J. W. Meier

CANADA

PROPERTIES OF SAND-CAST MAGNESIUM ALLOYS

Part III: Effect of Titanium Additions to Magnesium-Zinc Alloys

B. LAGOWSKI & J. W. MEIER

DEPARTMENT OF MINES AND TECHNICAL SURVEYS, OTTAWA

MINES BRANCH

RESEARCH REPORT

R 56

PHYSICAL METALLURGY DIVISION

JANUARY 1960

Price 75 cents

RELEASED FOR GENERAL DISTRIBUTION - 1964

Available by mail from the Queen's Printer, Ottawa,
and at the following Canadian Government bookshops:

OTTAWA
Daly Building, Corner Mackenzie and Rideau

TORONTO
Mackenzie Building, 36 Adelaide St. East

MONTREAL
Aeterna-Vie Building, 1182 St. Catherine St. West

or through your bookseller

A deposit copy of this publication is also available
for reference in public libraries across Canada

Price 75 cents Catalogue No. M38-1/56

Price subject to change without notice

ROGER DUHAMEL, F.R.S.C.
Queen's Printer and Controller of Stationery
Ottawa, Canada
1965

Mines Branch Research Report R56

PROPERTIES OF SAND-CAST MAGNESIUM ALLOYS

Part III: Effect of Titanium Additions to Magnesium-Zinc Alloys

by

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

ABSTRACT

A study was undertaken to determine the effect of titanium additions on the properties of sand-cast magnesium-zinc alloys. Results indicate that some grain refinement was obtained for alloys containing 1-8% Zn which resulted in improved mechanical properties.

The most effective grain refinement was obtained in the range of 6-7% Zn, with properties in the fully heat treated (T6) condition of UTS-39 kpsi, 0.2% YS - 24 kpsi and 8% elongation. Although these values are higher than those obtained on the binary Mg-Zn alloys, they are still not comparable with those obtainable from zirconium-containing alloys (ZK61-T6).

* Scientific Officer and ** Principal Metallurgist (Non-Ferrous Metals), Physical Metallurgy Division, Mines Branch, Department of Mines and Technical Surveys, Ottawa, Canada.

Direction des mines

Rapport de recherches R 56

PROPRIÉTÉS DES ALLIAGES DE MAGNÉSIUM COULÉS EN SABLE

Partie III: Effet des additions de titane dans les alliages de magnésium-zinc

par

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

RÉSUMÉ

Les auteurs ont entrepris de déterminer l'effet des additions de titane sur les propriétés des alliages de magnésium-zinc coulés en sable. Les résultats indiquent qu'un certain affinement du grain a été obtenu avec les alliages contenant de 1 à 8 pour cent de Zn, améliorant ainsi leurs propriétés mécaniques.

Le meilleur affinement du grain a été obtenu avec les alliages contenant de 6 à 7 pour cent de Zn. Après un traitement thermique (T6) ces alliages ont présenté les caractéristiques suivantes: résistance à la traction, 39 kpsi; limite conventionnelle d'élasticité (à 0.2 pour cent), 24 kpsi; allongement, 8 pour cent. Quoique ces valeurs soient plus fortes que celles obtenues avec les alliages binaires Mg-Zn, elles ne sont pas comparables aux valeurs obtenues avec les alliages contenant du zirconium (ZK61-T6)

*Agent scientifique, **Métallurgiste principal (métaux non ferreux), Division de la métallurgie physique, Direction des mines, ministère des Mines et des Relevés techniques, Ottawa, Canada.

CONTENTS

= = =

TABLES

FIGURES

INTRODUCTION

As part of the investigation on binary magnesium-zinc casting alloys, reported in the first two reports[1,2] of this series, a study was undertaken to explore the effects of titanium additions to these alloys.

The considerable success in the use of zirconium in grain refinement of magnesium and magnesium alloys prompted a parallel study of titanium additions. In view of the metallurgical similarity of titanium and zirconium, and from theoretical considerations of alloying principles, titanium appeared to offer attractive possibilities as an alloying element in magnesium alloys.

An exploratory investigation conducted in 1946-47 at these laboratories[9] had shown encouraging results obtained with titanium additions to magnesium-zinc alloys. In reviving this study it was hoped that titanium additions might also help to overcome difficulties encountered with layer-type porosity in some magnesium-zinc alloy compositions[1].

LITERATURE SURVEY

As early as 1938[3], attempts were made to introduce titanium into magnesium, and since that time several patents have been granted on magnesium alloys containing titanium. Two of these patents[4,5] claimed improved mechanical properties, in the presence of titanium, for magnesium alloys containing aluminum and other elements. The third patent[6] claimed improved physical and chemical properties, without any sacrifice in density, in magnesium alloys containing titanium, silicon, and various other elements.

Carapella[7] compiled data on the alloying behaviour of titanium in magnesium. The hexagonal, close-packed structure of titanium and the small relative difference in atomic diameters would favour the solid solution of titanium in magnesium, but the solubility would be expected to be restricted because of an apparent alloying valence of zero in magnesium and its relative electronegativity. Kroll[8] considered titanium an attractive possibility as an alloying element in magnesium.

Spence[9] reported improvement in as-cast properties and grain size of magnesium-zinc alloys to which titanium was added. The results, however, were inconclusive, and the grain refinement leading to improved properties could not be consistently produced by titanium additions. A maximum of approximately 0.037% Ti was found in the Mg-5% Zn alloy, using Mg-50% Ti master alloy as a source of titanium.

Aust and Pidgeon[10] investigated the solubility of titanium in liquid magnesium and reported that titanium dissolves to the extent of 0.0025% Ti at the freezing point of magnesium and the solubility increases with increasing temperature to 0.015% Ti at 850°C (1562°F).

Busk[11] suggested that the Mg-Ti system, like the Mg-Zr, shows a peritectic reaction.

Eisenreich[12] also investigated the solubility of titanium in magnesium, employing $TiCl_4$ saturated in dried $BaCl_2$. The results indicated that the solubility of titanium in liquid magnesium increased from approximately 0.003% at 655°C (1210°F) to 0.064% Ti at 760°C (1400°F). The presence of hydrogen was found to decrease the solubility of titanium, and when hydrogen was expelled by the addition of zirconium the solubility increased to 0.115% Ti at 800°C (1470°F). An equilibrium diagram was proposed showing a peritectic reaction at about 655°C (1210°F).

Eisenreich et al[13] also investigated the addition of titanium to binary magnesium alloys with silicon, manganese and aluminum, and found that titanium could not be introduced into liquid magnesium containing any of these elements. He also observed significant grain coarsening after addition of titanium tetrachloride to Mg-1.4% Si and Mg-0.6% Zr alloys.

Obinata et al[14] reported much higher values for solubility of titanium in magnesium, increasing from 0.17% at 700°C (1290°F) to 0.85% Ti at 1200°C (2190°F). Jones et al[15] found no grain refinement from additions of titanium in the form of Al-68 Ti master alloy to Mg-5% Zn alloy; no improvement in properties of hot-rolled sheet was found.

Nash et al[16] investigated the effect of titanium additions on as-cast structure and on mechanical properties of hot-rolled magnesium alloy sheet. Titanium was added as titanium sponge, titanium dioxide, halides of titanium, potassium fluotitanate, and Mn-35% Ti and Al-39% Mg-0.01% Ti master alloys. Some of these forms were added to magnesium alloy base compositions Ml, Z3, AZ31, AZ33, AZM331, and KO. The retention of titanium in magnesium was extremely small (maximum, 0.012% Ti) and no significant improvement in mechanical properties was achieved. Titanium dioxide was found to cause grain refinement.

