CANADA

PROPERTIES OF SAND-CAST MAGNESIUM ALLOYS

PART IV: Mg-Ag, Mg-Ag-Zr and Mg-Ag-Zn-Zr Alloys

B. LAGOWSKI & J. W. MEIER

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PROPERTIES OF SAND-CAST MAGNESIUM ALLOYS. Part IV: Mg-Ag, Mg-Ag-Zr and Mg-Ag-Zn-Zr Alloys.

by

B. Lagowski* and J. W. Meier**

ABSTRACT

The long-term research program on high-strength magnesium alloys, being conducted since 1945 at the laboratories of the Physical Metallurgy Division, Mines Branch, Department of Mines and Technical Surveys, Ottawa, has included a study of binary and more complex alloys based on the magnesium-silver system.

The results of the investigation related to sand-cast Mg-Ag, Mg-Ag-Zr and Mg-Ag-Zn-Zr alloys are presented and show that all three of these alloy groups have good ductility and are amenable to solution strengthening.

Precipitation-hardening, to any appreciable extent, was found only in certain alloys of the Mg-Ag-Zn-Zr system. Some of these alloys show exceptionally high yield strength.

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PROPRIÉTÉS DES ALLIAGES DE MAGNÉSIUM COULÉS EN SABLE

Partie IV: Alliages de Mg-Ag, Mg-Ag-Zr et Mg-Ag-Zn-Zr

par

B. Lagowski* et J. W. Meier**

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RÉSUMÉ

Les recherches à long terme menées depuis 1945 dans les laboratoires de la Division de la métallurgie physique, Direction des mines, ministère des Mines et des Relevés techniques, Ottawa, sur les alliages de magnésium à haute résistance, comprennent une étude des alliages binaires et plus complexes du système magnesium-argent.

Les auteurs présentent les résultats des recherches sur les alliages de Mg-Ag, Mg-Ag-Zr et Mg-Ag-Zn-Zr, coulés en sable. Ces trois groupes d'alliages ont montré une bonne ductilité. Il est possible d'augmenter leur résistance par mise en solution.

Seuls, certains alliages du système Mg-Ag-Zn-Zr ont présenté un vieillissement appréciable. Un certain nombre de ces alliages ont une très haute limite apparente d'élasticité.

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Cet exposé a été présenté à l'assemblée générale annuelle de l'Institut canadien des mines et de la métallurgie, à Toronto, le 26 avril 1960.

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INTRODUCTION

In continuation of the broad research program on high-strength magnesium casting alloys[1-3], conducted since 1945 at the Physical Metallurgy Division, an investigation was carried out on the effect of silver additions to magnesium and some of its alloys.

Published data on magnesium-silver alloys showed that, although wrought magnesium alloys containing silver have been known for more than twenty years, and a silver-containing, magnesium-rare earths casting alloy has recently been introduced, no information was available on the mechanical properties of the magnesium-silver casting alloys, with or without further alloying additions.

The present work was started, in 1957, with a systematic investigation of mechanical properties of sand-cast alloys of the magnesium-rich end of the binary magnesium-silver alloy system, with and without grain refinement by zirconium additions. The later phases of this study have dealt with zinc additions to the magnesium-silver-zirconium casting alloys and with their heat treatment.

LITERATURE SURVEY

The magnesium-silver alloy equilibrium diagram has been studied extensively by researchers, and numerous accounts are available. The general form of the diagram was first worked out by Zemczuzny[4]. Further studies by Payne and Haughton[5], Hume-Rothery and Butchers[6], Ageev and Kuznetsov[7], Andrews and Hume-Rothery[8], and others, have established the currently accepted equilibrium diagram, which is reproduced in Figure 1, from Hansen and Anderko[9]. The maximum solid solubility is given as 15.5 wt % Ag at the eutectic temperature of 471 °C (880 °F), decreasing to approximately 3 wt % Ag at 300 °C (572 °F).

Very little has been reported on ternary alloys based on the Mg-Ag system. Haughton[10], and Kuznetsov and Guseva[11], investigated Mg-Ag-Al alloys; Koester and Kam[12] studied the Mg-Ag-Tl, Hume-Rothery et al[13] the Mg-Ag-Li, and Laves and Moeller[14] the Mg-Ag-Cd systems. The section $MgZn_2$-$MgAg_2$ has been investigated by Witte[15] and appears to be quasi-binary.

Published information on the properties of magnesium alloys containing silver is very fragmentary, especially for cast alloys; and a systematic study of the tensile properties of cast binary, or more complex, alloys based on the Mg-Ag system could not be found.

Tensile properties of rolled Mg-Ag alloys with up to 12% Ag were reported by MacDonald[16]; maxima in strength and ductility were reached at low silver content. According to Nielsen and Cramer[17], the binary alloy with 9.65% Ag in the extruded condition shows a slight tendency to age-hardening. Nagashima[18] found a slight hardening caused by precipitation of the Mg_3Ag phase in the 12.6% Ag alloy.

According to Beck[19], hardness in the binary extruded alloys increases with increasing silver content. Kuznetsov and Skryabin[20] investigated, at room and elevated temperatures, ternary casting alloys of Mg-Ag-Al with Ag/Al ratios of 4:1, 1:1 and 1:4, and reported two quaternary alloy compositions as the most promising: Mg-4.25Al-0.5Ag-0.4Mn, and Mg-3.09Al-1.04Ag-0.27Mn.

Haughton and Prytherch[21] reported high tensile properties of forged 8Al-8Cd-2Ag and 8Al-2.5Ag-0.4Mn-0.2Cu alloys; the latter alloy could be still further improved by the addition of 0.66% Zn.

Naguro[22] investigated alloys of magnesium with 2, 3, and 5% Zn and 0.5, 1, and 2% Ag. Corrosion resistance was not affected by silver to any great extent, and the alloys responded to age-hardening at 150°C (302°F).

Leontis[23] included, in his investigation of cast magnesium alloys containing zinc, two silver-containing alloys: Mg-3.6Zn-2.9Ag-0.66Zr, and Mg-2.9Zn-2.8Ag-2.5R.E.-0.41Zr (the zirconium contents in both cases are doubtful, because "total Zr" instead of "sol. Zr" were reported). The first composition showed some effects of age-hardening on tensile properties at room temperature; the second alloy showed improved elevated-temperature properties.

Exceptionally high tensile strengths of a Mg-6Ag-6Zn-Zr sheet alloy and a Mg-6Ag-3Zn-Zr extrusion alloy were reported in Product Engineering[24]. Mikkeev[25] patented a heat-treatable magnesium extrusion alloy containing 7-9% Al, 5-8% Cd, 1-4% Ag, and 0.2-0.8% Mn.

Recently, Payne and Bailey[26] reported the introduction of a new casting alloy containing 1-3.5% Ag, 1-3.5% R.E. and 0.4-1% Zr and, according to them, this alloy combines good foundry characteristics, good weldability, and good elevated temperature properties. High yield strength is developed by a two-stage heat treatment, the age-hardening phase containing silver and rare earths.

Various physical properties of Mg-Ag alloys are given by Beck[19], such as electrical and thermal conductivity. Also, silver additions in magnesium alloys containing aluminum as main alloying element are stated to increase the corrosion rate in tap water and improve the resistance to salt water, through the formation of a protective film of silver chloride. Small amounts of silver (up to 0.5% Ag) decrease the oxidation of molten magnesium to a great extent, according to Peredelsky[27].

MATERIALS AND EXPERIMENTAL PROCEDURES

Materials used for the preparation of the experimental alloys included Domal 99.98% Mg ingots, Tadanac 99.99% Zn ingots, and 99.99% Ag shot. Zirconium was introduced as a fused salt mixture containing 50% $ZrCl_4$ and 25% each of KCl and NaCl. The melts were prepared in welded steel pots of 40 lb capacity, using Domal crucible flux[28]. Standard melting and alloying techniques, established earlier for ZK61 alloy[29], were used.

About 120 experimental alloy melts, each of approximately 25 lb weight, were made. If only virgin metal had been used, the cost of the materials, especially silver, would have been considerable. To avoid this, the following procedure was established: Alloy compositions of highest silver content, in each series of alloys, were prepared from virgin metals; all others were made using up to 80% scrap from the preceding melts, with additions of zinc or zirconium if necessary. Very strict control of the recirculated metal (ingots, gates, risers, broken test bars) and careful selection to meet the experimental alloy compositions were necessary to avoid mistakes, but in general this alloying method proved very successful and efficient.

Test bars were cast to shape (Figure 2) into green sand, using standard sand compositions and characteristics for magnesium alloys[28], and were tested without machining.

Solution heat treatments were carried out in a circulating-air furnace with automatic control of a 1% SO_2-containing protective atmosphere, heated electrically and controlled to $\pm$ 2 °C. Ageing was carried out in an electric oven with air circulation and close temperature control (to $\pm$ 1 °C).

To avoid the effect of room-temperature ageing, all tensile tests were carried out within seventy-two hours after casting or solution heat treatment. Samples for chemical analyses were drilled from one-half of the broken test bars, and the other half was used for density, grain size and hardness determinations.

Designations of experimental alloys and tempers used throughout the paper are according to the Canadian Standards Association's codes H.1.1-1958 (alloy designations) and H.1.2-1958 (temper designations). As-cast products are designated "F"; solution heat treated, "T4"; solution heat treated and artificially aged, "T6"; and artificially aged only, "T5".

Results of ultimate tensile and 0.2% yield strengths are reported in kpsi (1000 psi) and elongations in per cent on 2-inch gauge lengths.

EXPERIMENTAL RESULTS

For clarity reasons, all experimental results are shown in this report in graphs (Figures 3 to 11).

The detailed results of chemical analyses, of grain size, density and hardness determinations, and of tensile tests, are presented in Tables 1 to 6.

