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PREMIUM STRENGTH IN SAND-CAST MAGNESIUM ALLOYS

B. LAGOWSKI & J. W. MEIER

PHYSICAL METALLURGY DIVISION

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PREMIUM STRENGTH IN SAND-CAST MAGNESIUM ALLOYS

by

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

ABSTRACT

Increasing demand for higher-strength magnesium alloy castings made it necessary to investigate optimum properties obtainable in commercial castings, especially in heavier sections. The paper describes results of a study of some of the factors affecting high mechanical properties and their proper distribution throughout the casting. Experimental work was carried out first on test plates of 1/2-inch to 2-inch thickness, and later checked on more complicated castings. Variables studied included proper use of chills to ensure directional solidification and elimination of the effect of unsoundness in plates of various thickness, as well as more efficient heat treating techniques for the various alloys. Results on commercial casting shapes showed that high properties, even in sections of 2-inch thickness, could consistently be obtained which are equal or in some cases higher than typical properties reported for separately-cast test bars. Mg-Al-Zn alloys show a greater sensitivity to adverse solidification conditions than the finer-grained zirconium-containing alloys. The newly developed Mg-Zn-Ag-Zr alloys showed exceptionally high properties, exceeding those obtainable in any commercial magnesium alloy.

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Direction des mines

Rapport de recherches R 138

RÉSISTANCE SUPÉRIEURE D'ALLIAGES AU MAGNÉSIUM POUR MOULAGE AU SABLE

par

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

RÉSUMÉ

Vu la demande croissante de moulages faits d'alliage au magnésium à haute résistance, il a fallu étudier quelles sont les meilleures caractéristiques qu'on puisse obtenir pour les moulages industriels, spécialement dans le cas des pièces volumineuses. Les auteurs décrivent les résultats d'une étude de certains des facteurs qui influent sur les hautes propriétés mécaniques et leur répartition convenable dans la masse du moulage. Les essais ont porté d'abord sur des plaques épaisses d'un demi-pouce à 2 pouces, puis on a fait des contre-essais sur des moulages plus complexes. Parmi les facteurs variables, on a étudié l'emploi convenable de refroidisseurs en vue d'obtenir une solidification orientée et l'élimination de l'effet de la porosité dans les plaques de diverses épaisseurs, ainsi que des méthodes plus efficaces de traitement thermique pour les divers alliages. D'après les résultats obtenus sur des pièces moulées industrielles, on pourrait toujours obtenir, même dans le cas de pièces de 2 pouces d'épaisseur, des propriétés égales ou parfois supérieures aux propriétés caractéristiques obtenues dans le cas d'éprouvettes moulées séparément. Les alliages au Mg-Al-Zn se révèlent plus sensibles à des conditions défavorables de solidification que les alliages au zirconium à texture plus fine. Les alliages récemment mis au point, au Mg-Zn-Ag-Zr, ont révélé des propriétés exceptionnellement bonnes, dépassant celles qu'on obtient dans le cas de tout alliage industriel au magnésium.

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Rapport présenté sous la forme d'une étude écrite au 68^e Concrès sur les moulages, American Foundrymen's Society, Atlantic City (N.J.), le 28 avril 1964.

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INTRODUCTION

The aircraft and spacecraft industries were the first to request castings of guaranteed and strictly controlled properties, which would permit their use for structural parts and allow the designer to calculate performance requirement data without the use of the prohibitive "casting factor". In 1952, the Aircraft Research and Testing Committee set up a special project to "survey the use of castings in aircraft and to establish the reason for the apparent limited use of this metal-working process"(1). The reaction of the foundry industry was slow, because it was difficult to change a philosophy based on quantity production and a dislike of the idea of guaranteed casting properties. There was, too, a hesitation to employ the skilled quality-control personnel necessary for the comparatively small volume of highest-quality castings.

Within the next few years, however, it was demonstrated by various research institutions not only that high properties could be obtained in castings but also that these results could be obtained consistently; in this work, the systematic efforts of the Massachusetts Institute of Technology team under the late Professor Howard F. Taylor and his successor M.C. Flemings should be especially mentioned (2) (3) (4). Industrial development work followed, in close cooperation with the aircraft industry, and resulted in strict control of all the founding and heat treating factors (5) affecting soundness and mechanical properties of castings. Considerable improvement in mechanical properties obtainable in critical areas of castings was achieved and reported by Nelson (6). The cooperative effort was so successful that recently a U.S. Military Specification MIL-M-46062 (MR) for High-Strength Magnesium Alloy Castings was issued, which for the first time specifies minimum properties in designated areas of the casting, graded according to the importance of the area from design considerations. Since Nelson (7) has already discussed this specification in detail, Table 1 shows the specified values only for the three alloys of highest strength, so that they may be compared with minimum properties of magnesium alloy forgings and extrusions, listed in Table 2. It may be seen that the minimum properties of high-strength castings are very close to those specified for the wrought products. If the recently developed (8) Mg-Zn-Ag-Zr alloys should become available commercially, the values obtainable (e.g. for alloy ZQ64-T6* typical values are: UTS - 50 to 51 kpsi; 0.2% YS - 35 kpsi; and 8 to 10% elongation) will be equal to those of wrought products.

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* All alloy and temper designations throughout the report are according to Canadian designation codes CSA. H. 1-1958.

It is, of course, realized that the properties listed in Table 1 are possible only in limited areas of the casting (designated by agreement of designer and foundry), and that, in contrast, wrought alloys show uniform (although directional) properties throughout the whole product. Taking under consideration the possibility of casting to almost any final shape and to reasonably close tolerances, it seems that the higher material cost of premium-quality castings will be easily absorbed by elimination of machining and other fabricating costs associated with wrought products.

The meaning of "Premium Quality", as applied to castings, and all the conditions necessary to produce it have been repeatedly and ably described (4) (6) (7) (9) in the past few years. From the point of view of the designer or user, the most desirable characteristic of these castings is their reliability, which means that high quality has to be produced consistently.

Most of the work described earlier dealt with the "easy" alloy AZ91-T6 and with thinner casting sections. The work described in the present paper deals with "difficult" alloys and shows that, by proper solidification conditions and some modifications in heat treating schedules, properties in heavy sections can be obtained that are equal to or better than those typical for separately-cast test bars or thinner sections.

MATERIALS AND EXPERIMENTAL PROCEDURES

Materials

Materials used for the test castings were

(a) for all Mg-Al-Zn alloys: high-purity Domal magnesium alloy ingots. Standard melting techniques with lampblack grain refining and chlorine degassing were used (10).

(b) for Zr-containing alloys: Domal 99.98% Mg ingots, Tadanac 99.99% Zn ingots, suitable scrap (up to 75% of the charge), mischmetal (for alloys EZ33 and ZE41), Mg-14% Th master alloy (for alloys HK31 and HZ32), Mg-14% didymium master alloy (for alloy QE22), and 99.99% Ag shot (for alloys QE22 and ZQ64). Zirconium was introduced in all cases as a fused salt mixture containing 50% $ZrCl_4$ and 25% each KCl and NaCl. Standard melting and alloying techniques established earlier for ZK61 alloy (11) were used (with the exception of alloy QE22 where a special magnesium-chloride-free flux was used).

Test Castings

For the purpose of this investigation, which was undertaken mainly to study the effect of section thickness and of variations in heat treatment on the properties obtainable on a simple casting shape, it was essential to have castings, or at least parts of the castings, that were radiographically sound. The design of the gating and risering of the plate sections was therefore chosen to satisfy this requirement, so that in the thinnest section some over-risering and in the heavy sections some intensive chilling were found unavoidable.

Figure 1 shows the design of the thinner-section plate castings. To produce a radiographically sound 1/8-inch plate, it was necessary to prolong the solidification time by running the metal through the plate section, thereby heating the sand, so that by the end of the pouring thermal gradients were established between the two risers and consequently directional solidification could take place.

In the case of the 1/4-inch plate, a radiographically sound plate was obtained by running the metal through the risers on both sides of the plate. The two risers established predominantly longitudinal temperature gradients.

For the 1/2-inch plates, it was found that the properties of unchilled and end-chilled plates were the same, and the use of chills for this plate section was therefore discontinued. However, it should be added that for larger plates of this thickness the effect of chilling might be beneficial.

Figure 2 shows the casting design for the 1-inch and 2-inch plates. To obtain sound material in these heavier section plates, it was found necessary to establish favourable thermal gradients and to increase the cooling rate by the use of end-chilling. Water-cooled welded steel chills, coated with zircon wash (Foseco 825), were chosen to have chilling conditions as constant as possible. In both plate sections, at least 1- to 2-inch radiographically-sound material was obtained; in the more difficult alloys (e.g. ZK61) slight porosity was present, but it appeared parallel to the axis of the test bars and therefore had no significant effect on the properties.

Two test castings of each thickness were poured from each melt, starting with the thinnest (1/8-inch) at 820°C (1510°F) and ending with the thickest (2-inch) at 720°C (1330°F).

All test castings, after heat treatment, were sectioned parallel to the chill and/or riser into 1-inch-wide coupons, from which test bars were machined.

Test Bars

Cast-to-shape "Dow" test bars* were used for melt quality and heat treatment control and tested without machining.

