts seemed to impair hot working characteristics by inducing some cracking.

Structural Study

A limited study was performed to determine the extent to which magnesium changed the microstructure of the alloy.

Microstructural examination of the alloy in the as-heat treated condition revealed that magnesium additions promoted the formation of substantial amounts of an additional phase, which has been identified as TiC. This is illustrated in Figure 5 by microstructures of heats with and without magnesium added. The heat without magnesium (Figures 5a and 5b) had the expected microconstituents, i. e. the γ matrix, the

γ' -Ni₃ (Al, Ti) intragranular precipitate (not resolved - but indicated by the stain), and white Cr₇C₃ intra- and intergranular carbides. The heat with magnesium had an additional microconstituent (Figures 5c and 5d), bluish-grey intragranular particles with irregular angular shapes. This phase was randomly distributed and often had white carbide particles precipitated on it. The occurrence of this bluish-grey phase was the only microstructural effect that was observed for the magnesium additions.

There was no apparent difference in the alloy microstructure which could be attributed to the presence of boron and zirconium (compare Figures 5a and 5b with 5c and 5d).

The shape and distribution of the bluish-grey phase in the high magnesium heats suggested that it had formed during solidification. Examination of the microstructure of a high magnesium heat in the as-cast and as-cast plus two hours at 2150°F and water quenched conditions (Figures 6a and 6b) confirmed this. The same bluish-grey particles were found in both conditions, the latter representing the structure after the pre-rolling soak. The mode of formation, morphology, color and stability of the phase are consistent with its being TiC.

Further confirmation of the phase's identity was obtained by X-ray diffraction analysis. Using a technique known³ to preferentially extract Ti₄C₂S₂ and Ti (C, N) (digestion in hot concentrated HCl), a substantial amount of residue was obtained from as-cast Heat 1386B (0.094 percent magnesium). A qualitative X-ray diffractometer survey of the residue showed that it was primarily TiC with a lattice parameter of about 4.32Å. The amount of residue obtained suggested that there was a substantial amount of TiC in the alloy, which was consistent with microstructural observations on the abundance of the bluish-grey phase (Figure 5d).

It was also interesting to note that the X-ray diffraction analysis did not show any indication of the presence of Ti₄C₂S₂. Although this is still subject to verification by a more quantitative analysis of the residue, it does suggest that the magnesium prevented the formation of the titanium carbosulfide compound.

DISCUSSION

The results of this investigation demonstrated that magnesium had a beneficial effect on the the rupture test ductility of the 20Cr-1.2Al-3.8Ti alloy at 1200°F when the alloy contained boron and zirconium. Under this set of conditions, 0.02 to 0.04 percent magnesium suggested a nearly twofold increase in average rupture ductility. However, at 1500°F in the alloy containing boron and zirconium, up to 0.4 percent magnesium was not beneficial and was deleterious at high levels. In alloys which did not contain boron and zirconium, magnesium had no proven influence on rupture ductility.

From a practical viewpoint, the addition of magnesium to heat resistant alloys seems to have some merit. But as shown in this investigation, magnesium is not always beneficial and can be harmful. Presently it appears that additions would be useful only in alloys designed for intermediate temperature service, i. e. in the neighborhood of 1200°F, and only in alloys that also have boron and zirconium added. These limitations are important and further work on defining the role of magnesium is firmly indicated. Other alloys should be investigated and possible service temperature limitations defined.

The reasons for the influence of magnesium on rupture ductility are not at all clear. The observation that TiC formed on adding magnesium suggests that magnesium was indirectly affecting phase relationships. Yet the TiC should not have affected rupture ductility because of its amount and distribution. The types of effects and small amounts of magnesium required suggest a mechanism related mainly to grain boundary properties. Two such possibilities are:

- (1) Magnesium acts as a "cleanser" by reacting with deleterious trace elements to form innocuous compounds.
- (2) Magnesium segregates at grain boundaries where it behaves in a manner similar to boron and zirconium, i. e. as a surface active element which stabilizes or embrittles grain boundaries, depending on the concentration and temperature.

