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MAGNESIUM CONTENT EFFECT ON PROPERTIES OF BINARY ALUMINUM-MAGNESIUM ALLOYS

W. A. POLLARD

PHYSICAL METALLURGY DIVISION

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Magnesium Content Effect on Properties of Binary Aluminum-Magnesium Alloys

In both normal purity and high purity cast aluminum-magnesium alloy there is a critical magnesium content below which the tensile properties of separately cast test bars of the Dow type show a marked decrease in ductility.

by W. A. Pollard, Sr. Scientific Officer
Non-Ferrous Metals Section
Dept. of Mines and Tech. Surveys
Ottawa, Canada

Abstract

In spite of many years of experience in casting the aluminum-10 per cent Mg alloy G10, difficulties owing to inconsistent properties were still encountered from time to time. In particular, G10 made using normal purity materials sometimes gave properties (in separately cast-to-shape test bars) which, although usually above minimum specified values, were considerably lower than those obtainable by apparently identical foundry practice. Thus, the higher level of properties would be about 50,000 psi ultimate tensile strength and 30 per cent elongation, whereas the lower level would be about 46,000 psi ultimate tensile strength and 10 to 16 per cent elongation.

In aluminum-10 per cent Mg alloy made up from super purity aluminum, however, the properties obtained were consistently high. They usually equalled or exceeded the higher values, as mentioned for normal purity alloys.

It was shown that, at least in some cases, the low properties obtained on test bars of normal purity could be connected with the presence of layer porosity in the gage length. This phenomenon has been shown by Jay and Cibula[1] to occur in these alloys when the magnesium content falls below a certain critical value. Thus, although several other possibilities were recognized and were shown to be important in certain cases, the main part of the work to be reported was a comparison between the effects of varying magnesium content and casting shape (cast-to-shape test bars and test bars cast from heavily chilled sand cast plates) on binary aluminum-magnesium alloys made from normal and high purity materials.

Previous Work

PROBLEMS CONNECTED with foundry technology of the aluminum-10 per cent Mg type alloy have been frequently mentioned in the literature. In general, G10 has the reputation of being difficult in the foundry. Many authors[2, 3] have commented on the precautions necessary with the alloy such as proper degassing, grain refinement, melt purity, etc., which are necessary in order to obtain optimum properties. A useful, detailed manual on the general foundry technology of the alloy has been prepared by the Battelle Memorial Institute.[4]

Meier and Couture[5] have shown that high melt temperatures cause serious reduction in strength. This deterioration could not be entirely explained by the accompanying increase in grain size or gas content, or a combination of these but appeared to be related to another factor that was not determined in their work. They found that the temperature of a G10 melt should not exceed 720 C (1330 F).

Pollard and Meier[6] have shown the effects of a number of variables on the properties of G10, as determined on various types of test bars. This

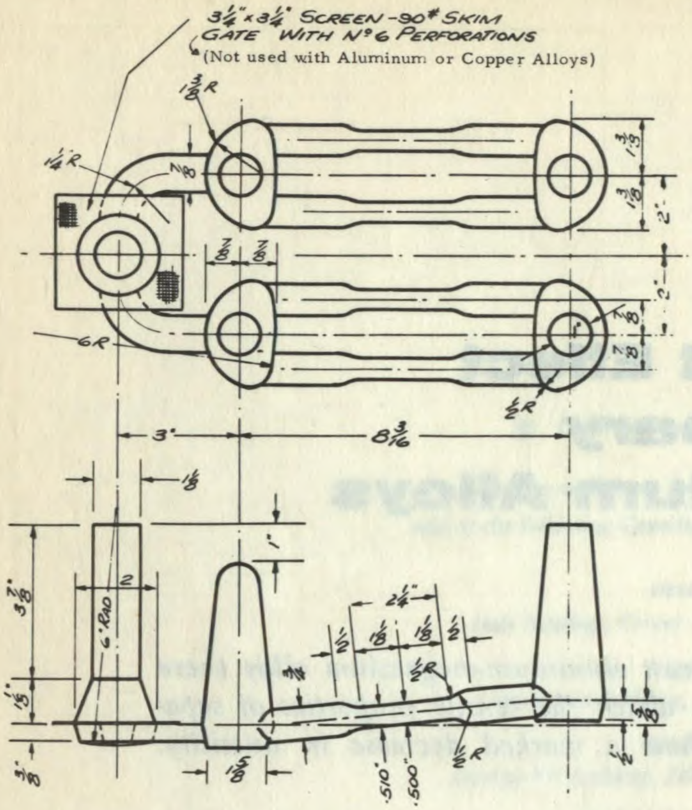

Fig. 1. Test bar design according to U.S. Federal Specification QQ-M-56, referred to in this paper as Dow.

work showed that the properties obtained and the effects of melt variables (such as gas content, purity and magnesium content) were less dependent on the type of test bar employed for G10 than were those for other alloys examined, i.e., C4, SG70 and SC51.

Hirsch, et al,[7] began a close examination of melting and pouring practice, chemical composition and other variables, to determine why some melts of aluminum-10 per cent Mg alloy gave what they termed better than typical tensile properties (about 53,000 psi ultimate tensile strength and 20 per cent elongation). They were unable to obtain consistent results and their investigation was inconclusive.

Fig. 2. Plate casting showing gating and risering. The chilled face can be seen in the foreground.

Magnesium Content vs. Tensile Properties

The relationships between magnesium content and tensile properties for binary aluminum-magnesium alloys in the form of ½-in. diameter cast-to-size test bars are given by Sicha and Keller.[8] However, the property levels shown for ultimate tensile strength and elongation are low, and hardly exceed the minimum specification properties.

Jay and Cibula[1] investigated the effects of varying magnesium content on the properties of binary aluminum-magnesium alloys of commercial purity. They also studied the effects of gas content and feeding. Most of their work was done on DTD test bars (vertically cast one in. diameter bars with a 2¾-in. feeder. The tensile test bar is machined before testing), but some 1½-in. and 4 in. diameter bars were also cast and also some horizontally cast test bars of the E type were made.

They found that well fed DTD test bars made from degassed metal and containing from 10.8 to 12 per cent Mg gave optimum properties (ultimate tensile strength about 50,000 psi and elongation about 28 per cent). However, they found that if the magnesium content fell below about 10.8 per cent Mg the properties obtainable were much less owing to the occurrence of layer porosity. As Jay and Cibula's work is in many ways complementary to the present study, it will be discussed in detail later.

Recently, Lagowski and Meier,[9] who studied binary magnesium-zinc alloys, have found a similar situation to that described by Jay and Cibula. They found that between certain critical zinc contents layer porosity was produced, and that this resulted in a break in the otherwise smooth curve obtained by plotting ultimate tensile strength against zinc content.

Materials, Melting and Casting

Melts of normal commercial purity were made from alloy ingot, with additions of pure magnesium (for the melts with higher magnesium content) or 99.8 per cent Al (for the low magnesium melts). The ingot material contained about 9.9 per cent Mg, 0.14 per cent Fe, 0.10 per cent Si and 0.004 per cent Be. The 99.85 per cent Al contained about 0.06 per cent Fe and 0.05 per cent Si. No extra beryllium was added to the melts.

High purity melts were made from 99.99 per cent Al, 99.98 per cent Mg and aluminum-5 per cent Ti and aluminum-5 per cent Be hardeners.

The melts were made in carbon bonded silicon carbide crucibles in a gas injector furnace. The normal melt size was 70 lb. No protective flux was used and degassing was done by flushing with chlorine gas. The melts were checked before pouring by means of a reduced pressure gas tester. The pouring temperature employed was 700 C (1292 F), and the melt temperature was never allowed to exceed this value by more than about 5 C (9 F).

From each melt six Dow* type molds with four cast-to-size test bars in each and two one in. x 4 in. x 6 in. end chilled flat plates were cast. The design of the Dow mold is shown in Fig. 1, and that of the plate casting in Fig. 2. Synthetic sand, consisting of no. 70 AFS washed silica sand, 3 per cent water, 4 per cent bentonite and 2 per cent boric acid, was used for all molds.

Cooling Conditions in Molds

Thermocouples were placed at various points on the center line of a test bar, and at various distances from the chilled face of a plate. The positions of the couples and the cooling curves obtained are shown in Figs. 3 and 4. It will be seen that the cooling rate at the center of the test bar was similar to that near the chill in the plate casting. Also, the temperature gradient in the gage length of the test bar was about the same as that between couples 2 and 4 in the chilled plate. However, the influence of cooling in transverse directions was probably much more pronounced in the test bar than in the plate casting.

