

An Investigation of Running Quality of Magnesium and Its Alloys.

By

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Introduction.

The first requisite to get the sound castings in the foundry is that molten metals and alloys must flow into the mould uniformly and fill it up perfectly, even the very thin section, before one part solidifies and impedes the inflow of the remainder. This property of molten metals and alloys which is indicated by its ability to flow into the mould and perfectly fill up all the spaces in it has been called the "running quality," a name proposed by C. M. Saeger and A. T. Krynitsky in America. This property has also been given various other titles in order to avoid a confusion with "fluidity," that is, the reciprocal of "viscosity" of physical meaning: coulabilité in France; flowing power, runnability, flowability, life in England and America; Fliessvermögen, Formfüllungsvermögen in Germany. Specifically, the running quality is the synthetic property which is governed by many factors and the most important factor of castability of molten metals and alloys.

There are few writings on this subject at present. A. Portevin and P. Bastien⁽¹⁾⁽²⁾ measured the running quality of pure magnesium, Mg-Al and Mg-Cu-binary alloys and Mg-Al-Cu-ternary magnesium alloy whose content of aluminium and copper is below 15% in the total. They also determined the influence of a remelting on the running quality of the alloy containing 6% Al using the sand spiral mould at the pouring temperature of 700°C and the relation between the composition of the moulding sand and the running quality of magnesium alloys. L. Losana⁽³⁾ studied the influence of aluminium and zinc. Lately, K. Achenbach, H. A. Nipper and E. Piwowarsky⁽⁴⁾ reported the results of the studies for the relations between the running quality of 7% Al-Mg-binary alloy and 6% Al-3% Zn-Mg-ternary alloy and the maximum heating temperature at the mould temperature 250°C and 300°C and the pouring temperature 720°C and 760°C.

The author has designed a new apparatus for measuring the running quality of molten metals and alloys to study the running quality of pure magnesium and some industrial magnesium alloys, and the influence of aluminium, zinc, manganese and copper within the quantity to be added to the

industrial alloys upon the property in question of pure magnesium.

It is the object of this study to clarify relations between the running quality and the composition of the industrial magnesium alloys and to give some suggestions for their practical operations.

Materials used.

The chemical compositions of magnesium ingot, aluminium ingot and four varieties of industrial magnesium alloys, the so-called "Elektron," used through this investigation are given in Table 1. These alloys were supplied from the principal manufacturers in our country as 1.5 to 2.4 kg ingots cast from the same heat and letters A, B, C and D in Table 1 denote the manufacturers. It is considered that each ingot from the same manufacturer has the same composition.

Table 1.

Chemical Composition of Magnesium, Aluminium and Industrial Magnesium Alloys.

| Mark | Al % | Zn % | Mn % | Cu % | Si % | Fe % | Ti % | Mg % |
|---------------------------|-------|------|------|------|-------|-------|-------|-------|
| Magnesium | 0.01 | — | — | — | 0.026 | 0.007 | — | — |
| Aluminium | 99.67 | — | — | tr. | 0.14 | 0.17 | 0.014 | 0.005 |
| Elektron A ⁽¹⁾ | 3.57 | 1.96 | 0.25 | 0.46 | 0.16 | 0.17 | — | — |
| " B | 3.95 | 2.98 | 0.29 | 0.10 | 0.13 | 0.04 | — | — |
| " C | 4.69 | 3.13 | 0.30 | 0.02 | 0.04 | 0.02 | — | — |
| " D | 9.95 | — | 0.14 | — | tr. | 0.08 | — | — |

(1) A, B, C and D denote the manufacturers.

As alloying materials, the granulated zinc for chemical analysis, the hardner containing 2.34% Mn supplied from one of those manufacturers and the hardner containing 31.49% Cu prepared from the pure electrolytic copper and the above mentioned magnesium were used.

For melting the magnesium and its alloys, the flux containing 57.8% MgCl₂ and 42.2% NaCl prepared by Asahi Denka Kogyo K. K. was used. The fluxes for melting Elektrons were supplied from the same manufacturers of Elektron in order to measure its running quality under similar conditions and their compositions are shown in Table 2 where A, B, C and D correspond to those in Table 1.

