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THE EFFECT OF VARIOUS FACTORS ON THE MECHANICAL PROPERTIES OF MAGNESIUM ALLOY CASTINGS

by

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PHYSICAL METALLURGY DIVISION

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ABSTRACT

The designer and the producer of mechanically stressed equipment considers the use of castings for components exposed to severe service conditions only if detailed information on casting properties is available. Unfortunately, there still exist some misconceptions in the interpretation of test results obtained on various kinds of cast test bars (separately cast, cast on, or cut out of castings) and, in some cases, lack of understanding of the numerous foundry and testing variables which affect either the mechanical properties of the casting or the results of the tests.

These variables are related to the melt quality (composition, impurities, melting procedure, holding time), to casting conditions (casting design, gating, section size, pouring temperature and technique) to heat treatment (if applicable), and to testing methods (design, preparation, size and shape of test bars, tensile speed, gauge length).

Some of these factors were investigated on various magnesium sand casting alloys in the as-cast, aged, and fully heat treated conditions. Results of this investigation are presented and discussed.

In the conclusions it is suggested that full advantage be taken of the direct relationship between the mechanical properties of casting sections and their grain size and structure. Greater use of metallographic inspection of critical sections in castings is proposed, to reduce the number of mechanical tests needed in final acceptance tests.

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The Effect of Various Factors on the Mechanical Properties of Magnesium Alloy Castings

by J. W. MEIER[1]

Introduction.

It is well known that the art of making castings is a very ancient craft, but it is not so long ago that metallurgists started to change the art to a « science » by learning how to make consistently sound castings and established ways of improving their properties by suitable alloying, careful founding and proper heat treating techniques. Great effort by the foundry industry was necessary to persuade designers and producers of mechanically streassed equipment that a casting can be a high-quality product and to induce them to consider castings for use in components exposed to severe service conditions.

It is natural that the designer should request detailed information on various mechanical properties of castings, as otherwise he cannot efficiently calculate the expected performance of his equipment. But this very request for exact information on casting properties can cause complications and misunderstanding, and sometimes is the main stumbling block to the use of castings.

The metallurgist and the foundryman know that these properties vary not only with the casting size and shape, but depend — even in one and the same casting — on thermal gradients in various locations, affected by section thickness, distance from gate or riser, use of chills, etc. The metallurgist and the foundryman, however, know also that, if all casting variables are kept constant, a check of the melt quality should guarantee consistent properties in the resultant casting.

The designer and user of castings are not interested in melt quality tests; indeed, they often consider them unnecessary and useless. Of prime importance to them, however, are the actual properties of the production castings. The determination of these properties is very complicated problem, involving destruction o usable castings and considerable costs.

This problem is not new. Fifty years ago it wa as controversial as it is today. A glance through th technical literature of the early years of this centur reveals a mounting interest in problems connecte with cast test bars, the effect of pouring temperature, section thickness, suitable mould material for tes bars, the question of using separately—cast o cast—on test bars, and other similar subjects.

A survey of the literature of the past fifty years showed well over three hundred references in this field, many of them dealing with, or applicable to, light alloy castings. A review of the more important contributions was prepared recently [1] and will, therefore, not be repeated in this paper.

General considerations.

Before any mechanical test results can be interpreted properly, two basic questions have to be answered: 1) how to assess or test mechanical properties of complex casting shapes, and 2) which are the factors affecting mechanical properties of the casting or the test results.

First is the problem of testing mechanical properties of cast products. It is quite obvious that fully reliable performance characteristics of any product can be obtained only in tests conducted

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under actual or, at least, simulated service conditions. This kind of testing is, in most cases, either too costly or not practical. For example, a somewhat simplified service test is the static breakdown test, involving loading of the entire casting in a manner similar to that encountered in service; this is very costly and time consuming because of the size and complexity of castings for modern engineering applications, the necessity of special jigs and fixtures, etc. Thus, most material specifications confine mechanical testing to the simple tensile test performed on a cast specimen of standard dimensions.

The most common way of testing is the use of test bars cast separately from actual production castings. They can be cast-to-shape or machined from specified test bar shapes. Another way of producing test bars is to use a common sprue with the production casting, to assure the buyer that the test bar has been cast from the same melt and under the same conditions as the casting. Cast-to-shape test bars may be cast on the casting; test bars can also be machined from test coupons cast on the casting or cut out directly from a production casting.

TABLE 1

Correlation of Test Bar and Casting Properties

Type of Test Bar	Are Test Bar Properties Correlated With:	
	Melt Quality	Properties of Casting
a) Separately-cast under controlled (standardized) casting conditions . . .	Yes	No
b) Separately-cast without control of casting variables	Unlikely	No
c) Joined to same sprue as casting	No	No
d) Cast on the casting . .	No	No
e) Machined from coupon cast on the casting . .	No	No
f) Cut out from the casting.	No	Depends on casting design (thermal gradient) - in most cases correlation is limited to section from which test bar was taken.

Table 1 illustrates in a very simple way the significance of test results obtained on the different kinds of test bars, as related to the melt quality and the properties of the production castings. This table shows that there is no compromise: either we use test bars separately cast under strictly controlled casting procedure (a) and assess the melt quality, or we have to cut production castings into test bars (f) to check actual casting properties. All other ways, such as the use of a common sprue (c), cast on test bars (d) or coupons (e), are useless and, in most cases, misleading. They are, also, very often detrimental to the quality of the production casting, because these cast-on additions may change the solidification pattern and cause defective castings.