In neutralizing trace elements, magnesium should have been beneficial with or without boron and zirconium present; but the beneficial effects were observed only in the presence of boron and zirconium. Thus, the role of magnesium seems to be that of a surface active element. It is very similar to zirconium with regard to alloying behavior in nickel and these two elements have almost identical atomic diameters. Magnesium was most beneficial when added in combination with boron and zirconium, which is the same behavior exhibited by zirconium when added in combination with boron⁴.

It appears that other elements may have beneficial effects similar to magnesium. Svistunova and Estulin⁵ claimed that cerium, lanthanum and neodymium additions improved the creep-rupture properties of an air melted 20Cr-0.8Al-2.5Ti-balance Ni alloy at 1300°F. From their work, one cannot be certain if the effects are real because of the lack of control and/or recognition of important variables, such as boron content. Nevertheless, the possibility of improving creep-rupture properties with additions of these and other elements warrants further exploration.

CONCLUSIONS

- (1) Any effects of magnesium on the properties of the 20Cr-1.2Al-3.8Ti alloy were secondary to the influence of boron and zirconium on properties.
- (2) About 0.02 to 0.04 percent magnesium substantially improved the 1200°F rupture ductility of the 20Cr-1.2Al-3.8Ti alloy with boron and zirconium added. Increasing magnesium content above 0.04 percent reduced its beneficial effects.
- (3) Magnesium did not significantly improve the 1500°F rupture ductility of the 20Cr-1.2Al-3.8Ti alloy with boron and zirconium added and was deleterious if present in significantly high levels.
- (4) Magnesium did not significantly affect the 1200° or 1500°F 100-hour rupture strength of the 20Cr-1.2Al-3.8Ti alloy either with or without boron and zirconium.

- (5) On adding magnesium, a substantial amount of TiC formed in the alloy during solidification. The TiC appeared to act like a stable innocuous non-metallic inclusion during processing and creep-rupture testing.
- (6) The beneficial effect of magnesium on rupture ductility suggested a behavior similar to that assumed for boron and zirconium, i. e. segregation at and stabilization of grain boundaries.
- (7) Magnesium contents of about 0.1 percent induced cracking of the 20Cr-1.2Al-3.8Ti alloy during hot rolling at 2150°F. No effects were noted at lower levels.

REFERENCES

1. Decker, R. F., and DeWitt, R. R.: Private communication.
2. Schultz, J. W., and Freeman, J. W.: "The Effects of Lead on the Creep-Rupture Properties and Hot-Workability of Two Ni-Cr-Ti-Al Alloys", University of Michigan, Report No. 02947-4-P, December 1963.
3. Schultz, J. W., and Freeman, J. W.: "The Influence of Sulfur on the Creep-Rupture Properties and Hot-Working Characteristics of Several Experimental Nickel-Base Alloys", University of Michigan, Report No. 02947-5-F, December 1964.
4. Decker, R. F., Rowe, J. P., and Freeman, J. W.: "Boron and Zirconium from Crucible Refractories in a Complex Heat-Resistant Alloy", NACA Report No. 1392, 1958.
5. Svistunova, T. V., and Estulin, G. V.: "Influence of the Rare-Earth Elements on the Properties of High-Temperature Nickel-Base Alloys, J.P.R.S. Report No. 21, 895, 18th November 1963. (Translated from Stal, No. 9, September 1963, pp. 835-838.)

TABLE I

CHEMICAL COMPOSITION OF EXPERIMENTAL MATERIALS
(in weight percent)