EXPERIMENTAL PROCEDURE

Alloying Technique

Various means for introducing titanium into molten magnesium-zinc alloys were tried and evaluated by the following criteria:

a) Effectiveness in improving tensile properties
b) Reproducibility of the results
c) Ease of introduction

The additions of titanium were made to magnesium alloy containing approximately 6% Zn, since this alloy was found to be the most sensitive of the zinc series. The following materials as possible sources of titanium were available and were tried:

a) Potassium fluotitanate ($KTiF_6$)
b) Fused salt containing NaCl, KCl, $TiCl_3$ and $TiCl_2$
c) Magnesium-titanium-zinc master alloy prepared from titanium hydride
d) Commerical titanium tetrachloride ($TiCl_4$)
e) Purified titanium tetrachloride ($TiCl_4$)
f) Zinc-titanium master alloys

Introduction of $KTiF_6$ into Mg-6% Zn alloy resulted in very poor mechanical properties and very low titanium content (0.004% Ti), hence this source of material was eliminated from further testing. The addition of fused salt containing $TiCl_3$ and $TiCl_2$ was tried because of possible breakdown of $TiCl_3$ and $TiCl_2$ into titanium metal and $TiCl_4$, and subsequent reduction of the latter into Ti metal and forming $MgCl_2$. An alloy treated in this manner showed very poor mechanical properties and contained only 0.006% titanium. This method, too, was abandoned. The poor results obtained were believed to be due to the presence of HCl in the fused salt.

The next material used for introducing titanium into magnesium was a Mg-Ti-Zn master alloy prepared from titanium hydride. The magnesium alloy to which this material was added had very poor mechanical properties in spite of the fact that the titanium content was fairly high, 0.034% Ti. It was observed that the metal was very gassy, which would, of course, account for the low properties. This material, too, was eliminated from further testing.

The ingenious method used by Eisenreich(8) for introducing titanium into molten magnesium was then tried. In this method, dry barium chloride saturated with liquid titanium tetrachloride was submerged into molten magnesium. Eisenreich found that this arrangement resulted in a very gentle release of titanium tetrachloride vapour which was immediately reduced by magnesium.

Several melts were prepared, using commercial titanium tetrachloride, before it was learned that the resulting alloys contained no titanium but approximately 0.2 to 0.8% silicon, depending on the amount of $TiCl_4$ added. On checking the $TiCl_4$ for purity, it was found to contain approximately 40% silicon dichloride (Si_2Cl_6). Further experimenting with this impure material was discontinued, but its use had indicated that, as with zirconium, titanium is incompatible with silicon in molten magnesium or magnesium-base alloys containing zinc.

Several melts were prepared using purified titanium tetrachloride following Eisenreich's method, and the resultant alloys showed improved tensile properties and titanium contents ranging from 0.032 to 0.042% Ti.

So far as reproducibility of the tensile properties is concerned, the ranges for ultimate tensile strength, 0.2% yield strength, and elongation were 28.0 - 31.8 kpsi, 10.7 - 12.3 kpsi and 8.2 - 13.2%, respectively. This method of titanium introduction was considered to be quite attractive.

The last group of materials to be assessed consisted of zinc-titanium master alloys containing various amounts of titanium (4-15% Ti) and, in some trials, 5-10% magnesium. These master alloys were prepared by dissolving titanium metal sponge in molten zinc under boric acid flux. The properties of Mg-6% Zn alloy obtained by treatment with these master alloys were higher than those of binary Mg-Zn alloys, and the titanium content ranged from 0.031 to 0.045% Ti. The ranges of results for ultimate tensile strength, 0.2% yield strength, and elongation were 29.0 - 30.1 kpsi, 11.1 - 12.1 kpsi and 8.5 - 10.8%, respectively. It was found that the properties of the alloy and the titanium recovery were not affected by the titanium content of the master alloy, with or without magnesium, so long as the addition to the molten Mg-6% Zn alloy was at least 0.2% Ti.

Of all the materials used for alloying titanium to magnesium, only purified titanium tetrachloride and Zn-Ti master alloys were effective in improving tensile properties. Taking into consideration the reproducibility of the results and also the ease of introduction of titanium into molten magnesium, it was decided to use zinc-titanium master alloys as the main source of titanium, and that purified titanium tetrachloride was to be used only when the zinc content of the master alloy did not allow the introduction of enough titanium to ensure at least 0.2% Ti in the charge. In such cases, the highest possible titanium addition was made in the form of Zn-Ti master alloy and the required additional amount was added in the form of purified $TiCl_4$. Various melting techniques were investigated as well, and the melting procedure that gave the most consistent properties of the alloys is described in the next paragraph.

Materials and Melting Procedure

To investigate the effect of titanium on the tensile properties of Mg-Zn alloys, a series of melts was prepared containing nominally from 1 to 15% Zn, as listed in Table 1. Domal 99.98% magnesium ingots were used, and the zinc and titanium were added in the form of a zinc-5% titanium master alloy. In alloys with 1, 2 and 3% Zn, additional titanium was introduced in the form of purified titanium tetrachloride. Domal crucible flux was used throughout the melting cycle, to protect the molten metal from burning.

Zinc-5% titanium master alloy was prepared by adding the required amount of titanium sponge (produced by the Kroll process) to the molten zinc at approximately 500°C (930°F) and covering the melt with boric acid. The temperature was raised to 700°C (1290°F) and the melt was held at that temperature for 16 hr, the viscous boric flux cover preventing vapourization and burning of zinc. The resultant master alloy was chill-cast into steel moulds.

During pouring operations the molten metal was protected by dusting with a mixture of sulphur, boric acid and potassium fluoroborate.

The following melting procedure was used to prepare the experimental alloys of the series, with the exception of alloys containing 1, 2 and 3% Zn.

Pure magnesium ingots were melted in a clean steel crucible of 40 lb capacity, preheated in a gas-fired furnace, using crucible flux to protect molten metal from burning. When the melt reached a temperature of 780°C (1435°F) the Zn-5% Ti master alloy was added, and the melt was stirred for 5 min; after the melt settled at that temperature for 10 min, the flux from the surface of the metal was skimmed off and replaced by a sulphuric-boric acid-potassium fluoborate mixture and five sets of green sand moulds yielding twenty cast-to-shape* tensile tests were poured, starting at 770°C (1420°F), followed by one sand-cast 48 in. long bar for measuring total linear shrinkage.

---

* Test bar design according to Canadian Draft Standard CSA.H.G.1-1956 and U. S. Federal Specification QQ-M-56, Figure 1A.

This procedure was modified for alloys with 1, 2 and 3% Zn whereby the Zn-Ti master alloy was stirred in only for 1/2 min and followed by the addition of titanium tetrachloride. The titanium tetrachloride was poured into a steel container filled with anhydrous barium chloride, preheated for 2 hr at 400°C (750°F), and cooled to room temperature immediately before charging. The container was gently submerged into the melt and held there until the reaction ceased, followed by stirring for 3 min before the removal of the container. The top portion of barium chloride, which might contain the reduced titanium metal, was removed from the container while submerged, and dumped into the melt. The melt was stirred at 780°C (1435°F) for an additional 2 min, and the melting procedure described above was followed.

Heat Treatment

Solution heat treatment was used according to the solidus line of binary Mg-Zn alloys, as described in Part I[1] and listed in Table 3. Two ageing cycles were used, namely:

a) aged 16 hr at 180°C, designated as A,
b) aged 48 hr at 150°C, designated as B.

Alloy and Temper Designations

Alloy and temper designations used throughout this report are according to Canadian standards CSA.H.1.1. - 1958 (alloy designations) and CSA.H.1.2. - 1958 (temper designations). The letter Z in the alloy designates zinc; the letter F was chosen arbitrarily to designate titanium;

and the following numbers represent the percentages of the respective alloy contents; for example, "ZF60" designates a ternary Mg alloy containing 5.5 to 6.5% Zn and less than 0.5% Ti. In the temper designations, "F" designates the as-fabricated (as-cast), "T4" the solution heat treated, "T5" the artificially aged only, and "T6" the solution heat treated and artificially aged condition.