TABLE 2

Factors Affecting Mechanical Properties of Castings

1. *Alloy Composition*
   purity of metals used, sensitivity to small variations in alloy content (within specified range), gas content, non-metallic inclusions etc.
2. *Melting Conditions*
   melt temperature, melting time and procedure, degassing, grain refining, holding time, pick-up of impurities, etc.
3. *Casting Procedure*
   pouring temperature and technique (speed, height, use of pouring basin or screens), thermal gradients in mould (mould material, use of chills, die thickness, die dressing), gating and risering, metal flow (turbulence), mould reactions, etc.
4. *Casting Design*
   gross weight of casting, volume/surface area ratio, variations in section thickness, geometry (location in casting, distance from gates, risers, chills, bosses), segregation (e.g. healed hot tears), internal stresses, etc.
5. *Heat Treatment*
   variations in time and temperature, heating and cooling rates, etc.
6. *Test Bar Preparation*
   separately-cast test bars vs. specimens cast-on or cut-out of castings, test bar design of separately-cast test bars, cast-to-shape vs. machined bars, shape (round vs. flat) and size of test bars, soundness of test bar (saleable casting quality), etc.
7. *Testing Variables*
   tensile speed, gauge length, method of yield strength determination, etc.

The second problem which must be considered is the appreciation and understanding of all factors affecting either the mechanical properties of cast test bars or the results of the tests. Table 2 lists these factors, divided into seven groups, as related to the alloy composition, melting conditions, casting procedure, casting design, heat treatment (whenever applicable), test bar preparation, and testing variables. Groups 1 and 2 affect the melt quality, groups 3 and 4 the casting conditions, and groups 6 and 7 the testing technique.

All of these factors are very well known to the foundryman and the metallurgist; their number should not alarm the designer. The table shows just how many variables have to be kept constant to obtain consistent casting properties. It shows also that by keeping the conditions listed under 3 to 7 constant and using separately-cast test bars to control melt quality factors listed under 1 and 2, it is possible to produce consistently good quality castings.

A recently conducted survey of literature [1] showed a considerable number of publications containing experimental data on the effect of the variables listed in Table 2 on mechanical properties of magnesium alloy castings, although in most cases these data were limited to specific alloys or foundry procedures. The review also revealed various statements which appeared to be controversial or misleading, and it was therefore considered useful to carry out additional experimental work in this field. Results of this work were recently reported [2, 3, 4, 5] and some of these results are used to illustrate the following discussion.

Experimental procedures and results.

Materials and Procedures.

An investigation of some of the more important factors was carried out on the four casting alloys specified in Tables 3 and 4, Alloy and temper designations used in these tables and throughout the paper are according to Canadian standards [6]. Of the almost fifty factors listed in Table 2, fifteen were investigated in this study. In all cases, all other factors, except the variable under investigation, were kept constant; standard commercial foundry and heat treating techniques [7, 8] were used. All Mg-Al-Zn alloy melts were produced from commercial high-purity alloy ingots. The other alloys were prepared using high-purity magnesium ingots, high-purity zinc, zirconium sponge or salt mixture, and thorium pellets.

Separately-cast test bars were cast-to-shape [9] in green sand and tested without machining (except in the study of the effect of machining); test bars cut out of test castings were machined to dimensions having a gauge length-to-section area ratio identical to that of the separately-cast test bars, namely $4.5 \sqrt{\text{area}}$.

TABLE 3

Chemical Compositions of Magnesium Casting Alloys *

Alloy **	Al %	Zn %	Mn %	Zr %	Th %
AZ80	7.5 - 8.5	0.3 - 0.7	0.2 - 0.4	—	—
AZ91	8.3 - 9.3	0.4 - 1.0	0.2 - 0.4	—	—
ZK61	—	5.5 - 6.5	—	0.6 - 1.0	—
ZH62	—	5.2 - 6.2	—	0.5 - 1.0	1.4 - 2.2

* According to Canadian draft specification GSA. HG.9 - 1956 (for AZ80, AZ91, ZK61) and ASTM Specification B80 - 1956 (for ZH62).

** Alloy Designations according to Canadian Code CSA.H.1.1 - 1957.

TABLE 4

Minimum Tensile Properties Specified for Separately-Cast Test Bars*

Alloy **	Heat Treatment		Ultimate Tensile Strength, 1000 psi	0.2 % Yield Strength, 1000 psi	Elongation % in 2"
	Solution	Ageing	min.	min.	min.
AZ80-F	—	—	23	—	3
-T4	24 hr/410C	—	34	—	7
AZ91-F	—	—	23	12	—
-T4	24 hr/410C	—	34	12	7
-T6	24 hr/410C	16 hr/200C	34	16	3
ZK61-F	—	—	35	18	8
-T6	2 hr/500C	48 hr/130C	42	26	5
ZH62-T5	—	16 hr/180C	35	22	4

* According to Canadian draft specification CSA. HG.9 - 1956 (for AZ80, AZ91, ZK61) and ASTM Specification B80 - 1956 (for ZH62).

** Temper Designations according to Canadian Code CSA.H.1.2 - 1957 (F - as cast, T4 - solution heat treated, T5 - aged only, T6 - solution heat treated and aged).

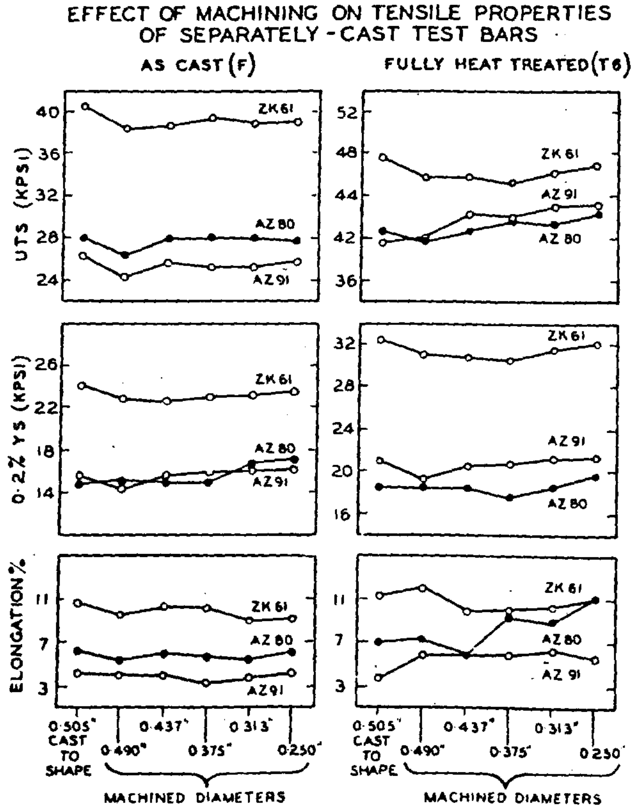

Fig. 1. — Effect of Machining on Tensile Properties of Separately-Cast Test Bars.