Heat	Mode of Mg Addn.	Total Mg Added	Mg	C	Cr	Al	Ti	B	Zr	S	Pb
	Aim Composition		(a)	0.06	20.0	1.2	3.8	(b)	(c)	LP	LP
1314A	-	none	<0.01	0.10	19.94	0.99	3.75	<0.0010	<0.01	0.0049	0.0004
1314B			<0.01	0.10	19.85	1.01	3.70	0.0031	0.025	0.0089	0.0004
1330A	Mg	0.02	<0.01	0.09	19.83	1.20	4.05	<0.0010	<0.01	0.0070	-
1330B			<0.01	0.09	19.87	1.20	3.97	0.0068	0.038	0.0070	-
1388A	NiMg	0.04	0.049	0.09	19.6	1.22	3.70	ND	ND	0.0052	-
1388B			0.061	0.09	19.9	1.24	3.65	0.0060	0.057	0.0045	-
1387A	NiMg	0.08	0.076	0.10	19.5	1.23	3.76	ND	ND	0.0045	-
1387B			0.065	0.08	19.6	1.22	3.76	0.0060	0.053	0.0049	-
1386A	NiMg	0.20	0.10	0.07	19.6	1.32	3.80	ND	ND	0.0053	-
1386B			0.094	0.07	19.7	1.24	3.70	0.0060	0.047	0.0060	-
Estimated* levels of other elements -			Mn	Si	As	Sb	Sn	Bi	Zn	Cu	Fe
			<0.01	0.02	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.01	<0.1

(a) The aim Mg contents were one-half the amount of total Mg added

(b) 0.0035 percent B added to B ingot of each heat

(c) 0.045 percent Zr added to B ingot of each heat

LP - Low as possible

ND - Non-determined

* - Based on results from previous studies 2, 3

TABLE II

INFLUENCE OF MAGNESIUM ON THE 100-HOUR RUPTURE STRENGTH AND RUPTURE DUCTILITY OF A 20Cr-1.2Al-3.8Ti ALLOY AT 1200° AND 1500°F

Heat	Analyzed Mg (%)	1200°F		1500°F	
		100-hr. Rupt. Strength (psi)	Avg. Red. of Area(%)	100-hr. Rupt. Strength (psi)	Avg. Red of Area (%)
1314A	<0.01	81,500	3	25,300	10
1314B	<0.01	105,000	10	34,500	22
1330A	<0.01	83,000	5	19,500	4
1330B	<0.01	107,000	13	34,500	23
1388A	0.049*	76,000	3	17,300	5
1388B	0.061*	107,500	18	33,000	24
1387A	0.076	76,000	3	17,300	4
1387B	0.065	106,000	15	33,500	18
1386A	0.10	76,000	1	18,800	3
1386B	0.094	105,000	10	33,500	10

* - 100-percent recovery of magnesium would have given 0.04 percent

TABLE III

CREEP-RUPTURE TEST RESULTS FOR EXPERIMENTAL MATERIALS

Heat	Analyzed Mg Content (%)	No B and Zr Added.			0.0035%B and 0.045%Zr Added			Elongation (% in 1 in.)	Reduction of Area (%)			
		Temp. (°F)	Stress (psi)	Rupture Time (hours)	Temp. (°F)	Stress (psi)	Rupture Time (hours)					
1314A	<0.01	1200	90,000	59.1	1200	120,000	18.4	10	13			
			70,000	302.0		100,000	182.5	8	10			
			60,000	364.2		90,000	644.3	5	7			
		1500	40,000	9.6	1500	50,000	12.2	15	20			
			25,000	105.7		35,000	97.3	13	20			
			15,000	758.9		25,000	487.3	19	26			
1330A	<0.01	Base Heat - No Mg Added			Heat			shut off at 1106.8 hours				
		0.02%Mg Added As Pure Mg			1330B							
		1200	120,000	3.8	1200	120,000	24.2				9	16
			100,000	29.4		110,000	69.1				4	8
			90,000	79.8		100,000	220.0				9	15
			75,000	170.8		80,000						
		1500	35,000	12.8	1500	50,000	13.7	22	30			
			30,000	24.5		40,000	54.4	17	25			
			15,000	232.3		25,000	394.3	13	15			
			12,000	468.3								
		0.04%Mg Added As NiMg			1388B							
		1200	100,000	23.7	1200	120,000	23.1				9	15
	80,000	79.8		100,000	251.5	13	18					
	60,000	280.1		90,000	954.1	13	21					
1500	25,000	33.7	1500	50,000	12.1	24	31					
	15,000	129.6		35,000	76.1	12	21					
1387A	0.076	0.08%Mg Added As NiMg			1387B							
		1200	100,000	16.8	1200	120,000	23.6				10	13
			80,000	97.8		100,000	234.3				12	17
			60,000	235.2		90,000	735.5				11	16
		1500	35,000	6.3	1500	50,000	15.6				12	20
			15,000	166.9		35,000	72.8				13	20
1386A	0.10	0.20%Mg Added As NiMg			1386B							
		1200	100,000	7.3	1200	120,000	18.1				7	10
			80,000	119.6		100,000	171.5				5	8
			60,000	241.2		90,000	616.9				9	13
		1500	25,000	28.6	1500	50,000	11.5				10	13
			15,000	267.7		35,000	105.2				7	9
	11,000	747.3		25,000	256.5	7	7					