Testing Procedure

Three unmachined test bars were tested for ultimate tensile strength, 0.2% yield strength and elongation in the "as-cast" condition within 72 hr of casting (to avoid the effects of possible room temperature ageing). Samples for chemical analysis were drilled from one-half of the broken test bars; the other half was used for the determination of density, grain size and Rockwell E hardness.

Two test bars from each alloy were tested at room temperature in the solution heat treated (T4), aged (T5), and fully heat treated (T6) conditions for tensile properties. One test bar from each alloy was used for more detailed metallographic study.

Approximately 3, 6 and 12 months after casting, two additional as-cast test bars from each alloy were tensile tested to check the effect of room-temperature ageing.

EXPERIMENTAL RESULTS

The results of chemical analyses and tensile tests in the as-cast (F) condition, grain size, density and linear shrinkage determinations are given in Table 1. Table 2 lists the hardness values in various conditions. Table 3 gives tensile testing results in the T4, T5A, T5B, T6A and T6B conditions. It also gives the solution heat treatments used for each composition. Table 4 lists tensile testing results after 0, 3, 6 and 12 months of room-temperature ageing. Table 5 gives the results of chemical analyses and grain size determinations, and the as-cast tensile properties, of alloys containing titanium with various additions of zirconium.

DISCUSSION OF RESULTS

The solubility of titanium in molten magnesium-zinc alloys, under experimental foundry conditions, was found to increase from about 0.025% Ti in Mg-1% Zn to approximately 0.050% Ti in Mg-15% Zn alloy (Figure 1). This is in contrast to the much lower solubility of titanium in liquid magnesium, reported both by Aust and Pidgeon(10) and by Eisenreich(12).

The effect of titanium additions on grain size, hardness, and density of magnesium-zinc alloys is presented in Figure 2. Grain size decreases in the range of 1% to 8% Zn, but appears to increase for higher zinc contents as a result of the same difficulties in determination as were found in binary Mg-Zn alloys[1]. Density is unaffected by titanium additions, and hardness increases with the zinc content and is higher for alloys with titanium additions.

The effect of titanium additions on tensile properties of magnesium-zinc alloys in the as-cast (F) and various heat treated conditions is shown in Figures 3 to 6. No layer porosity was found in the gauge lengths of test bars in titanium-containing alloys and, therefore, no difficulties with "true" mechanical properties, as experienced in the binary alloys in the range of 3 to 9% Zn (described in Part I of this report series)[1], were encountered.

In the as-cast condition (see Figure 3), the titanium addition increases ultimate tensile strength and elongation in alloys containing not more than 6 to 7% Zn, whereas the yield strength increases over the whole alloy range.

Figures 4 to 6 show that the titanium addition to magnesium-zinc alloys does not affect their amenability to heat treatment. The optimum combination of properties in the T6 conditions was obtained for alloys containing 6 to 7% Zn, showing 39 kpsi UTS, 24 kpsi 0.2% YS, and 8% El. Although these values are higher than those obtained on the binary alloys, they compare very unfavourably with the properties that can be obtained from the zirconium-containing alloys (average ZK61-T6 alloy properties are 46 kpsi UTS, 32 kpsi 0.2% YS, and 10% El).

Figure 7 compares the effect of various heat treatments on tensile properties of sand-cast Mg-Zn-Ti alloys.

Figure 8 shows that the titanium addition to magnesium-zinc alloys does not alter their tendency to room-temperature ageing.

Figure 9 shows that titanium additions have no effect on the linear shrinkage of sand-cast magnesium-zinc alloys.

ZIRCONIUM ADDITION TO Mg-Zn-Ti ALLOYS

Eisenreich(12) found that the solubility of titanium in molten magnesium can be significantly increased (up to 0.115% Ti at 800°F) by adding zirconium, which combines with the hydrogen present in the melt and prevents it from affecting the solubility of titanium. This was therefore tried out in the present investigation, and Figure 10 shows the change in properties obtained by adding zirconium to the Mg-6% Zn alloy saturated with titanium.

As may be seen, zirconium additions coarsen the grain and cause a decrease in both ultimate tensile strength and elongation of the alloy; only the yield strength increases slightly. No increase in solubility of titanium was found and, on the contrary, a slight decrease was noticed with higher zirconium additions. It was observed, also, that the solubility of zirconium in molten magnesium-zinc alloys decreased significantly in the presence of titanium.

METALLOGRAPHY

Three Mg-Zn-Ti alloys, containing nominally 1, 6 and 15% Zn, were selected for metallographic study. Microstructures of these alloys at 100 and 1000 magnifications are presented in Figures 11 to 13. A more detailed discussion of the microstructures of binary Mg-Zn alloys was presented in Part II of this report series.

In the as-cast condition the structure is composed of magnesium solid solution matrix and a second phase of Mg_7Zn_3 divorced eutectic. This phase is partially decomposed into a eutectoid of Mg solid solution and MgZn, the transformation being inoculated at the interface of Mg and Mg_7Zn_3. Second phase is not present in the Mg-1% Zn alloy, but, because of non-equilibrium freezing, was noticed in alloys with as low as 2% Zn.

Comparing the structures with binary Mg-Zn alloys, it can be seen that titanium to some extent inhibits the decomposition of the Mg_7Zn_3 phase, making this reaction even more sluggish. Solution heat treatment dissolves the second phase in alloys with up to approximately 7% Zn, the undissolved phase being Mg_7Zn_3 which is retained on quenching. Ageing at both temperatures (150°C and 180°C) enables the phase Mg_7Zn_3 to decompose completely into eutectoid of Mg solid solution and MgZn compound.

CONCLUSIONS

1. Under experimental foundry conditions, the solubility of titanium in molten magnesium was found to be 0.025% Ti in the Mg-1% Zn alloy, increasing to 0.050% Ti in the Mg-15% Zn alloy.
2. Titanium additions refine grain in magnesium alloys containing 1 to 8% Zn, and eliminate layer-type porosity encountered in binary Mg-Zn alloys in the gauge lengths of cast-to-shape test bars.
3. Titanium additions only slightly improve the tensile properties of some magnesium-zinc alloys. The optimum combination of properties was obtained for alloys containing 6-7% Zn, but even these properties were inferior to those of the comparable Mg-Zn-Zr alloys.
4. Zirconium additions do not increase the solubility of titanium in magnesium-zinc alloys. It was, however, observed that the solubility of zirconium in Mg-Zn alloys decreases in the presence of titanium.

REFERENCES

1. B. Lagowski and J. W. Meier - "Properties of Sand-Cast Magnesium Alloys. Part I: Binary Magnesium-Zinc Alloys" - Mines Branch Research Report R 9, Department of Mines and Technical Surveys, Ottawa (1958).

2. B. Lagowski - "Properties of Sand-Cast Magnesium Alloys. Part II: Metallography of Magnesium-Zinc Alloys" - Mines Branch Research Report R 22, Department of Mines and Technical Surveys, Ottawa (1958).

3. I. Obinata and Hayasi - "Investigations of Complex Magnesium Alloys Based on the Magnesium-Cadmium System. II" - Tetsu-to-Hagane 24, 34-42 (1938).

4. A. Burkhardt, R. Knabe and K. Riederer - U. S. Patent 2,251,266 (1941), Chem. Abstr. 35, 6921 (1941).

5. F. Christen - U. S. Patent 2,340,795 (1944), Chem. Abstr. 38, 4247 (1944).

6. D. Gardner - U. S. Patent 2,823,996 (1958).

7. L. A. Carapella - "The Fundamental Alloying Nature of Magnesium" - Metal Progress 48, 297-307 (1945).

8. W. J. Kroll - "Rare Earth Metal Alloys of Magnesium" - Light Metal Age 3(12), 23-30 (1945).

9. N. S. Spence - "Exploratory Investigation of Titanium Additions to Magnesium Alloys" - Research Report 35, Physical Metallurgy Research Laboratories, Bureau of Mines, Ottawa (1947).