All other test bars were cut out from the test plates. Flat test bars (1/2-inch gauge width and 2-inch gauge length) were cut out of 1/8-inch and 1/4-inch plate, so that the flat surfaces were left unmachined. Round test bars were machined from 1/2-inch plates (0.313-inch gauge diameter and 1.25-inch gauge length) and from the two heavier section plates (0.505-inch gauge diameter and 2-inch gauge length). All round test bars were taken out of the centre of the casting coupons.

Heat Treatment

Solution heat treatments were carried out in an electrically heated circulating-air furnace with an automatically controlled protective atmosphere containing 1% SO_2, the temperature being controlled to ± 2°C. Ageing was carried out in an electric oven with air circulation and close temperature control (to ± 1°C).

When air-blast cooling was used after solution heat treatment, a special arrangement of electrical fan and suspension of castings was used to ensure uniform cooling of all sides of the castings.

INITIAL INVESTIGATION ON ZK61-T6 ALLOY

It was stated earlier (11) that alloy ZK61-T6, which until recently(8) was the highest-strength magnesium casting alloy, was foundrywise a difficult alloy, and that good-quality castings could be obtained only if special refining (high zirconium content) and casting (gating, risering, chilling) procedures were established and strictly adhered to. Reluctance to take the trouble to master these " foundry difficulties ", and discouragement after early failures to obtain satisfactory castings, were the reasons why this alloy was so little used outside of Canada.

In view of conflicting information published by various authors about alloy ZK61-T6, it was considered desirable to investigate optimum properties obtainable in castings, not in separately-cast test bars. The work was carried out first on plates having from 1/8-inch to 2-inch section thickness, and then checked on prototype castings produced by a commercial foundry to U.S. Military Specification MIL-M-46062 (MR).

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* According to Canadian Standard CSA.HG.1-1963 and U.S. Federal Specification QQ-M-56, Fig. 1A.

It should be added here that in recent years considerable development work on high-strength magnesium-casting alloys has been carried out in the U.S.A., and that very favourable properties in high-quality ZK61-T6 alloy castings have been reported by Flemings (4) and Nelson (6), for example.

Effect of Heat Treatment

Although a considerable amount of research was carried out on proper heat treating conditions (11), most of it was done on separately-cast test bars and relatively thin-walled castings. Hence, to adapt the usual heat treating conditions to heavier sections and to improve the properties in unchilled or insufficiently chilled parts of the casting, the following alterations of the "standard" (T6) heat treating schedule were tried:

(a) increase of solution time from two to five hours at 500°C (930°F);

(b) increase in the cooling rate after solution heat treatment, by change from still air to uniform blast of air; and

(c) increase of ageing time from 48 hr to 96 hr at 130°C (265°F).

The effect of these modifications on tensile properties of an end-chilled 2-inch ZK61 alloy plate is presented in Figure 3. The considerable increase in tensile strength, and especially in yield strength, is accompanied by some sacrifice in ductility. The more uniform distribution of properties throughout the casting (distance from chill) should be also noted. For better appreciation of the values obtained in this 2-inch-thick section, it should be recalled that ASTM-B80 specifies for the 0.505-in.-diameter cast-to-shape test bar, 39 kpsi UTS, 26 kpsi YS, and 5% elongation.

The increase in ageing time to 4 days was found to be beneficial, although it was realized that in commercial foundry operation such long ageing cycles can be used only in exceptional cases where top quality is more important than economy.

Effect of Chilling

The graph also shows that all properties decrease progressively with the distance from the chilled end, although very high properties were obtained even on test bars cut out of the 4th-inch coupon, which solidified predominantly under the influence of the adjacent heavy riser.

A more detailed survey of tensile properties, as affected by the distance from the chill, is presented in Figure 4. The 2-inch-thick plates were cut parallel to the chilled face, at 1/4-inch intervals, and flat test pieces (1/8-inch thick with 1/2-inch width and 2-inch length of the gauge portion) were machined from the coupons. The modified heat treatment (T6C) again proved very successful and exceptionally high property values were obtained at the chilled face of the 2-inch section: over 51 kpsi UTS, 32 kpsi YS, and 15% elongation. The values for UTS and elongation are much higher than those typical for cast-to-shape ZK61 alloy test bars (46-32-10).

Effect of Plate Thickness

It is a popular belief, among foundrymen, that the mechanical properties of castings decrease appreciably with the increasing section thickness. This is, in general, true for unchilled and similarly gated and risered castings, as was shown by various authors (5) (12) (13). However, there are some qualifications to this statement, which will be discussed later.

It was considered important, therefore, to check the optimum properties obtainable in heavy sections of ZK61 alloy plates when directional solidification and X-ray soundness are assured.

Figure 5 shows the results obtained on unchilled ZK61 plates of different thickness, using the "standard" (T6) heat treatment.

The values for the end-chilled plates of 1-inch and 2-inch thickness were obtained on test bars cut out from the 1st-inch from the chilled face. The graph shows that, by proper solidification (chilling) and the use of the revised heat treating schedule (T6C), properties of the heavier section plates can be obtained that are equal to or even higher than typical values for separately-cast test bars or thinner plates.

STUDY OF OTHER MAGNESIUM ALLOYS

The second phase of the investigation was extended to include all other magnesium alloys used commercially at present, and one chosen from a recently developed (8) series of Mg-Zn-Ag-Zr alloys (ZQ64-T6).

Effect of Cooling Rate from Solution Temperature

It is known that the rate of cooling from the solution heat treating temperature appreciably affects the properties of subsequently aged casting alloys. Mechanical properties are improved in varying degree in all alloys by increasing the cooling rate. Water quenching was investigated for Mg-Al-Zn alloys by Busk and Anderson (14), for ZK61 alloy by Meier (11), and was recently again proposed by Nelson (6), and Bailey and Bossert (15).

To explore the effect of variations in the cooling rate after solution heat treatment on the tensile properties of a 2-inch-thick section, the following four cooling media were used:

(a) still air,
(b) uniform air blast,
(c) boiling water,
(d) oil at 150°C (300°F).

Cooling rates were measured on the centre-line of 2-inch plates and maximum cooling rates of approximately 30, 60, 215 and 1400°C/min, respectively, were recorded.

Alloys studied were AZ63-T6, AZ80-T4, AZ91-T6, AZ92-T6, HK31-T6, ZK61-T6, and ZQ64-T6. The results showed that alloy AZ80-T4 was not sensitive to cooling rate. All the other alloys showed improvement of properties with increasing cooling rate, and alloy HK31-T6 was found the most sensitive.

It was found that the improvement in properties due to quenching in oil at 150°C (the highest cooling rate tested) was generally not significantly different from that obtained by quenching in boiling water, but caused much more difficulty because of cracking of the test pieces.

The results obtained for alloy ZK61-T6 plates (2-inch thick) are presented in Figure 6. Values for oil quenching could not be obtained, because the majority of test pieces showed cracks. Although, as would be expected, the higher cooling rates increased the ultimate tensile and yield strengths, with only some insignificant decrease in elongation, the use of boiling water quenching for ZK61-T6 alloy castings is not recommended for complex casting shapes. Well designed air-blast cooling seems to be sufficiently moderate to minimize introduction of internal stresses and avoid the possibility of warping or cracking of the castings.

Effect of Section Size

(a) Unchilled Castings

As previously mentioned, in general the mechanical properties decrease with increasing section size. Figure 5 showed some results obtained on ZK61-T6 alloy plates. Additional work was undertaken to extend the study to other magnesium alloys, which are listed, with chemical analyses of the melts used, in Table 3. Heat treating schedules used for the test castings (Figure 1 and 2) are given in Table 4, and average results obtained on separately-cast test bars, which were used to control the melt quality and to check the heat treatment, are listed in Table 5.

Ruddle (16) showed a good correlation between the tensile properties of aluminum alloy plate castings and the longitudinal temperature gradients existing during the later stages of freezing, when interdendritic feeding was occurring. He found an optimum plate thickness (in his case, it was the 1/2-inch thickness, where thermal gradients were steepest) the tensile properties of which were considerably superior to those of plates of other thicknesses.

Eastwood and Davis (17) reported that optimum soundness (freedom of porosity) in magnesium Mg-Al-Zn alloy plates was obtained in 1/2-inch sections and that the greatest difficulties in producing sound material were found in much thinner or much thicker sections (in their case, 3/16-inch and 1-1/2-inch, respectively).

Green (18) observed that a minimum thermal gradient of 5°F/inch was necessary to produce porosity-free plates in AZ63 alloy. Flemings (19), in discussing Green's paper, stated that much higher thermal gradients, in the order of 100°F/inch or above, are necessary to avoid finely dispersed microporosity and its effect on mechanical properties of the casting.

Similarly, Chamberlin and Mezoff (20) demonstrated the importance of sufficiently high thermal gradients in securing sound castings and showed good correlation between thermal gradients and mechanical properties of AZ63 castings. No correlation was found between the cooling rates (at 1000°F, 540°C) and tensile strength. They state that a thermal gradient greater than 98°F/inch was necessary to obtain mechanical properties better than typical for the alloy.