The plate castings were radiographed, but although they were all apparently sound, subsequent metallographic examination showed considerable layer porosity in some sections. Thus radiography is not thought to be a useful indication of this defect in aluminum-magnesium alloys. One separately cast test bar from each mold (six in all) was tested immediately after heat treatment.

Four test bars (0.505 in. diameter, 2 in. gage length) were machined from each plate after heat treatment. The bars were taken parallel to, and at 0.5, 1.5, 2.5 and 3.5 in. from the chilled face.

It is known[10] that aluminum-10 per cent Mg alloys containing more than about 10.2 per cent Mg age harden at room temperature. Therefore, as a considerable time elapsed between quenching the plates and testing the machined bars, extra separately cast test bars were tested on the same day as the machined bars of the same melt. In this way it was hoped to minimize the effect of property changes due to aging, but, as will be discussed later, this was not altogether successful owing, apparently, to the effect of casting size on aging rate.

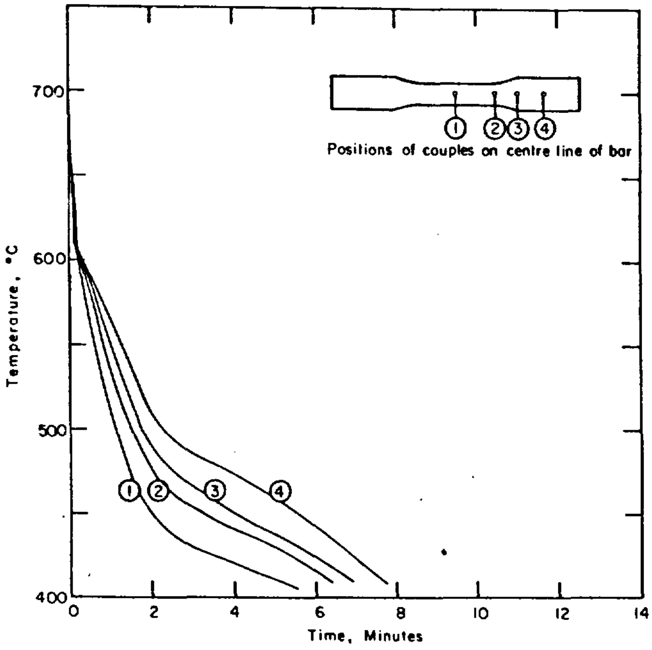

Fig. 3. Cooling curves taken at various points along the center line of a Dow test bar.

Chemical Analysis and Tensile Tests

Samples for chemical analysis were taken from the gage lengths of separately cast test bars from each melt. The results obtained are shown in Tables 1 and 2. It will be seen that the magnesium content of the test bars exceeded the nominal

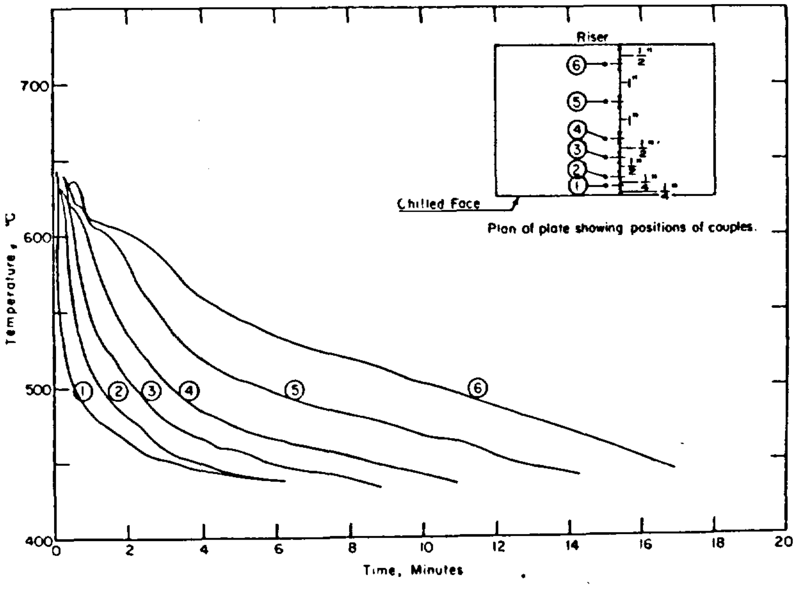

Fig. 4. Cooling curves taken at various distances from the chilled face of an end chilled plate casting.

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*U.S. Federal Specification QQ-M-56 (1950) p. 6 Fig. 1A (called in this report "Dow" because it was introduced by the Dow Chemical Co.).

TABLE 1. Chemical Analysis Results — Normal Purity Melts

Nominal Wt. %Mg	Dow Bars, Wt. %					Bars From Plates,** Mg Wt. %							
	Mg	*Diff.	Si	Fe	Be	1	*Diff.	2	*Diff.	3	*Diff.	4	*Diff.
12.2	13.1	0.9	0.09	0.14	0.005								
11.4	12.1	0.7	0.11	0.12	0.005	11.9	+0.5	11.6	+0.2	11.4	0.0	11.3	−0.1
10.9	11.6	0.7	0.10	0.12	0.005	11.5	+0.6	11.5	+0.6	10.9	0.0	10.9	0.0
10.4	11.2	0.8	0.11	0.12	0.005	11.0	+0.6	10.8	+0.4	10.4	0.0	10.5	+0.1
9.9	10.8	0.9	0.12	0.12	0.005	10.8	+0.9	10.6	+0.7	10.4	+0.5	10.2	+0.3
9.4	10.2	0.8	0.11	0.12	0.005								
8.9	9.7	0.8	0.12	0.13	0.005	9.5	+0.6	9.4	+0.5	9.1	+0.2	9.1	+0.2
8.4	9.0	0.6	0.10	0.12	0.005								
7.9	8.5	0.6	0.10	0.12	0.005	8.4	+0.5	8.3	+0.4	8.2	+0.3	8.0	+0.1
7.4	8.3	0.9	0.09	0.14	0.004								
6.9	7.5	0.6	0.10	0.15	0.003			7.2	+0.3				
6.4	6.9	0.5	0.09	0.14	0.002								
5.9	6.1	0.2	0.09	0.15	0.002			6.2	+0.3				

*Differences — indicated analysis over "nominal."
**No. one near chill, No. 4 near riser.

melt content by approximately 0.8 per cent for the higher magnesium melts. This is due to inverse segregation of magnesium along the test bar and has been noted elsewhere.[1, 6]

In order to obtain an indication of the extent of segregation in the chilled plates, samples were taken from the gage lengths of plate bars from some of the higher magnesium content melts. The results obtained are also shown in Tables 1 and 2, and it will be seen that inverse segregation of magnesium occurred towards the chilled ends of the plates. In general, the degree of segregation was similar for all alloys in the range 8 to 12 per cent Mg.

The tensile test data are summarized in Figs. 5 to 14. In plotting these figures each point for the separately cast bars represents the average of six test values, and for the bars taken from plates, two test values (i.e., one bar from each of the two plates cast in each melt). Exceptions to these were when some individual results were discarded owing to the presence of visible flaws in the fractures, etc.

In Figs. 5, 6, 7, 10, 11 and 12, in which the Dow bar results are compared with those of bars taken from plates, the actual, i.e., gage length, magnesium content is plotted against tensile properties. Values for the magnesium content of some of the intermediate bars, taken from plates for which chemical analyses were not available, were estimated by interpolation.

In Figs. 8, 9, 13 and 14, the properties of bars cut from plates are plotted against nominal magnesium contents.

Normal Purity Melts

Figures 5 to 7 show the variation of tensile properties with magnesium content for separately cast test bars and bars from chilled plates. For this comparison the properties of the bar taken approximately 1.5 in. from the chilled end were used, because in most cases this bar had approximately the same grain size as the corresponding Dow bar. Above about 10 per cent Mg the two curves for the separately cast test bars show the effect of age hardening that occurred in the time (about 40 days) which elapsed between solution treatment and testing of the machined bars. The machined bar properties, however, show less age hardening than the separately cast bars.