○ - no B and Zr added

● - 0.0035%B and 0.045%Zr added

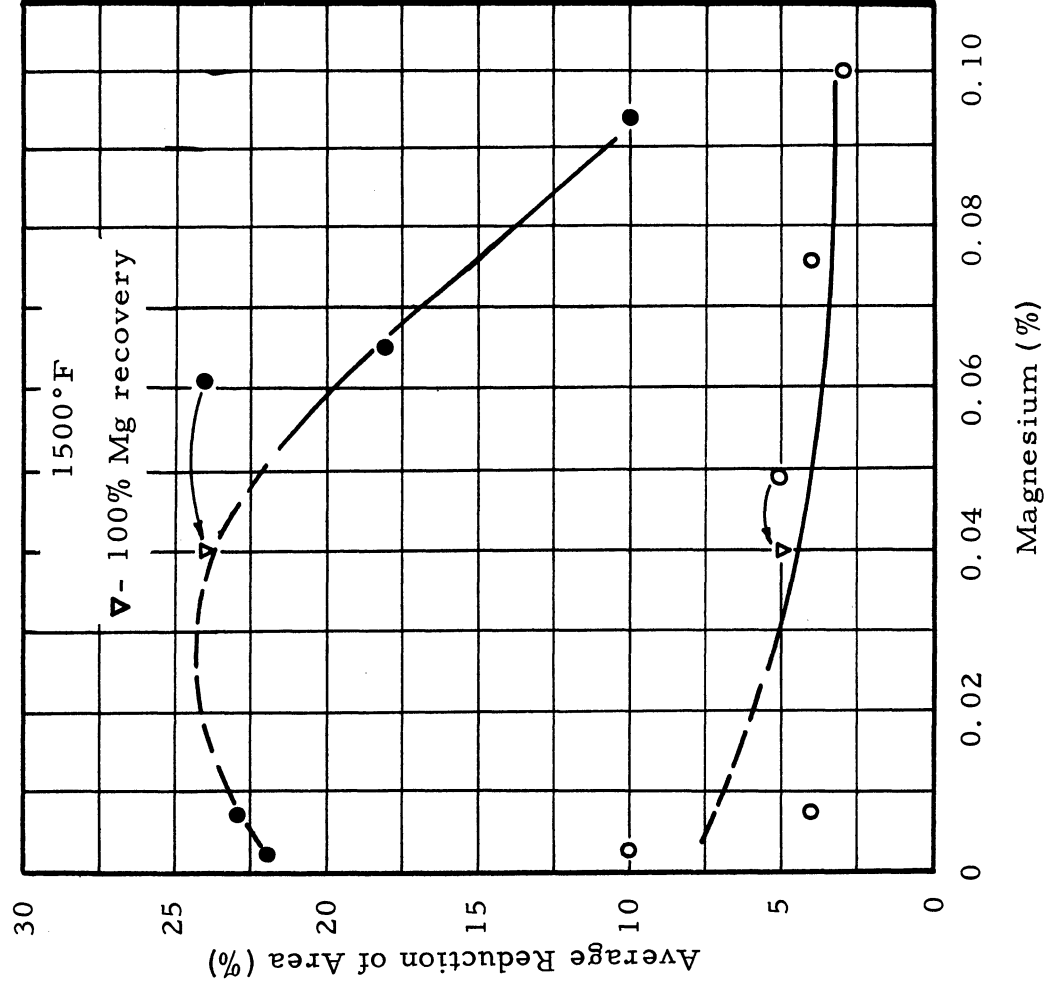
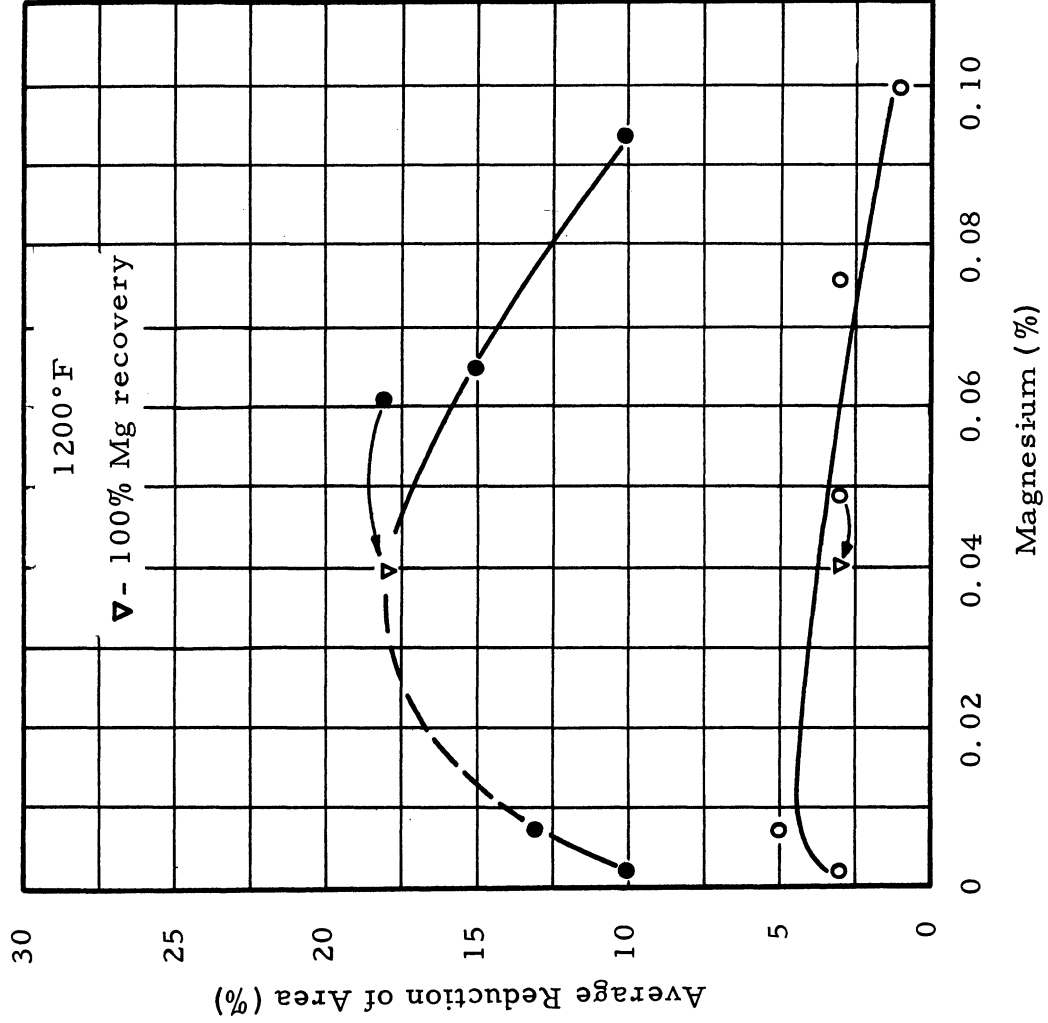