Table 2.

Chemical Composition of Fluxes for Melting and Refining Magnesium Alloys.

| Mark. | MgCl ₂ | NaCl | KCl | CaCl ₂ | MgO | MgSO ₄ | SiO ₂ | Fe ₂ O ₃ | Al ₂ O ₃ | H ₂ O |
|-------|-------------------|-------|-------|-------------------|-----|-------------------|------------------|--------------------------------|--------------------------------|------------------|
| A* | 38.81 | — | 25.28 | 2.61 | — | 1.10 | 1.26 | 1.30 | 0.87 | — |
| B* | 31.76 | — | 12.01 | 14.99 | — | 0.59 | — | 0.70 | 0.51 | — |
| C | 53.88 | — | 26.0 | 5.94 | 6.0 | 0.57 | 0.6 | 1.45 | | 5.40 |
| D* | 57.75 | 42.25 | — | — | — | — | — | — | — | — |

* Sample A, B and D were analysed after drying at 110°C for 3 hrs. A, B, C and D correspond to those given in Table 1.

Experimental Apparatus and Procedure.

The length of the solidified part of a metal flowed in the canal of a certain cross section of the test mould has been adopted as a most pertinent and quantitative measure of the running quality of molten metals and alloys. Lately, L. W. Eastwood and L. W. Kempf⁽⁶⁾ reported that as a measure of the running quality of aluminium alloys they adopted the volume of the solidified part of the metal flowed in the flat spiral canal whose cross section is $\frac{1}{16}$ inch thick and $1\frac{3}{4}$ inch wide, because they could not adopt the length of flow as the molten alloys solidified in an irregular form in such a very thin section.

The author studied this problem in various ways and adopted as the measure the length of the solidified part of a metal flowed in the canal of a certain cross section as a measure of the running quality in this investigation. Though the value of the running quality varies with the apparatus used we can compare the results obtained on a certain mould with one another after a thorough consideration of the literatures hitherto published on this subject, the author designed a new apparatus for measuring the running quality of metals and alloys.

Materials of Mould:—It is extremely necessary in the measuring of the running quality to keep the test mould at a uniform condition. In case of the sand mould, it is very difficult to maintain its uniform condition, because chemical composition, grain size, moisture and volatile matter content, ramming degree (hardness of the sand mould), etc. influence permeability, thermal conductivity, surface condition. Furthermore, it is difficult to hold a constant ramming degree, even if the same moulder is engaged in this operation. If a metallic mould is used, a constant experimental condition is easily obtainable, but there are some disadvantages, that is, it is expensive, more difficult to handle than the sand mould, and it is necessary to heat the mould in order to increase the accuracy of the running quality measurement for metals and alloys with high melting points; there is also the difficulty of keeping a uniform temperature of the mould

and consequently the surface oxidation of the ferrous mould. The author, however, adopted the metallic mould from the experimental point of view on the constancy of condition and the necessity of using the steel mould.

Form of Measuring Canal:—Dr. D. Saito and Mr. K. Hayashi⁽⁶⁾ in this country originated the spiral canal. W. Ruff⁽⁷⁾ lately used the straight one. As it is relatively difficult, especially in case of the metallic mould, to make the spiral canal with uniform sections, a rectangular, inverted trapezoidal or triangular section was usually used hitherto in order to eliminate such a difficulty. The author adopted the straight canal from the constructional point of view. If a metallic mould is used, which necessitates a lower temperature in order to protect its surface from an oxidation and make a temperature control easy, a length of the straight flow is short, but an accuracy of the measurement lowers. In order to improve the accuracy, the author adopted a mould temperature which is higher than the room temperature, but easily adjustable.

The cross section of the measuring canal should be circular to minimize the heat loss from its walls; but the author adopted the equilateral triangular cross section which is easily producible, will be explained later, since it is very difficult to make the cross section uniformly circular throughout the straight canal.