TABLE 2. Chemical Analysis Results — High Purity Melts

Nominal Wt. %Mg	Dow Bars, Wt. %						Bars From Plates,** Mg Wt. %							
	Mg	*Diff.	Fe	Si	Ti	Be	1	*Diff.	2	*Diff.	3	*Diff.	4	*Diff.
12.0	12.8	+0.8	0.02	0.01	0.08	0.005	12.4	+0.4	12.4	+0.4	11.8	−0.2	11.8	−0.2
11.5	12.3	+0.8	0.01	0.007	0.09	0.005								
11.0	11.8	+0.8	0.02	0.01	0.07	0.005	11.5	+0.5	11.3	+0.3	11.2	+0.2	11.0	0.0
10.5	11.6	+1.1	0.02	0.01	0.08	0.005								
10.0	10.9	+0.9	0.02	0.01	0.09	0.005	10.6	+0.6	10.5	+0.5	10.4	+0.4	10.0	0.0
9.5	10.4	+0.9	0.02	0.01	0.11	0.005								
9.0	9.9	+0.9	0.02	0.01	0.11	0.004	9.6	+0.6	9.5	+0.5	9.3	+0.3	9.0	0.0
8.5	9.2	+0.7	0.02	0.01	0.10	0.005								
8.0	8.9	+0.9	0.02	0.02	0.08	0.005	8.5	+0.5	8.5	+0.5	8.1	+0.1	7.8	−0.2
7.5	8.3	+0.8	0.02	0.01	0.12	0.005								
7.0	7.6	+0.6	0.02	0.02	0.09	0.003			7.3	+0.3				
6.5	6.7	+0.2	0.03	0.02	0.11	0.002								
6.0	6.5	+0.5	0.02	0.02	0.09	0.003			6.2	+0.2				
5.0	5.4	+0.4	0.01	0.01	0.12	0.002			5.2	+0.2				
4.0	4.3	+0.3	0.01	0.01	0.11	0.003			4.2	+0.2				
3.0	3.2	+0.2	0.01	0.01	0.12	0.004			3.0	0.0				
1.0	0.96	−0.04	0.01	0.01	0.12	0.003			0.92	−0.08				

*Differences — indicated analysis over "nominal."
**No. one near chill, No. 4 near riser.

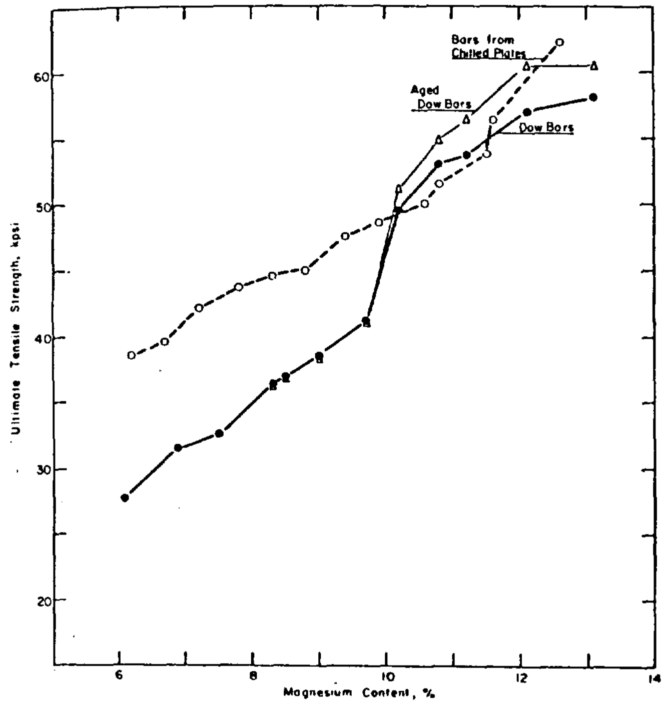

Fig. 5. Variation of ultimate tensile strength with magnesium content for Dow bars and test bars cut from end chilled plates (1.5 in. from chill), of normal purity alloys. The magnesium contents are gauge length values (Table 1).

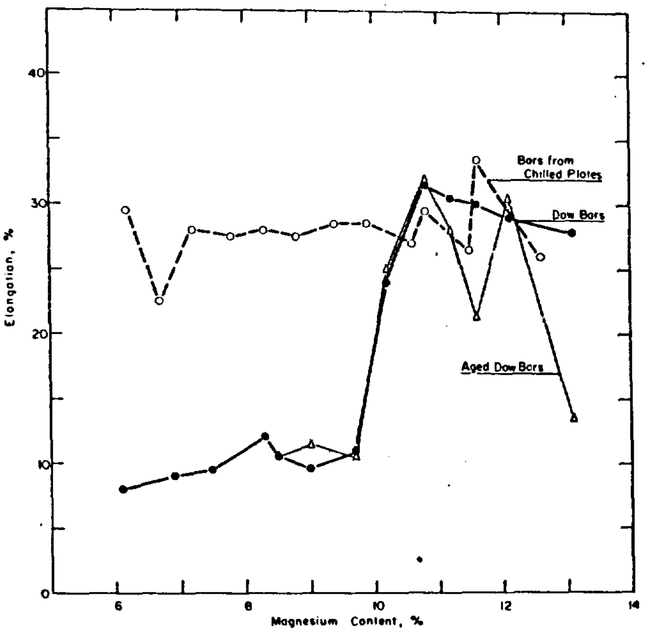

Fig. 6. Variation of elongation with magnesium content for Dow bars and test bars cut from end chilled plates (1.5 in. from chill), of normal purity alloys. The magnesium contents are gage length values (Table 1).

From Fig. 5 it will be seen that for both Dow bars and plates the ultimate tensile strength increases with increasing magnesium content. However, at about 10.5 per cent Mg there is a break in the curve for the separately cast bars, which is not shown in the plate results. A more pronounced break is apparent in the elongation curves (Fig. 6) for separately cast test bars, whereas the elongation of the bars taken from plates does not vary with magnesium content.

At higher magnesium contents there is also some indication of a fall in elongation, although the results are confused by the effects of age hardening. The 0.2 per cent yield strength (Fig. 7) is approximately proportional to magnesium content for freshly solution treated material, but at higher magnesium contents (above 10 per cent) there is a deviation from linearity caused by age hardening.

Figures 8 and 9 show that although the tensile properties of the plate castings decrease in going from the chilled end to the riser end, as would be expected, there was no indication of a sudden reduction in properties as the magnesium content decreased.

High Purity Melts

The effects of magnesium content on the tensile properties of Dow bars from the higher purity melts are shown in Figs. 10, 11 and 12. The yield strength results (Fig. 12) show similar trends to those of the normal purity material. Again, the affect of age hardening is apparent at the higher magnesium contents. In the ultimate tensile strength results (Fig. 10) no break is apparent at any magnesium content (Fig. 5), and the properties of the separately cast test bars are similar to those of the bars cut from plates.

The elongation results, however, (Fig. 11) show a break similar to that of Fig. 6, although the reduction in elongation is much less. The effects of age hardening are marked in these results at higher magnesium contents.

Figures 13 and 14 give the ultimate tensile strength and elongation results for bars cut from

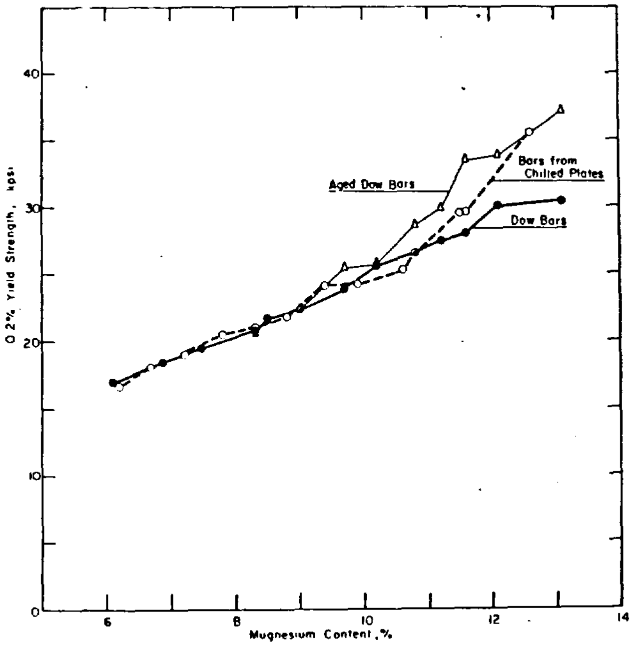

Fig. 7. Variation of 0.2 per cent yield strength with magnesium content for Dow bars and test bars cut from end chilled plates (1.5 in. from chill), of normal purity alloys. The magnesium contents are gage length values (Table 1).