Watkins and Kondic (21) consider the alloy composition and solidification cooling rate as the two most significant variables affecting cast structure and related mechanical properties. It is claimed by Form, Ahearn and Wallace (22) that average thermal gradients in the solidifying casting do not correlate with tensile strength. The actual thermal gradient at the instant of solidification is significant but is difficult to determine experimentally. Good correlation is obtained between strength and solidification time. They suggest that the important factor controlling the strength of a casting is time of solidification, not section size.

The foregoing indicates that no agreement has been reached in this field and that further research is necessary. From the practical aspect of producing premium-quality castings it seems obvious that the control of both the thermal gradients and the cooling rate through proper chilling is very important, especially in heavier sections and complex casting shapes.

The present investigation showed very similar results to those reported by Eastwood and Davis (17). Sound castings with good mechanical properties were consistently obtained for 1/2-inch sections; thinner sections showed definitely lower properties; and in heavier sections, high properties could be obtained only by the use of extensive chilling.

Since the main effort in this investigation was directed to obtaining optimum properties in heavy sections, less work was carried out on the improvement of the thinner sections, which in commercial foundries are not considered as difficult. This is why some of the tensile properties, presented in Table 6, are not necessarily maximum values obtainable under optimum conditions.

It should also be mentioned that the values shown in Table 6 were affected by the following variables:

(a) Shape of the Test Bar: Flat test bars were used for the 1/8-inch and 1/4-inch sections, and round test bars were used for the 1/2-inch section. The effect of test bar shape on tensile properties of some magnesium alloys was reported earlier (5).

(b) Surface Condition: Unmachined (as-cast) flat surface of test bars from the thinner sections vs. fully machined, round test bars from the 1/2-inch section.

(c) Heat Treatment: The schedules were not adapted to the various thicknesses, and shorter solution time for thinner plates may be more advantageous.

Results for Mg-Al-Zn alloys are not given here, because they showed considerably lower properties in thinner sections and it is considered that additional work is necessary before a final report can be made.

Results for high-strength alloy compositions (in Table 6) show that remarkably good results were obtained in the 1/2-inch plates, but that in all cases the thinner sections show lower values in spite of the smaller grain size.

(b) End-Chilled Castings

Heavy chilling, used to obtain proper solidification conditions which resulted in the improvement of properties in ZK61-T6C alloy plates (Figures 3 to 6), was again employed in the casting of 1-inch- and 2-inch-thick plates in all the other magnesium alloys. Results obtained on these plates are shown in Tables 7 and 8.

The properties obtained on bars machined from coupons closest to the chill (1st-inch coupons) were very high, being, in most alloys, equal to or superior than those obtained on cast-to-shape test bars from the same melts (see Table 5). As would be expected, the properties decrease with increasing distance from the chilled end and correspondingly coarser grain size. The grain size of Mg-Al-Zn alloys changes considerably with increasing distance from the chilled face, whereas alloys containing zirconium show only a relatively small difference in grain size.

To illustrate better the sensitivity of the various alloys to the chill distance, Figures 7 to 9 present graphically the effect of chilling on tensile properties of 2-inch plates. The alloys were divided into three groups:

(a) Mg-Al-Zn alloys.
(b) Specialty alloys containing zirconium (alloys developed for elevated temperature service, weldability, etc.).
(c) High-strength alloys containing zirconium. To this group was added an experimental alloy, ZQ64-T6, which exhibits remarkably high strength(8).

The properties of Mg-Al-Zn alloys (Figure 7) decrease rapidly with increasing distance from the chill, except alloy AZ63-T6 which is less sensitive; this alloy shows also much less grain coarsening than the other Mg-Al-Zn alloys. These results indicate that in order to obtain optimum properties in these alloys, chilling and risering have to be closely spaced to produce steep thermal gradients.

Alloys in the other two groups (Figures 8 and 9) are less sensitive to the distance from the chill. As already mentioned, in these alloys the grain coarsening is relatively less pronounced, indicating more effective grain refinement by zirconium (especially under adverse conditions).

The high properties of alloy ZK61-T6C, and especially those of the experimental alloy ZQ64-T6, are to be noted. The combination of properties shown for alloy ZQ64-T6 (50 to 51 kpsi UTS, 34 kpsi YS, and 7 to 11% elongation) is not obtainable in any other magnesium casting alloy and compares favourably with specified properties of wrought products (see Table 2).

Alloy QE22 (see Figure 9) exhibits a very high yield strength, which is little affected by the distance from the chill, although the ultimate tensile strength and elongation values are relatively low. This is a limitation of the alloy because a large margin of UTS over YS and higher ductility increase the reliability of castings to the point that the designer will consider them for structural parts without the penalty of a casting factor (23). The much higher UTS and elongation of ZK61-T6 and, especially, of the new ZQ64-T6 alloy are therefore very important.

Press-Forging

It has been shown (24) that the properties of castings of simple shapes can be improved by press-forging. This process seems to be particularly attractive when applied to premium-quality castings. Work to explore these possibilities has been started on end-chilled 1-inch- and 2-inch-thick plates. The first results of preliminary press-forging tests show that additional increases in UTS and YS are possible (e.g., alloy ZQ64-T8 showed 53.5 kpsi UTS, 38 kpsi YS and 7% elongation; alloy ZK61-T8 showed respectively 49.5, 36, and 8).

Inverse Segregation

In discussing the effect of chilling on the properties of heavy sections, consideration should be given to the possibility of compositional changes by inverse segregation, as was reported (25) for Z6 and ZK61 alloys. In particular, it was considered important to determine whether segregation is confined to the higher zinc contents in these two alloys, or whether other alloys behave similarly. Inverse segregation affects, of course, heat treatment response and mechanical properties in different parts of a casting.

Table 9 reveals that a marked inverse segregation of the major alloying elements can be found in all commercial magnesium casting alloys. A detailed account of the study on inverse segregation in various magnesium casting alloys will be given in a separate paper; this short note is intended only to draw attention to this problem.

PROTOTYPE CASTINGS

To check the results obtained on the test plates, a series of about 50 prototype castings, similar to the design shown earlier (11) (26), was produced by a commercial foundry. The mould design was carefully chosen to obtain the required mechanical properties in critical areas, but, otherwise, standard equipment and routine foundry methods were used. The gross weight of the casting (before trimming) was 42 lb; net weight before shipping, 25 lb. The total weight of cast-to-shape magnesium chills used in the cope was 5-1/2 lb, and an additional 12 lb of cast-to-shape copper chills was used in the drag. The heat treatment of the castings was carried out according to commercial routine schedules, which provided a solution heat treatment for 10 hr at 480°C (900°F), uniform air blast cooling, and ageing for 48 hr at 130°C (265°F).

Since gating, risering and chilling were designed for alloy ZK61-T6, only a few castings were made, for comparison, in alloys AZ92-T6 and QE22-T6. Test bars were cut out from some randomly chosen castings in the ZK61-T6 series, and from all of the AZ92-T6 and QE22-T6 alloy castings. Table 10 shows the results obtained on test bars from areas designated as Class 1 or 2 (according to U.S. Military Specification MIL-M-46062 (MR), dated 25 June, 1963) and from unspecified areas. Although some of the test bars showed values slightly below the specified minimum, in general the results may be considered as very satisfactory, especially if the less favourable heat treatment schedule and the small amount of risering and total weight of chills are taken into account. This may be compared with a premium-quality aircraft casting tested recently (6), where 70 lb of magnesium and 78 lb of chills were used for a casting of 10 lb shipping weight. For comparison, results obtained on one prototype casting in experimental alloy ZQ64-T6 are also listed in Table 10.

SUMMARY

Figures 7 to 9 and Tables 6 to 8 show that the minimum properties specified in the new U.S. Military Specification MIL-M-46062 (MR) are obtainable for all alloys, if proper solidification and heat treating conditions are provided. It should be understood that "radiographically sound" sections are not sufficient to obtain "Class 1" properties, but that careful mould design, including proper spacing of chills and risers (especially for Mg-Al-Zn alloys), is essential.

The results of the investigation may be summarized in the following conclusions:

1. Properties of heavier sections in ZK61-T6 alloy were significantly improved by modifying the heat treatment.

2. Chilling of heavier sections (1-inch and 2-inch plates) was necessary to produce porosity-free material and resulted in remarkably high properties of ZK61-T6C alloy at the chilled face (over 51 kpsi UTS, 32 kpsi YS, and 15% elongation). The properties decrease with the distance from the chill, accompanied by a relatively small increase in grain size.

3. High properties could be obtained in unchilled sections of ZK61-T6 alloy up to 1/2-inch thickness; heavier sections required extensive chilling and modified heat treatment.

4. The cooling rate from solution temperature of all commercial magnesium casting alloys affects the properties; the UTS and YS increase, and the elongation decreases, with increasing cooling rates.

5. Results obtained on end-chilled 1-inch and 2-inch plates showed that exceptionally high properties can be obtained at the chilled face (equal to or higher than those for separately-cast test bars) and that, for alloys containing zirconium, very good properties can be obtained even at a considerable (3-1/2-inch) distance from the chill. AZ-type alloys, with the exception of alloy AZ63, are very sensitive to chill distance and show a marked drop in properties at a short distance from the chill.

6. It was shown that the requirements of the new MIL-M-46062 (MR) specification for premium-quality magnesium alloy castings can be met without undue difficulties in all commercial alloys, even in heavy sections, by proper chilling and, if necessary, by modification of heat treatment.