10. K. T. Aust and L. M. Pidgeon - Solubility of Titanium in Liquid Magnesium" - Trans. AIME 185, 585-587 (1949).

11. R. S. Busk - "Lattice Parameters of Magnesium Alloys" - Trans. AIME 188, 1460-1464 (1950).

12. H. Eisenreich - "Investigations on the Solubility of Titanium in Magnesium" - Metall 7, 1003-1006 (1953).

13. H. Eisenreich, Nachrodt and H. Puetter - "Investigation on Magnesium-Titanium Ternary Systems" - Metall 8, 624-625 (1954).

14. I. Obinata, Y. Takeuchi and R. Kawanishi - "The System Titanium-Magnesium" - Metall 13, 392-397 (1959).

15. A. Jones, R. D. Malin and R. R. Nash - "New Magnesium Alloys" - Technical Report No. 5734, U.S.A.F. Air Material Command, Wright-Patterson Air Force Base, Dayton, Ohio (1948).

16. R. R. Nash, H. K. Adams, A. E. Bibb, M. C. Huffstutter and E. J. Tullock - "Magnesium Alloys with High Melting Point Additions" - WADC Technical Report 55-207, Wright Air Development Centre (1957).

= = =

BL:JWM:(PES):vb

TABLE 1

Properties of Mg-Zn-Ti Alloys in the As-Cast Condition

Melt No.	Zn, %	Ti, %	As-Cast Condition (F) UTS, kpsi	0.2% YS, kpsi	El., % in 2 in.	Grain Size, 0.001 in.	Density, g/cc	Shrinkage, %
4387	1.08	0.023	22.7	4.32	12.5	60	1.751	1.82
4388	2.12	0.025	26.9	6.39	16.6	15	1.765	1.72
4389	3.13	0.032	28.9	8.14	15.75	15	1.780	1.56
4408	3.97	0.030	28.4	8.76	12.5	15	1.792	1.50
4411	5.02	0.028	29.9	10.45	12.1	10	1.808	1.46
4413	6.22	0.030	30.9	11.7	11.4	10	1.827	1.34
4393	7.50	0.035	29.2	12.5	8.8	10	1.846	1.30
4394	8.18	0.037	27.3	12.9	7.25	15	1.860	1.27
4396	9.29	0.042	22.8	12.9	4.5	15	1.876	1.24
4418	10.24	0.035	21.4	13.2	3.0	15	1.892	1.20
4402	12.50	0.043	21.4	14.8	2.1	15	1.933	1.04
4405	15.26	0.049	19.6	16.3	1.1	30	1.979	0.98

TABLE 2

Hardness Values in Various Tempers

Melt No.	Zn, %	Ti, %	Hardness, Rockwell "E" Scale					
			"F"	T4*	T5A	T5B	T6A*	T6B*
4387	1.08	0.023	37.9	34.0	33.8	35.3	37.5	37.3
4388	2.12	0.025	47.2	44.8	44.3	46.8	46.5	46.8
4389	3.13	0.032	51.9	48.0	53.3	55.0	53.3	51.3
4408	3.97	0.030	48.3	54.3	58.5	61.5	58.0	54.5
4411	5.02	0.028	50.4	57.5	65.0	66.8	68.3	65.5
4413	6.22	0.030	56.5	60.0	67.0	70.0	71.3	76.5
4393	7.50	0.035	61.4	68.5	74.0	75.8	79.8	78.5
4394	8.18	0.037	63.6	65.3	73.0	79.5	75.0	76.3
4396	9.29	0.042	64.5	63.5	78.5	80.5	77.5	76.0
4418	10.24	0.035	58.3	63.5	79.5	82.5	79.8	80.8
4402	12.50	0.043	72.1	69.0	81.8	87.5	81.8	82.3
4405	15.26	0.049	78.1	75.0	86.3	89.8	85.5	86.5

* For solution heat treatment, see Table 3.

TABLE 3

Effect of Various Heat Treatments on Tensile Properties of Mg-Zn-Ti Alloys

Melt No.	Zn, %	Ti, %	T4 Condition UTS, kpsi	T4 Condition YS, kpsi	T4 Condition El, % in 2 in.	T5A Condition UTS, kpsi	T5A Condition YS, kpsi	T5A Condition El, % in 2 in.	T5B Condition UTS, kpsi	T5B Condition YS, kpsi	T5B Condition El, % in 2 in.	T6A Condition UTS, kpsi	T6A Condition YS, kpsi	T6A Condition El, % in 2 in.	T6B Condition UTS, kpsi	T6B Condition YS, kpsi	T6B Condition El, % in 2 in.	Solution Heat Treatment Used T4
4387	1.08	0.023	24.2	5.46	15.5	22.5	4.31	12.3	23.3	4.21	14.8	24.3	4.50	16.25	23.7	4.33	14.5	$2\frac{1}{2}$ hr at 520°C
4388	2.12	0.025	27.5	5.98	17.0	26.9	7.44	15.8	27.4	7.24	15.0	27.7	6.38	17.5	27.8	6.23	19.75	"
4389	3.13	0.032	28.5	7.00	15.5	29.6	12.2	12.0	30.3	12.2	12.0	29.4	8.61	16.25	28.7	7.74	15.0	"
4408	3.97	0.030	30.8	8.4	14.8	30.3	13.6	9.8	29.9	14.5	8.8	33.3	13.0	13.3	32.8	10.3	15.3	3 hr at 500°C
4411	5.02	0.028	33.1	9.20	14.8	30.9	16.75	7.8	30.8	17.7	7.0	36.0	18.1	10.0	37.0	19.7	8.8	4 hr at 470°C
4413	6.22	0.030	33.2	10.4	13.5	32.0	18.6	7.3	33.2	20.5	7.0	37.4	21.2	7.0	38.5	25.8	7.0	$5\frac{1}{2}$ hr at 440°C
4393	7.50	0.035	36.3	14.7	12.0	34.1	21.0	6.0	33.9	22.4	3.8	41.3	25.7	7.5	39.0	27.5	4.0	$11\frac{1}{2}$ hr at 380°C
4394	8.18	0.037	27.3	12.5	6.5	31.6	19.5	3.8	34.7	22.0	4.5	34.9	22.2	4.25	33.2	25.6	3.5	16 hr at 330°C
4396	9.29	0.042	23.8	12.0	5.5	35.8	21.0	5.5	34.4	24.9	2.8	31.9	22.2	3.0	34.4	23.9	3.0	"
4418	10.24	0.035	22.6	12.3	4.5	35.0	21.1	4.5	36.3	24.6	3.5	35.5	22.7	4.0	33.1	24.4	2.5	"
4402	12.5	0.043	22.0	14.4	3.8	30.3	24.0	3.0	36.0	28.2	3.3	29.1	24.5	2.0	31.5	26.8	2.25	"
4405	15.26	0.049	20.7	15.0	2.0	33.3	26.2	2.5	36.2	29.2	2.5	31.9	24.8	2.0	37.8	27.7	2.75	"

TABLE 4

Effect of Room-Temperature Ageing on Tensile Properties

Melt No.	Zn, %	Ti, %	As-Cast			3-Months Aged			6-Months Aged			12-Months Aged		
			UTS, kpsi	0.2% YS, kpsi	El, %	UTS, kpsi	0.2% YS, kpsi	El, %	UTS, kpsi	0.2% YS, kpsi	El, %	UTS, kpsi	0.2% YS, kpsi	El, %
4387	1.08	0.023	22.7	4.32	12.5	22.5	3.46	12.5	21.9	5.1	11.5	21.6	4.7	10.3
4388	2.12	0.025	26.9	6.39	16.6	27.1	5.76	12.5	27.5	6.5	18.75	26.9	6.8	15.5
4389	3.13	0.032	28.9	8.14	15.75	29.0	7.65	14.5	28.5	8.9	15.0	29.3	9.0	14.0
4408	3.97	0.030	28.4	8.76	12.5	28.1	8.7	11.5	28.7	10.1	11.75	28.0	9.6	10.5
4411	5.02	0.028	29.9	10.45	12.1	30.4	10.01	11.0	30.5	11.1	11.0	30.7	11.6	8.0
4413	6.22	0.030	30.9	11.7	11.4	30.1	11.6	9.0	32.0	13.0	11.5	32.0	15.0	9.0
4393	7.50	0.035	29.2	12.5	8.8	28.7	13.0	7.0	29.4	14.5	6.5	29.9	16.2	5.8
4394	8.18	0.037	27.3	12.9	7.25	25.7	12.6	5.0	27.1	14.4	5.5	26.4	14.8	2.0
4396	9.29	0.042	22.8	12.9	4.5	23.8	12.4	3.0	25.2	14.2	3.5	24.6	14.7	2.0
4418	10.24	0.035	21.4	13.2	3.0	22.5	12.6	3.0	22.6	14.5	4.0	24.6	18.0	1.5
4402	12.5	0.043	21.4	14.8	2.1	22.4	15.0	1.25	23.6	16.6	1.0	25.0	17.9	0.8
4405	15.26	0.049	19.6	16.3	1.1	20.8	16.7	0.5	22.3	18.6	2.0	24.6	20.9	0.5