DISCUSSION OF RESULTS

Phase I: Mg-Ag and Mg-Ag-Zr Alloys

Zirconium is a very efficient grain refiner of magnesium and is, therefore, used in several of its commercial alloys. Sauerwald[30] found that zirconium may be used as a grain refiner in magnesium-silver alloys.

The solubility of zirconium in pure magnesium is limited to approximately 0.65%, and the maximum content of zirconium is essential for optimum mechanical properties. As may be seen from Figure 3, silver additions to the magnesium-zirconium alloy melt markedly reduce the solubility of zirconium, which decreases to 0.4% in the 16% Ag alloy.

The effect of silver additions on grain size, hardness, and density is shown in Figure 4, for both the magnesium-silver and the magnesium-silver-zirconium alloy systems. The graph shows that the decrease in the solubility of zirconium does not affect the resultant grain size in the sand-cast test bar. Hardness of both the binary and the zirconium-containing alloys increases progressively with the silver content.

The effect of silver additions on the as-cast tensile properties of binary Mg-Ag, with and without zirconium additions, is presented in Figure 5. Maximum ultimate tensile strength was obtained at between 6% and 7% Ag; the yield strength increases progressively with the silver content; and the elongation starts to decrease above 8% Ag. The improvement of all properties as a result of zirconium additions is obvious.

Heat treatment of both the magnesium-silver and the magnesium-silver-zirconium alloys was carried out as follows: Solution heat treatmen for 16 hours at 450°C (840°F), which is 20°C (36°F) below the eutectic point; cooling in still air; and ageing for 48 hours at 150°C (300°F).

Figure 6 presents the tensile properties obtained on the heat treated binary magnesium-silver alloy test bars. It should be noted that alloys with up to 6% Ag do not respond to any of the heat treatments; alloys with higher silver contents show strengthening by solution treatment (both ultimate tensile strength and elongation increase markedly). None of the alloys shows any additional tensile property changes after the ageing treatments, in spite of the precipitation of the Mg_3Ag phase.

The tensile strength curves of the magnesium-silver alloys in the T4 and T6 conditions show a very sharp peak at 10-11% Ag, and it seems that in this composition range the silver content is very critical if optimum strength is to be obtained.

The effect of heat treatment on the tensile properties of the magnesium-silver-zirconium alloys is shown in Figure 7. As may be seen, zirconium additions are responsible for higher ultimate tensile strength, yield strength and elongation values, but otherwise the shape of the curves shown is the same as in Figure 6. Again, alloys up to 6-7% Ag do not respond to any heat treatment, and higher silver additions make the alloy amenable to strengthening by solution treatment but do not confer age-hardenability.

The decrease of ultimate tensile strength and of elongation in the F and T5 conditions above 6% Ag in magnesium-silver and 6-7% Ag in magnesium-silver-zirconium, is due to the presence of the brittle Mg_3Ag compound in the as-cast structure. Similar decreases in properties in the T4 and T6 conditions occur at 11% Ag in magnesium-silver, and at 10% Ag in magnesium-silver-zirconium alloys.

Phase II: Mg-Ag-Zn-Zr Alloys (Exploratory Study)

In both series of the magnesium-silver and the magnesium-silver-zirconium alloys, ageing had no effect at all on the mechanical properties of the alloys. It was decided, therefore, to improve the amenability to age-hardening by means of further alloying additions. Earlier work on magnesium-zinc[1] and magnesium-zinc-zirconium[29] casting alloys suggested that zinc would be the most promising addition element.

The second phase of the investigation consisted, therefore, of an exploratory study of the magnesium-silver-zinc-zirconium alloy system. A fixed weight ratio of silver-to-zinc contents of 1.65:1 (or 1:1 atomic ratio) was arbitrarily chosen for this series. In order to distinguish this from the later series, where the silver and zinc were present in different ratios, this fixed ratio is being referred to, in Figure 8, as AgZn.

Figure 8 illustrates the effect of the combined silver-zinc additions on the mechanical properties of the magnesium-zirconium alloy in the as-cast and various heat treated conditions. Heat treatment for this series was as follows: Solution heat treatment for 16 hours at 425°C (800°F), cooling in still air, and ageing for 48 hours at 150°C (300°F). The solution heat treating temperature was chosen as 5°C (9°F) below the lowest solidus determined for any of the alloys in this series.

The choice of this arbitrary solution heat treatment temperature for the whole series of alloys (instead of using, for each individual alloy, a proper temperature in relation to its solidus) was necessitated by limitations of the time allotment for the investigation, although it was realized that optimum mechanical properties could not be obtained in this way. It was hoped that this limited study would make possible the evaluation of the age-hardening potentialities of the alloys, and, if successful, thereby justify a more detailed investigation.

Figure 8 also shows that the as-cast (F) ultimate tensile strength of alloys containing more than 4% AgZn can be raised by solution heat treatment (T4) and, still more, by additional ageing (T6). The highest values were achieved after ageing without previous solution treatment (T5 condition). A similar increase in yield strength can be noted in both the T5 and the T6 conditions. As might be expected, the elongation values are increased after solution heat treatment, and ageing alone (T5) decreases elongation.

The results shown in this graph indicate very clearly that the addition of zinc to magnesium-silver-zirconium alloys was successful and, as was hoped, developed a system responsive to age-hardening.

As will be appreciated, the combination of 46,000 psi ultimate tensile strength and 34,000 psi 0.2% yield strength with an elongation of some 5% is very attractive commercially in any magnesium casting alloy, and hitherto could be obtained only in the highest-strength sand-casting alloy ZK61A-T6 (Mg-6Zn-Zr)[29].

Phase III: Mg-Ag-Zn-Zr Alloys (Detailed Study)

In view of the exploratory results on magnesium-silver-zinc-zirconium alloys, the next phase of the study was to investigate this system in more detail. A total of 77 experimental alloy compositions was prepared, covering the range of silver contents from 0-16% and zinc contents from 1-8%. In each alloy, the zirconium content was kept at the maximum solubility to ensure effective grain refinement. Figures 9-11 summarize the results obtained in the as-cast and various heat treated conditions.

The heat treating cycles were similar to those for the Mg-(AgZn)-Zr alloys, with the exception of the solution heat treating temperature, which was 415°C (780°F) for the same arbitrary reasons as stated earlier.

Figure 9 illustrates the effect of the silver and zinc contents on the ultimate tensile strength. The lines of these ternary diagrams represent compositions having the same ultimate tensile strength, given in kpsi (1000 psi). The first graph shows that for alloys in the as-cast condition there is an area of maximum strength of 40-42 kpsi at approximately 4.5% Zn and 2% Ag. In the T4 condition, this high strength area is slightly enlarged and shifted to higher zinc and higher silver contents; the maximum strength is also slightly higher here.

The graph at the lower left (Figure 9) shows that ageing without solution treatment appreciably increases the tensile strength values (to 44-46 kpsi at 3.5% Zn, 5% Ag) and moves the maximum strength region toward lower zinc and higher silver contents. The lower right-hand graph indicates that ageing after solution treatment increases the tensile strength without shifting the location of the maximum value when compared to the T4 condition. It should be emphasized that the solution temperature was fixed much too low for most of the alloys and that this, of course, precluded obtaining maximum solid solubility of the alloying elements in alloys having appreciably higher solidus temperatures.

Figure 10 presents the yield strength values of the alloys. Maximum yield strength in the "as-cast" condition was obtained for an alloy of approximately 6% Zn and 5% Ag. It was found that this maximum value is critically dependent on the zinc content and that a small increase of zinc reduces the yield strength considerably.

The upper right graph of Figure 10 shows that solution heat treatment decreases the yield strength. Ageing after solution heat treatment resulted in some improvement of the yield strengths, but it should be appreciated that a much greater improvement might be realized if optimum solution temperatures and/or times were used.

As is shown in the lower left graph of Figure 10, ageing without previous solution heat treatment was much more effective and a very high yield strength, 36,000 psi, was obtained in alloys containing 5% Zn and 10-11% Ag.

Figure 11 shows the elongation values obtained in the various conditions. As would be anticipated, the elongation decreases in the region of high alloy concentration.

FURTHER WORK

The results of the above investigation of the magnesium-silver-zinc-zirconium system disclosed a range of casting alloys of remarkably high properties. It became obvious that additional work on the most promising alloys in this system was necessary and that it should include (a) a more detailed study of proper heat treating conditions to improve the response of solution heat treated material to age-hardening and (b) the exploration of various foundry characteristics of the finally selected alloys.

After closer study of the effect of alloy content on the mechanical properties (Figures 6-9), it was decided that the range of alloys meriting a more detailed investigation of proper heat treatment should contain 4-7% Zn and 2-5% Ag, and preferably the sum of Zn + Ag should be less than 10% (Figure 6). The choice of an alloy having optimum properties (best compromise between strength and ductility) must, of course, also be affected by economic considerations (e.g., maximum silver content).

CONCLUSIONS

1. Silver additions decrease the solubility of zirconium in molten magnesium without affecting the resultant grain size.

2. Mg-Ag and Mg-Ag-Zr alloys of higher silver content are amenable to strengthening by solution heat treatment, but do not respond to age-hardening.

3. Alloys which respond to age-hardening can be developed by addition of zinc to the Mg-Ag-Zr system.

4. Further work on proper heat treating conditions of the most promising Mg-Zn-Ag-Zr alloys and on their foundry characteristics is under way.