Fig. 1. Effect of Magnesium on Rupture Ductility.

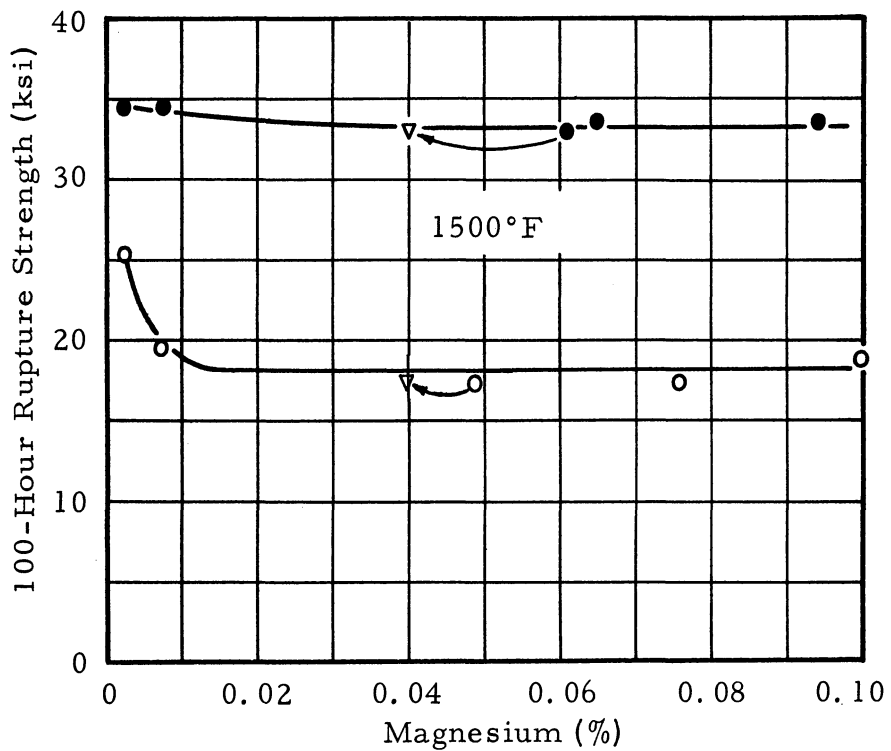
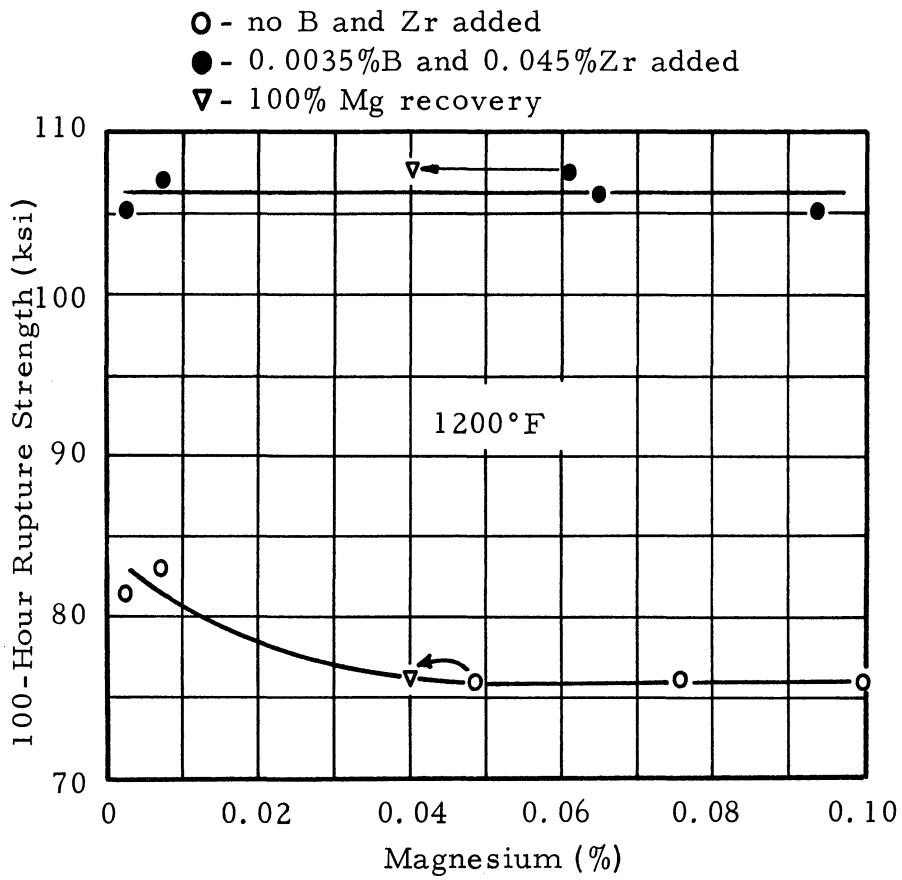


Fig. 2. Effect of Magnesium on 100-Hour Rupture Strength.