TABLE 5

Properties of Mg-Zn-Ti Alloys with Added Zr

Melt No.	Zn, %	Ti, %	Zr sol, %	Zr Addition, %	Grain Size, 0.001 in.	As-Cast Properties UTS, kpsi	0.2% YS, kpsi	El,% in 2 in.	Hardness, Rockwell "E"
4427	6.35	0.033	0.01	0.1	10.0	28.0	11.3	11.0	59.0
4428	6.42	0.033	0.05	0.2	10.0	27.4	12.0	8.2	58.5
4429	6.18	0.033	0.09	0.3	10.0	26.5	12.3	7.7	59.2
4430	6.60	0.032	0.16	0.4	10.0	26.0	12.2	7.0	58.8
4432	6.50	0.033	0.22	0.5	15.0	27.3	13.6	7.0	64.2
4433	6.25	0.033	0.24	0.75	20.0	23.0	13.3	3.5*	61.2
4435	6.16	0.033	0.25	1.0	15.0	27.6	13.4	6.8	63.2
4436	6.17	0.032	0.36	1.25	15.0	26.8	14.4	6.0	63.7
4438	5.94	0.029	0.38	1.5	20.0	26.3	14.7	5.0	63.2
4439	5.7	0.026	0.51	2.0	15.0	27.0	15.2	5.5	66.3
4441	5.78	0.028	0.48	2.5	15.0	27.7	15.4	5.5	66.2

* Each bar broke outside gauge length.

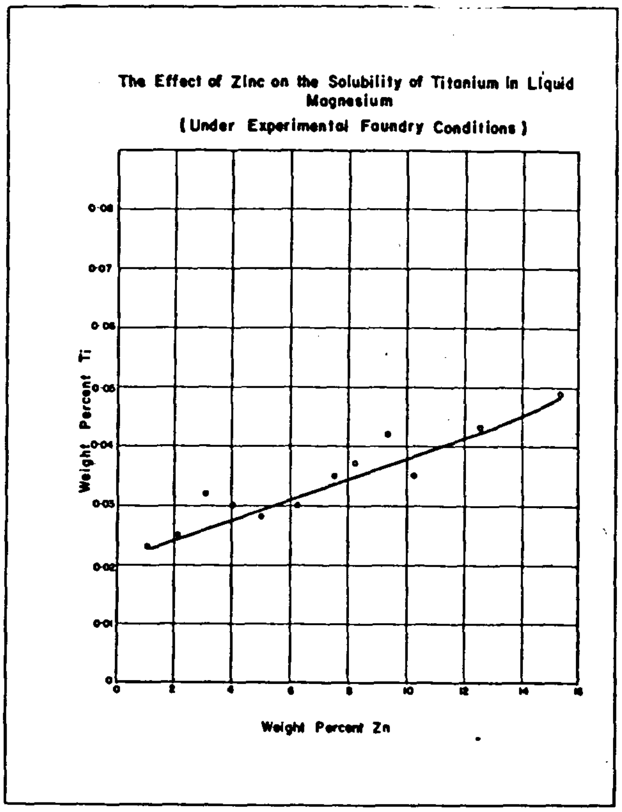

Figure 1.

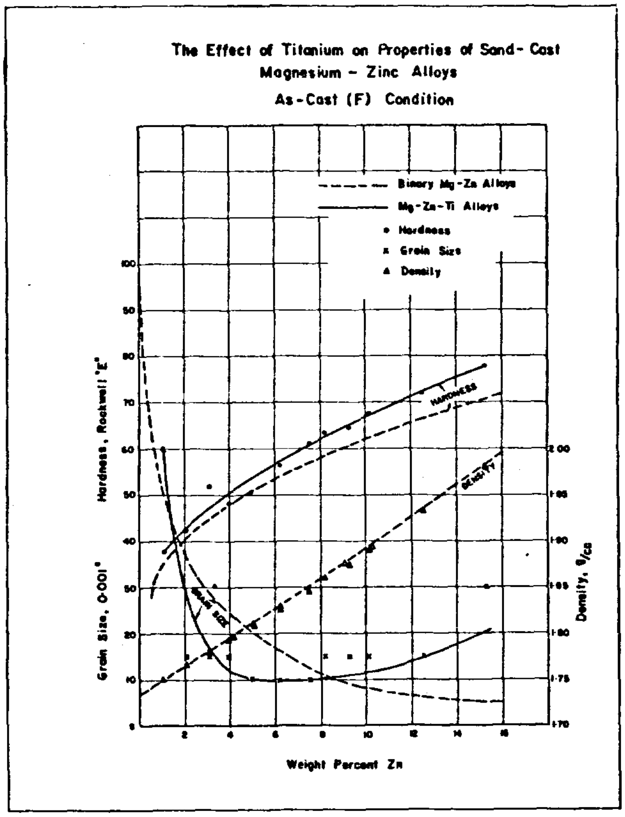

Figure 2.

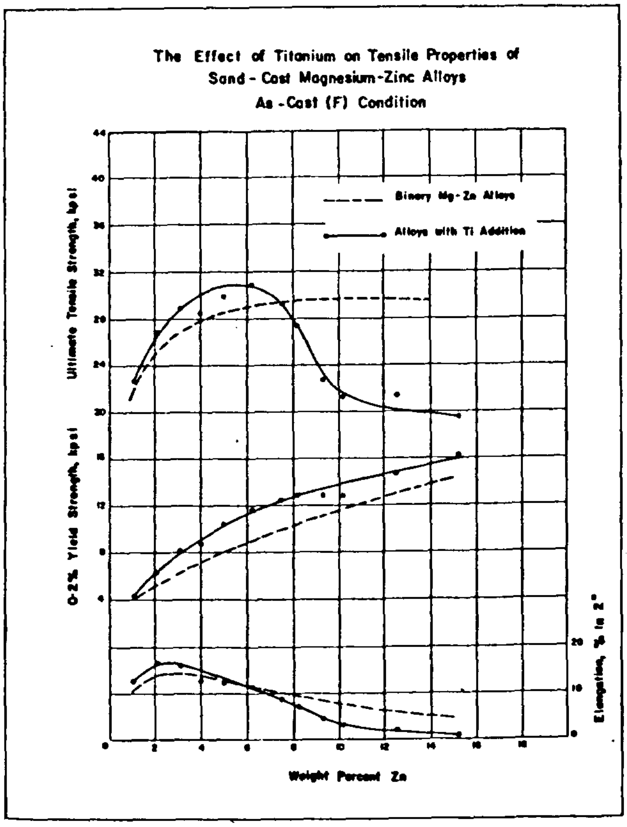

Figure 3.