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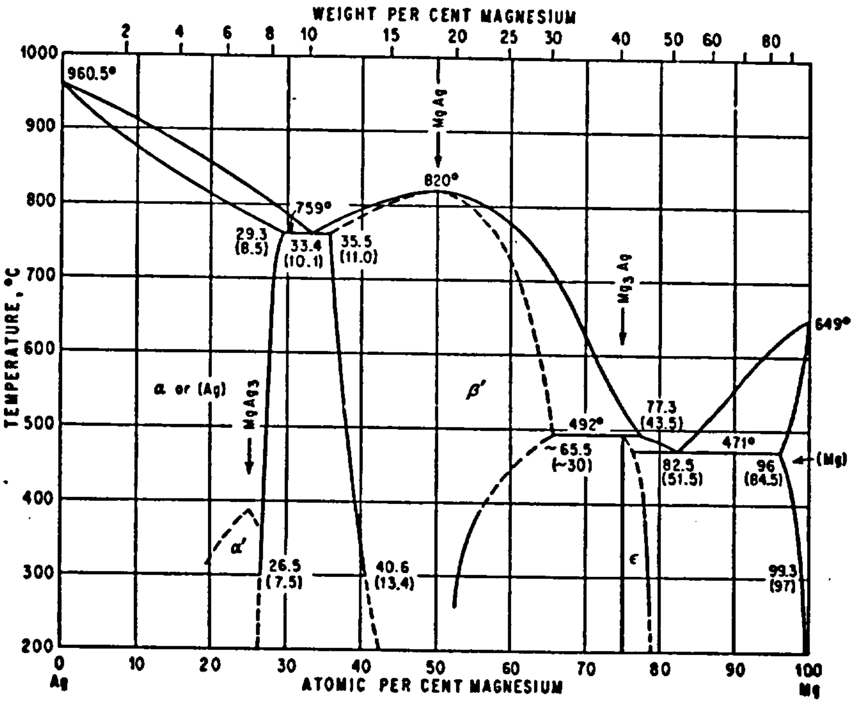

Figure 1. Ag-Mg alloy equilibrium diagram (according to Hansen and Anderko[9]).

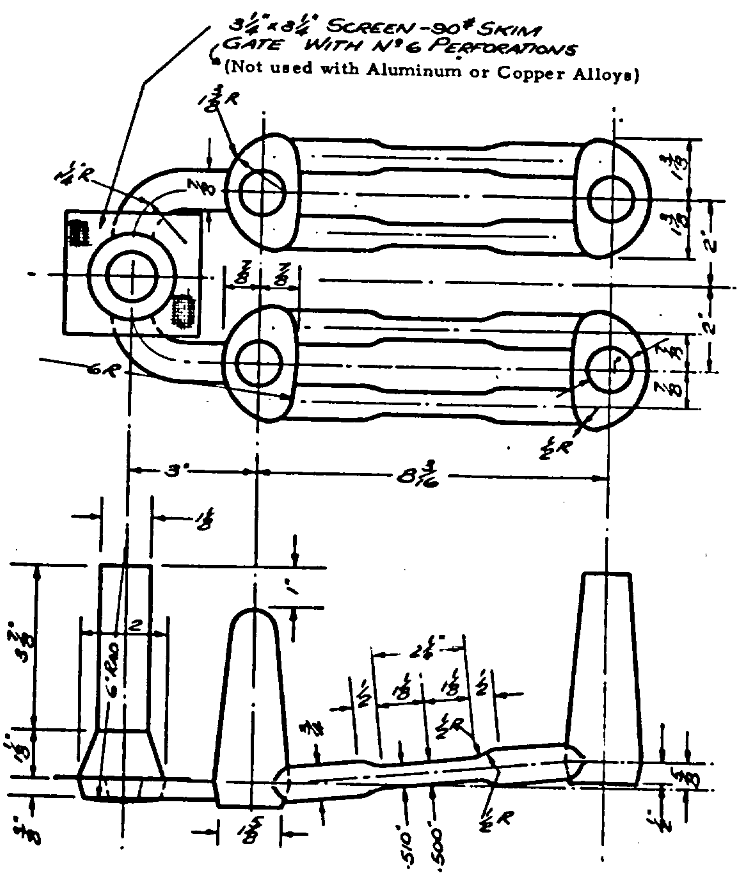

Figure 2. Test bar design according to Canadian draft standard CSA.HG.1-1956 and U. S. Federal Specification QQ-M-56.

The Effect of Silver on Solubility of Zirconium in Molten Magnesium (Under Experimental Foundry Conditions)

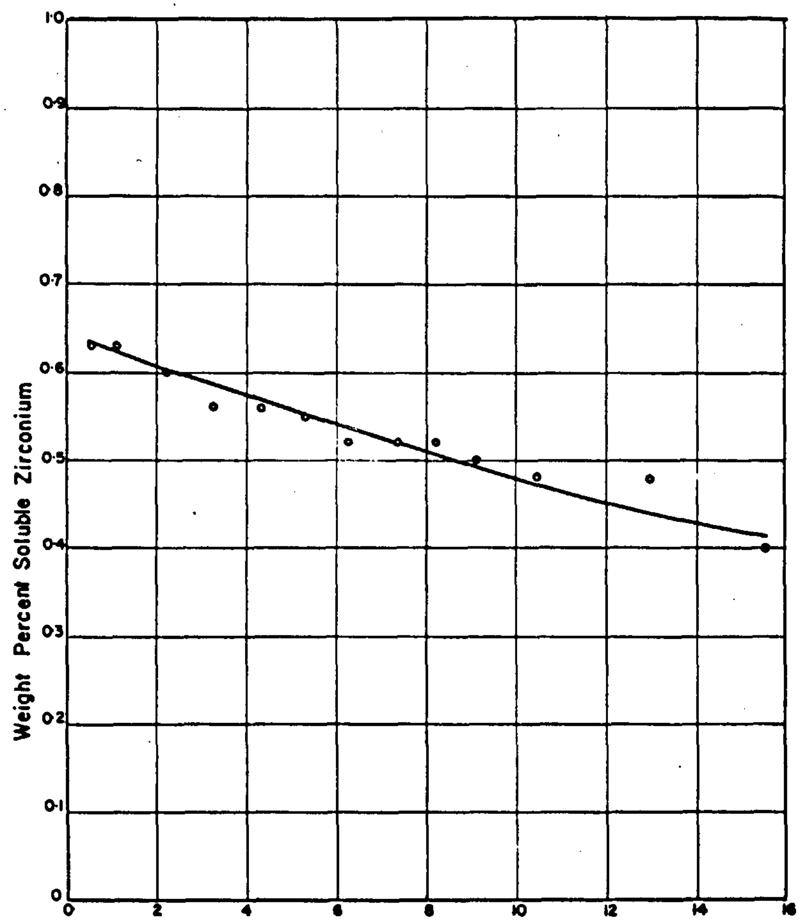

Figure 3.

Properties of Sand-Cast Mg-Ag and Mg-Ag-Zr Alloys As Cast (F) Condition

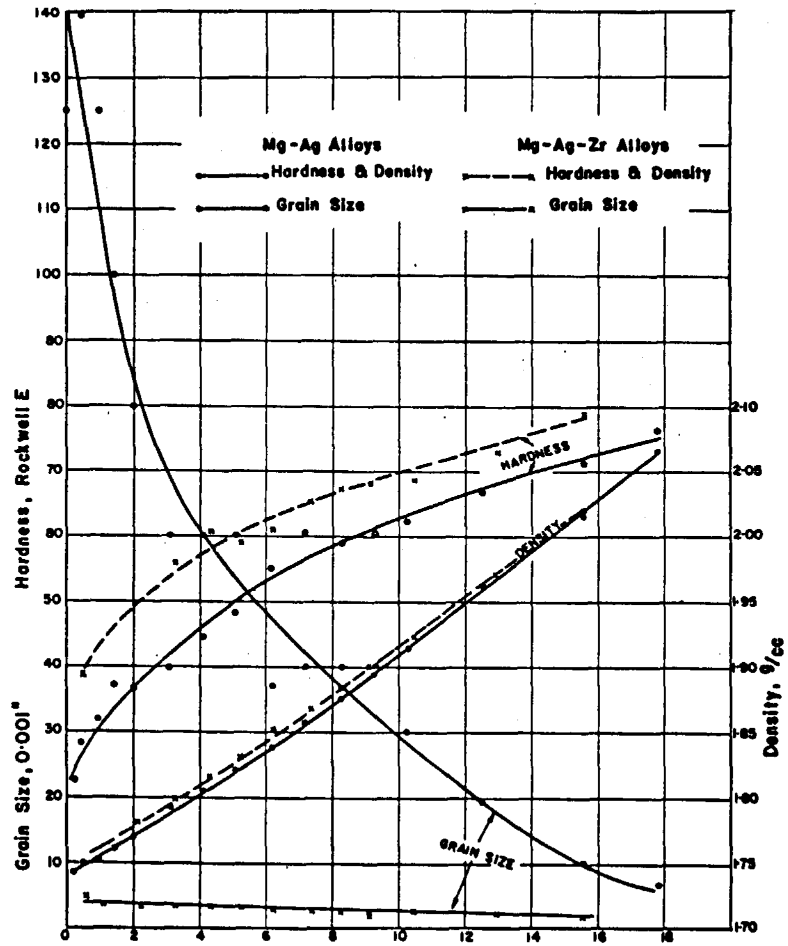

Figure 4.