On the preliminary test by which the flowing speed of molten metals was measured by an oscillograph, the author admitted the fact that the molten metals flowed in spherical drops because of extreme smoothness of the surface when the surface of the measuring canal was thinly coated with soots, and such phenomena did not exist when coated with fine alundum cement powder. Therefore, he adopted the latter coating method in which it is very important to apply the cement uniformly on the surface, thereby lessening the experimental hazards.

Hydrostatical Head of Molten Metal at Pouring:—Various procedures have been used by many investigators in order to maintain the hydrostatical head of molten metal during pouring. One

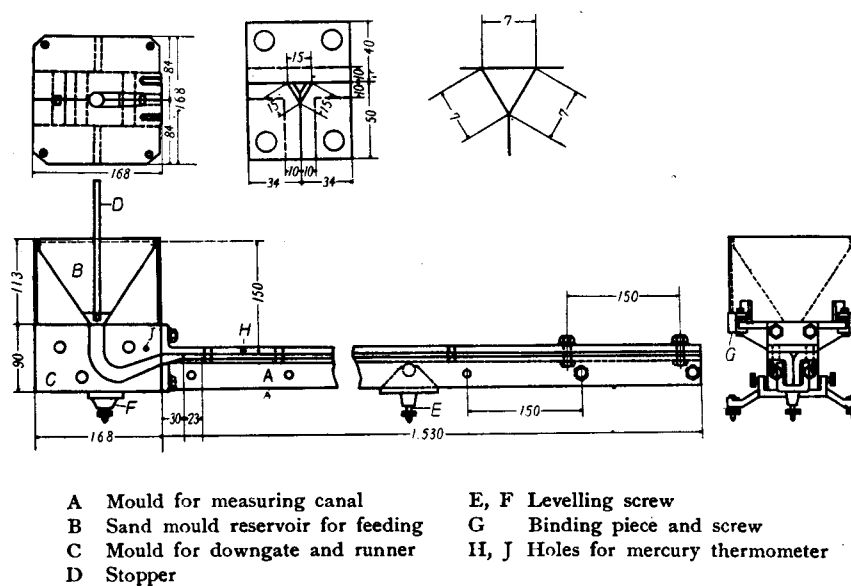
method is to pour the molten metal from a crucible or a spoon into the reservoir where it reaches a certain level before flowing into the measuring canal. The other is to pour the metal as above mentioned into the blind reservoir just before the entrance of the measuring canal until the molten metal is charged to the certain level in the reservoir. In the former method there is some danger that molten metal will flow into the measuring canal before reaching the certain level in the basin and that the molten metal irregularly flows in the canal because of its irregular supply. In the second

method violent stirring of the pouring metal results because of increase of the distance between the reservoir and the crucible or the spoon.

The author adopted the sand basin fitted with a stopper which is removed after filling up the basin with the molten charge. This stopper is made in such a form as to prevent the molten metal in the basin from agitation.

With these ideas in mind, the author has designed a relatively simple apparatus for measuring the running quality as shown in Fig. 1.

A is a metallic mould whose length is 153 cm



A Mould for measuring canal
 B Sand mould reservoir for feeding
 C Mould for downgate and runner
 D Stopper
 E, F Levelling screw
 G Binding piece and screw
 H, J Holes for mercury thermometer

Fig. 1.

Experimental Apparatus used for Determining the Running Quality of Molten Magnesium and its Alloys.

and cross sectional area is 0.212 cm^2 . This mould consists of two steel angles and one flat steel; the outer sides of the angles are finely machined; and both of them are fastened with bolts and the surface of the latter is also precisely machined and firmly bolted up to each angle. After heating at about 130°C , the surface of the canal is thinly coated by a brush with fine powdered alundum cement, which is prepared by fine grinding, elutriation for 60 min. and precipitation of its upper emulsified layer for 24 hrs, and dried at about 130°C in the furnace. H, the hole bored so that the mercury bulb of the thermometer is closely fitted in it, at the point about 10.7 cm from the end on one side of the flat steel, is 6 mm diameter and 20 mm deep. There is a hole also at about 68 cm from the same end. The mercury thermometers are inserted in these holes for measuring the temperature of the mould. As the cross section of the canal near the entrance is tapered, the measurement of the length of flow is started from the point about 2.3 cm from the tapered end.