7. Although much more development work on complex casting shapes in commercial conditions has to be done, it appears from the limited data already available that for one or more of the alloys in Mg-Zn-Ag-Zr series (e.g. ZQ64-T6), specified minimum properties for "Class 1" casting areas could be expected in the range of 45-48 kpsi UTS, 30-32 kpsi YS and 5-8% elongation.

8. It has been established that inverse segregation of the major alloying elements can be found in all commercial magnesium casting alloys.

9. A comparison of strength-to-weight properties of magnesium alloy, aluminum alloy and steel castings of premium quality shows (Figure 10) the very favourable position of the high-strength magnesium alloys.

   In the chart, the bases of the columns represent the guaranteed minimum properties specified for Class 1 areas in MIL-M-46062 (MR), and the base of the ZQ64-T6 column a preliminary proposal for this alloy. The tops of the columns show the maximum results obtained in the present investigation on plates of various thickness.

   The specified minimum properties for aluminum alloy SC51-T6 (50-40-5, according to MIL-A-21180B) and for steel (180-150, according to MIL-S-46052 (MR)) are inserted for comparison based on their strength-to-weight ratios (densities: 1.84-2.70-7.85 respectively).

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BL:JWM:(PES) ac

TABLE 1

Mechanical Properties in Designated Areas of High-Quality Magnesium Alloy Castings

(According to U.S. Military Specification
MIL-M-46062 (MR), dated 25 June 1963)

Alloy Designation*	Designated Area Class	Minimum Properties in Designated Areas		
		UTS, kpsi	0.2% YS, kpsi	Elongation, %
AZ92-T6	1	40	25	3
	2	34	20	1
	3	30	18	0.75
	X**	17	13.5	0.25
QE22-T6	1	40	28	4
	2	37	26	2
	3	33	23	2
	X	28	20	(2)***
ZK61-T6	1	42	29	6
	2	37	26	4
	3	34	23	2
	X	30	21	1.25

* Alloy and temper designations according to Canadian designation codes CSA.H.1-1958.

** X - unspecified areas of casting.

*** This elongation value for unclassified areas in alloy QE22-T6 casting is definitely too high. It should be, as for all the other alloys, 25% of the elongation specified for separately-cast test bars, which ASTM-B80 lists as 2%; in any case, this elongation minimum should not exceed 1%.

TABLE 2

Mechanical Properties of Wrought Magnesium Alloys

ASTM Spec.	Alloy Designation	UTS, kpsi	0.2% YS, kpsi - minimum -	Elongation, %
Die Forgings				
B91-63	AZ80A-T5	42	28	2
	ZK60A-T5	42	26	7
Extruded Bars and Shapes*				
B107-63	AZ80A-F	42 to 43	27 to 28	4 to 9
	AZ80A-T5	45 to 48	30 to 33	2 to 4
	ZK60A-F	40 to 43	28 to 31	4 to 5
	ZK60A-T5	45 to 46	36 to 38	4

* Range of minimum properties, depending on cross-section of area.

TABLE 3

Chemical Analyses of Alloys Used for Test Castings

(Per Cent)

Alloy Designation	Al	Zn	Mn		
AZ63	6.25	3.12	0.49		
AZ80	8.25	0.50	0.46		
AZ91	9.18	0.96	0.35		
AZ92	9.04	2.07	0.32		
	R.E.	Th	Zn	Zr*	
EZ33	2.72		3.37	0.65	
HK31		3.02		0.75	
HZ32		2.88	1.9	0.82	
ZE41	1.42		4.49	0.72	
	Zn	Zr*	Ag	Di**	Th
QE22		0.49	2.67	2.54	
ZH62	6.04	0.89			2.15
ZK51	4.87	0.76			
ZK61	6.34	0.81			
ZQ64	5.93	0.80	4.15		

* Zr - soluble zirconium

** Di - didymium

TABLE 4

Heat Treatment of Magnesium Alloy Test Castings

Alloy	Solution Heat Treatment			Cooling from Solution Temp.	Ageing		
	Temperature		Time, hr		Temperature		Time, hr
	°C	°F			°C	°F	
AZ63-T6	338	640	3	a.b.	180	355	18
	382	720	16				
AZ80-T4	415	780	24	a.b.	-	-	-
AZ91-T6	410	770	24	a.b.	190	375	8
AZ92-T6	405	760	24	a.b.	190	375	8
EZ33-T5	-	-	-	-	170	340	10
HK31-T6	565	1050	2	a.b.	205	400	16
HZ32-T5	-	-	-	-	315	600	4
ZE41-T5	330	625	2	a.b.	177	350	16
QE22-T6	525	975	8	w.q.	200	390	8
ZH62-T5	330	625	2	a.b.	177	350	16
ZK51-T5	-	-	-	-	177	350	12
ZK61-T6C	500	930	5	a.b.	130	265	96
ZQ64-T6	455	850	5	a.b.	130	265	48

a.b. - cooled in air blast.
w.q. - quenched in water at 60°C (140°F).

TABLE 5

Tensile Properties Obtained on Separately-Cast Test Bars

Alloy Designation	Ultimate Tensile Strength, kpsi	0.2% Yield Strength, kpsi	Elongation in 2 in., %	Grain Size, 0.001 in.
AZ63-T6	42.3	20.9	7	3.5
AZ80-T4	39.8	14.4	17	3
AZ91-T6	40.3	22.2	3	3
AZ92-T6	43.7	24.8	2.5	3
EZ33-T5	25.2	16.0	5	1.8
HK31-T6	36.2	17.5	12	3.5
HZ32-T5	30.4	12.8	17	2.2
ZE41-T5	29.8	22.4	2.5	2.2
QE22-T6	40.7	31.3	3.5	2
ZH62-T5	40.2	25.2	8.5	2.5
ZK51-T5	40.7	26.1	9.5	2.4
ZK61-T6C	46.6	33.5	10	2
ZQ64-T6	48.6	34.8	4.5*	2

* Flaw in fracture.

TABLE 6

Properties of Unchilled Sand-Cast Plates

Alloy Designation	1/8" Plate				1/4" Plate				1/2" Plate			
	UTS, kpsi	0.2 YS, kpsi	Elong., %	G.S., 0.001"	UTS, kpsi	0.2 YS, kpsi	Elong., %	G.S., 0.001"	UTS, kpsi	0.2 YS, kpsi	Elong., %	G.S., 0.001"
QE22-T6	38.8	31.0	2.0	2.2	38.3	31.1	2.0	1.9	40.3	29.9	4.5	2.6
ZH62-T5	36.2	22.4	7.5	1.8	35.5	22.0	5.5	2.0	38.5	22.4	9.0	3.0
ZK51-T5	37.8	24.0	6.0	1.8	38.5	24.2	6.5	2.2	40.4	22.7	14.5	2.7
ZK61-T6C	44.3	32.4	7.0	1.8	43.9	31.9	6.0	2.2	46.4	31.3	15.0	2.4
ZQ64-T6	46.9	33.9	6.5	2.0	47.4	33.1	6.5	2.1	50.7	33.7	9.5	2.2

TABLE 7

Properties of End-Chilled 1-Inch-Thick Sand-Cast Plates

Alloy Designation	1st inch				2nd inch				3rd inch				4th inch			
	UTS, kpsi	0.2 YS, kpsi	Elong., %	G.S., 0.001"	UTS, kpsi	0.2 YS, kpsi	Elong., %	G.S., 0.001"	UTS, kpsi	0.02 YS, kpsi	Elong., %	G.S., 0.001"	UTS, kpsi	0.2 YS, kpsi	Elong., %	G.S., 0.001"
AZ63-T6	46.4	19.9	14.0	3.3	45.6	19.4	11.5	3.0	42.1	17.6	9.0	3.8	38.6	16.7	7.5	4.0
AZ80-T4	41.1	13.1	22.0	2.8	38.3	11.9	15.0	3.8	35.8	10.6	14.0	5.5	33.8	11.7	12.5	9.0
AZ91-T6	44.6	22.2	6.0	2.5	40.3	18.8	5.5	4.8	35.1	17.8	5.0	6.0	32.3	16.5	4.0	7.0
AZ92-T6	47.8	24.3	4.0	2.5	43.5	20.3	5.0	3.5	36.5	18.5	4.0	8.0	32.4	17.7	3.5	12.0
EZ33-T5	26.7	15.8	5.5	1.8	24.3	14.7	5.0	2.0	23.6	14.1	4.0	2.5	23.2	14.3	4.0	2.5
HK31-T6	38.1	16.1	13.5	2.4	37.9	15.7	14.0	2.5	36.8	15.9	12.5	2.5	35.4	15.4	11.0	2.8
HZ32-T5	32.9	13.6	27.0	1.8	30.9	12.0	14.0*	2.7	31.5	11.6	17.0	2.8	31.1	12.1	11.0	3.0
ZE41-T5	35.0	21.3	6.0	1.8	30.5	21.0	4.0*	2.5	33.3	20.4	5.5	2.5	32.7	20.9	3.5	3.0
QE22-T6	42.6	32.1	5.5	2.0	40.7	31.0	4.0	2.7	40.0	30.6	4.0	2.7	40.0	29.5	4.0	3.0
ZH62-T5	41.3	23.8	16.5	1.9	40.2	22.0	10.0	3.0	39.9	22.0	10.0	3.7	39.7	21.3	10.5	3.7
ZK51-T5	42.1	24.3	15.0	1.9	41.6	23.8	15.0	2.2	41.5	23.4	14.5	2.5	40.9	22.6	13.0	3.0
ZK61-T6C	46.4	30.8	17.0	2.1	45.2	28.6	13.5	2.6	44.3	27.7	10.5	2.9	43.9	26.8	12.0	3.3
ZQ64-T6	51.0	33.8	8.5	2.0	51.1	32.8	11.5	2.0	49.6	31.3	11.5	2.0	47.3	30.2	8.5	2.3

* Flaw in fracture.