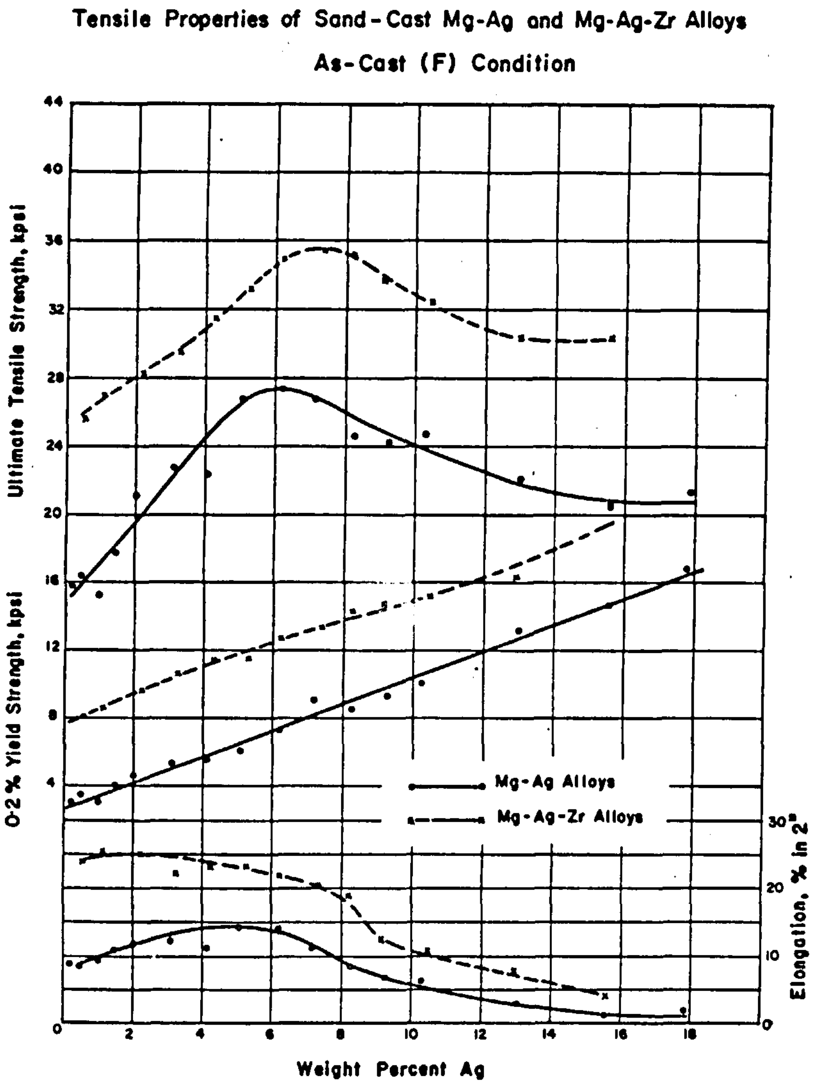

Figure 5.

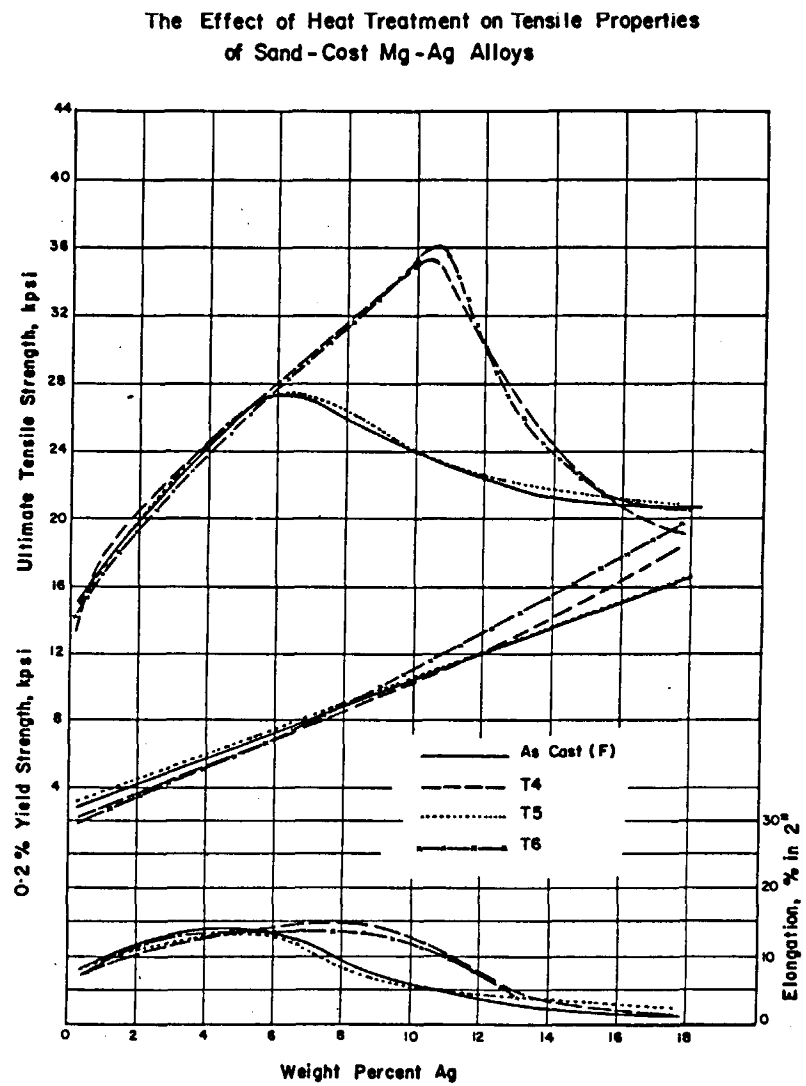

Figure 6.

The Effect of Heat Treatment on Tensile Properties
of Sand-Cast Mg-Ag-Zr Alloys

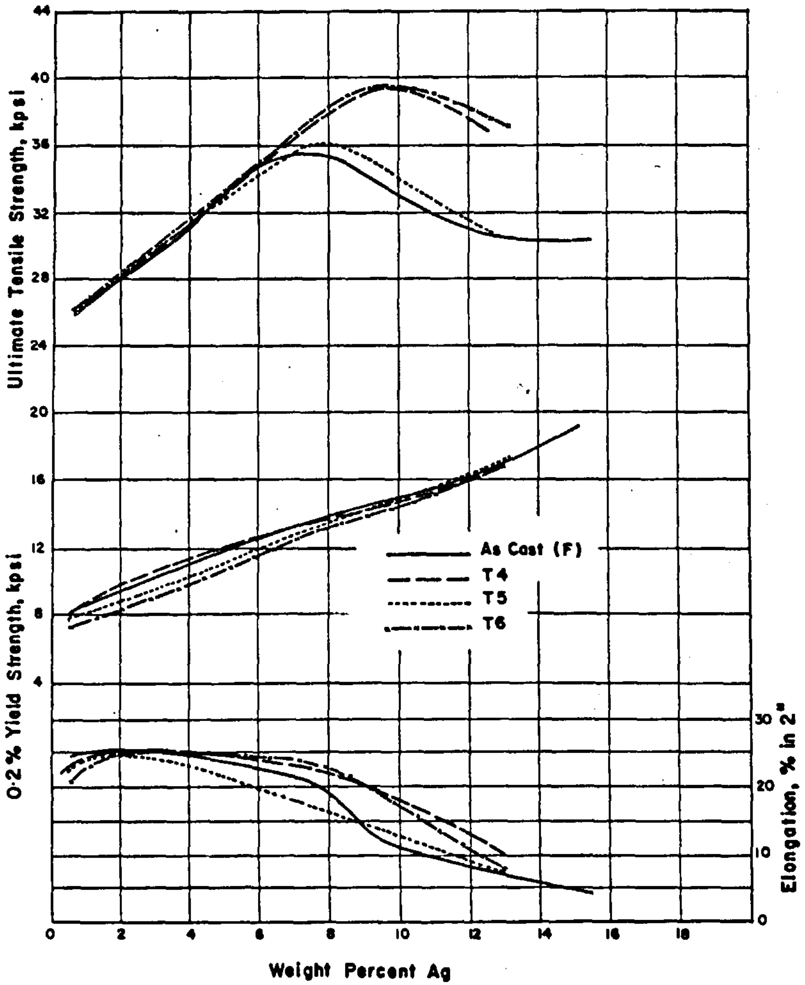

Figure 7.

The Effect of Heat Treatment on Tensile Properties
of Sand-Cast Mg-AgZn-Zr Alloys

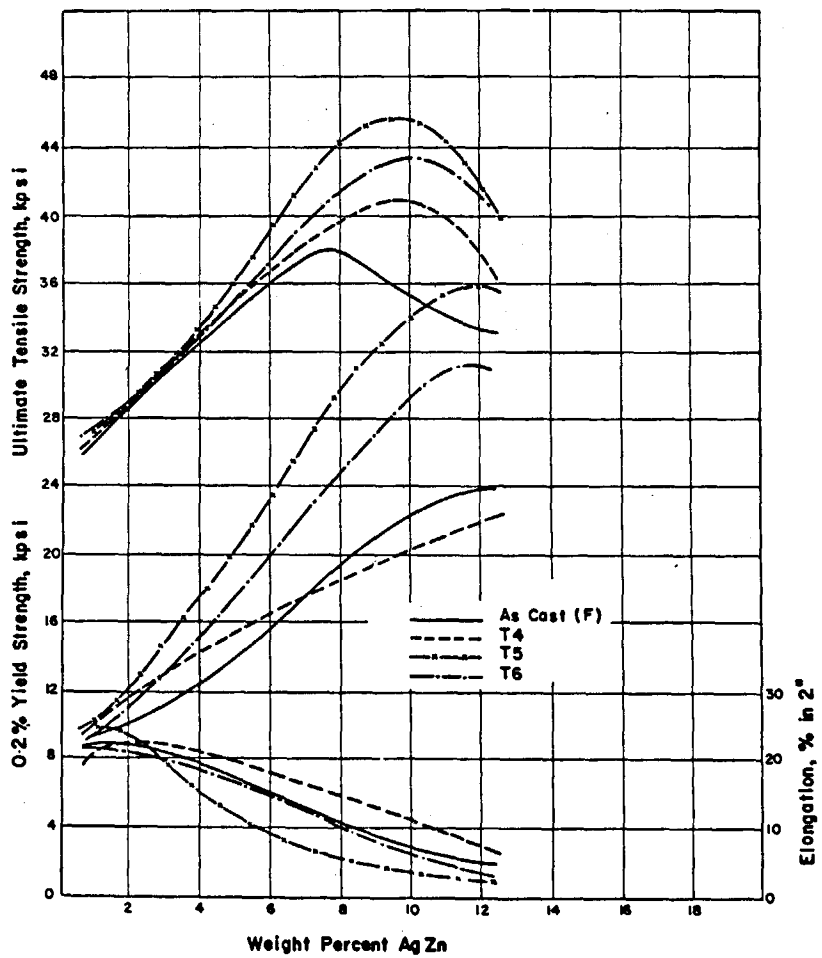

Figure 8.