B is the sand mould reservoir for feeding of the inverted circular cone type. Its diameter is about 14.4 cm at top and 2 cm at bottom; and its wall is almost vertical up to 1.4 cm from the top where its diameter is 14 cm. As the volume of its upper part is relatively large, the decrease of height of the molten charge in the basin during flow in the measuring canal is only about 2 mm. Even if the metal completely fills it up, the hydrostatical head of the molten charge over the upper surface of the measuring canal at the instant that the head of the metal reached the entrance of the canal is 15 cm; and therefore we may conclude that the hydrostatical head is constant during the measurement. Owing to the more gentle inclination of the lower part of its wall, the metal may flow into the mould without violent turbulence from the opening formed by a small rise of the stopper. This mould is made of the clay bearing foundry sand mixed with about 3% sulphur flower and a little amount of boric acid and is dried at about 250°C .

The stopper is made of electrode graphite. This graphite head is so machined to the form of right circular cone frustum, 2 cm lower diameter, 3.8 cm upper diameter and 1.5 cm height, that it is closely fitted to the bottom part of the sand mould and a 8 mm iron rod is screwed into it. It is coated with alundum cement on the graphite head, dried and heated at about 500°C before using. The graphite head needs to be replaced by a new one as it wears off with repeated using.

C is the cast iron mould for connecting A and B. It consists of two sections which are bolted to each other. A form of the downgate and the runner was determined as results of the preliminary tests on various types as shown in Fig. 2. According to those tests, when a stopper was used, the blind reservoir, as shown in A, B and C in Fig. 2, gave the molten metal turbulent motion and irregular flow into the measuring canal. Therefore, the author adopted D as shown in Fig. 2 in order to make the flowing metal perfectly fill up the runner and minimise the temperature difference between the sand reservoir and the measuring canal. The surface of the down gate and the runner is coated with alundum cement and dried at about 250°C. The portion that the circular cross section changes to the triangular is made a curved surface in order to avoid a sudden change of the cross section. The section at the

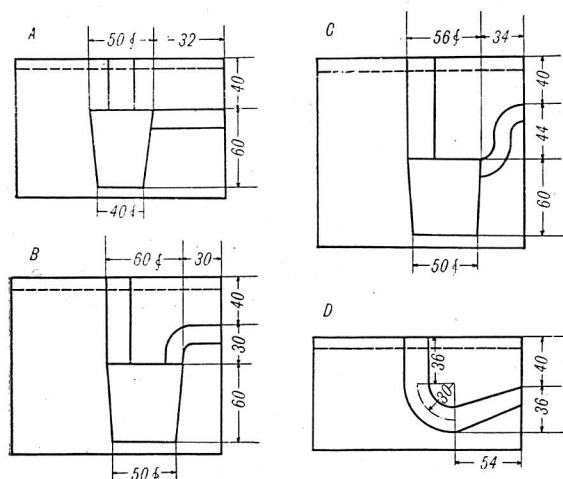


Fig. 2.

Various Types of Down Gate and Runner used for Preliminary Test.

end of the runner is an inverted equilateral triangle, a side of which is 15 mm. J, the same hole as H bored in the side of this mould is used for inserting the mercury thermometer. The end surface of this mould against A is finely machined and these are fastened to each other with four bolts. The sand mould is mounted on this mould and bonded by pieces and screws G shown in Fig. 1. An asbestos plate, whose thickness is about 2 mm, is inserted

between these moulds in order to prevent the former from the fall of temperature.

After assembling these three parts the apparatus is equipped with levelling screws E and F as shown in Fig. 1 and is placed in a horizontal position.