TABLE 8

Properties of End-Chilled 2-Inch-Thick Sand-Cast Plates

	1st inch				2nd inch				3rd inch				4th inch			
Designation	UTS, kpsi	0.2 YS, kpsi	Elong., %	G.S., 0.001"	UTS, kpsi	0.2 YS, kpsi	Elong., %	G.S., 0.001"	UTS, kpsi	0.2 YS, kpsi	Elong., %	G.S., 0.001"	UTS, kpsi	0.2 YS, kpsi	Elong., %	G.S., 0.001"
AZ63-T6	44.2	19.0	8.0*	3.0	42.9	19.6	9.0	3.8	41.2	17.9	8.0	6.0	35.9	16.7	6.5	6.0
AZ80-T4	39.9	12.5	19.5	3.5	34.2	10.9	13.0	8.0	32.0	10.8	12.5	13.0	31.7	11.5	10.0	14.0
AZ91-T6	44.9	21.1	6.0	2.8	36.1	17.6	5.0	8.0	30.8	17.3	3.0	12.0	28.7	16.6	3.0	13.0
AZ92-T6	47.5	24.0	4.0	2.5	37.4	18.9	4.0	6.0	31.7	17.8	3.0	8.0	28.5	16.9	2.0	12.0
EZ33-T5	25.5	16.0	5.0	1.9	23.0	14.5	3.0	2.3	22.4	14.4	3.5	2.8	21.6	14.2	3.0	3.0
HK31-T6	38.6	15.3	11.0	2.5	37.0	15.6	14.0	2.7	35.8	15.1	11.0	2.5	33.8	15.5	8.5	2.8
HZ32-T5	32.2	13.1	24.0	2.0	31.4	12.1	21.0	2.5	31.1	11.6	16.0	3.0	31.0	11.7	16.0	3.5
ZE41-T5	33.9	20.9	6.0	1.8	32.2	20.6	4.0	2.5	30.7	19.9	4.5	3.0	29.8	19.6	4.0	3.0
QE22-T6	42.3	30.8	4.5	2.2	41.2	31.6	4.5	3.0	39.8	30.9	4.0	3.0	38.5	28.7	2.5	3.0
ZH62-T5	41.2	22.7	12.5	2.0	40.1	21.5	11.0	3.0	39.6	21.5	9.5	4.0	38.9	21.1	8.5	4.0
ZK51-T5	41.7	23.7	18.0	2.0	41.0	22.6	12.5	2.7	40.3	21.8	10.5	3.0	39.2	21.8	8.0	3.0
ZK61-T6C	46.5	31.3	18.0	2.4	45.0	28.2	14.5	2.8	44.3	27.0	12.5	3.0	43.8	26.2	10.5	3.5
ZQ64-T6	50.1	33.8	7.0	2.0	50.9	32.4	10.5	2.4	47.2	30.2	7.5	2.7	45.1	29.0	6.5	3.0

* Flaw in fracture.

TABLE 9

Segregation of Major Alloying Elements in Unchilled 1-Inch-Thick Sand-Cast Magnesium Alloy Plates

Distance from End Face*, Inches	Zn % in Z6	Zn % in ZK61	Zn % in ZH62	R.E. % in EZ33	Th % in HK31	Ag % in QE22	Al % in AZ80**
1/16	6.70	6.44	6.40	3.22	3.85	2.96	8.60
5/16	6.49	6.28	6.29	3.06	3.68	2.86	8.44
9/16	6.47	5.90	6.19	3.01	3.40	2.82	8.43
13/16	6.36	5.87	6.14	2.94	3.40	2.74	8.35
17/16	6.31	5.90	6.12	2.96	3.32	2.72	8.31
21/16	6.28	5.90	6.07	2.92	3.22	2.70	8.25
25/16	6.24	5.90	5.99	2.92	3.27	2.72	8.24
29/16	6.18	5.90	5.94	2.92	3.29	2.70	8.27
35/16	6.13	5.87	5.89	2.87	3.34	2.67	8.25
43/16	6.00	5.82	5.81	2.78	3.26	2.59	8.19
51/16	5.95	5.72	5.69	2.67	3.04	2.50	8.11
57/16	5.77	5.66	5.56	2.62	2.88	2.37	8.05
63/16	5.74	5.69	5.48	2.65	2.98	2.31	8.05
Melt analysis	6.36	5.85	6.04	2.74	3.24	2.61	8.34

* Samples were machined parallel to end face of the plate.

** AZ80 alloy plate was cast with chilled face.

TABLE 10

Tensile Properties of Test Bars Cut Out of Prototype Castings

Alloy Designation		Designated Areas Class 1			Designated Areas Class 2			Unspecified Areas			Simulated Service Tests, Breaking Load-lb
		UTS, kpsi	YS, kpsi	El., %	UTS, kpsi	YS, kpsi	El., %	UTS, kpsi	YS kpsi	El., %	
ZK61-T6	max	46.4	33.2	14.0	44.5	30.2	10.0	41.5	29.5	6.5	236,000
	min	44.4	28.3	8.0	43.2	28.2	8.0	38.2	20.0	2.5	
	ave.	(10) 45.5	31.8	10.0	(8) 43.9	29.4	9.1	(12) 39.4	25.9	4.1	
	Mil*	42	29	6	37	26	4	30	21	1.25	
QE22-T6	max	42.2	35.0	5.5	41.2	32.8	5.5	40.1	30.2	3.5	217,000
	min	39.7	30.1	3.5	39.6	31.7	3.5	38.4	25.8	2.5	
	ave.	(7) 40.7	33.4	4.3	(6) 40.5	32.3	4.2	(8) 39.3	28.3	2.7	
	Mil*	40	28	4	37	26	2	28	20	2	
AZ92-T6	max	46.2	25.6	4.5	41.8	26.8	4.5	38.9	25.2	2.0	178,000
	min	41.7	20.2	3.5	35.1	21.4	2.5	35.1	20.5	1.0	
	ave.	(6) 43.9	22.8	4.5	(5) 36.9	24.0	3.2	(6) 36.6	23.2	1.4	
	Mil*	40	25	3	34	20	1	17	13.5	0.25	
ZQ64-T6	max	49.2	40.1	9.5	47.2	31.5	7.5	45.9	30.1	7.0	254,500
	min	48.7	32.8	8.0	44.0	29.9	6.0	39.2	19.1	4.5	
	ave.	(3) 49.0	36.0	8.5	(3) 45.7	30.7	6.5	(4) 42.9	26.0	6.0	

* Mil - minimum in Military Specification MIL-M-46062(MR) dated 25 June, 1963.

Note: Numbers in brackets give number of specimens tested.
Test bars for Class 1 and Class 2 areas were cut out from 1-1/4-inch-thick sections.

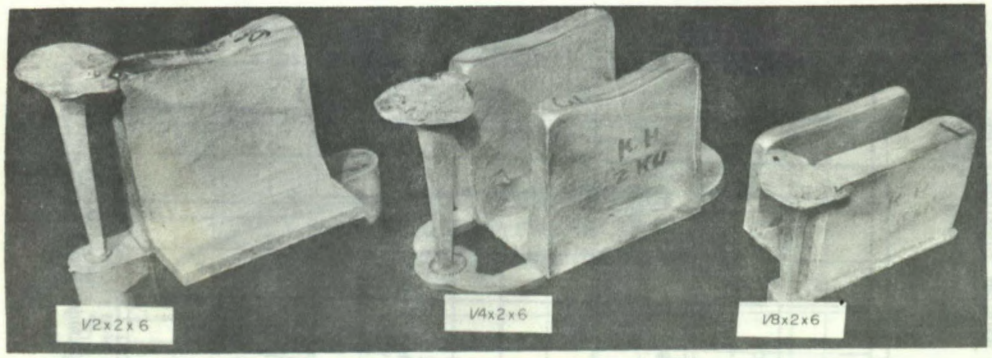

Figure 1. 1/2-, 1/4- and 1/8-inch test plate castings.