Effect of Test Bar Preparation.

Figure 1 shows the effect of machining of test bars to various diameters on the tensile test results for three magnesium casting alloys. The test bars were cast-to-shape in green sand and machined to five different diameters as listed. A statistical analysis of the results [4] revealed that machining had a significant effect in several cases. However, there is no simple relationship between the degree of machining and any of the tensile properties. Since the differences due to machining are of the same order of magnitude as the differences between melts of the same alloy, it may be stated that, for all practical considerations, and within the diameter range for the alloys studied, the tensile properties of « cast-to-shape » and of machined bars differ only very slightly. Nevertheless, it should be borne in mind that tensile test results on subsize test bars may differ significantly from those obtained on standard test bars and that the degree of variation cannot be predicted. One of the reasons for this is the exaggerated effect of small local discontinuities or other minute defects on the results of mechanical tests on subsize test bars.

There is still some controversy on the merits of using « cast-to-shape » test bars or machined test

TABLE 5

Effect of Test Bar Shape on Tensile Properties of Sand Cast Magnesium Alloy Plates

(All results are averages of 4 tests)

Alloy Designation	Plate Thickness inches	Round Bars *			Flat Bars *		
		UTS **	YS**	E, % **	UTS	YS	E, %
AZ80-F	1/4	29.7	17.4	5.5	27.4	15.5	5
	3/8	28.1	16.6	5.5	26.2	14.6	4.5
	1/2	25.1	14.3	5	23.0	14.4	3
	Average	27.6	16.1	5.5	25.5	14.9	4
	Separately-cast Test Bars - ave	27.2	14.9	5.8			
AZ80-T4	1/4	40.9	17.6	20	40.4	14.4	18.5
	3/8	40.5	14.9	17.5	40.3	13.6	20
	1/2	37.6	12.3	14.5	37.4	12.8	14
	Average	39.7	14.9	17.5	39.4	13.6	17.5
	Separately-cast Test Bars - ave	40.1	14.0	17			
AZ91-F	1/4	29.4	18.9	4	27.4	15.9	4
	3/8	28.5	17.4	4.5	25.0	16.3	4
	1/2	25.6	15.6	4	24.0	15.3	3.5
	Average	27.8	17.3	4	25.5	15.8	4
	Separately-cast Test Bars - ave	26.5	16.0	4.5			
AZ91-T6	1/4	48.2	23.8	10	41.7	22.3	5
	3/8	47.2	21.6	9	39.5	23.0	2.5
	1/2	43.4	22.6	4.5	39.6	21.8	3
	Average	46.3	22.7	8	40.2	22.4	3.5
	Separately-cast Test Bars - ave	41.0	23.5	3.5			

* Gauge diameters for round bars and thickness of flat bars were 1/8" for 1/4" plates, 3/16" for 3/8" plates, and 5/16" for 1/2" plates.

** UTS – Ultimate Tensile Strength in 1000 psi.
YS – 0.2 % Yield Strength in 1000 psi.
E % – Elongation in $4.5 \sqrt{\text{area}}$.

bars. Most European standards specify test bars machined to finished dimensions, while North American specifications for light alloys always refer to « cast-to-shape » test bars. There is no doubt that test results depend on the accuracy of dimensional measurements of the cross section in the gauge length, and that the test results may be affected by the uniformity of cross section as well as the degree of surface smoothness. Nevertheless, it is known, from long established and general use of cast-to-shape test bars in North American light alloy foundries, that the slight differences in tensile results are not significant enough to justify costly and time consuming machining, which is especially impractical where large numbers of routine tests are made.

Another controversial point is the so-called « skin-effect » on mechanical test results, especially when machined production castings are used in actual service. This skin-effect is quite pronounced in some ferrous and in some copper-base alloys, but is insignificant in aluminium and magnesium alloys.

Effect of Test Bar Shape.

Another important factor is the shape of the test bar cut out of the casting. Although in many cases the shape, e.g. a round or a flat bar, depends on the dimensions of the casting, it was considered necessary to compare properties obtained on round and flat bars cut out from the same locations of a casting. For this purpose, plates of three different thicknesses were cast for each alloy. All plates were X-rayed and only castings of saleable quality were used for the investigation [4]. Table 5 shows the results of tensile tests on round and flat bars machined from plates cast in alloys AZ80 and AZ91, in the as-cast and heat-treated conditions.

The results show very definitely that round bars gave much higher tensile test results than did flat bars cut out from the same locations. This was confirmed, also, on test bars cut out of some large production castings.

To obtain comparable results, therefore, it is not enough to require minimum properties in production castings; the size and shape of the test bars to be used should also be specified.

Test results listed in Table 5 illustrate also the effect of plate thickness (casting section) on the properties of the casting. Although this variable will be discussed later, it should be mentioned here that the unusually high results for AZ91-T6 are, at least to some extent, due to the use of very small size test bars.

Effect of Gauge Length.

Another variable affecting test results is the gauge length. It is known from many papers published in the past fifty years that elongation values can be compared only if measured on test specimens having

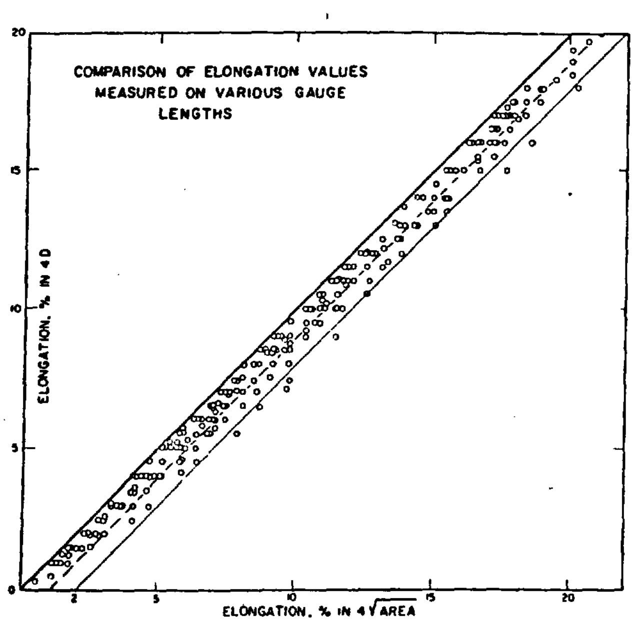

Fig. 2 (a). — Comparison of Elongation Values Measured on Various Gauge Lengths.