The electric furnace as shown in Fig. 3 is used for heating and drying the mould of the measuring canal. This furnace is constructed with the steel pipe, 12.9 cm inner diameter, 5.5 mm thick and 190 cm long, partitioned longitudinally in two parts. Each half part of the pipe is equipped with three nichrome wires on its outer side, settled in the iron plate box and insulated

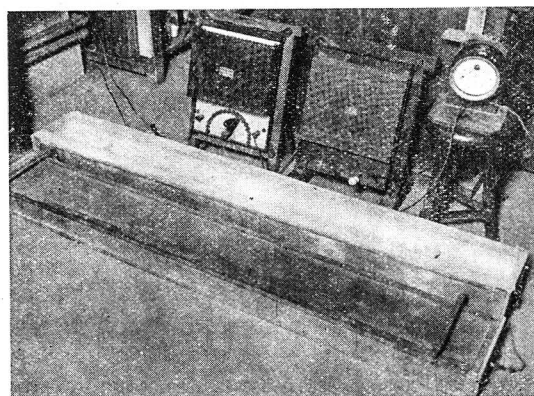


Fig. 3.

A Photograph of the Furnace for Drying Test Mould.

with kieselguhr. The joining surfaces of these parts are coated with cement. The lower part of this furnace is fixed and the upper part is put on and off by hand by two operators.

The Melting Method:—The cylindrical electric resistance furnace wound with nichrome wire, 14.7 cm inner diameter and 30 cm high, is used for melting. The materials are charged in the flat bottom pot made of steel plate, 11 cm inner diameter and 14.5 cm high, and this pot is heated in the furnace.

Two melting methods are used in this investigation. The method used in case of pure magnesium and its binary alloys is as follows: when the steel pot is heated to nearly a dull red, the flux, about 250 to 300 gram, is charged in it. After the flux is fused in a very fluid state, a piece of magnesium ingot which is cut down to about 2 cm thick is horizontally placed in the bottom. As the magnesium melts, the molten metal rises up passing through the flux layer and its surface is covered with very thin film of flux. When the magnesium is charged, a small quantity of flux finely powdered and dried is sprinkled on the place where the flux film on the bath is torn in order to prevent its melting from contact with

the air. Almost 1.4 kilogram magnesium can be melted. Then, the molten bath is very slowly stirred carefully with an iron rod whose diameter is 5 mm making sure that the bottom flux does not be mixed in the metal. Then for a little while it is allowed settle down in the furnace, and the thermocouple is gently immersed. When the bath reaches 850°C, maximum heating temperature which is generally adopted in practice, the current supply to furnace is cut off. The author noticed that the higher the maximum heating temperature of the melt is, the better the running quality of magnesium and its alloys is; and this fact has been noticed also by Piwowarsky and his co-operators. But the author made no further investigation of that phenomenon, as the purpose of this study is to find relations between the running quality and the superheating temperature, whose definition is mentioned afterwards.

In case of alloy additions, pieces of the alloying materials are immersed into the molten bath, supporting it with the tongs so that it will not sink down to the bottom before the pieces are totally dissolved into magnesium. The temperature of the molten bath before an alloy addition is about 750°C. In an hour after the addition the temperature rises to 850°C, and then settles to constant.

In the case of industrial alloys, Elektron D is melted in the same way as magnesium, but Elektron A, B and C are melted in the following manner: when the pot placed in the furnace is heated to dull red, the oxide scales and dirty matters on it are sufficiently removed; and then a small quantity of flux is charged. When the flux become a viscous fluid, two or three pieces of Elektron are charged and a little flux is sprinkled on them. As the temperature rises, the Elektron melts and the level of the molten bath rises up, always covering with the viscous film of the flux. About 1.5 to 1.6 kg of Elektron is melted at a time. When all charges melt down, the temperature of the bath is almost about 730° to 750°C. Then the bath is stirred up and down with an about 9 mm round steel rod whose one end is flattened and the flux is continually sprinkled on the molten surface during the stirring. This refining process has some variations according to the manufacturers.

In case of A and B, the adhesive matters are scraped off from the wall of the pot and the molten bath is stirred up and down for about ten minutes, with an about 6 mm round steel rod to whose one end the 4 cm × 3 cm × 2 mm steel plate is fitted.

In case of C, the bath is vortically stirred only three times for about 30 sec. altering the direction of a vortical motion at each time. When it is observed that the bath is sufficiently refined

its surface is covered with a little flux afresh, and the pot and the furnace are both covered up and heated up to the maximum temperature.