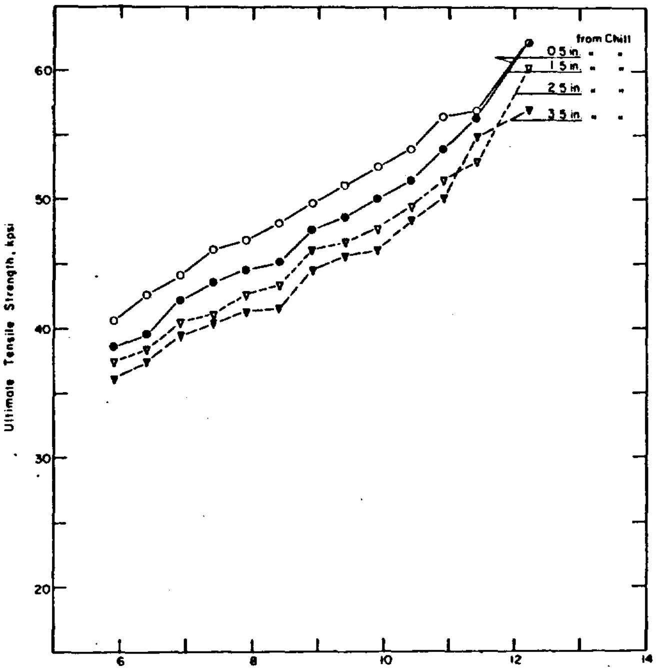

Fig. 8. Variation of ultimate tensile strength with magnesium content for test bars cut from end chilled plates of normal purity alloys. The magnesium contents are 'nominal' values (Table 1).

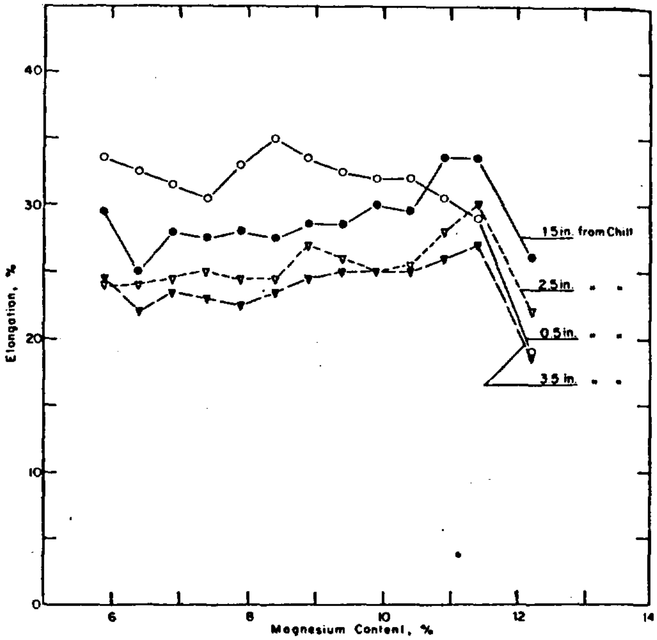

Fig. 9. Variation of elongation with magnesium content for test bars cut from end chilled plates of normal purity alloys. The magnesium contents are 'nominal' values (Table 1).

the chilled plates. The results are similar to those for the normal purity material (Figs. 8 and 9), but are generally somewhat higher. At lower magnesium contents the elongation values tend to increase.

Metallography

The distribution of porosity in the Dow bars was studied by polishing longitudinal sections of bars and examining them under oblique lighting. Figures 15 and 16 show photomacrographs of se-

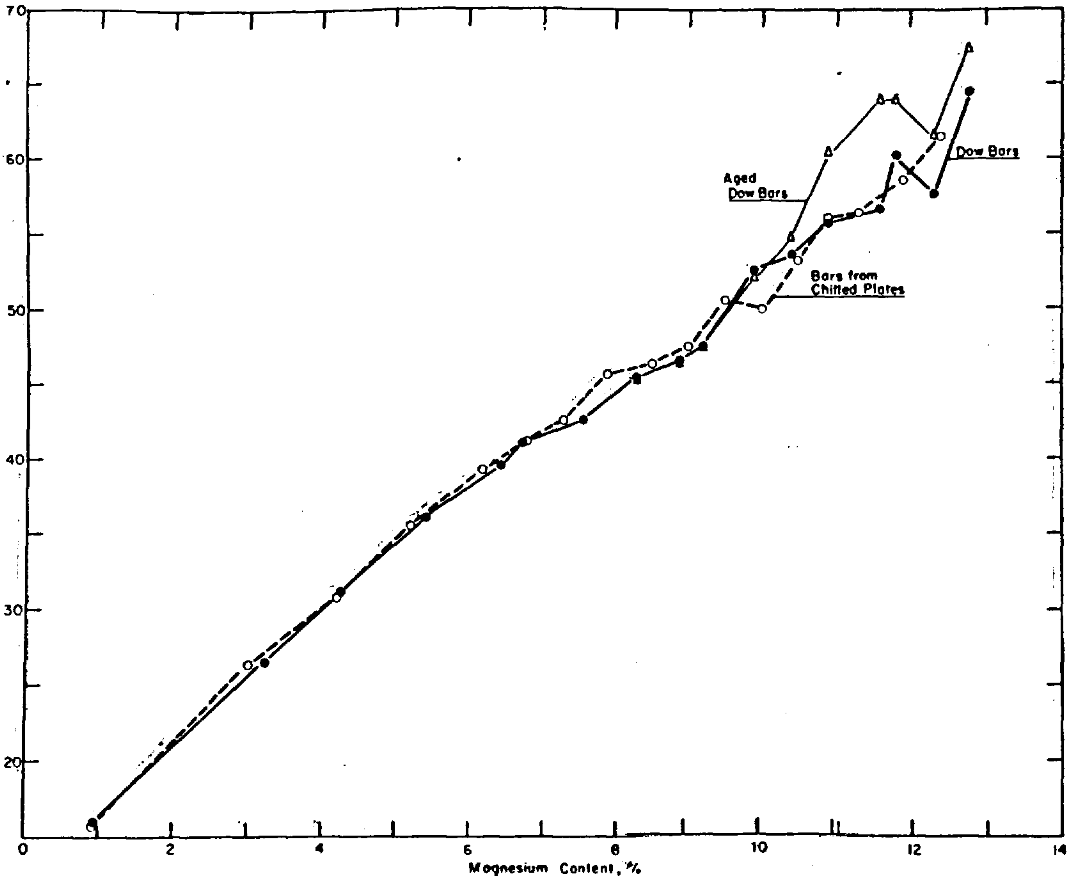

Fig. 10. Variation of ultimate tensile strength with magnesium content for Dow bars and test bars cut from end chilled plates (1.5 in. from chill), of high purity alloys. The magnesium contents are gage length values (Table 2).

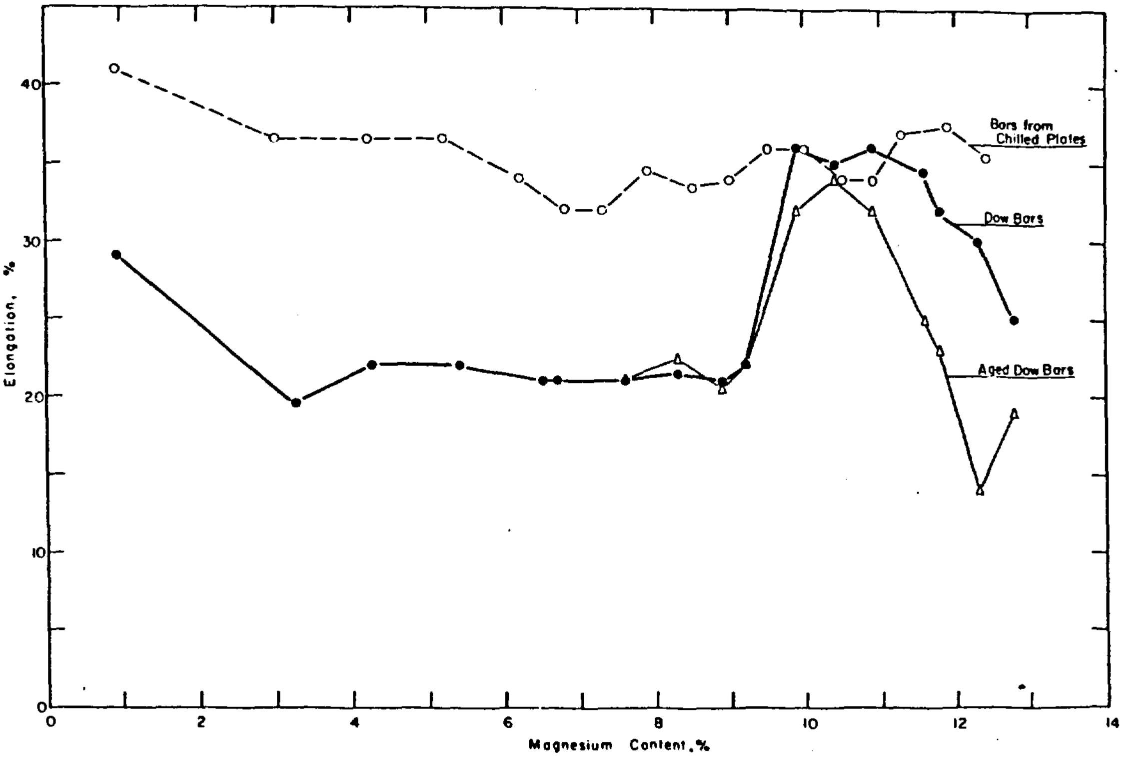

Fig. 11. Variation of elongation with magnesium content for Dow bars and test bars cut from end chilled plates (1.5 in. from chill), of high purity alloys. The magnesium contents are gage length values (Table 2).

ries of bars of each purity. The preparation and lighting employed tend to exaggerate the porosity, and Fig. 17, which is a view of the section of the bar marked by the arrow in Fig. 15 at higher magnification and by incident light, gives a truer indication of the degree of porosity present.