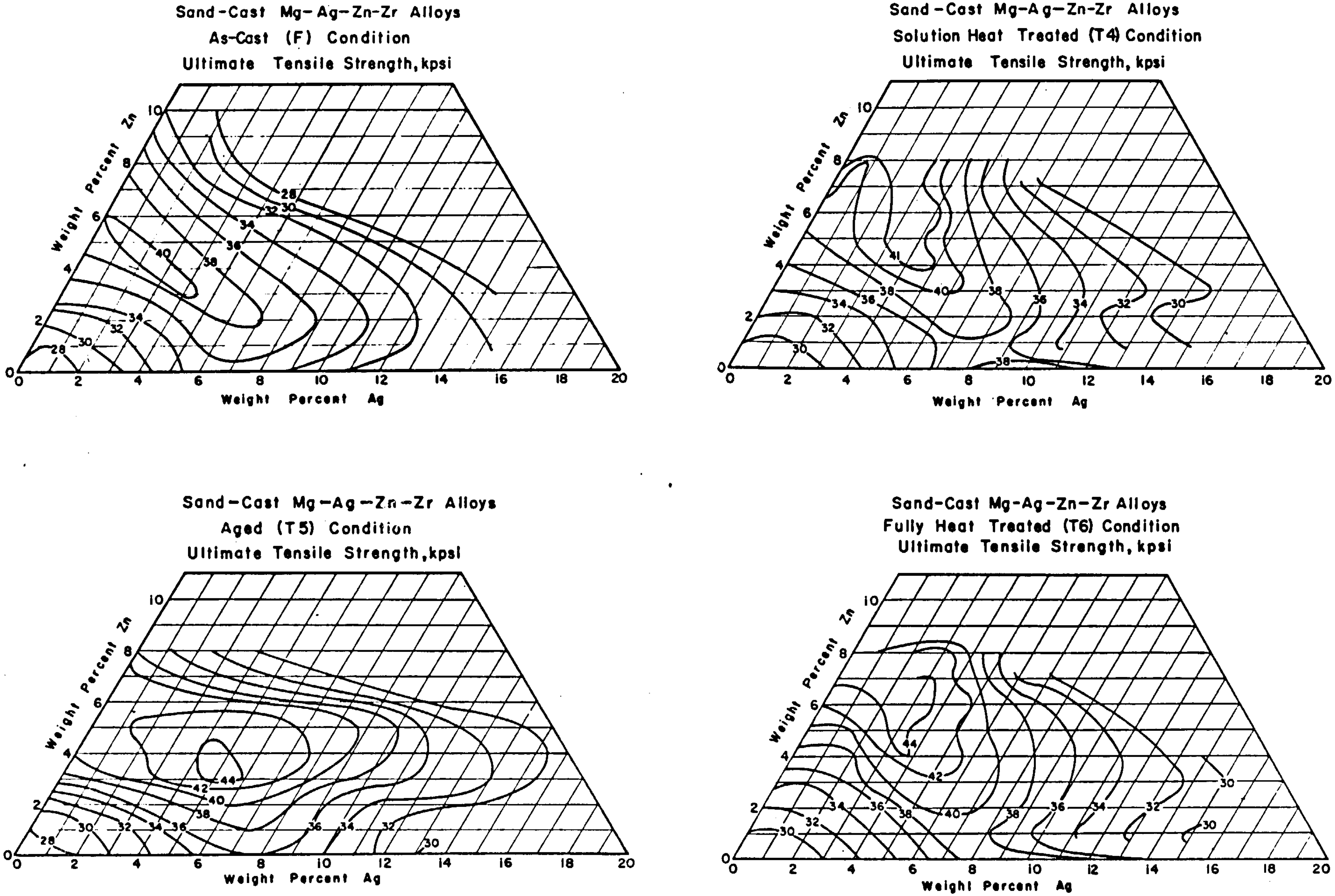
Sand-Cast Mg-Ag-Zn-Zr Alloys
As-Cast (F) Condition
Ultimate Tensile Strength, kpsi
Weight Percent Zn
Weight Percent Ag
Sand-Cast Mg-Ag-Zn-Zr Alloys
Solution Heat Treated (T4) Condition
Ultimate Tensile Strength, kpsi
Weight Percent Zn
Weight Percent Ag
Sand-Cast Mg-Ag-Zn-Zr Alloys
Aged (T5) Condition
Ultimate Tensile Strength, kpsi
Weight Percent Zn
Weight Percent Ag
Sand-Cast Mg-Ag-Zn-Zr Alloys
Fully Heat Treated (T6) Condition
Ultimate Tensile Strength, kpsi
Weight Percent Zn
Weight Percent Ag

Figure 9.

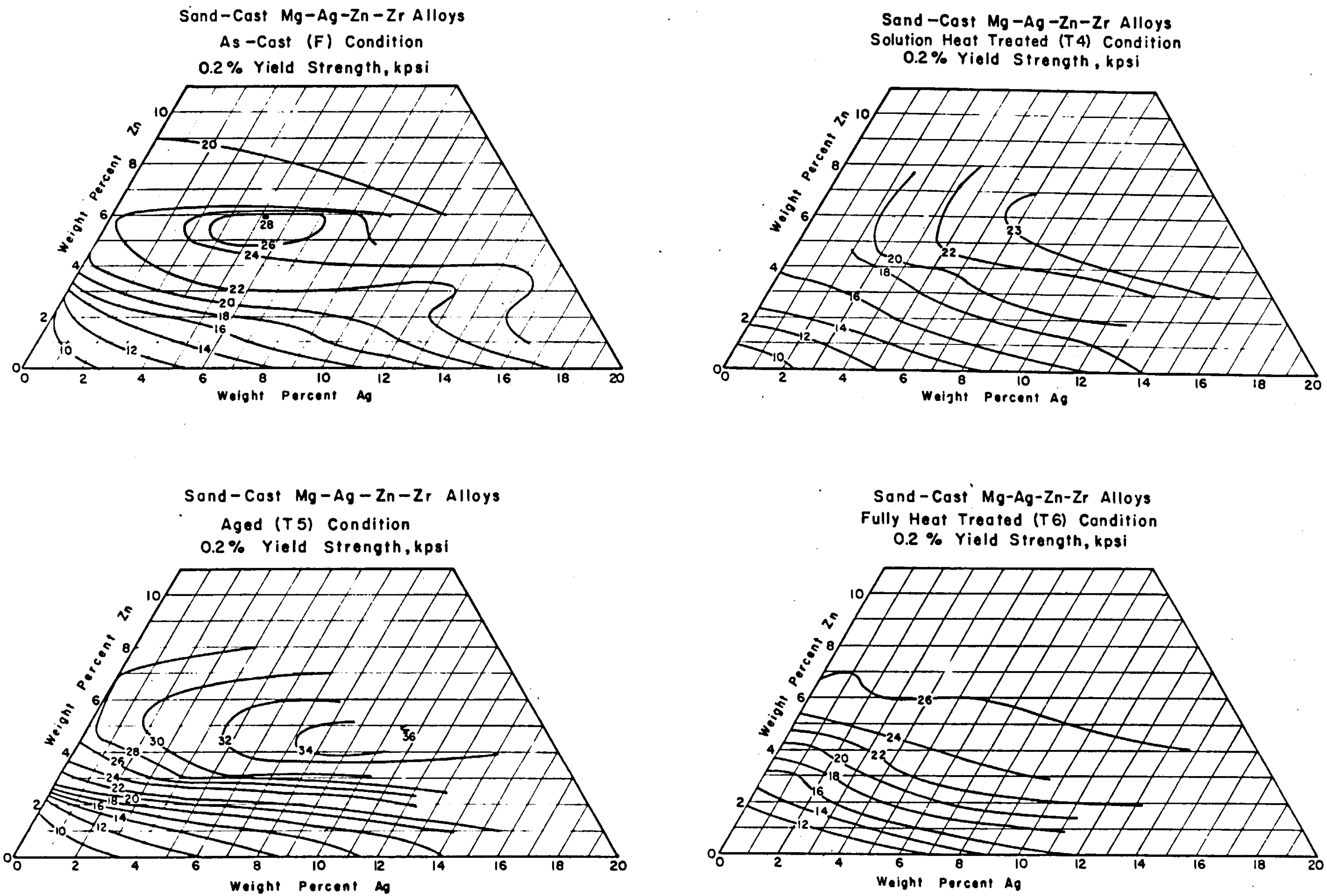
Sand-Cast Mg-Ag-Zn-Zr Alloys
As-Cast (F) Condition
0.2% Yield Strength, kpsi
Weight Percent Zn
Weight Percent Ag
Sand-Cast Mg-Ag-Zn-Zr Alloys
Solution Heat Treated (T4) Condition
0.2% Yield Strength, kpsi
Weight Percent Zn
Weight Percent Ag
Sand-Cast Mg-Ag-Zn-Zr Alloys
Aged (T5) Condition
0.2% Yield Strength, kpsi
Weight Percent Zn
Weight Percent Ag
Sand-Cast Mg-Ag-Zn-Zr Alloys
Fully Heat Treated (T6) Condition
0.2 % Yield Strength, kpsi
Weight Percent Zn
Weight Percent Ag

Figure 10.