The molten bath of A and B is held in the furnace at the maximum temperature for about 25 min. and then the current supply is cut off. In case of C, the current is cut off as soon as the bath reached the maximum temperature.

The maximum heating temperature of A, B, C and D is 900°, 900°, 850° and 800°C respectively.

The melting temperature is measured in the crucible by the alumel-chromel thermocouple. The couple is 0.6 mm diameter and inserted into an iron tube whose one end is closed. This tube is immersed in the molten metal.

The Temperature of the Moulds:—The temperature of the moulds is 70°C and measured by the mercury thermometers as above-mentioned. This temperature is higher than the room temperature and relatively easy to be controlled uniformly.

The Pouring Temperature:—As it is plain that the running quality increases with lowering of the liquidus temperature at the constant pouring temperature, it is meaningless to compare the running qualities at the constant pouring temperature. The author chooses the pouring temperature to be the constant difference between the pouring temperature and the liquidus temperature and call this difference "superheating temperature."

The standard superheating temperature is 10°, 50° and 85°C in case of magnesium, 10°, 50° and 90°C in case of the addition of aluminium and 50°C in case of the addition of the other alloying elements. These temperatures are determined from the binary equilibrium diagrams as shown in Fig. 4, 5, 6 and 7 at the time of the experiment and the correct superheating temperatures are determined for the liquidus corresponding to the compositions obtained by the chemical analysis after the experiment.

In case of Elektrons, pouring temperatures are 680°, 720°, and 760°C. After the experiment the test piece, 13 mm × 13 mm × 20 mm, is taken from the bottom center of the block solidified in the sand reservoir, placed in the Tamman tube, covered with the flux melted in the furnace and is subjected to the differential thermal analysis, utilizing the Saladin's apparatus. The flux is prepared with 24.3% potassium bichromate, 72.7% sodium bichromate and 3% potassium chromate. The differential couple is alumel-chromel and the temperature of the melt is specially measured by Pt-Pt-Rh couple. The Results of thermal analysis are shown in Fig. 8. The liquidus temperatures of A, B, C and D are 631°, 630°, 620° and 602°C respectively. The superheating temperatures are determined from these temperatures.

The pouring temperature is measured by im-

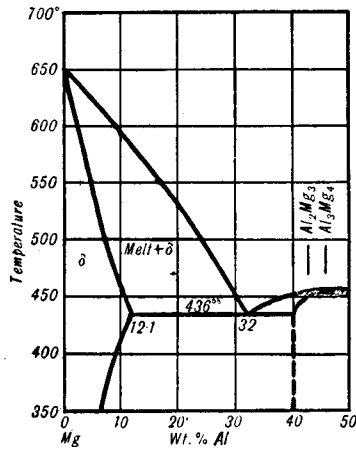


Fig. 4.

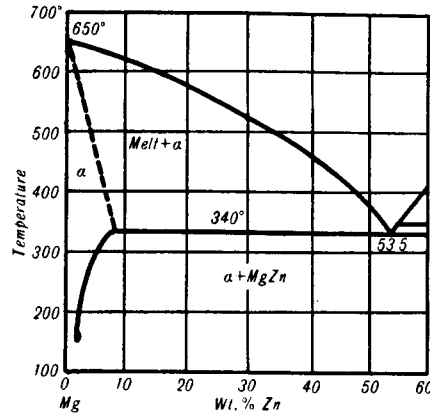


Fig. 5.

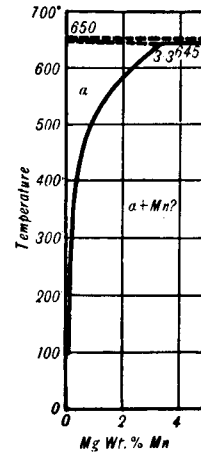


Fig. 6.

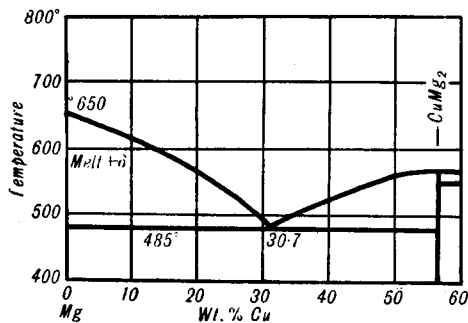


Fig. 7.