However, it is considered that the macrographs of Figs. 15 and 16 give an accurate picture of the distribution of the porosity. Examination of the bars at higher magnification has failed to reveal significant amounts of macroporosity in regions shown to be sound by the macro examination.

It will be seen from Fig. 15, that as the magnesium content decreases, the severe porosity, which occurs in the characteristic layer form, gradually spreads from the grips towards the gage length. The first appearance of layer porosity in the gage length is coincident with the first drastic fall in elongation (9.7 per cent Mg, Fig. 5). At lower magnesium contents the layer porosity extends into the gage length.

As would be expected, of the test bars in which the porosity first appeared in the gage length (*e* of Fig. 15) all 12 broke close to the bottom of the shoulder. At lower magnesium contents the fracture position was less localized. Of

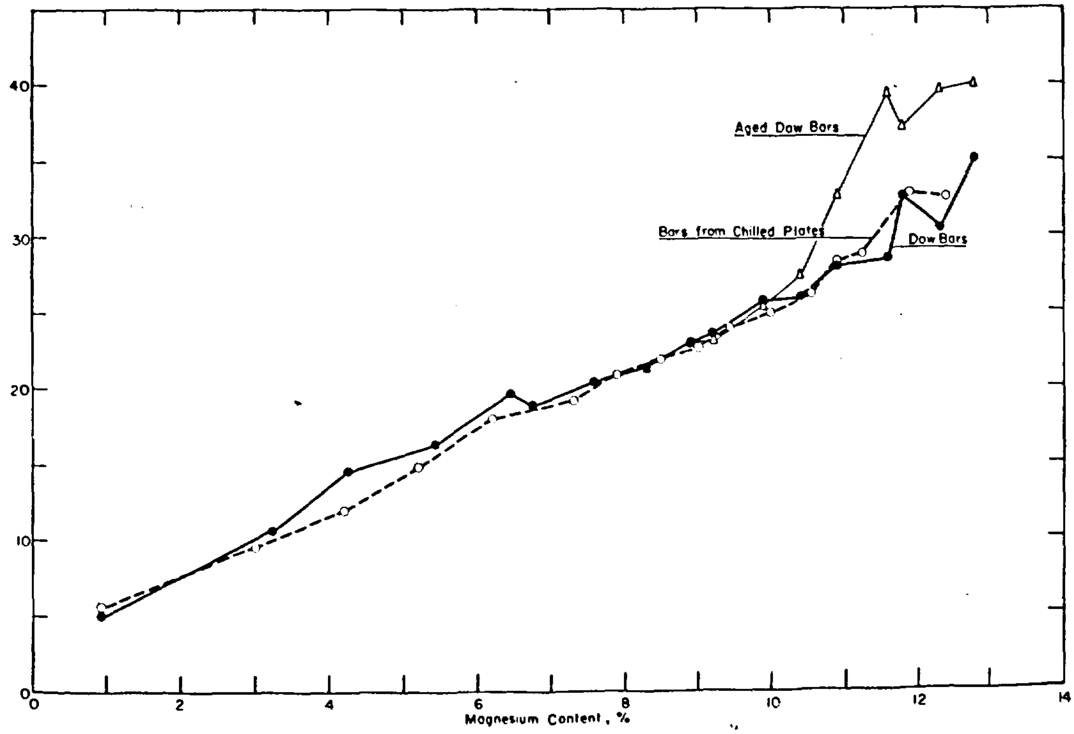

Fig. 12. Variation of 0.2 per cent yield strength with magnesium content for Dow bars and test bars cut from end chilled plates (1.5 in. from chill), of high purity alloys. The magnesium contents are gage length values (Table 2).

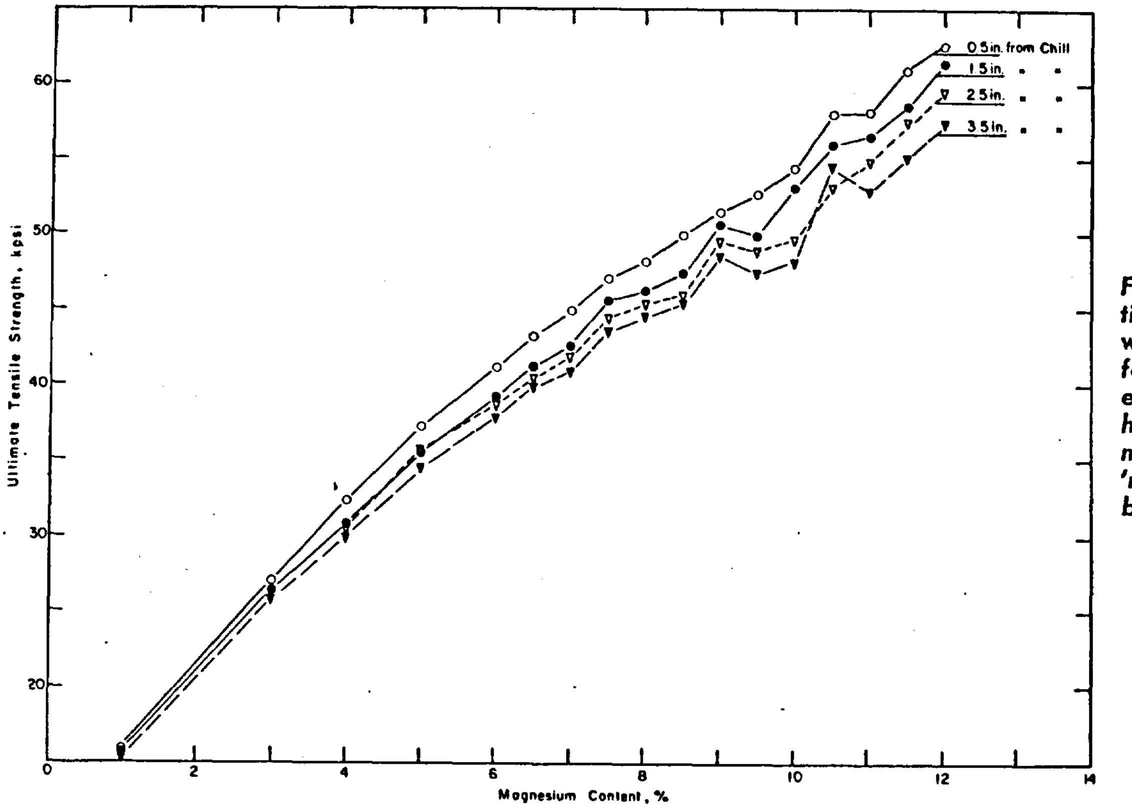

Fig. 13. Variation of ultimate tensile strength with magnesium content for test bars cut from end chilled plates of high purity alloys. The magnesium contents are 'nominal' values (Table 2).

the test bars containing 10.2 per cent Mg (*d* of Fig. 15) 5 out of 12 tested broke near the shoulder and these had low properties (Table 3). Examination of several bars from this melt showed that in some a trace of layer porosity occurred at the extreme end of the gage length. It is thus apparent that this magnesium content is critical for the casting configuration and solidification conditions of the present work.

High Purity Alloys

A similar correlation between porosity distribution and magnesium content occurs in the higher purity alloys (Fig. 16), although in this series the first appearance of layer porosity in the gage length was much more severe than in the lower purity series.