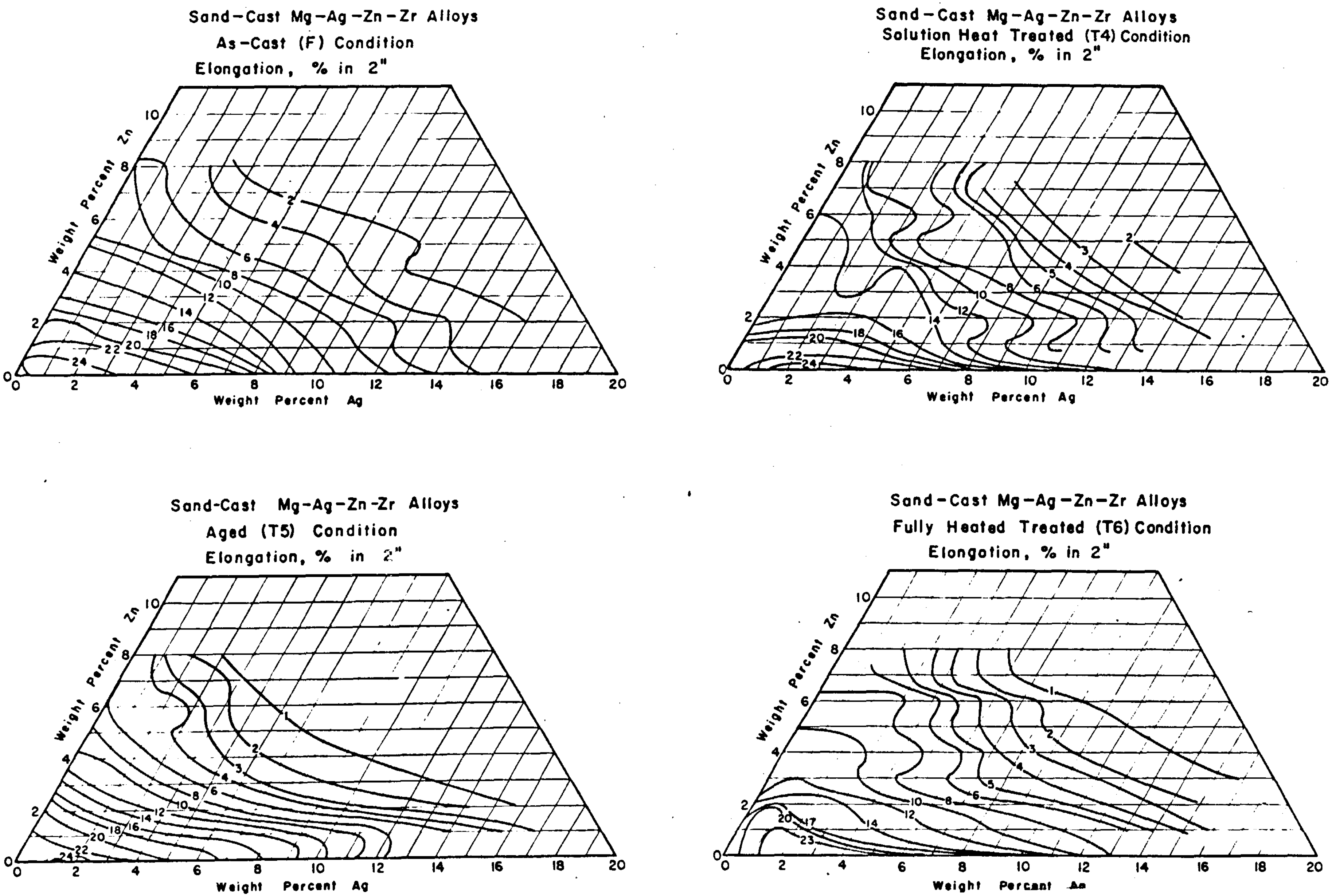
Sand-Cast Mg-Ag-Zn-Zr Alloys
As-Cast (F) Condition
Elongation, % in 2"
Weight Percent Zn
Weight Percent Ag
Sand-Cast Mg-Ag-Zn-Zr Alloys
Solution Heat Treated (T4) Condition
Elongation, % in 2"
Weight Percent Zn
Weight Percent Ag
Sand-Cast Mg-Ag-Zn-Zr Alloys
Aged (T5) Condition
Elongation, % in 2"
Weight Percent Zn
Weight Percent Ag
Sand-Cast Mg-Ag-Zn-Zr Alloys
Fully Heated Treated (T6) Condition
Elongation, % in 2"
Weight Percent Zn
Weight Percent Ag

Figure 11.

TABLE 1

As-Cast Properties of Sand-Cast Mg-Ag Alloys

Melt No.	Ag, %	Grain Size	Density	As-Cast Properties			Hardness, Rockwell "E"			
				UTS, kpsi	YS, kpsi	El, % in 2 in.	"F"	T4	T5	T6
4409	0.19	125.0	1.742	15.8	3.07	9.0	22.5	11.8	20.8	15.3
4407	0.45	140.0	1.750	15.4	3.51	8.5	28.2	21.5	27.3	24.5
4406	0.96	125.0	1.752	15.2	3.11	9.3	31.8	25.3	28.0	23.8
4404	1.46	100.0	1.760	17.7	4.08	10.7	37.2	28.5	32.5	24.5
4403	1.99	80.0	1.769	21.1	4.64	11.8	26.7	35.5	31.5	26.0
4401	3.08	60.0	1.786	22.8	5.30	12.3	39.8	44.3	37.0	40.5
4400	4.08	60.0	1.804	22.3	5.63	11.0	44.5	45.0	39.0	42.5
4399	5.07	60.0	1.820	26.8	6.13	14.2	48.3	48.5	41.0	48.8
4397	6.18	37.0	1.837	27.4	7.39	13.8	56.5	51.0	53.0	49.5
4395	7.16	40.0	1.857	26.8	9.09	11.2	60.5	57.8	53.0	58.0
4384	8.25	40.0	1.875	24.6	8.62	8.5	59.0	57.8	53.8	59.5
4383	9.26	40.0	1.894	24.3	9.32	6.7	60.5	61.0	56.5	63.3
4382	10.25	30.0	1.914	24.7	10.1	6.3	62.2	63.8	56.8	66.0
4381	13.00	15.0	1.962	22.1	13.2	3.2	66.7	68.5	64.5	72.0
4380	15.54	10.0	2.015	20.5	14.7	1.3	71.0	73.0	69.3	74.0
4379	17.80	7.0	2.067	21.4	16.9	2.0	76.5	75.3	74.8	77.5

TABLE 2

Effect of Heat Treatment on Tensile Properties of Sand-Cast Mg-Ag Alloys

Melt No.	Ag, %	Temper T4			Temper T5			Temper T6		
		UTS, kpsi	YS, kpsi	El, % in 2 in.	UTS, kpsi	YS, kpsi	El, % in 2 in.	UTS, kpsi	YS, kpsi	El, % in 2 in.
4409	0.19	13.3	2.25	6.75	14.7	3.17	8.0	14.0	2.12	7.5
4407	0.45	19.1	2.62	10.5	17.0	3.40	9.5	16.4	2.54	8.3
4406	0.96	16.3	3.18	6.75	16.0	3.30	9.75	15.0	2.58	7.5
4404	1.46	19.1	3.14	10.5	18.9	3.70	10.25	18.8	3.27	9.5
4403	1.99	20.3	3.90	10.0	20.6	4.40	11.5	20.8	3.77	12.0
4401	3.08	22.0	5.65	11.5	23.4	6.40	11.75	22.4	5.42	11.8
4400	4.08	22.4	5.93	9.75	22.8	6.44	10.75	23.2	5.52	11.5
4399	5.07	26.2	7.04	14.0	26.2	7.22	13.5	26.6	6.14	13.5
4397	6.18	27.9	6.95	14.0	27.1	7.61	13.0	26.8	6.57	11.9
4395	7.16	30.8	8.13	14.75	27.4	9.01	10.5	30.0	8.66	13.3
4384	8.25	31.5	8.30	12.75	25.1	9.04	7.75	31.8	9.40	12.8
4383	9.26	33.3	9.63	14.75	23.3	9.25	6.0	33.5	10.2	13.3
4382	10.25	36.1	10.4	15.5	25.1	10.9	7.25	36.9	12.5	14.3
4381	13.00	26.6	14.7	4.75	22.4	13.4	3.75	26.1	15.1	3.5
4380	15.54	21.1	16.2	2.25	20.9	14.4	3.5	21.4	17.6	0.5*
4379	17.80	19.3	18.4	1.25	21.4	16.6	2.0	20.6	19.6	0.5*

* Broke outside gauge length.