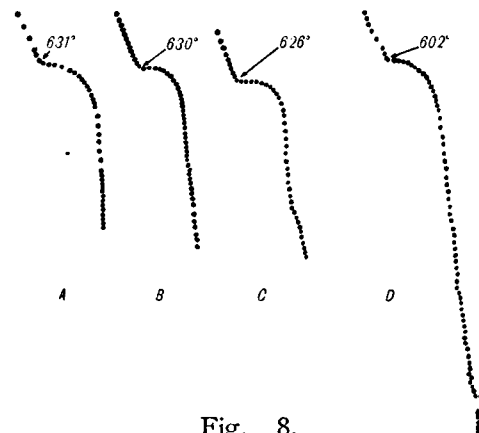


Fig. 8.

Cooling Curves for Elektron A, B, C and D obtained by Differential Thermal Analysis.

mersion of the same couple as used for measuring the melting temperature in the molten metal of the sand reservoir, as it is thought that the temperature of the metal in the crucible is relatively much different from the temperature of the metal flowing in the canal and this difference is irregular according to conditions.

The direct measurement of the temperature of the metal flowing in the measuring canal is practically very difficult. According to the author's preliminary experiment with an oscillograph, the time required for the molten metal to enter the measuring canal and solidify perfectly is, in most cases, within about a half second. Therefore, it is very difficult to fix the deflection of the galvanometer needle and impossible to read the correct temperature in such a short time by the direct method. This time-lag between the removal of the stopper and the flowing of the metal into the canal can not be completely avoided by the author's method, but the more correct temperature may be read.

The Experimental Procedure:—First, the mould of down gate heated is taken out from the drying furnace and when its temperature became about

100°C, the mould of the measuring canal is taken out. During about 130° to 120°C of the latter, these moulds are assembled. This assemblage is placed on the stands; and the screws are so adjusted as to make the whole level. The sand mould heated to 250°C is then taken out from the furnace and fitted on the down gate, the level being carefully controlled. Then the steel tube with the thermocouple is quietly lead out from the molten metal in the pot so as not to agitate the flux film on the bath, and immediately fixed to the support so as to bring its closed end to the given position in the sand reservoir. The stopper heated at about 500° to 600°C in the other furnace is fitted on the sand mould just before pouring.

During these operations the temperature of each part of the mould descends uniformly to about 70°C. If necessary, cold metallic pieces are used for controlling the temperature of the mould.

When everything is ready, the pot containing the molten metal of the maximum heating temperature is taken out from the furnace and the molten metal is poured into the sand reservoir till it is filled up. Sulphur flower is sprinkled on the surface of the bath and the stream line from the

cloth bag. As soon as the metal in the reservoir reaches the given temperature, the stopper is removed as quietly and rapidly as possible and the molten metal is poured into the measuring canal.

In order to keep the constant pouring condition, the same operator did casting.

Fig. 9 shows the general arrangement and Fig. 10 shows the test casting after removing the upper cover of the measuring canal.

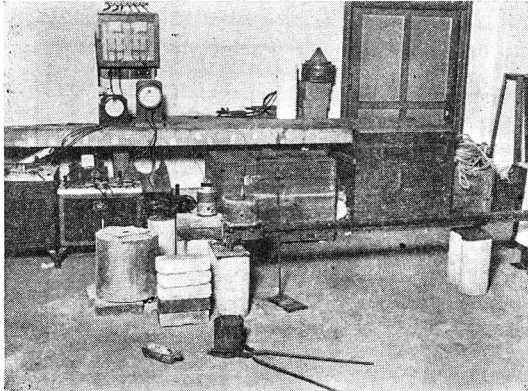


Fig. 9.

A Photograph Showing the General Arrangement for Determining the Running Quality of Molten Magnesium and Its Alloys.