Longitudinal and transverse sections were taken from the broken test pieces from the plate castings. The longitudinal sections were selected so that they were roughly parallel to the horizontal faces of the plates. All sections examined showed layer porosity aligned parallel to the chilled faces of the plates, i.e., along the axis of the bar. However, sections of bars from near the chill ends of plates usually had less porosity than

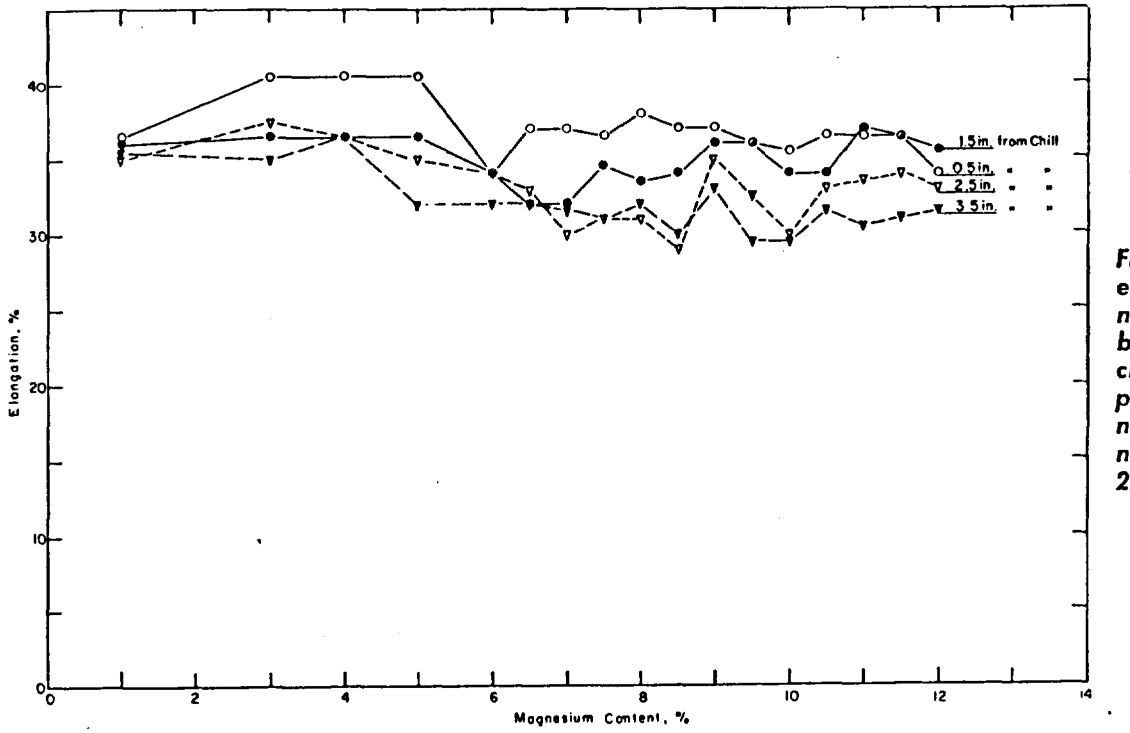

Fig. 14. Variation of elongation with magnesium content for test bars cut from end chilled plates of high purity alloys. The magnesium contents are nominal values (Table 2).

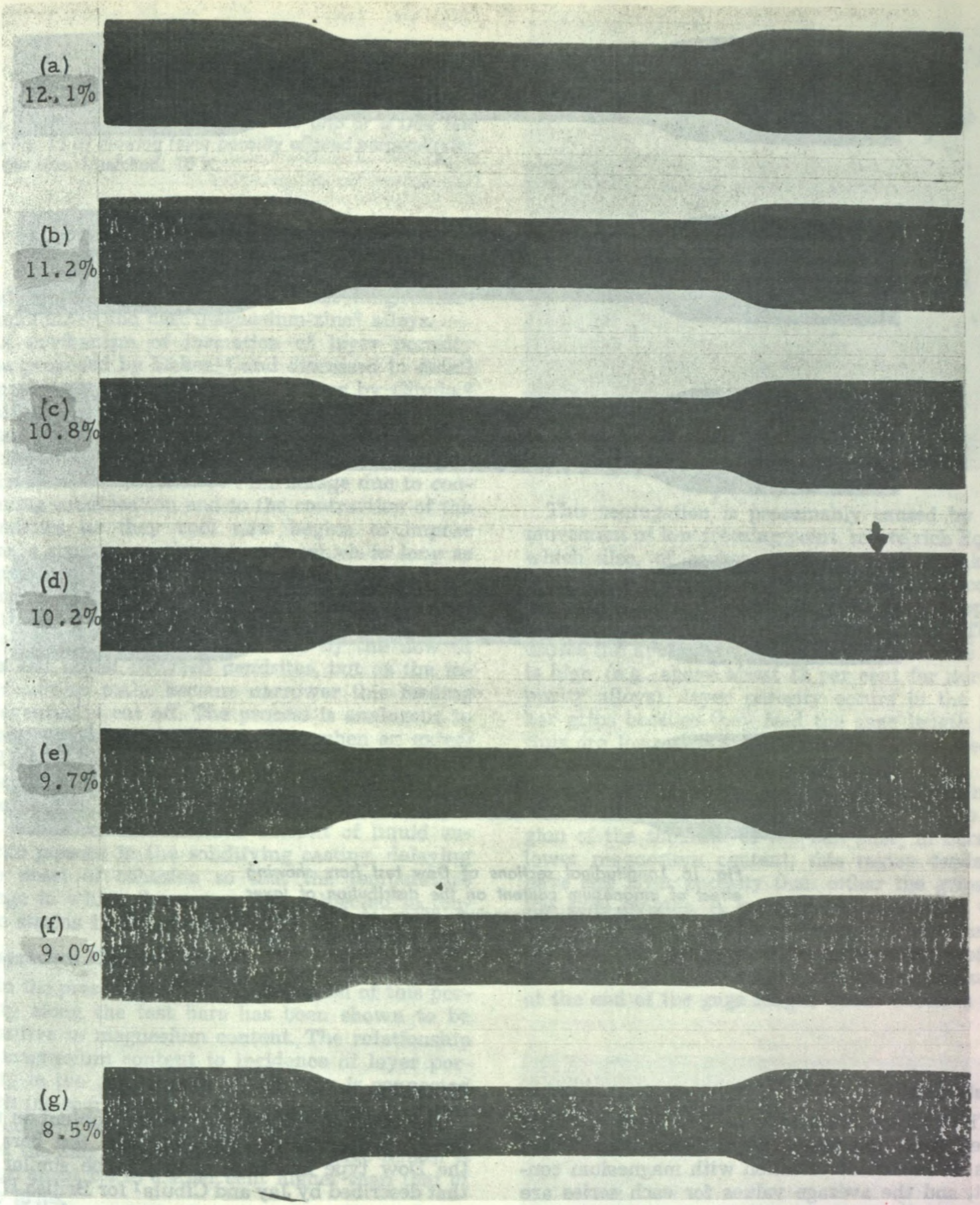

Fig. 15. Longitudinal sections of Dow test bars showing effect of magnesium content on the distribution of layer porosity in aluminum-magnesium alloys of normal purity. (Magnesium percentages given are gage length values Table 1).

those that were near the risers (Figs. 18 and 19).

Although a comprehensive correlation of the incidence of layer porosity and magnesium content was not attempted, there appeared to be little tendency for the amount of layer porosity to decrease with increasing magnesium content (as in the Dow bars) in the normal purity alloys. In the higher purity melts, on the other hand, the chilled ends of the lower magnesium content plates were much more porous than those with higher magnesium (Figs. 18 and 20).

It is apparent that the orientation of the layer porosity relative to the principal stress direction is much more important than the amount of porosity in determining the properties of this alloy in a casting.