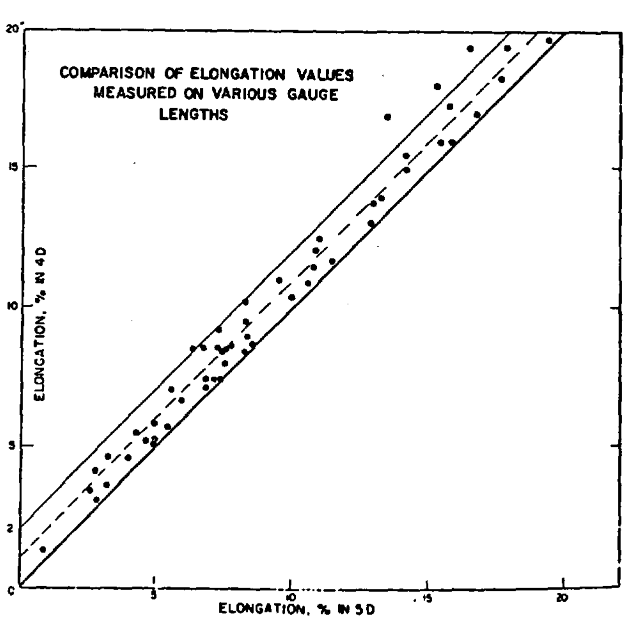

Fig. 2 (b). — Comparison of Elongation Values Measured on Various Gauge Lengths.

a constant gauge length-to-diameter ratio. This is very important when subsize test bars are cut out of production castings. Unfortunately, a difficulty also exists in regard to comparisons relating to standard test bars, because various countries specify different gauge lengths (4D in North America, 3.5D in Great Britain, 7.2D in France, and 5D or 10D in all other European countries). This is why research results published in different countries cannot be directly compared. There are complications, therefore, in the recent efforts to agree on international standards for light alloy products, undertaken by the International Standards Organization (ISO/TC79).

Figures 2a and 2b present, graphically, elongation results obtained on some 600 test bars marked for measurements on several gauge lengths. In this comparison, test bars from five magnesium casting alloys in various tempers were used, including separately cast test bars as well as test bars cut out of castings and machined to various sizes [4].

The graphs show that the difference in elongation values (obtained on three different gauge lengths) is almost constant so far as absolute values are concerned. But they show also that for low elongation values, say below 5 %, the differences expressed as percentage of the 4D elongation, are of the order of 40 to 50 % and higher. This is particularly significant in the case of those magnesium casting alloys which normally have a low elongation, especially in the as-cast (F) and in the fully heat

TABLE 6

Effect of Pouring Temperature on Properties of Separately-Cast Test Bars

(All results are averages of 8 tests)

Alloy Designation		Pouring Temperature				
		Normal **	850 C	800 C	750 C	700 C
AZ80 - T4	UTS *	39.8	39.5	40.3	39.7	39.1
	YS *	13.3	13.2	13.6	13.5	13.2
	E % *	17	15.5	17	16.5	15.5
	GS *	4	5	4	4	5
AZ91 - T6	UTS	41.8	36.8	39.7	42.5	40.8
	YS	21.5	21.3	21.6	21.7	20.8
	E %	4.5	2	3	4.5	4
	GS	4	4	3 1/2	3 1/2	4
ZK61 - T6	UTS	45.4	45.2	46.1	46.1	44.2
	YS	31.7	31.8	31.8	31.4	30.9
	E %	8.5	7.5	10	12	7
	GS	2 1/2	2 3/4	2 1/2	2 1/2	2 1/2
ZH62 - T5	UTS	39.5	37.7	41.1	40.5	39.2
	YS	25.4	25.6	25.6	25.0	24.3
	E %	7	5	9	10.5	8.5
	GS	3	2 3/4	2 3/4	3	2 3/4

* UTS – Ultimate Tensile Strength in 1000 psi.
YS – 0.2 % Yield Strength in 1000 psi.
E % – Elongation in 2 inches.
GS – Average Grain Diameter in 0.001 inch.

** Normal Pouring Temperatures: 740C for AZ80 and AZ91.
760C for ZK61 and ZH62.

treated (T6) conditions. The difference of one or two percent elongation would be very important in acceptance tests for such alloys.

Effect of Pouring Temperature and Holding Time.

As examples of factors affecting the melt quality, some results are presented on the effect of pouring temperature and of the holding time [2].

Unlike most other metals, whose highest mechanical properties are obtained at the lowest possible pouring temperature, magnesium alloys have an optimum casting temperature to produce a sound casting and highest mechanical properties. This temperature is considerably higher than the lowest possible casting temperature. According to published data, too low a pouring temperature tends to cause in some magnesium alloys grain coarsening, and higher pouring temperatures increase gassiness.