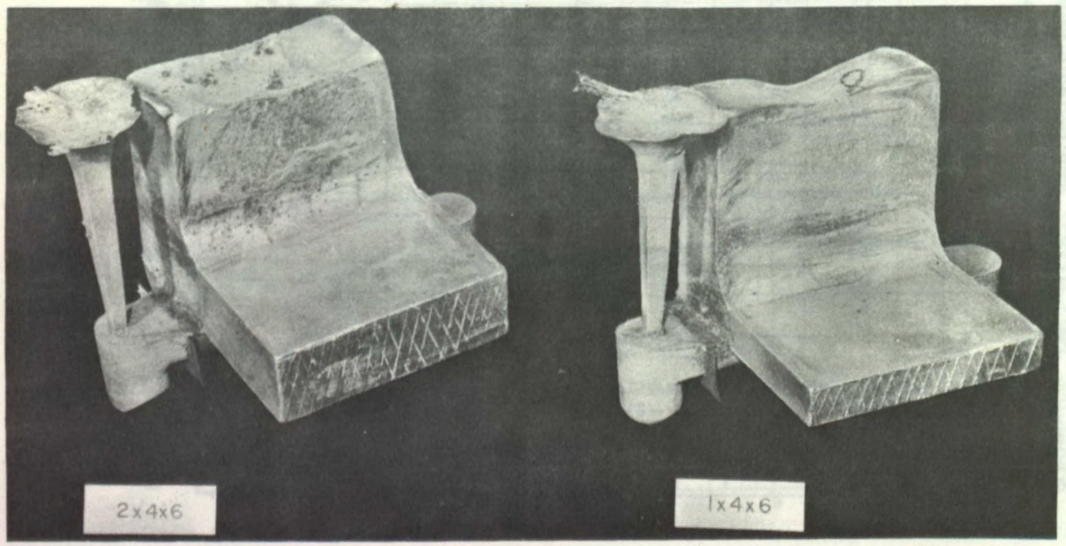

Figure 2. 2-inch and 1-inch test plate castings.

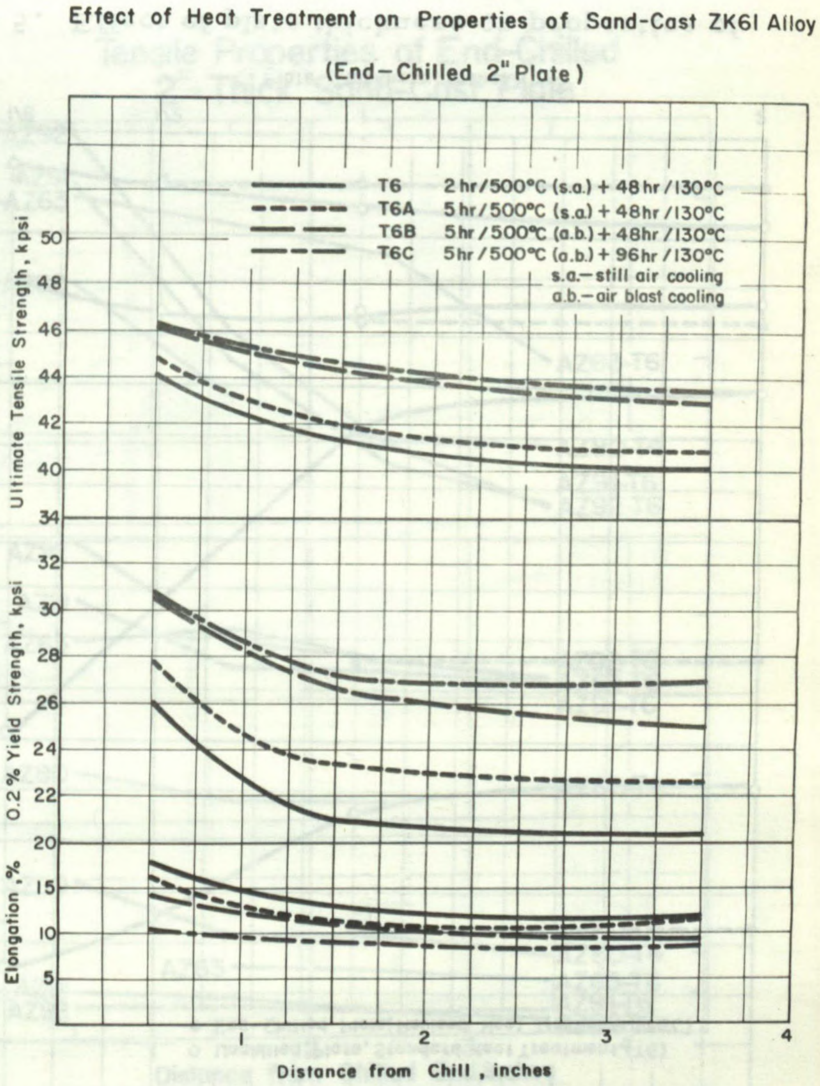

Figure 3. Effect of heat treatment on properties of sand-cast magnesium alloy ZK61-T6 (end-chilled 2-inch plate).

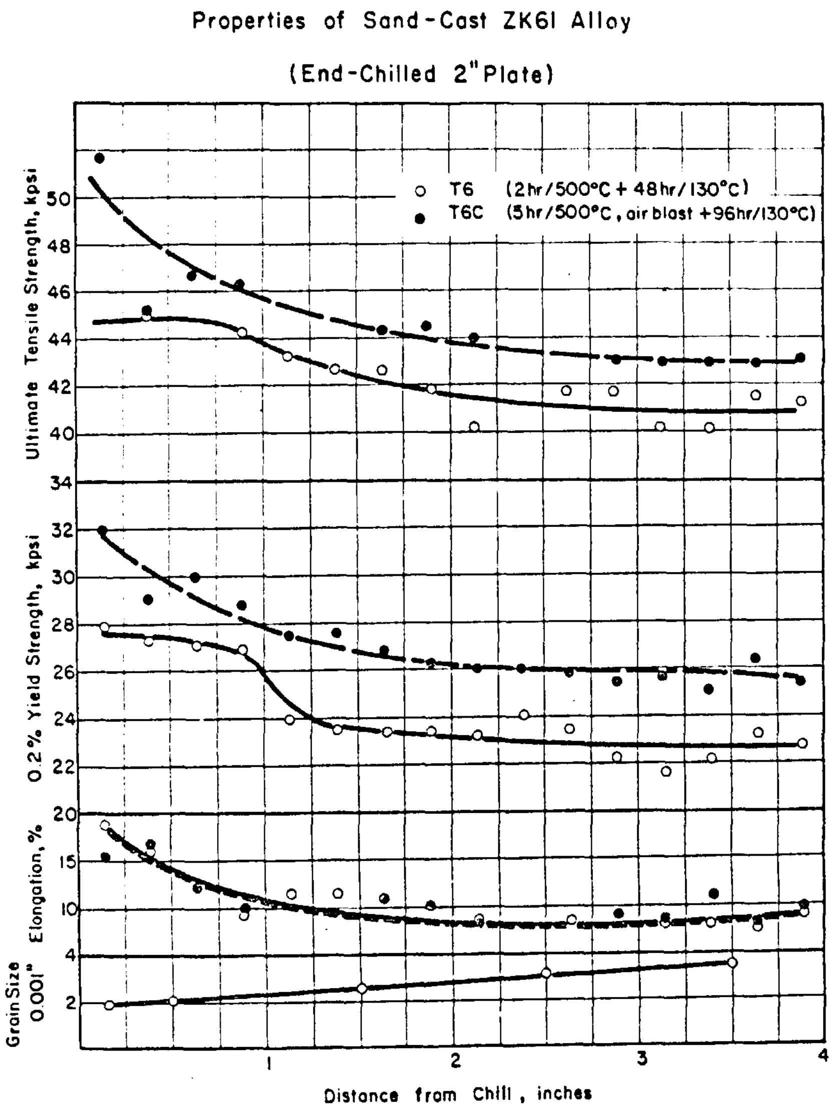

Figure 4. Effect of chilling on properties of sand-cast magnesium alloy ZK61-T6 (end-chilled 2-inch plate).