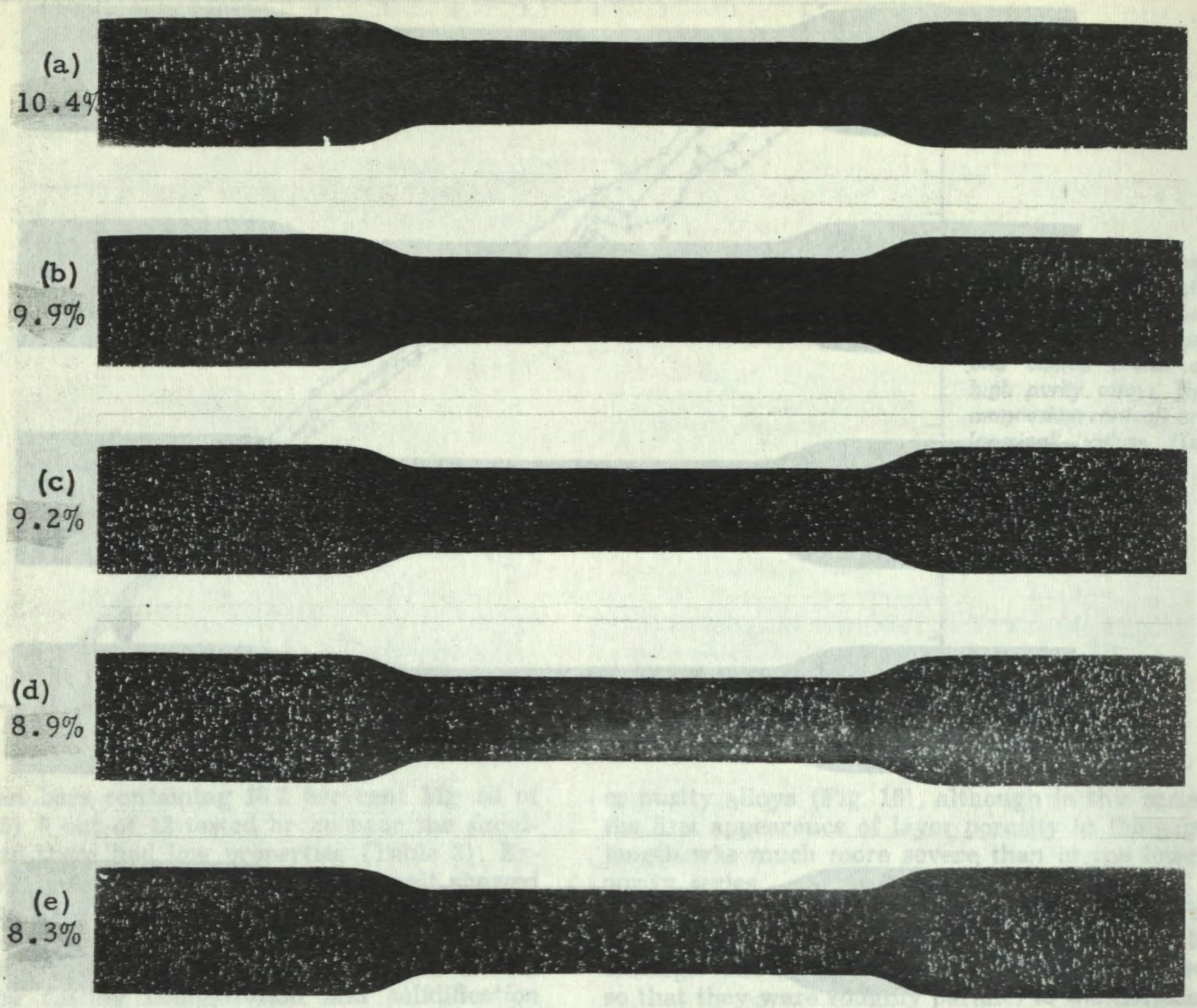

Fig. 16. Longitudinal sections of Dow test bars showing effect of magnesium content on the distribution of layer porosity in aluminum-magnesium alloys of high purity. (Magnesium percentages given are gage length values Table 2).

Grain Size

The average grain sizes of Dow bars and bars taken from the plates were determined. There was no consistent variation with magnesium content, and the average values for each series are given in Table 4. It will be seen that, as expected, the grain size of the bars taken from the plates increased in going from the chill end toward the riser end of the plate.

The dow bar grain sizes were intermediate between the first and second bar from the chill for the normal purity series and between the second and third for the higher purity melts.

The high purity metals tended to give finer grain sizes throughout, probably because a grain refining addition (0.1 per cent Ti) was made to these melts, whereas the normal purity melts were made from commercial ingot that contained little titanium.

Discussion

The effect of varying magnesium content on the tensile properties of separately cast test bars of the Dow type has been shown to be similar to that described by Jay and Cibula[1] for British DTD test bars. The characteristic feature of this behavior is that, as the magnesium content of melts is reduced through a comparatively narrow range, a large reduction in ductility occurs and, in the case of alloys of commercial purity, a corresponding abrupt reduction in ultimate tensile strength is observed.

In agreement with Jay and Cibula,[1] it has been found that this sudden reduction in tensile properties is caused by layer porosity in the gage lengths of the test bars. The occurrence of shrinkage porosity in layers, as described in this work, has been observed in the past for a wide variety of cast alloys including fine grained cast bronzes

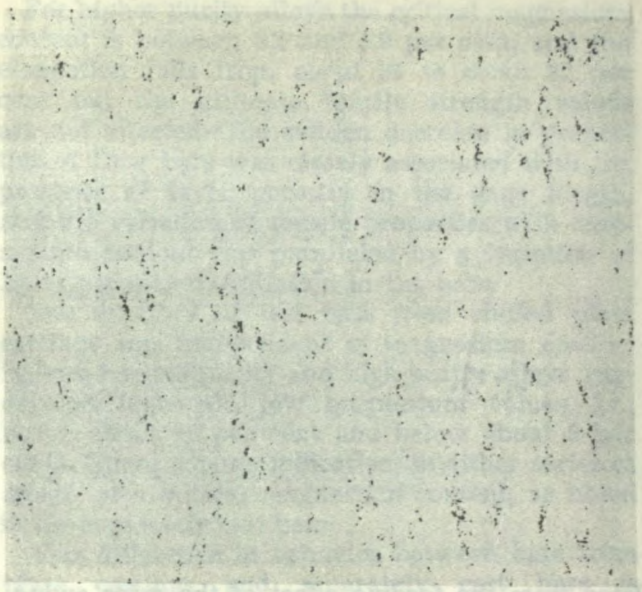

Fig. 17. Longitudinal section from the grip of a Dow test bar Fig. 15 d) showing layer porosity aligned perpendicular to the axis. Unetched. 10 ×.

and gun metals[12] as well as cast magnesium-aluminum[13] and cast magnesium-zinc[9] alloys.

A mechanism of formation of layer porosity was proposed by Baker[13] and discussed in detail for aluminum-10 per cent Mg alloys by Cibula.[1] This theory suggests that in the last stages of freezing the alloy consists of a semicoherent, interlocking network of dendrites separated by residual eutectic liquid. ". . . Shrinkage due to continuing solidification and to the contraction of the dendrites as they cool now begins to impose tensile stresses on the network, which as long as liquid persists, remains brittle and therefore tears perpendicularly to the temperature gradient (i.e., to the stresses) . . ."[1]

At first these tears are healed by the flow of residual liquid between dendrites, but as the interdendritic paths become narrower this feeding is eventually cut off. The process is analogous to that of hot tearing, which occurs when an external restraint is applied to a solidifying casting. The effect of increased magnesium content in reducing the amount of layer porosity is thought to be due to the increased amount of liquid eutectic present in the solidifying casting, delaying the onset of cohesion so that the temperature range in which the network is subjected to tensile strains is decreased.[1]

Magnesium Content Effect

In the present work the distribution of this porosity along the test bars has been shown to be sensitive to magnesium content. The relationship of magnesium content to incidence of layer porosity in the gage length of test bars is connected with the segregation of magnesium that is known to occur. Thus, Pollard and Meier[6] have shown that the magnesium content in the gage length is from about 0.4 to 0.8 per cent higher than that of the grips.

This segregation is presumably caused by the movement of low freezing point, solute rich liquid which also, of course, tends to heal shrinkage pores. This movement of residual liquid occurs towards the middle of the test bar, that is, opposite to the principal heat flow direction. Thus, unless the average magnesium content of the bar is high (e.g., above about 12 per cent for normal purity alloys), layer porosity occurs in the test bar grips because they feed the gage length and thus are lower in magnesium, when they freeze, than the rest of the test bar.

From Fig. 15 it will be seen in going from *d* to *e* the layer porosity does not occur in the region of the shoulder of the bar. Also, in bars of lower magnesium content, this region tends to have less layer porosity than either the grips or the gage lengths. A possible explanation of this is that owing to the local thermal conditions in the bar (for example, differential sand heating at the change of section), a hot spot is produced at the end of the gage length which becomes iso-

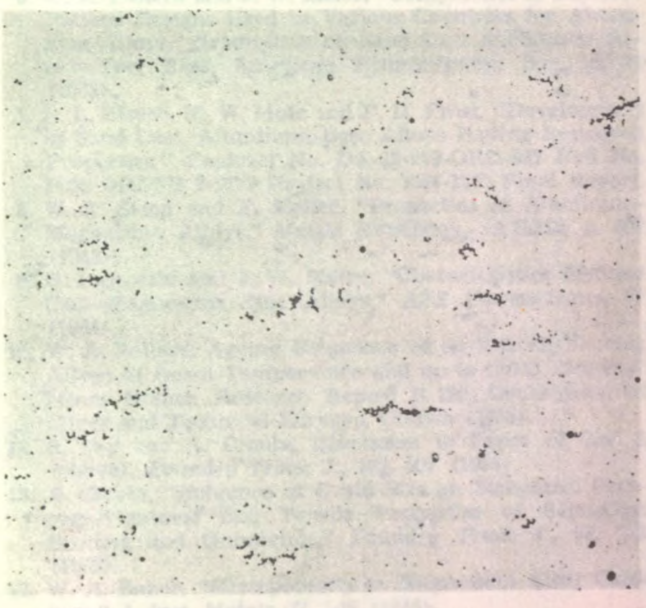

Fig. 18. Longitudinal section from a test bar cut from a chilled plate. Bar nearest riser, 10.5 per cent Mg (nominal), high purity. The layer porosity is aligned parallel to the axis of the test bar (horizontal). Unetched. 10 ×.