Of particular interest is the effect of pouring temperature on the properties of test bars cast separately under closely controlled conditions, because some materials specifications require test bars to be cast at the same pouring temperature as the production castings. It is generally known that the choice of pouring temperature for any casting depends on its size and shape. Either high pouring temperatures, necessary for castings of complex and thin-sectioned shapes, or very low pouring temperatures, unavoidable at the end of pouring a number of castings,

TABLE 7

Effect of Holding Time at Normal Pouring Temperature on Properties of Separately-Cast Test Bars

(All results are averages of 6 tests)

Alloy Designation		Holding Time in minutes			
		10	30	60	120
AZ80 - T4	UTS *	40.6	40.3	40.1	39.7
	YS *	13.4	13.7	13.4	13.8
	E % *	17.5	17.0	17.5	16.5
	GS *	4	4	4	4
AZ91 - T6	UTS	41.5	41.1	42.3	41.5
	YS	22.5	21.9	22.1	21.7
	E %	3.5	3.5	4.0	3.5
	GS	4	4	3 1/2	4
ZK61 - T6	UTS	46.8	46.4	46.2	46.6
	YS	31.9	32.5	31.5	31.9
	E %	10.0	11.0	10.0	10.0
	GS	2 1/2	2 1/2	2 1/2	2 1/2
ZH62 - T5	UTS	38.6	38.9	39.6	38.1
	YS	25.2	23.8	24.8	22.8
	E %	8.0	8.0	9.0	8.0
	GS	3	3	3	3

* UTS – Ultimate Tensile Strength in 1000 psi.
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E % – Elongation in 2 inches.
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could therefore affect the properties of separately cast test bars. To investigate this, a series of test bar castings was cast at pouring temperatures of from 700 to 850°C, a range most likely to be used in actual foundry production. The tensile properties of these bars were compared with those obtained on bars cast at « normal » pouring temperature (740°C for alloys AZ80 and AZ91, 760°C for alloys ZK61 and ZH62).

Table 6 shows that pouring temperatures in the range from 700 to 850°C had no significant effect on the tensile properties or grain size of separately-cast test bars in any of the four alloys. This statement should not be generalized, however, since it relates specifically to a series of small melts (about 50 lb) prepared under carefully controlled experimental foundry conditions and to one casting shape. If further work confirms the above results, it would be possible to state that considerable variations in the pouring temperature of separately-cast magnesium alloy test bars, e.g. in the range of 720 to 800°C, would not affect significantly their tensile properties.

The holding time, i.e. the time of keeping the alloy in the molten state before pouring, has been claimed to be of critical importance for magnesium alloys. Published data on various Mg-Al-Zn alloys show that prolonged holding times cause grain coarsening and decreased mechanical properties. Regarding zirconium-containing alloys, it has been inferred that longer holding times cause settling out of zirconium and, therefore, larger grain size and lower mechanical properties. As in the case of pouring temperatures, the investigation was limited to small (50 lb) melts and separately-cast test bars.

Table 7 shows some of the results on four magnesium casting alloys. Holding times at the « normal » pouring temperatures (see above) varied between the usual settling time (ten minutes) and two hours (in some cases also up to almost four hours). All results are averages from three separate melts of each alloy. Chemical analyses of the various

TABLE 8

Effect of Holding Time at 850C on Properties of Separately-Cast Test Bars

Alloy Designation	Pouring Temperature, °C	Holding Time, minutes	UTS *	YS *	E % *	GS *
AZ80 - T4 (a)	740	10	40.1	13.5	16.5	4
(b)	850	30	39.6	13.0	15	8
(c)	740	10	38.8	12.6	15	4
AZ91 - T6 (a)	740	10	42.3	20.8	5	4
(b)	850	30	35.0	20.5	3.5	8
(c)	740	10	41.5	20.8	4	4
ZK61 - T6 (a)	760	10	46.0	31.6	10	2 1/2
(b)	850	30	45.5	33.1	5.5	3
(c)	760	10	46.5	31.2	12.5	2 1/2
ZH62 - T5 (a)	760	10	40.1	27.3	7	2 1/2
(b)	850	30	36.9	28.0	4.5	3
(c)	760	10	42.0	27.3	12	2 1/2

* UTS – Ultimate Tensile Strength in 1000 psi.
YS – 0.2 % Yield Strength in 1000 psi.
E % – Elongation in 2 inches.
GS – Average Grain Diameter in 0.001 inch.

test specimens showed no changes in the compositions, no iron pick-up in the Mg-Al-Zn alloys, and no drop in zirconium content in the other two alloys. The results showed that prolonged holding time at normal pouring temperature dit not affect significantly the mechanical properties of test bars in any of the four alloys.

A separate series of melts was investigated for the effect of prolonged holding time at low and very high temperatures. In all cases some test bars (a) were cast after a 10-minute settling time at the « normal » pouring temperature, and then the melt was brought up to the high (850°C) or cooled down to the low (700°C) temperature, held for thirty minutes, and some more test bars (b) were cast. The remainder of the melt was then brought back to the « normal » pouring temperature and, after a 10-minute settling, cast into test bars (c).

Tables 8 and 9 show the effect of holding the melt at the above pouring temperatures on the tensile properties and grain size of separately-cast test bars.

A statistical analysis of these and other [2] results reveals that holding the molten metal for thirty minutes at 700°C or 850°C may be detrimental to the mechanical properties of alloys AZ80, AZ91 and ZH62, whereas properties of alloy ZK61 were apparently not affected.

Effect of Section Size.

To illustrate the effect of casting variables, a series of round and flat test castings of varying dimensions was investigated [3] and some of the results are shown for alloy AZ91. Figure 3 shows the effect of cross section on the properties of round bars cast in green sand. On the left of the graph, properties of separately-cast test bars are indicated. All other results shown relate to test specimens machined from the test castings. As would be expected, both the ultimate tensile strength and the elongation decrease sharply with increasing casting section and grain size. The effect on the yield strength is less pronounced.

TABLE 9

Effect of Holding Time at 700C on Properties of Separately-Cast Test Bars

Alloy Designation	Pouring Temperature, °C	Holding Time, minutes	UTS *	YS *	E % *	GS *
AZ80 - T4 (a)	740	10	41.0	13.0	19	4
(b)	700	30	37.2	11.2	13	6
(c)	740	10	39.8	12.3	16	4
AZ91 - T6 (a)	740	10	41.8	20.6	4	4
(b)	700	30	41.2	21.0	5	4
(c)	740	10	39.3	21.2	3.5	3 1/2
ZK61 - T6 (a)	760	10	46.0	33.4	13	3
(b)	700	30	45.5	33.7	10.5	4
(c)	760	10	45.2	32.9	8.5	3 1/2
ZH62 - T5 (a)	760	10	40.8	25.8	8.5	3
(b)	700	30	38.2	23.1	8	4
(c)	760	10	38.3	23.0	9.5	4

* UTS – Ultimate Tensile Strength in 1000 psi.
YS – 0.2 % Yield Strength in 1000 psi.
E % – Elongation in 2 inches.
GS – Average Grain Diameter in 0.001 inch.