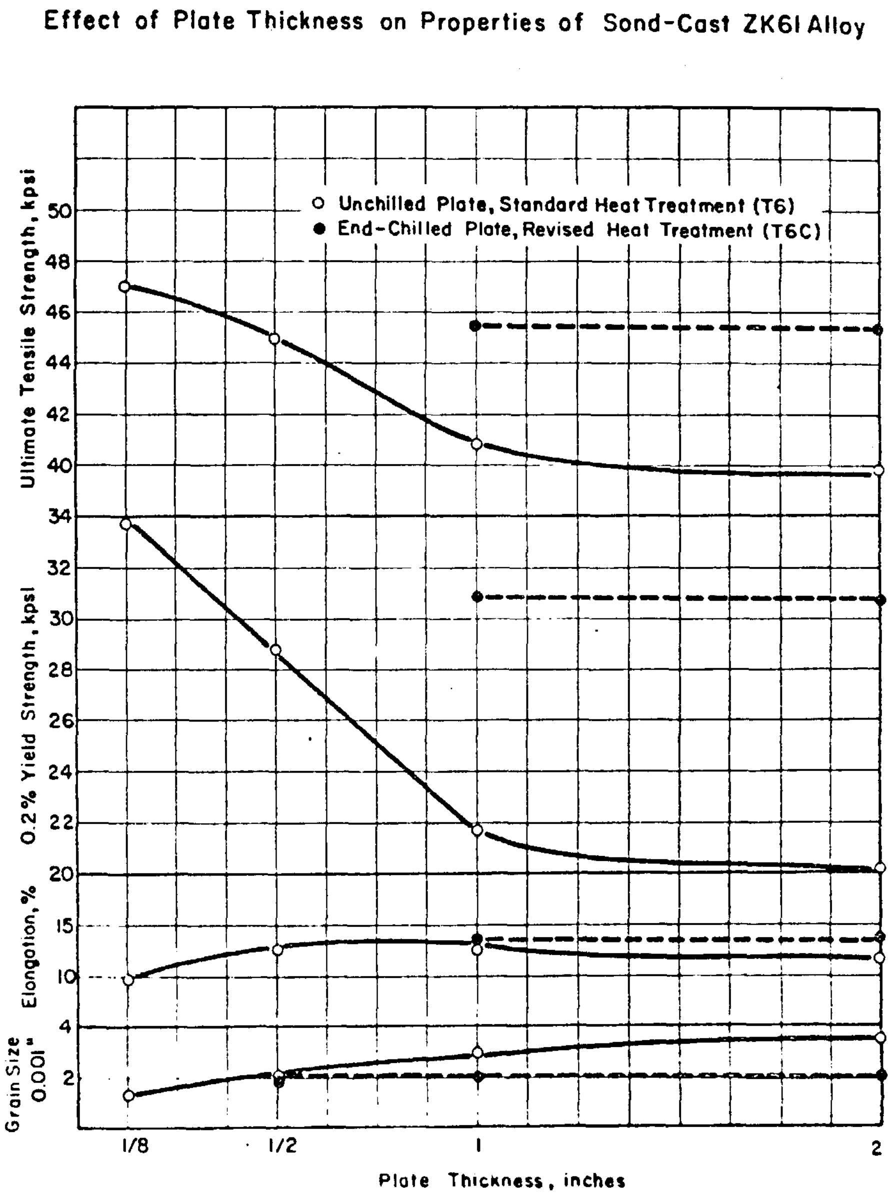

Figure 5. Effect of plate thickness on properties of sand-cast magnesium alloy ZK61-T6.

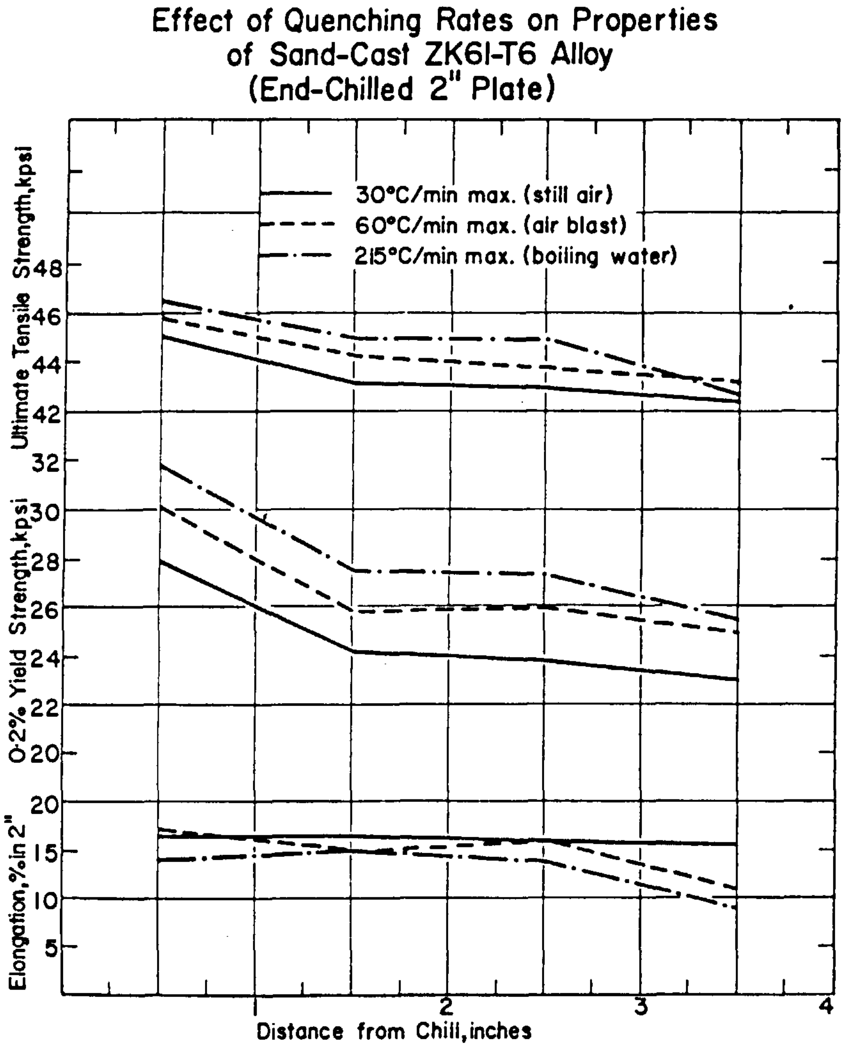

Figure 6. Effect of quenching on properties of sand-cast magnesium alloy ZK61-T6 (end-chilled 2-inch plate).

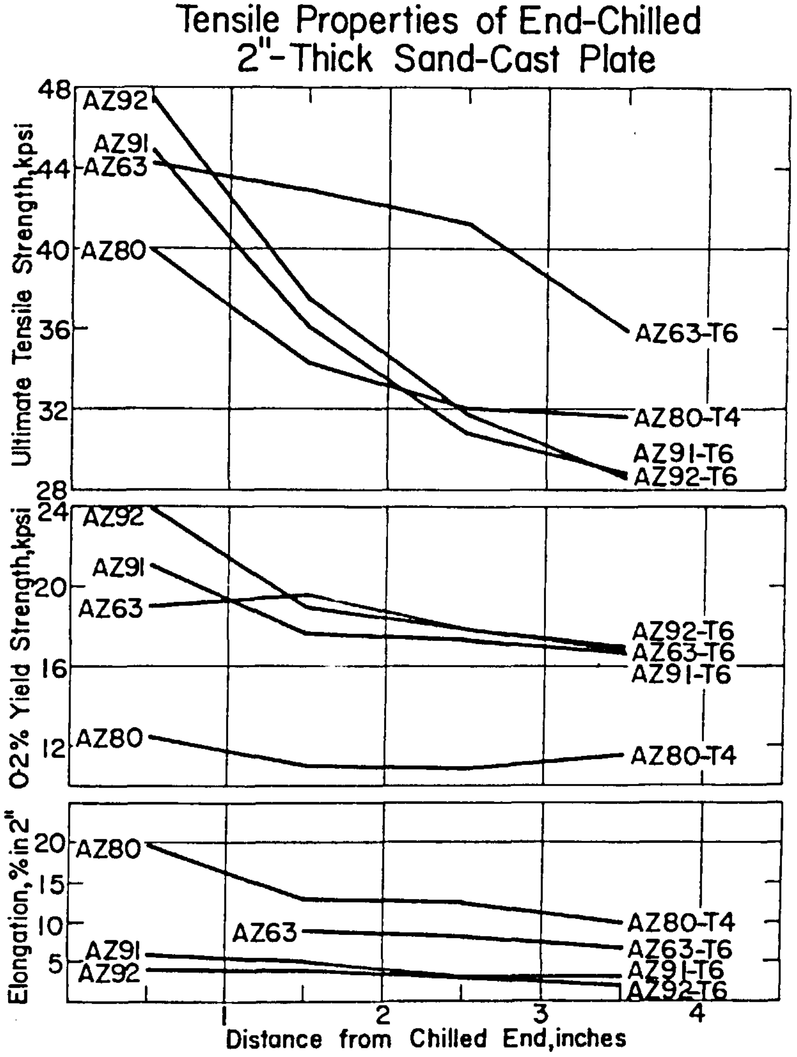

Figure 7. Effect of end-chilling on tensile properties of 2-inch-thick Mg-Al-Zn alloy plates.