TABLE 3

As-Cast Properties of Sand-Cast Mg-Ag-Zr Alloys

Melt No.	Ag, %	Zr, %	Grain Size	Density	As-Cast Properties			Hardness, Rockwell "E"			
					UTS, kpsi	YS, kpsi	El, % in 2 in.	"F"	T4	T5	T6
4442	0.56	0.63	5.0	1.754	25.6	8.00	24.0	38.8	36.0	35.8	36.0
4440	1.12	0.63	3.5	1.763	26.5	8.49	25.5	44.3	41.0	39.3	39.8
4437	2.22	0.60	3.5	1.781	28.4	9.62	25.0	49.5	45.0	45.3	45.3
4434	3.23	0.56	3.5	1.798	29.5	10.6	22.2	55.7	52.5	48.8	49.0
4431	4.28	0.56	3.5	1.814	31.5	11.4	23.2	60.7	56.3	52.0	54.5
4426	5.27	0.55	3.2	1.830	33.2	11.5	23.2	59.0	56.8	56.5	57.5
4423	6.21	0.52	3.0	1.852	35.0	12.7	22.0	61.0	59.5	59.3	61.0
4421	7.36	0.52	2.8	1.867	35.4	13.3	20.5	65.2	62.5	62.0	65.3
4419	8.22	0.52	2.8	1.882	35.2	14.3	18.7	67.3	65.0	64.3	65.8
4417	9.12	0.50	2.6	1.901	33.7	14.8	12.5	68.0	65.0	66.0	69.5
4415	10.44	0.48	2.5	1.923	32.5	15.2	10.3	68.5	67.8	64.3	71.8
4414	12.96	0.48	2.3	1.970	30.4	16.4	7.7	72.8	73.3	70.5	74.5
4410	15.52	0.40	1.8	2.020	30.3	20.8	4.0	79.0	-	-	-

TABLE 4

Effect of Heat Treatment on Tensile Properties of Sand-Cast Mg-Ag-Zr Alloys

Melt No.	Ag, %	Zr, %	Temper T4 UTS, kpsi	Temper T4 YS, kpsi	Temper T4 El, % in 2 in.	Temper T5 UTS, kpsi	Temper T5 YS, kpsi	Temper T5 El, % in 2 in.	Temper T6 UTS, kpsi	Temper T6 YS, kpsi	Temper T6 El, % in 2 in.
4442	0.56	0.63	25.6	8.01	20.3	25.6	7.3	22.25	26.0	7.2	20.0
4440	1.12	0.63	26.7	9.13	25.8	26.7	8.3	24.25	26.9	8.0	23.8
4437	2.22	0.60	28.4	10.2	25.0	28.4	9.1	25.0	28.7	8.8	24.0
4434	3.23	0.56	30.2	10.1	25.3	30.3	9.6	22.25	30.5	9.3	24.5
4431	4.28	0.56	31.4	11.2	22.0	31.6	10.6	20.5	32.1	10.4	22.3
4426	5.27	0.55	33.3	11.8	22.8	32.6	11.1	19.25	33.6	11.1	22.5
4423	6.21	0.52	35.7	12.5	21.5	34.5	12.0	18.75	35.8	12.5	22.5
4421	7.36	0.52	37.0	13.6	22.5	36.0	13.0	21.0	37.4	12.8	25.0
4419	8.22	0.52	38.1	13.6	21.0	35.4	13.5	17.0	38.7	13.2	23.25
4417	9.12	0.50	39.1	13.9	17.75	35.9	14.0	15.75	39.1	13.9	17.0
4415	10.44	0.48	37.3	14.6	20.5	33.1	14.4	11.5	39.5	14.5	17.25
4414	12.96	0.48	37.2	17.4	9.25	30.3	17.2	7.0	37.3	17.6	8.0

TABLE 5

Effect of Heat Treatment on Tensile Properties of Sand-Cast Mg-Ag-Zn-Zr Alloys

Melt No.	Composition, %				Temper F (As-Cast)			Temper T4			Temper T5			Temper T6		
	Ag	Zn	Zr sol.	Ag + Zn	UTS, kpsi	YS, kpsi	El, % in 2 in.	UTS, kpsi	YS, kpsi	El, % in 2 in.	UTS, kpsi	YS, kpsi	El, % in 2 in.	UTS, kpsi	YS, kpsi	El, % in 2 in.
4533	0.31	0.23	0.60	0.54	26.0	9.4	21.5	26.2	9.3	19.0	26.5	9.8	23.8	27.3	8.8	22.0
4532	0.50	0.47	0.60	0.97	26.8	9.3	23.0	27.0	10.2	20.0	27.7	9.7	25.0	27.0	9.5	24.5
4531	1.37	0.86	0.56	2.23	28.2	10.2	22.0	29.1	12.3	24.5	29.5	11.8	23.8	27.8	11.3	16.0
4528	1.86	1.47	0.60	3.33	32.3	12.8	18.0	32.8	14.5	19.25	33.1	16.1	15.0	33.3	15.4	18.5
4527	3.45	2.36	0.55	5.81	34.2	13.7	18.25	35.3	14.6	18.5	35.4	19.3	9.0	36.3	17.0	18.0
4526	4.61	2.89	0.56	7.50	38.8	19.0	12.0	38.8	17.3	15.0	43.2	29.6	5.8	40.7	23.6	10.5
4525	7.15	4.06	0.59	11.21	33.8	24.1	5.5	39.8	21.0	10.0	44.2	36.0	3.0	42.6	32.2	5.0
4524	7.88	4.51	0.57	12.39	33.3	23.4	5.75	36.4	22.7	6.25	40.3	35.4	2.5	39.6	28.5	3.0

TABLE 6

Properties of Sand-Cast Mg-Ag-Zn-Zr Alloys

Melt No.	Composition, %			Density	Grain Size	Temper F (As-Cast)			Temper T4			Temper T5			Temper T6		
	Ag	Zn	Zr			UTS, kpsi	YS, kpsi	% El	UTS, kpsi	YS, kpsi	% El	UTS, kpsi	YS, kpsi	% El	UTS, kpsi	YS, kpsi	% El
4721	nil	1.05	0.64	-	3.5	27.1	8.8	24.0	30.3	9.9	18.5	-	-	-	30.7	9.7	18.3
4722	nil	2.05	0.71	-	3.5	30.1	11.3	19.0	32.3	12.9	14.3	-	-	-	32.2	13.0	11.5
4723	nil	3.03	0.73	-	3.0	33.4	15.7	15.5	34.0	15.6	13.0	-	-	-	34.6	15.9	11.3
4724	nil	4.25	0.73	-	2.5	37.4	20.7	13.5	36.3	16.2	13.0	-	-	-	38.1	20.0	11.3
4725	nil	5.13	0.74	-	2.5	37.8	22.4	10.0	37.0	16.3	13.5	-	-	-	40.2	23.3	9.3
4726	nil	5.99	0.75	-	2.4	39.8	23.5	10.0	39.2	17.4	13.5	-	-	-	41.9	25.3	7.3
4727	nil	7.26	0.74	-	3.1	37.6	21.0	9.5	41.2	16.7	14.0	-	-	-	45.1	26.4	7.8
4728	nil	8.01	0.66	-	3.5	36.4	21.1	9.3	41.8	16.4	15.5	-	-	-	45.3	26.6	8.0
4608	1.01	1.02	0.53	1.775	3.0	28.7	10.6	23.3	29.9	11.5	19.5	28.7	10.1	20.5	29.6	11.3	22.0
4606	1.99	0.89	0.56	1.789	2.7	29.7	11.7	20.8	29.7	11.5	20.5	29.8	11.4	20.3	30.6	11.6	23.2
4604	2.91	0.97	0.57	1.805	2.8	31.0	11.9	22.0	31.4	11.6	19.0	31.2	11.5	20.5	31.8	11.7	20.0
4602	3.65	1.02	0.63	1.820	2.7	32.7	12.1	19.7	33.1	12.4	21.0	31.8	13.0	14.0	33.2	12.8	15.5
4600	4.83	1.07	0.58	1.842	2.5	34.7	14.1	17.5	33.2	13.5	14.3	35.6	15.9	14.5	35.2	14.1	14.0
4598	6.67	1.07	0.58	1.872	2.5	37.0	16.8	17.0	36.1	15.3	14.3	37.6	15.4	17.0	38.7	16.2	17.0
4596	9.08	1.12	0.47	1.915	2.0	35.1	17.7	11.2	35.9	16.3	11.0	36.4	16.7	12.8	36.7	17.2	10.0
4594	12.17	1.07	0.53	1.974	1.8	32.4	20.0	6.2	32.3	18.0	6.0	31.2	18.9	8.0	32.5	17.8	6.8
4593	15.71	0.99	0.48	2.049	1.8	29.7	23.3	2.5	29.4	19.6	4.0	31.1	22.2	3.0	29.4	20.0	3.0
4610	1.07	2.04	0.67	1.790	3.0	31.0	13.3	21.0	31.4	14.7	15.0	33.4	15.2	16.0	32.3	13.7	15.7
4609	2.00	1.89	0.65	1.803	2.8	32.4	14.0	17.3	32.7	14.3	17.0	33.9	16.3	13.5	33.7	15.0	16.0
4607	3.69	1.94	0.68	1.823	2.4	34.2	15.9	14.5	34.7	16.0	15.0	36.8	19.0	13.5	34.5	16.8	12.3
4605	3.90	1.91	0.60	1.837	2.4	34.5	15.5	14.7	32.3	14.4	11.0	36.7	18.9	10.5	36.5	16.7	12.8
4603	4.95	1.94	0.58	1.856	2.2	36.3	16.2	13.0	35.3	15.7	12.5	39.4	20.1	11.0	38.0	17.9	14.0
4601	6.25	1.94	0.59	1.887	2.2	38.6	16.6	14.2	39.3	17.5	12.5	40.2	22.7	8.3	41.6	20.3	10.5
4599	8.99	2.04	0.58	1.925	2.2	34.8	19.0	8.5	37.4	18.1	10.5	33.2	21.2	4.8	38.0	21.1	6.8
4597	11.99	2.02	0.54	1.989	1.8	33.1	21.9	6.0	31.2	19.9	6.0	34.2	24.2	3.5	33.0	21.5	4.0
4595	16.05	2.06	0.53	2.068	1.8	28.1	24.7	2.5	27.9	21.6	2.3	31.2	25.7	0.5	30.0	22.9	2.5

... continued

TABLE 6 (continued)