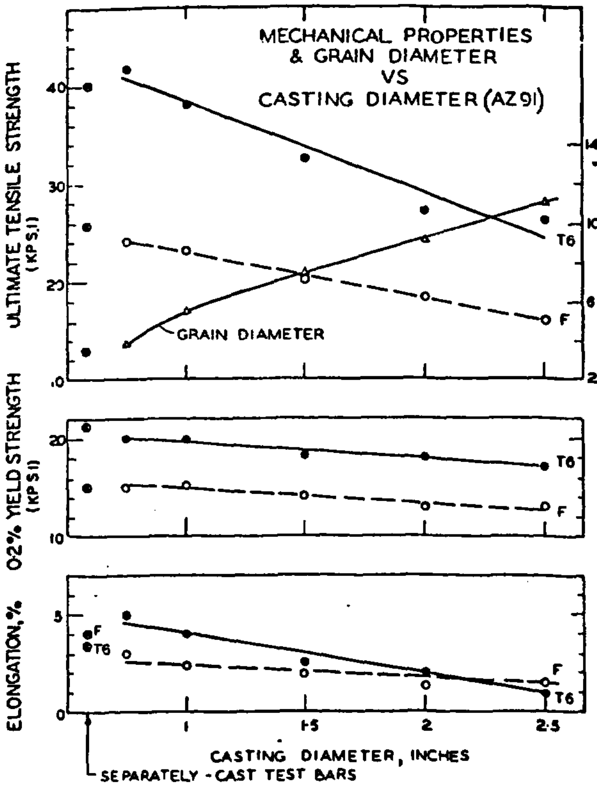

Fig. 3. — Mechanical Properties and Grain Diameter vs Casting Diameter (AZ91).

The next graph, Figure 4, shows a similar pattern for flat plates of different thickness cast in green sand. However, in this case it was found that there were statistically significant variations of properties between the inside and the outside bars. These variations could, of course, be overcome by changing the gating, but are shown in the graph because they emphasize the importance of the location of the test bar in the casting and the effect of changes of the solidification pattern due to variations in thermal gradients. Another experiment showed that in some cases the location of the test bar in the cross section is important, i.e. whether it is machined out from the middle of the section or from a location near the surface.

It is known, that the solidification pattern of a casting depends on the ratio between its volume and its surface area. Figure 5 shows the mechanical properties of test bars cut from both the round bars (Figure 3) and the flat plates (Figure 4), plotted against the volume/surface area ratio of the castings. The graph shows that cast sections of the same volume/surface area ratio have the same tensile properties.

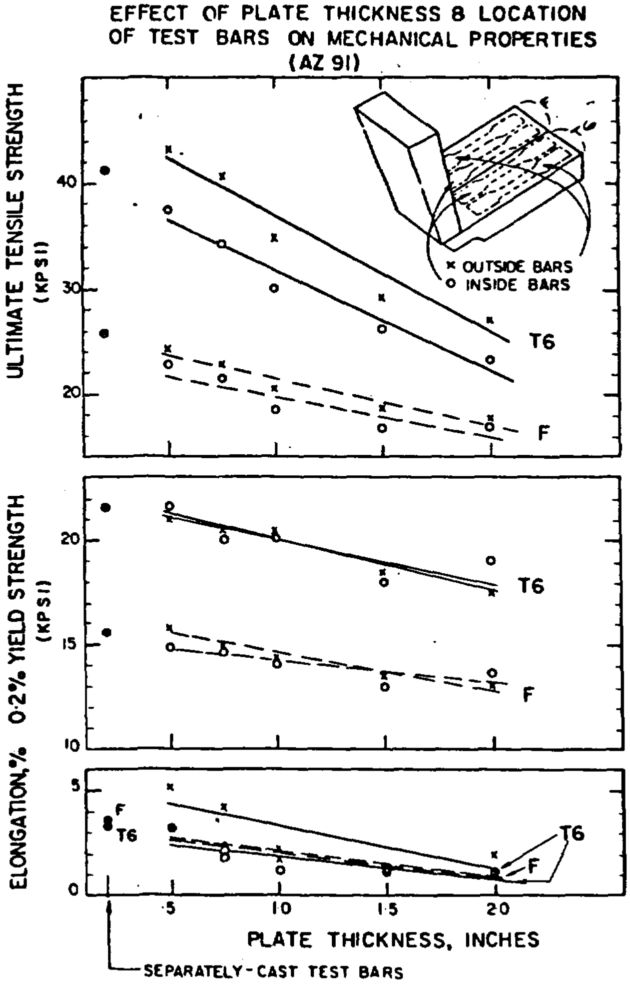

Fig. 4. — Effect of Plate Thickness and Location of Test Bars on Mechanical Properties (AZ91).

Effect of Grain Size.

The grain size in magnesium alloy castings depends, of course, on the alloy composition, as well as on various melting and casting variables. As an example of the relation between grain size and composition, Figure 6 shows the effect of zirconium content in casting alloy ZK61 [8].

Provided that the alloy composition be held within reasonably close limits, and the melting and casting procedure be strictly standardized, the mechanical properties of a sound (good quality) magnesium alloy casting section are closely related to its grain size (as affected by wall thickness, use of chills, location of riser, etc.). As an example, Figure 3 shows such a relationship for alloy AZ91.