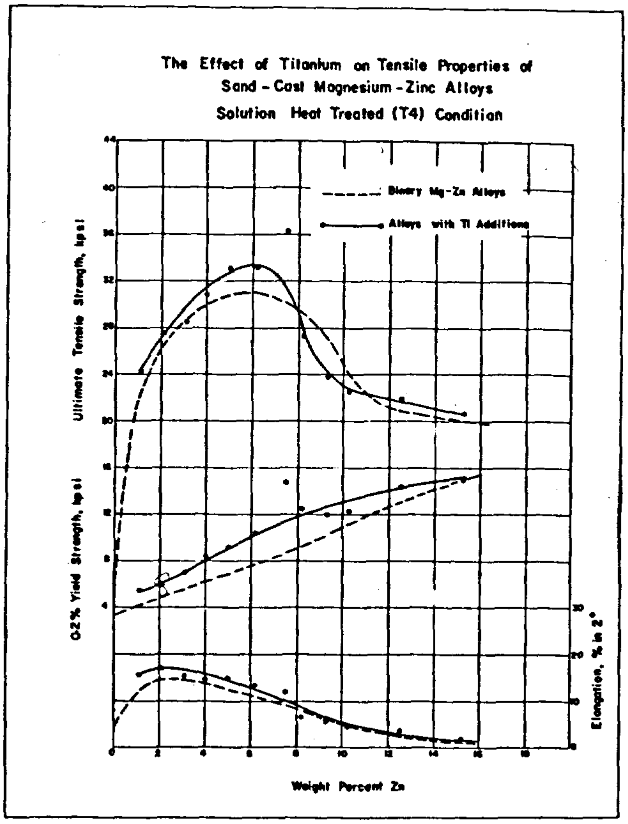

Figure 4.

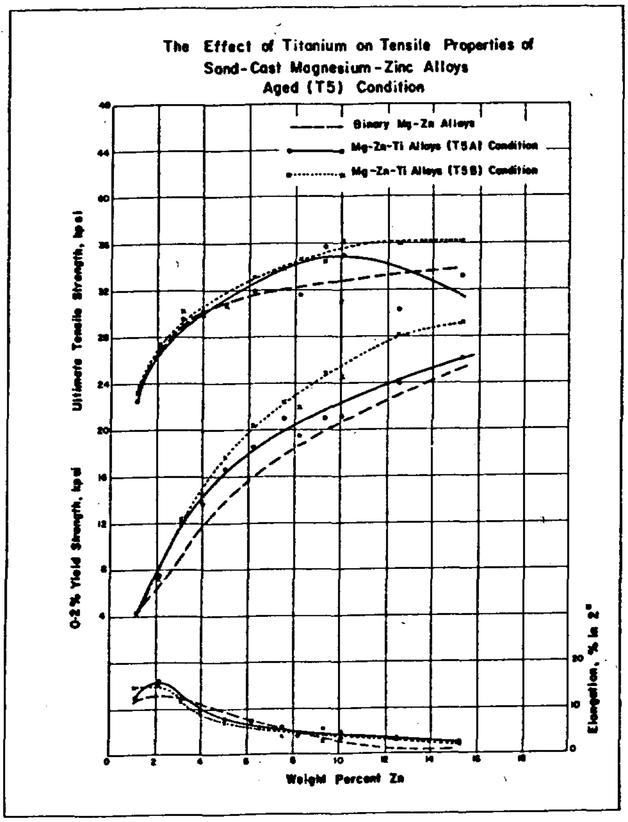

Figure 5.

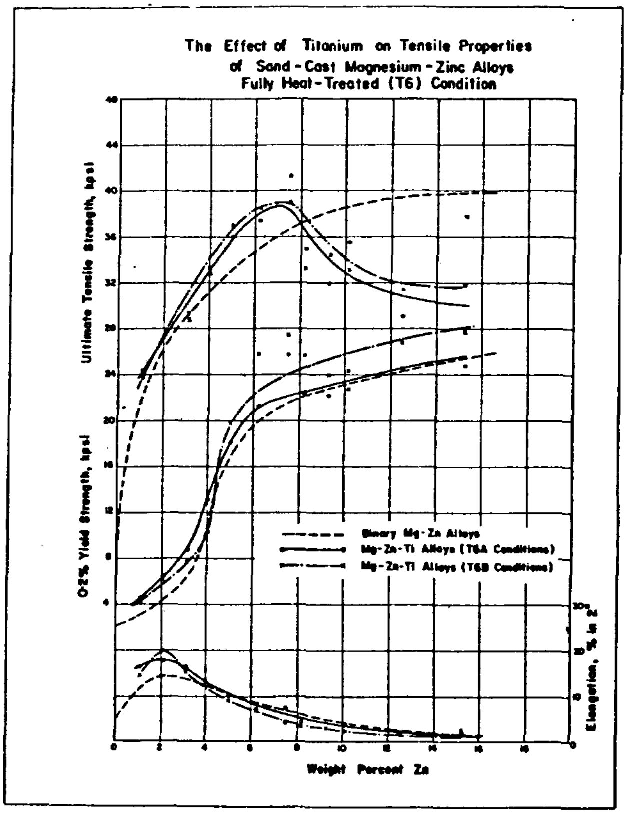

Figure 6.

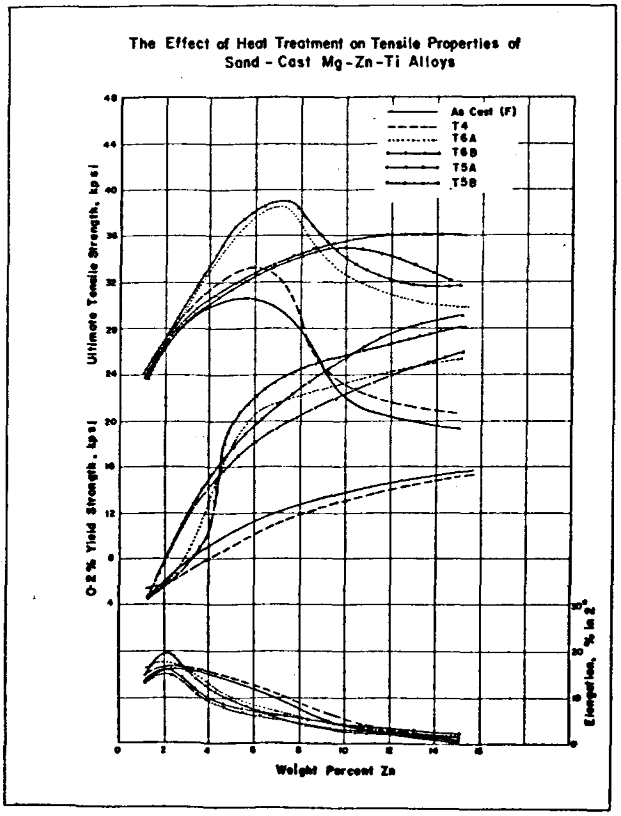

Figure 7.

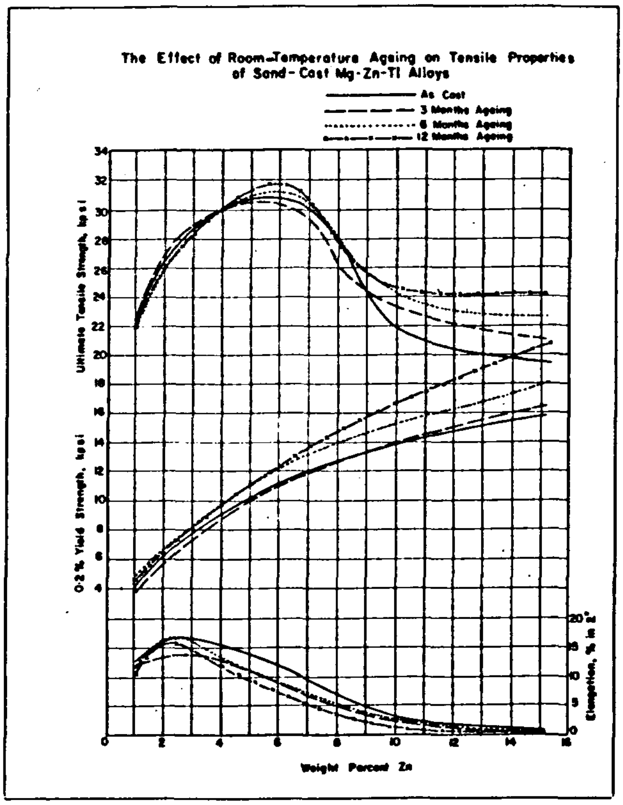

Figure 8.