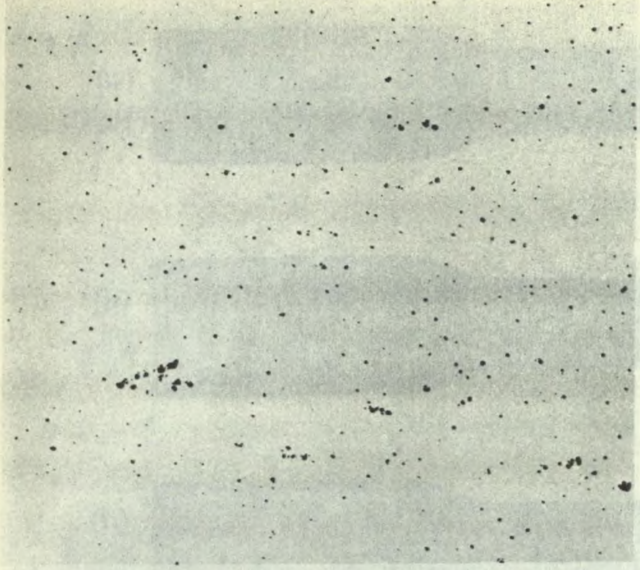

Fig. 19. Longitudinal section from a test bar cut from a chilled plate. Bar nearest chill, 10.5 per cent Mg (nominal), high purity. The layer porosity is much less than in Fig. 18, and is aligned parallel to the axis of the bar (horizontal). Unetched. 10 ×.

lated from the feeding effect of the grips owing to the complete solidification of the shoulder section.

This explanation is supported to some extent by the effect of the asymmetrical pouring of the Dow test bar on the distribution of layer porosity. Thus, in the bars of critical magnesium content (e.g., *e* of Fig. 15) the amount of layer porosity which occurred at the ends of the gage length, was always greater at the end nearest the sprue (the right hand side of Fig. 15). This would be expected, if the phenomenon were due to the heating effect of the metal stream on the sand at that point.

Magnesium Content vs. Layer Porosity

In the higher purity alloys a similar relationship of layer porosity to magnesium content was apparent, but the corresponding effect on the tensile properties was much less. Only the elongation was affected and that to a lesser extent than in the lower purity alloys (Figs. 6 and 11). This difference in behavior of the two series of alloys is not easily explained, although two factors which may be significant are — (a) as shown in Figs. 15 and 16, the layer porosity in the lower purity alloys is coarser than in the higher purity bars, and (b) in the lower purity material considerably more intermetallic constituent particles, principally MgSi and $FeAl_3$ are present than in the higher purity alloys and these are often associated with the pores.

It may be that the pores, which have a rounded shape in the microscale, do not act as severe notches in the higher purity alloys in which the matrix is relatively continuous and has high ductility. In the lower purity material the presence of brittle intermetallics and constituent/matrix boundaries may give the pores a considerably greater stress raising effect.

Comparison of Figs. 6 and 11 will show that the critical magnesium content is between 9.7 and 10.3 per cent for the lower purity alloys, and between 9.2 and 9.9 per cent for the higher purity melts. No explanation of this difference can be advanced. In this connection, the critical magnesium content found by Jay and Cibula[1] was higher than in the present work (about 10.8 per cent). In addition to using somewhat lower purity materials (iron content about 0.2 per cent) these workers studied the British DTD bar, which would be expected to have considerably different solidification conditions to those of the Dow bars of the present work.

As mentioned previously, the main reason for undertaking the present work was to determine the reason for the inconsistent tensile properties of Dow bars of ordinary purity G10 alloy. Test bars made from commercial G10 ingot nor-

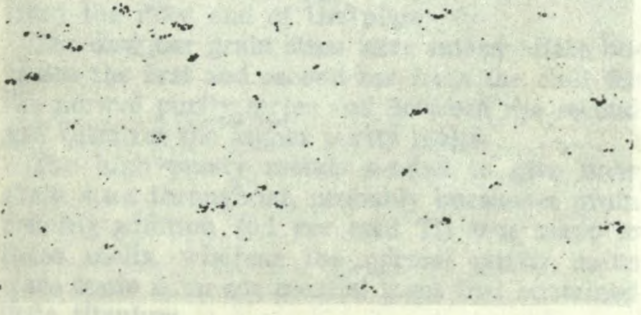

Fig. 20. Longitudinal section from a test bar cut from a chilled plate. Bar nearest chill, 8.0 per cent Mg (nominal), high purity. Note severe layer porosity compared with Fig. 19. Unetched. 10 ×.

mally contain about 10.8 per cent mg (in the gage length), and this is above the critical range of from 9.7 to 10.3 per cent Mg. However, it is presumed that a slight reduction in the magnesium content of the ingot or variations in technique sometimes causes a reduction in the magnesium content of the bars, which may result in the incidence of layer porosity in the gauge lengths.

In this work the critical magnesium content appeared to be determined within comparatively narrow limits. It is probable that wider variations in foundry conditions, such as mold properties, pouring temperature, gas content, impurity content, etc., would cause correspondingly wider variations in the critical magnesium content.

Chilled Plate Bars

The results obtained on bars taken from chilled plates show that if the layer porosity is aligned parallel to the testing direction it has little effect on the strength and ductility of the alloy. In the plate of nominal 10.5 per cent Mg (Fig. 14) the bar nearest the riser, which contained severe porosity (Fig. 19) had an elongation of about 31.5 per cent. In the bar nearest the chill, the significant reduction in porosity resulted in only a slight increase in elongation (to 36.5 per cent), which was probably at least partly attributable to the finer structure resulting from the higher freezing rate.

Jay and Cibula[1] recommend that in order to avoid layer porosity, the magnesium content of G10 melts should be kept towards the higher end of the specification range. However, as these authors mention in the paper[1] and in the discussion[11], the control of magnesium content within castings of this alloy is difficult. This is due to segregation, so that a high magnesium melt content will not necessarily ensure a high magnesium content in all parts of a complex casting. The present work has shown that the effects of layer porosity can be avoided by suitable casting design.

This would be difficult in a complex casting. It would require a detailed knowledge of the stress distribution in the casting, and the ability to design the rigging to produce the thermal conditions necessary to give the required orientation of the layer porosity.

Conclusions

In both normal purity and high purity cast aluminum-magnesium alloy there is a critical magnesium content below which the tensile properties of separately cast test bars of the Dow type show a marked decrease in ductility.

For normal purity alloys this critical magnesium content is between 9.7 to 10.3 percent. In addition to a large decrease in elongation (from about 30 to about 10 per cent), the ultimate tensile strength values, which normally decrease gradually with decreasing magnesium content, show a sudden decrease (from about 50,000 psi to about 40,000 psi) at the critical value.

For higher purity alloys the critical magnesium content is between 9.2 and 9.9 per cent, and the elongation falls from about 35 to about 22 per cent but the ultimate tensile strength values are not affected. The sudden decrease in properties of Dow bars was closely associated with the presence of layer porosity in the gage length, and the variation of tensile properties with magnesium content was paralleled by a variation of layer porosity distribution in the bars.

The ductility of test bars from chilled plate castings was independent of magnesium content in both normal purity and high purity alloys (except at high and low magnesium values, i.e., above about 12 per cent and below about 6 per cent). There was no indication, in either series of alloys, of a critical magnesium content, as noted in the separately cast bars.

This difference in behavior between bars from plate castings and separately. cast bars is thought to be mainly due to the difference in orientation of the layer porosity in the two types of castings. The embrittling effect of the porosity is marked when, as in the separately cast bars, the layers are roughly perpendicular to the bar axis, whereas when the layers are parallel to the bar axis, as in the bars taken from the plate castings, their effect is much less.

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