To take full advantage of this direct relationship between grain size and mechanical properties (e.g. as

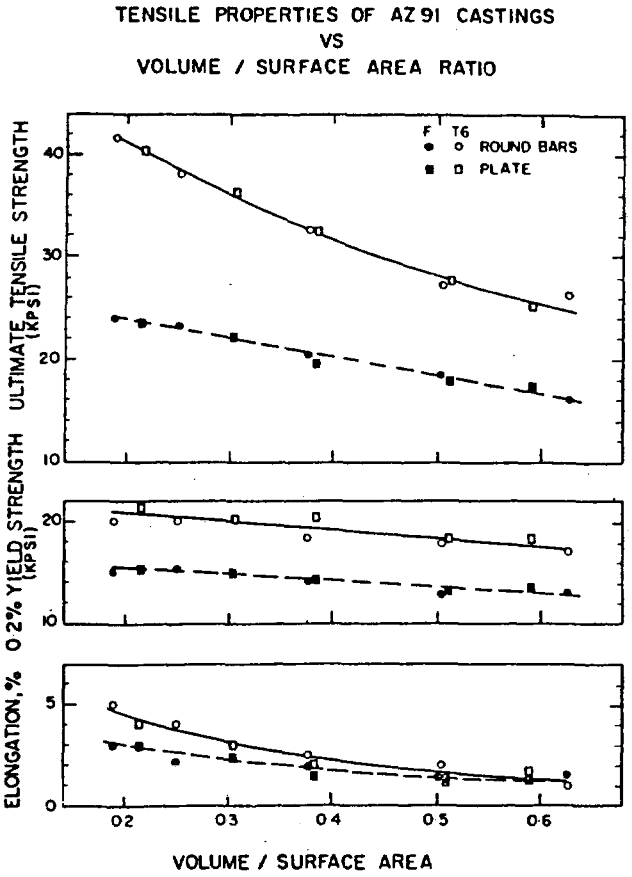

Fig. 5. — Tensile Properties of AZ91 Castings vs Volume/ Surface Area Ratio.

shown in Figures 3 and 6) it is, of course, essential that close control of melt quality and heat treatment be assured by the use of separately-cast test bars (produced under standardized casting conditions), and that the soundness of the production castings be checked by X-ray or other non-destructive tests.

Effect of Alloy Content and Heat Treatment.

Figures 6 to 10 illustrate various aspects of the effect of changes in alloy content and heat treating conditions. Figures 7 presents the effect of changes in aluminium and zinc contents on tensile properties of alloy AZ91-T6, and Figure 8 the effect of variations in the ageing conditions [5]. These two graphs show how castings of increased yield strength or higher elongation can be obtained by changes of alloy content (within the specification limits) as well as by changes in heat treating cycles.

Figure 6 stresses the importance of a high soluble zirconium content on the mechanical properties of

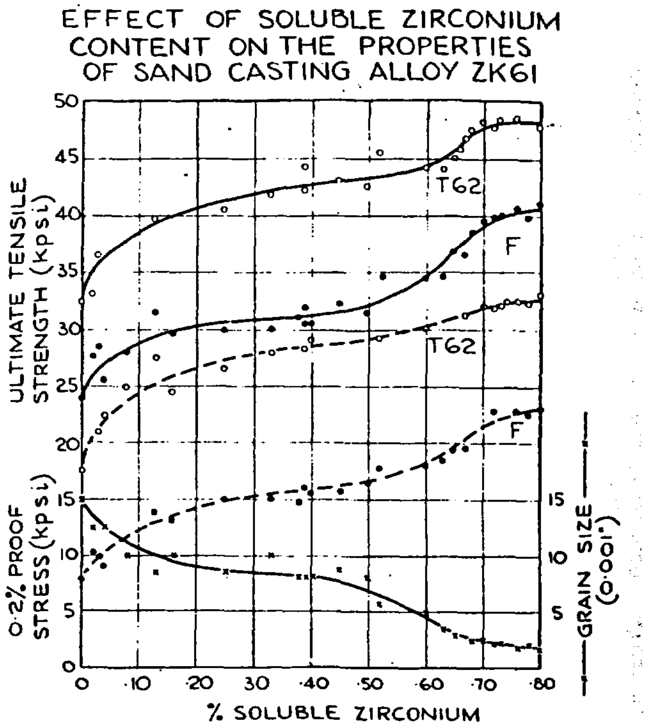

Fig. 6. — Effect of soluble Zirconium Content on Properties of Sand Casting Alloy ZK61.

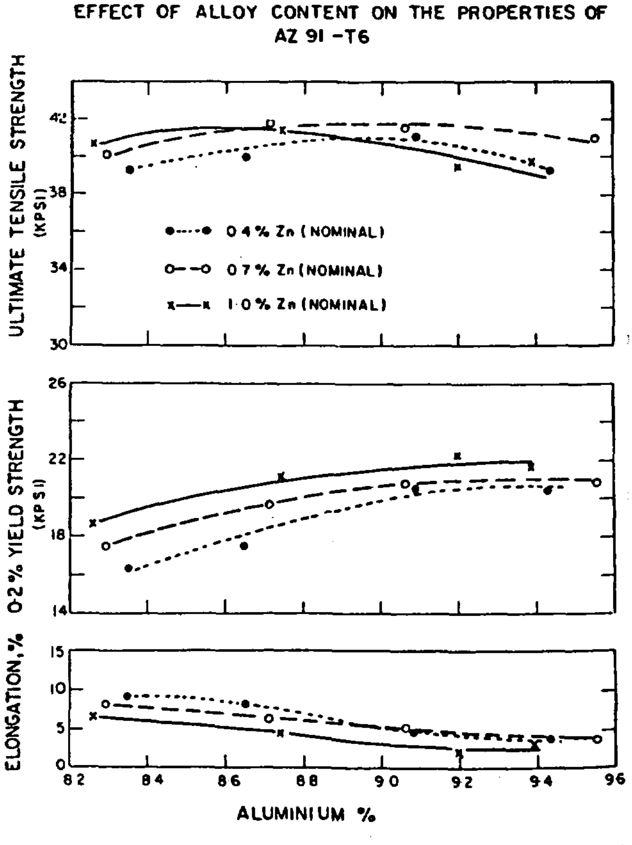

Fig. 7. — Effect of Alloy Content on the Properties of AZ91-T6.