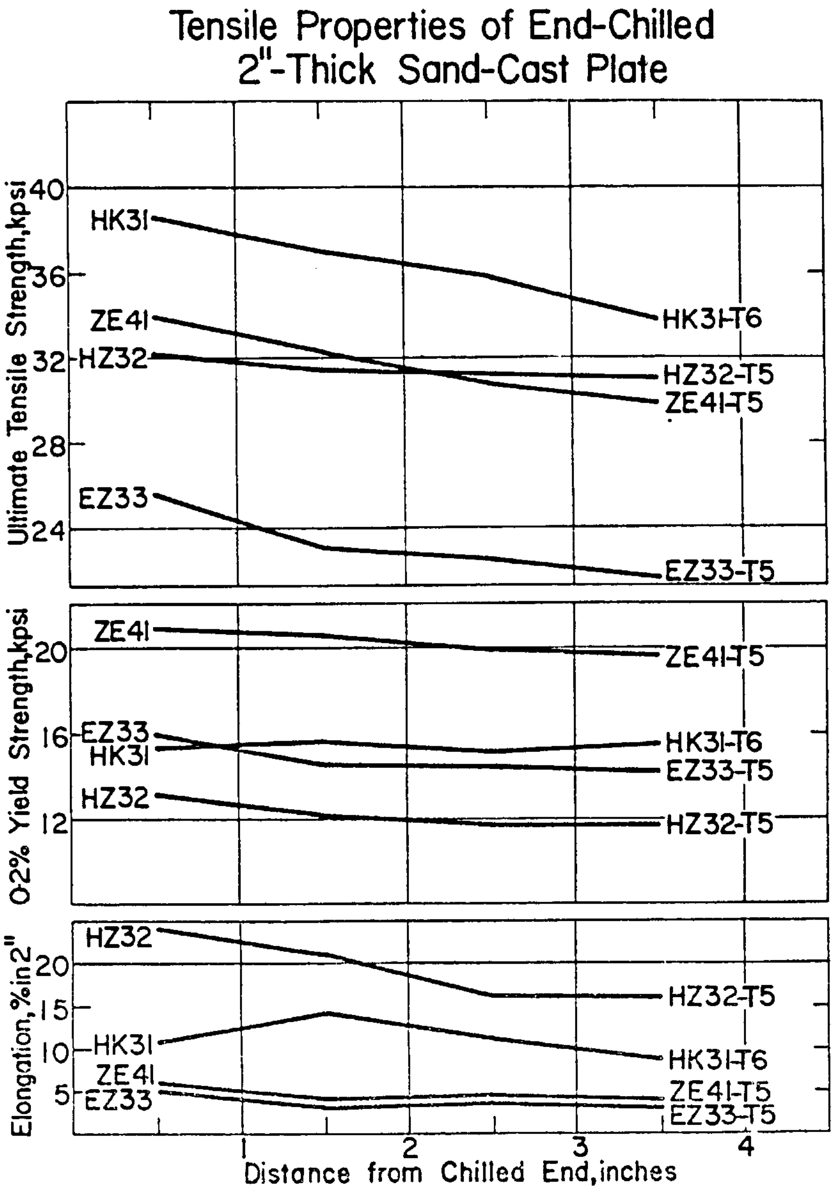

Figure 8. Effect of end-chilling on tensile properties of 2-inch-thick plates of Zr-containing magnesium specialty alloys.

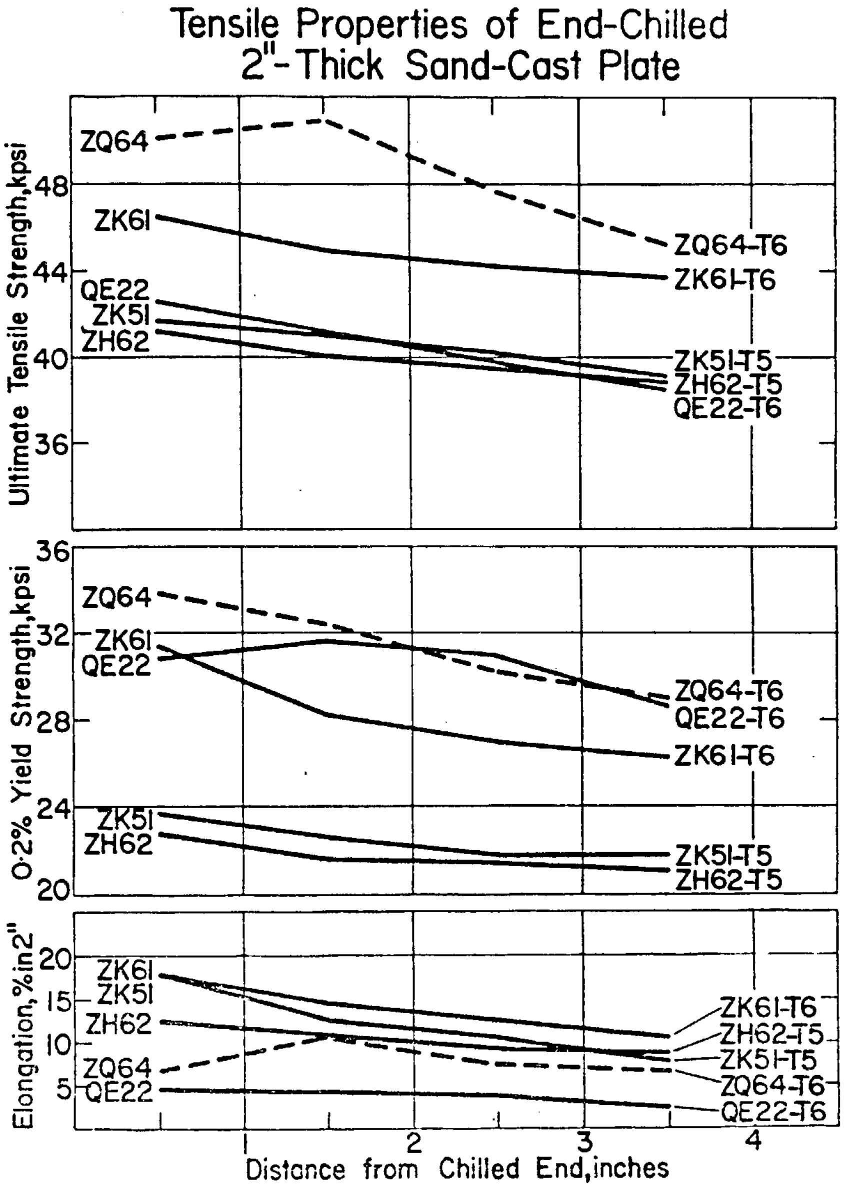

Figure 9. Effect of end-chilling on tensile properties of 2-inch-thick plates of high-strength magnesium alloys.

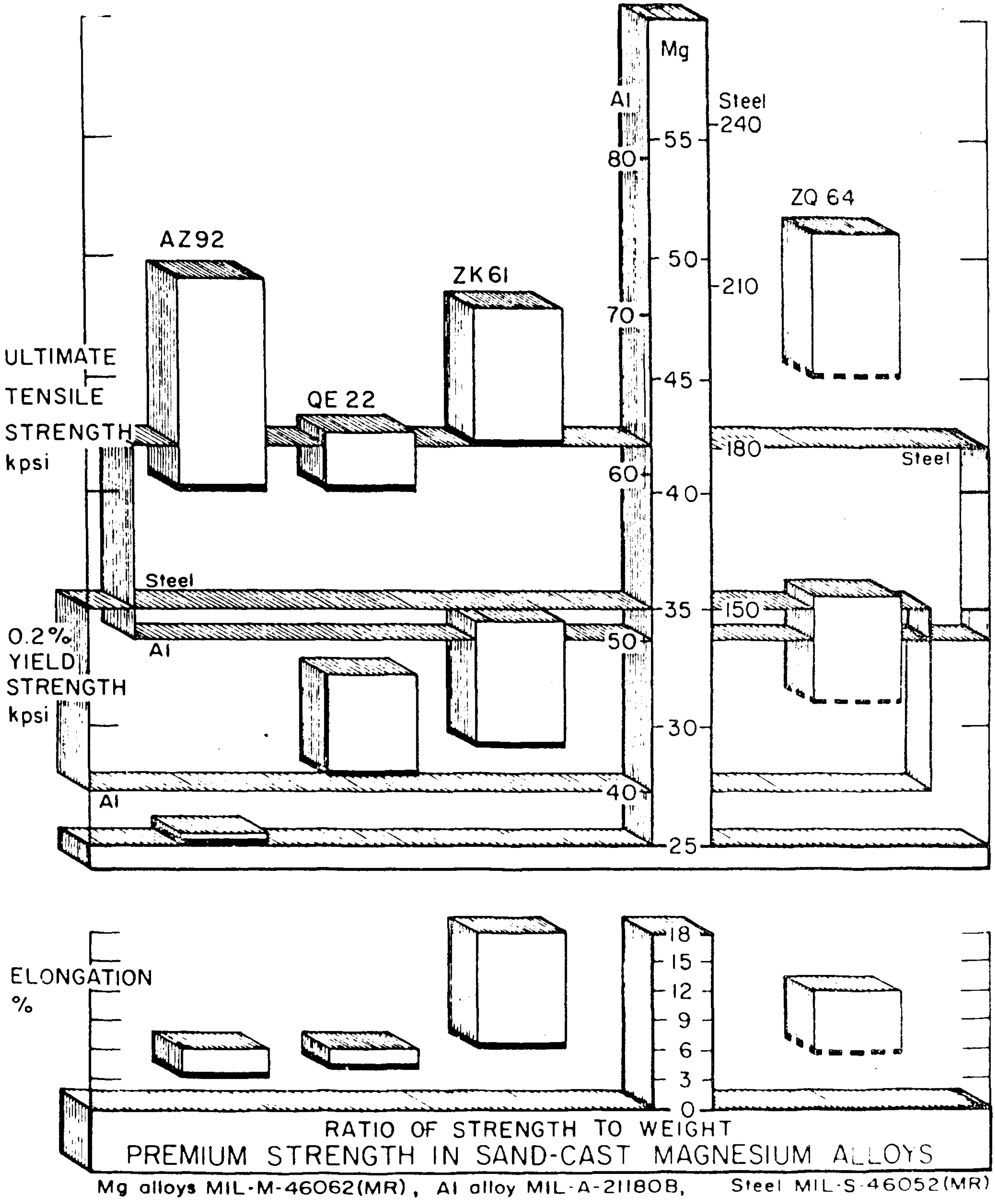

Figure 10. Comparison of strength-to-weight ratios of high-strength magnesium casting alloys with those of steel and aluminum casting alloys.