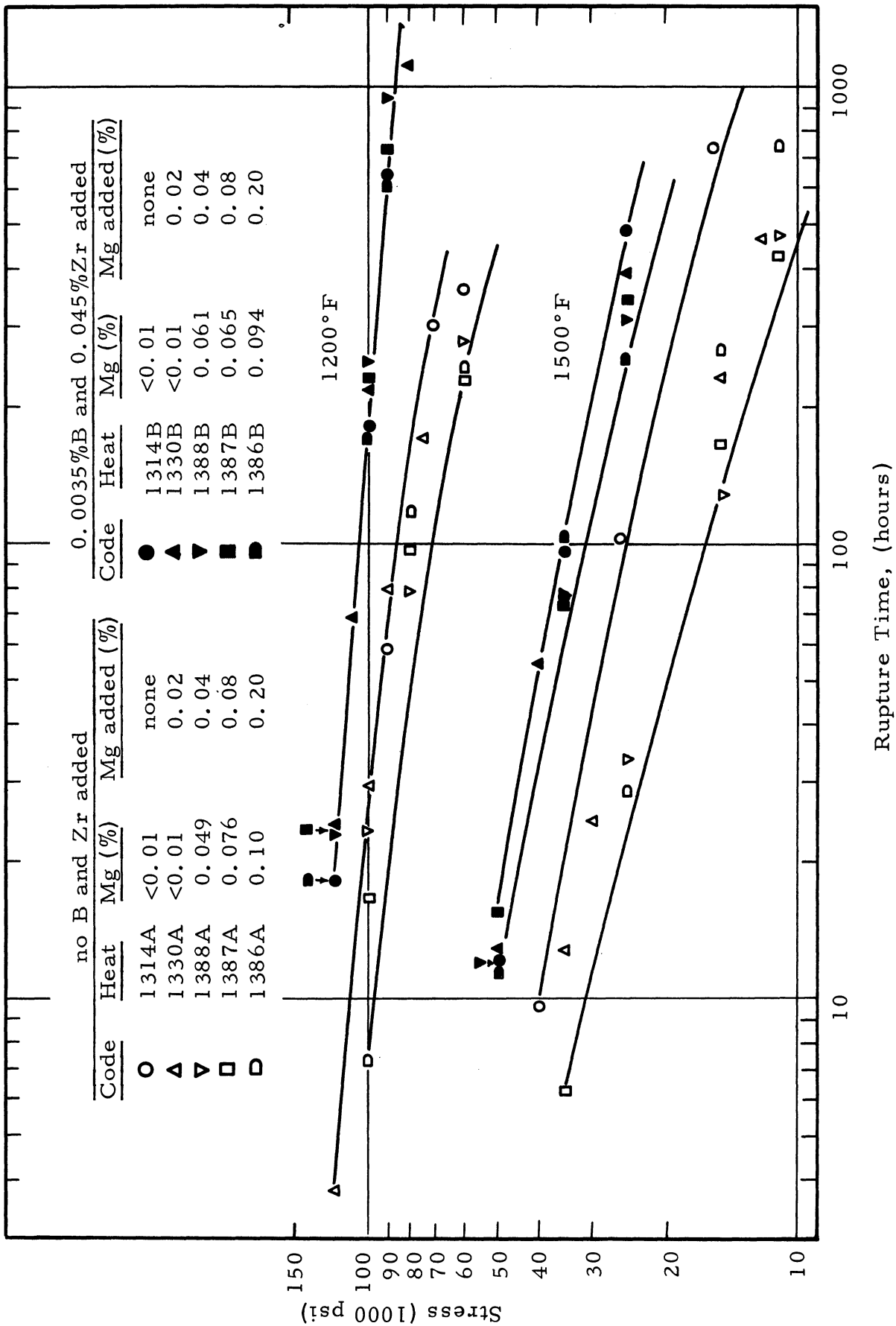


Fig. 3. Comparative Stress-Rupture Time Curves Showing the Effects of Magnesium.