Melt No.	Composition, % Ag	Zn	Zr	Density	Grain Size	Temper F (As-Cast) UTS, kpsi	YS, kpsi	% El	Temper T4 UTS, kpsi	YS, kpsi	% El	Temper T5 UTS, kpsi	YS, kpsi	% El	Temper T6 UTS, kpsi	YS, kpsi	% El
4633	1.01	3.03	0.70	1.805	2.2	34.5	16.5	14.8	34.4	14.9	13.8	38.1	22.1	11.5	34.1	16.1	10.0
4631	2.03	3.01	0.71	1.823	2.5	35.6	18.9	12.7	35.4	15.8	13.0	39.8	24.2	10.8	35.5	17.4	11.0
4629	3.00	3.01	0.70	1.840	2.2	37.7	20.7	13.2	36.6	16.2	13.0	41.9	26.3	9.3	38.4	19.2	12.0
4627	3.99	3.06	0.65	1.857	2.2	40.6	21.7	14.3	38.1	16.9	15.0	43.4	29.1	7.0	41.6	22.7	10.0
4625	5.10	3.26	0.66	1.873	2.2	37.4	19.5	9.0	39.4	17.9	11.5	41.3	28.8	4.0	40.7	21.6	6.0
4623	6.16	3.03	0.66	1.897	2.0	39.2	20.5	11.5	40.3	19.1	12.0	44.5	30.7	4.0	41.7	22.9	6.8
4621	7.41	3.11	0.64	1.920	2.0	35.4	20.2	8.8	34.8	20.6	6.0	38.7	28.1	2.5	39.1	23.7	4.3
4619	8.44	3.06	0.61	1.938	2.1	33.8	21.1	6.0	36.4	20.3	7.0	39.6	31.2	2.5	37.3	23.6	5.0
4616	10.85	3.22	0.54	1.985	2.0	31.7	21.1	3.8	34.2	21.1	6.0	37.6	29.7	2.0	35.9	23.6	3.5
4614	12.59	3.06	0.58	2.025	1.8	29.3	21.2	2.7	32.0	21.7	4.0	34.1	28.5	1.0	32.7	24.3	2.0
4611	15.77	2.99	0.55	2.084	1.8	29.1	24.5	1.7	29.2	23.4	3.0	33.3	28.9	0.8	30.5	25.4	1.0
4636	0.98	3.77	0.74	1.819	2.5	37.4	18.8	13.2	36.4	15.9	15.0	40.1	26.0	10.5	37.1	19.2	11.0
4634	1.99	3.77	0.71	1.836	2.2	37.7	21.9	11.2	37.5	16.9	14.0	41.1	27.7	7.0	37.8	20.6	9.5
4632	2.89	3.77	0.69	1.853	2.1	39.2	22.7	11.3	39.6	17.4	15.8	43.7	30.0	6.0	41.0	21.7	10.5
4630	3.91	3.93	0.69	1.873	2.1	39.1	23.0	9.0	41.1	18.9	14.0	42.8	30.4	4.5	44.1	24.5	10.0
4628	4.94	3.98	0.70	1.887	2.0	38.4	22.4	9.5	41.0	19.8	10.0	43.6	31.6	3.3	43.1	24.7	7.3
4626	5.95	3.93	0.68	1.908	2.0	36.5	23.3	7.2	38.1	20.4	6.0	42.3	32.7	2.0	35.3	24.5	1.5*
4624	7.20	3.82	0.66	1.934	1.9	34.5	22.8	6.0	37.9	20.9	7.0	44.7	34.3	2.0	39.4	24.0	4.0
4622	8.80	3.88	0.65	1.965	1.8	32.9	24.1	4.7	34.7	22.0	6.0	40.3	33.2	1.8	37.1	25.0	2.3
4620	10.43	4.03	0.63	2.000	1.8	31.2	23.9	2.8	34.3	23.2	3.0	37.3	33.8	0.8	36.3	25.6	3.0
4617	12.51	3.93	0.64	2.043	2.0	28.1	22.6	1.0	30.0	23.0	2.5	36.3	33.2	0.8	31.7	25.9	1.5
4615	15.49	4.08	0.59	2.107	1.9	25.9	24.2	0.3	27.1	23.9	1.3	31.6	31.3	1.0	27.5	26.2	1.0*
4656	1.05	5.25	0.77	1.841	2.4	40.6	21.8	9.3	39.4	18.8	16.5	40.8	29.3	5.8	39.0	23.4	7.5
4654	2.06	5.36	0.80	1.863	2.2	39.7	22.7	7.7	40.3	19.2	12.0	43.0	30.3	5.0	42.8	25.0	9.0
4646	6.27	5.25	0.73	1.939	2.3	33.9	26.2	4.3	36.8	22.4	6.3	40.0	32.3	1.3	38.8	25.5	4.0
4644	7.41	5.20	0.71	1.956	2.1	33.4	23.5	4.8	35.9	22.7	5.8	43.9	35.0	0.5	38.0	26.1	2.0
4641	8.54	5.02	0.68	1.977	2.1	31.8	24.4	3.7	35.9	24.2	5.5	39.7	33.8	0.8	37.1	26.1	2.5
4639	10.04	5.05	0.68	2.010	2.3	29.1	23.6	2.5	32.9	23.2	4.0	38.7	35.2	1.0	33.3	26.0	1.5
4635	11.13	4.95	0.70	2.035	2.1	30.0	24.5	2.0	29.8	23.2	2.0	37.1	35.7	0.5	31.7	26.1	1.0

(* Flaw in fracture.)

... concluded

TABLE 6 (concluded)

Melt No	Composition, %			Density	Grain Size	Temper F (As-Cast)			Temper T4			Temper T5			Temper T6		
	Ag	Zn	Zr			UTS, kpsi	YS, kpsi	% El	UTS, kpsi	YS, kpsi	% El	UTS, kpsi	YS, kpsi	% El	UTS, kpsi	YS, kpsi	% El
4655	1.08	6.27	0.82	1.859	2.6	37.5	21.7	7.0	39.9	19.0	12.3	40.5	29.3	4.3	42.9	26.4	9.0
4653	2.17	6.27	0.81	1.885	2.4	38.5	22.0	7.0	39.9	19.7	9.5	38.3	28.4	5.5	44.2	26.4	8.0
4652	3.24	6.00	0.76	1.884	2.5	37.5	24.0	7.0	42.9	20.7	11.0	40.6	31.4	3.0	44.2	25.6	8.0
4650	4.21	5.99	0.75	1.909	2.3	35.5	26.9	4.8	41.1	21.9	6.5	39.6	31.6	1.0	43.5	25.7	6.0
4648	5.13	6.12	0.77	1.934	2.4	33.7	28.1	6.3	38.8	23.4	6.8	40.4	32.7	2.0	39.9	26.5	3.0
4647	5.38	6.07	0.77	1.935	2.5	32.4	27.0	5.5	37.0	22.5	5.8	38.1	30.9	1.0	41.6	26.1	4.0
4645	6.38	6.02	0.77	1.955	2.5	31.5	24.0	2.8	34.2	22.6	3.5	39.6	32.1	1.0	38.9	26.1	4.0
4642	7.52	5.87	0.73	1.977	2.7	30.1	25.3	2.8	33.3	23.4	3.0	37.5	32.2	0.8	35.6	26.2	1.0*
4640	9.12	5.81	0.70	2.007	2.7	26.3	23.9	1.7	30.7	24.5	3.5	34.0	31.5	1.3	33.1	26.1	1.0
4637	9.91	5.92	0.70	2.028	2.7	24.7	21.6	1.0	28.6	23.1	1.5	32.5	31.6	1.0	31.8	26.6	0.5
4668	1.03	6.99	0.81	1.871	3.2	36.7	21.2	7.0	40.0	19.4	10.0	38.9	29.2	3.5	40.7	26.1	4.0
4667	2.08	6.83	0.82	1.891	3.3	33.7	20.9	5.2	40.3	19.2	9.8	38.1	28.1	3.3	41.0	25.8	4.3
4665	3.15	6.96	0.75	1.913	3.8	30.8	20.5	3.8	40.8	19.9	7.8	34.1	26.7	2.5	44.3	25.2	6.0
4663	4.10	6.99	0.72	1.931	3.3	29.9	21.1	2.7	39.2	23.0	6.5	33.5	27.7	1.5	40.5	25.3	3.0
4661	5.10	6.88	0.72	1.951	3.5	28.0	21.1	2.0	34.0	23.0	3.5	34.3	28.7	1.3	38.0	25.3	2.0
4659	6.14	6.99	0.64	1.971	3.0	26.1	20.9	1.0	34.0	23.5	3.0	34.9	29.0	0.5	33.7	24.7	1.0
4657	7.11	6.94	0.60	1.993	2.9	25.2	20.5	1.2	30.0	21.9	2.5	32.1	30.0	0.5	32.3	25.5	0.5
4666	1.10	7.96	0.71	1.892	4.0	34.7	19.1	7.2	41.2	19.2	11.5	36.3	26.2	3.5	40.4	25.3	5.0
4664	2.15	7.85	0.71	1.909	3.5	33.2	20.8	4.0	43.5	19.0	11.5	34.6	27.2	1.3	42.2	26.1	5.0
4662	3.17	7.80	0.69	1.927	4.0	28.0	20.3	2.2	40.1	22.8	6.8	33.0	27.2	1.3	43.1	25.8	4.0
4660	4.16	7.80	0.68	1.947	3.8	26.3	20.2	1.2	39.2	21.1	7.0	31.2	26.6	0.8	39.5	24.8	2.5
4658	5.19	7.80	0.60	1.967	3.8	25.5	20.7	1.0	34.6	21.9	4.5	32.1	28.1	0.8	35.5	24.5	1.5

(* Flaw in fracture.)