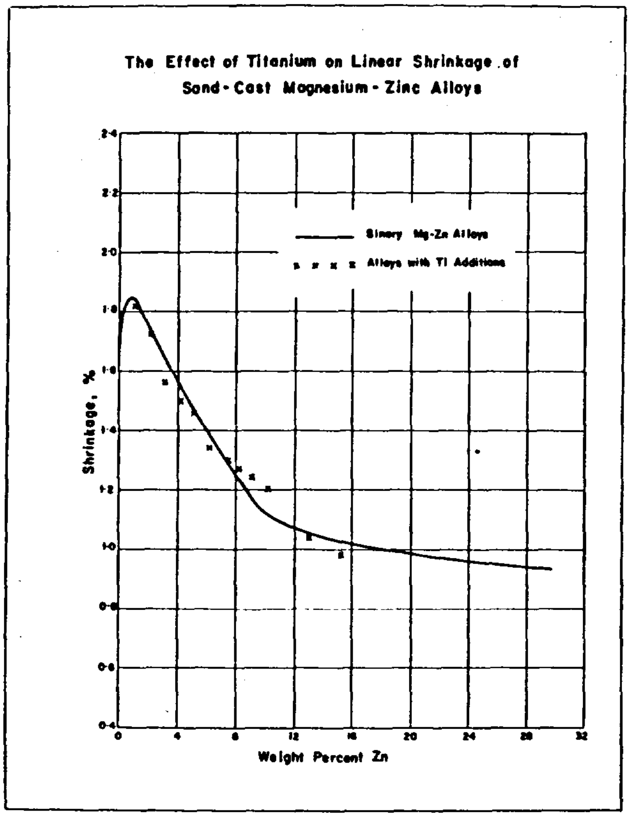

Figure 9.

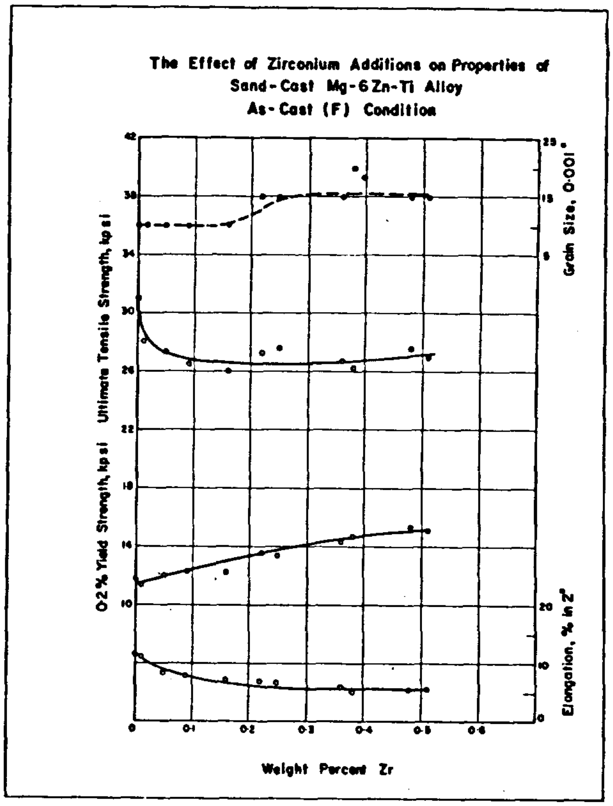

Figure 10.

X100 Temper X1000

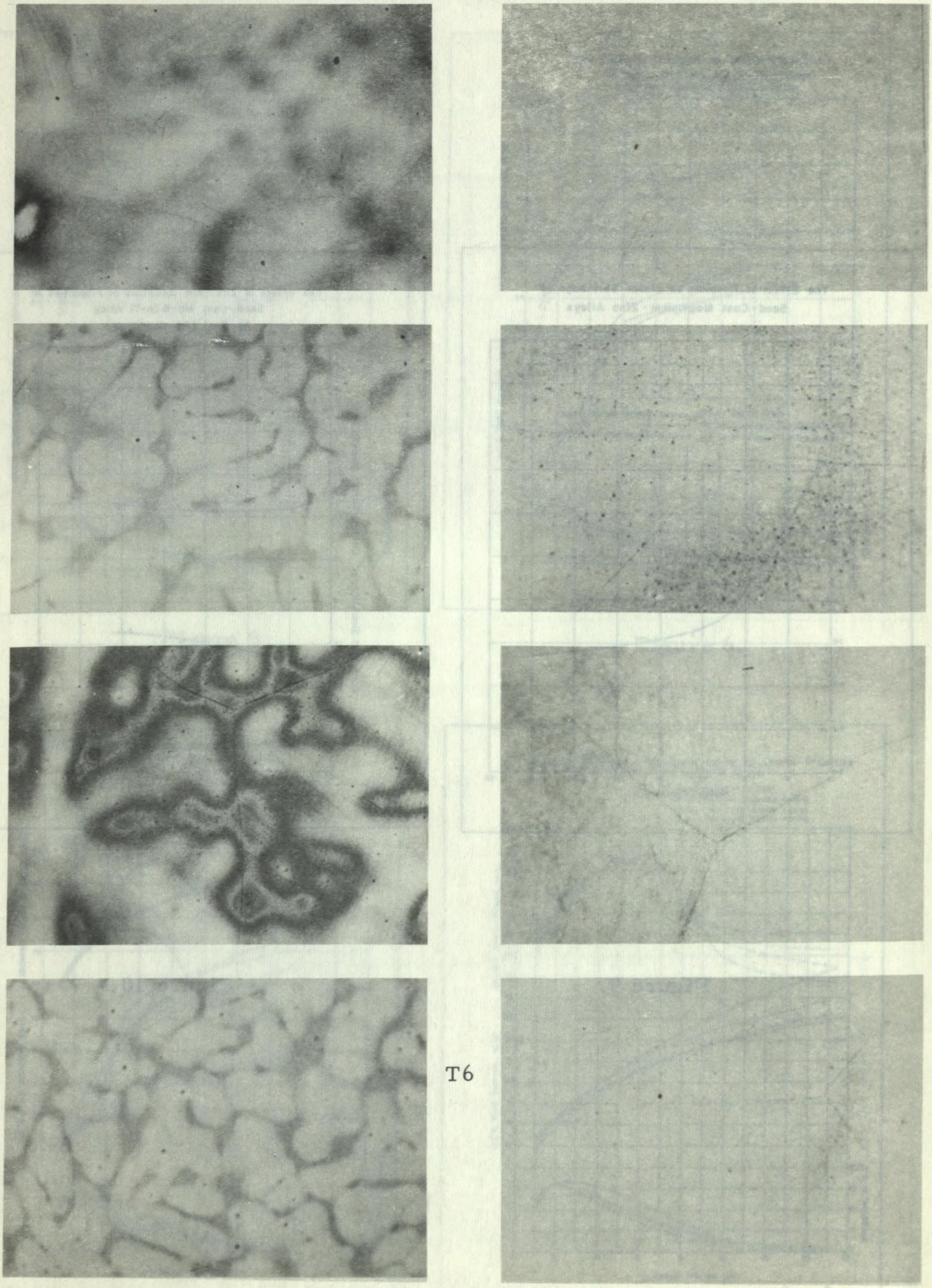

Figure 11. Microstructures of sand-cast magnesium alloy containing 1.08% Zn and 0.023% Ti. Etched in 0.5% HF.