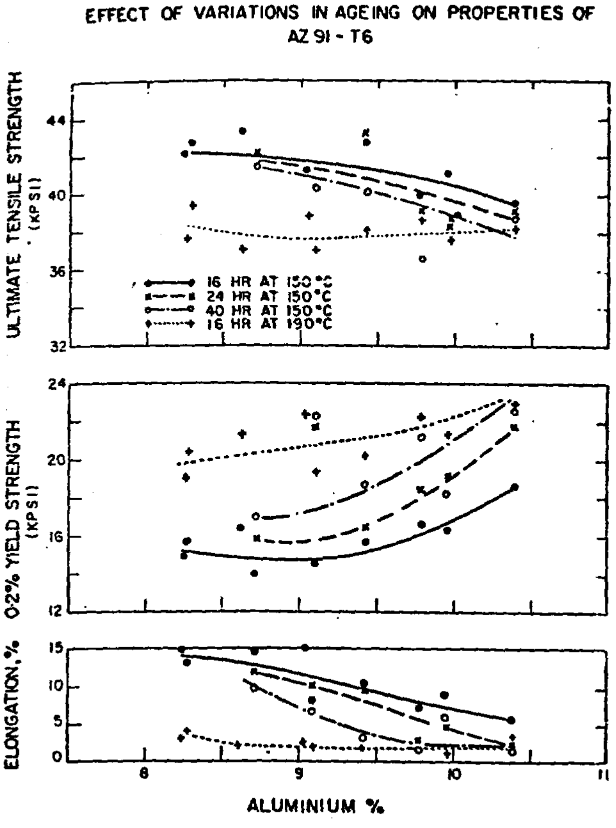

Fig. 8. — Effect of Variations in Ageing on Properties of AZ91-T6.

Mg-Zn-Zr alloys [8]. The graph shows that a minimum soluble zirconium content of about 0.6 % is essential to achieve high strength. Figure 9 emphasizes the effect of zinc content on the amenability to high temperature heat treatment necessary for highest strength and elongation values in this alloy system [8].

Figure 10 shows the effect of thorium additions to casting alloy ZK61 on its tensile properties and on its amenability to heat treatment [10]. The graph illustrates that high temperature heat treatment for alloy ZH62 (ZK61 + 2 % Th) is not practical (because of the lowering of the solidus temperature of the alloy with increasing thorium content).

The importance of proper heat treatment conditions to the mechanical properties of magnesium alloy castings is well known. It is essential that a suitable inspection method shall assure that the specified heat treating conditions were used and that the quality of the casting was not spoiled by lack of protective atmosphere, too high solution temperature, overageing, etc. The most efficient method of control is by the use of separately-cast test bars (cast under standard-

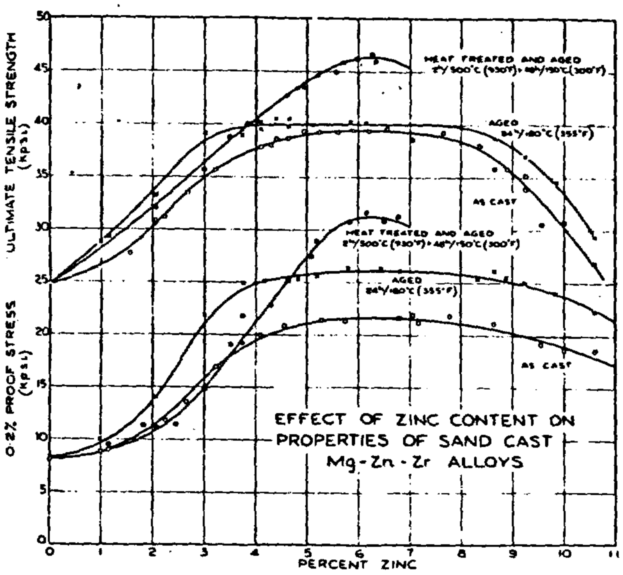

Fig. 9.
Effect of Zinc Content on Tensile Properties of Sand Cast Mg-Zn-Zr Alloys (containing over 0.7 % soluble zirconium).

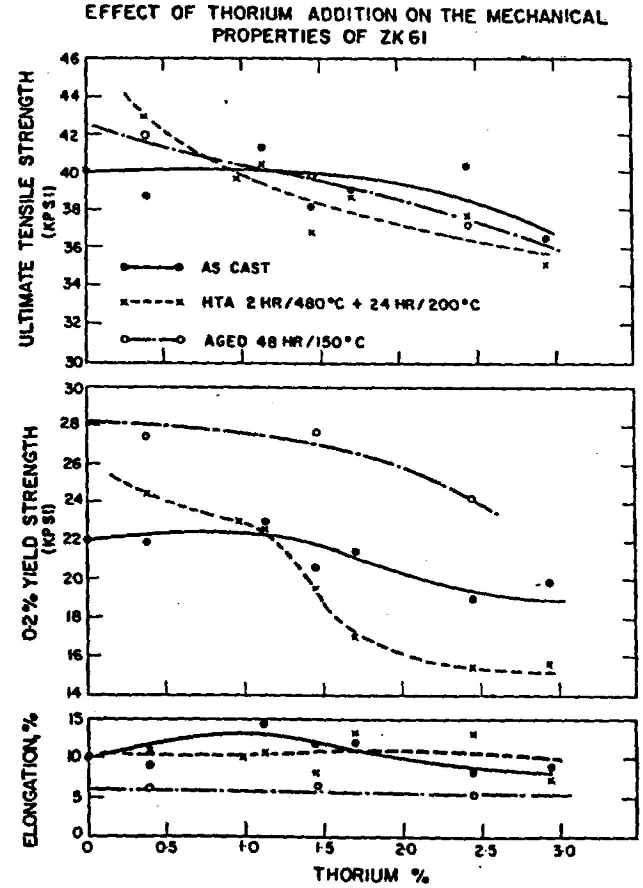

Fig. 10. — Effect of Thorium Additions to Magnesium Alloy ZK61.

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[1] There are numerous other references on the subjects discussed in this paper. Listed here are those which contain experimental data used in the tables and figures of this paper; other references are reviewed in Research Report PM227, listed above under 1.