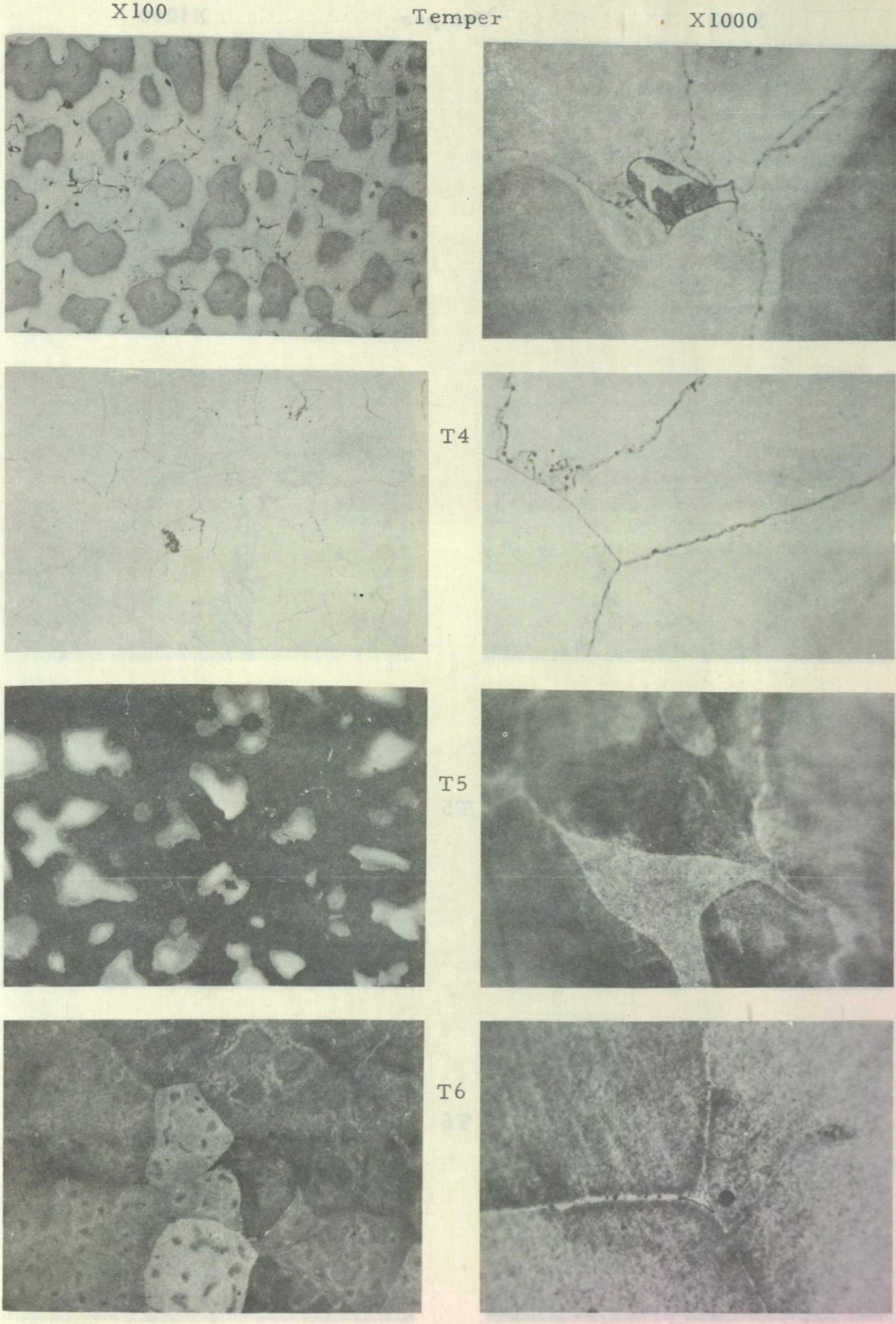

Figure 12. Microstructures of sand-cast magnesium alloy containing 6.22% Zn and 0.030% Ti. Etched in 0.5% HF

X100 Temper X1000

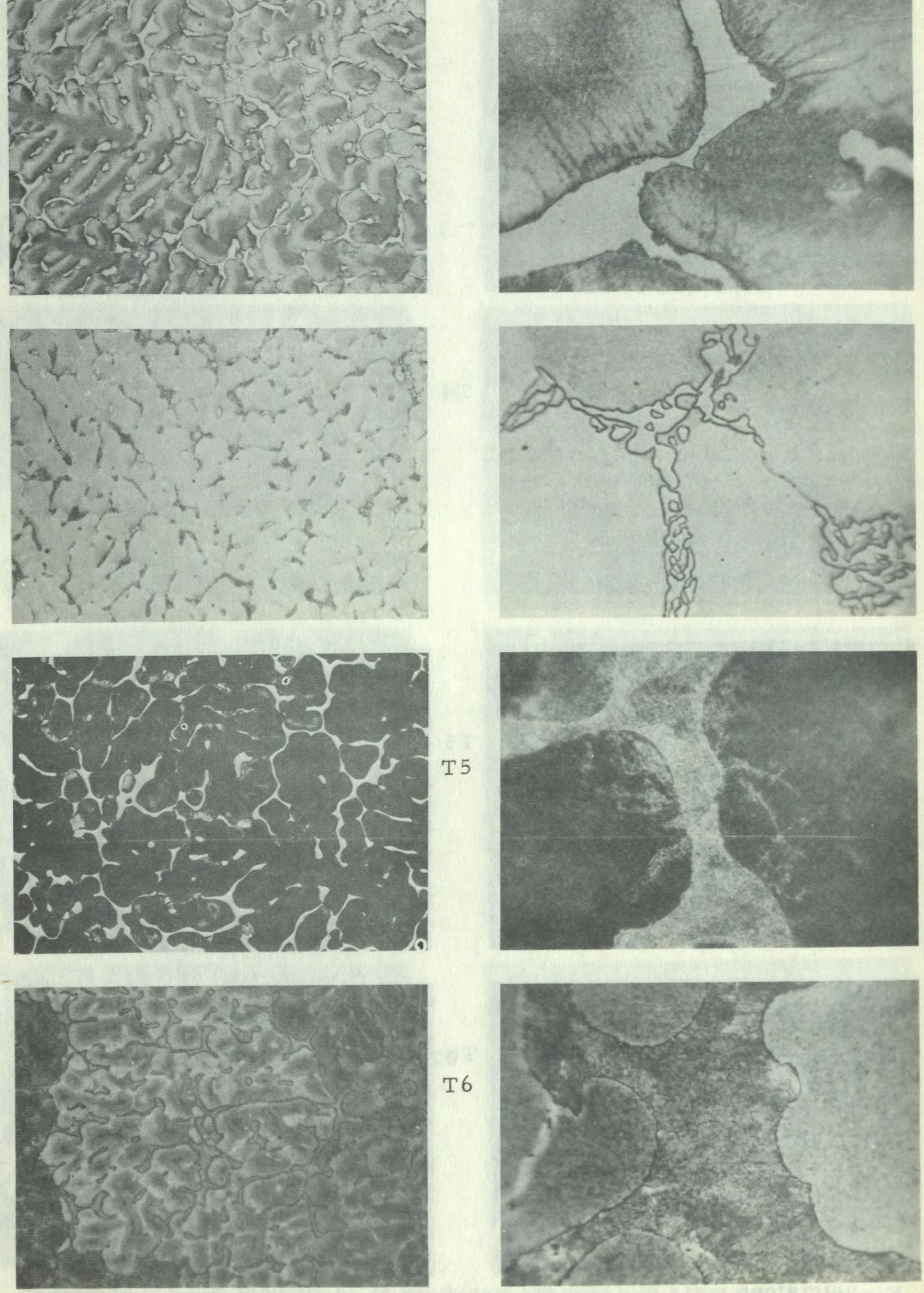

Figure 13. Microstructures of sand-cast magnesium alloy containing 15.26% Zn and 0.049% Ti. Etched in 0.5% HF.