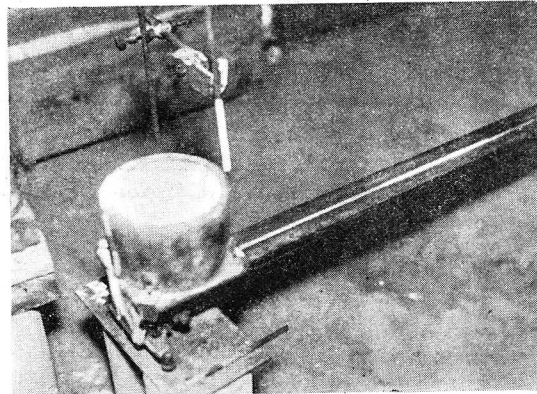


Fig. 10.

A Photograph Showing the Test Casting after Removing the Upper Cover of the Measuring Mould.

Results of Investigation.

A. Pure Magnesium.

The relation between the running quality of pure magnesium and the superheating temperature is shown in Table 3 and Fig. 11.

Table 3.

Results of Running Quality Measurement of Pure Magnesium at Various Pouring Temperatures.

| No. of Experiment | Temperature of Mould °C | | | Pouring Temperature °C | Superheating Temperature, i. e. Temperature Difference between Melting Point of Metal and Pouring Temperature °C | Length of Flow cm | |
|-------------------|-------------------------|-----------------|--------|------------------------|--|-------------------|------|
| | Down Gate | Measuring Canal | | | | | |
| | | Entrance | Center | | | | Mean |
| 1 | 72 | 65 | 64 | 64.5 | 655 | 5 | 18 |
| 2 | 68 | 71 | 69 | 70.0 | 655 | 5 | 21.3 |
| 3 | 72 | 68 | 68 | 68 | 668 | 18 | 26.0 |
| 4 | 72 | 69 | 71 | 70 | 685 | 35 | 29.7 |
| 5 | 70 | 68 | 72 | 70 | 695 | 45 | 32.7 |
| 6 | 65 | 64 | 63 | 63.5 | 700 | 50 | 36.2 |
| 7 | 70 | 71 | 69 | 70 | 700 | 50 | 34.0 |
| 8 | 67 | 65 | 62 | 63.5 | 700 | 50 | 36.0 |
| 9 | 70 | 64 | 65 | 64.5 | 730 | 80 | 41.8 |
| 10 | 68 | 65 | 65 | 65 | 730 | 80 | 40.1 |
| 11 | 70 | 71 | 71 | 71 | 735 | 85 | 40.5 |
| 12 | 68 | 65 | 65 | 65 | 735 | 85 | 43.1 |
| 13 | 67 | 65 | 65 | 65 | 735 | 85 | 38.9 |

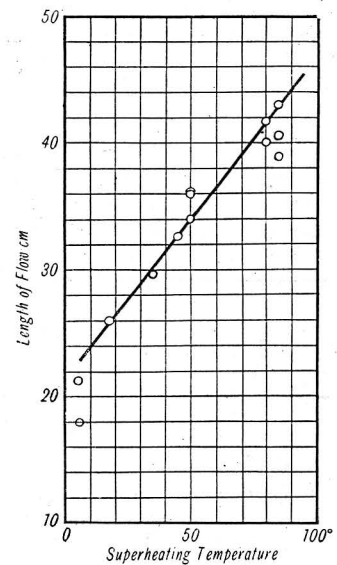


Fig. 11.

Relation between the Running Quality of Pure Magnesium and the Superheating Temperature, i. e. Temperature Difference between the Melting Point of Metal and the Pouring Temperature.

There is some discrepancy in the temperatures of the moulds despite the author's endeavour for maintaining them uniform all over the moulds; but it may be thought that this is so trivial that it has no great influence on the results because of the relatively great difference between the tem-

perature of the moulds and the melting point of magnesium. The accuracy of these measurements is 3-5% on an average.

The length of flow at the pouring temperature 700°C, namely the superheating temperature 50°C, is about 34 cm and far longer than the P. Bastien's

value. It appears to the author that this difference is caused by the experimental apparatus and procedure.

B. Influence of Aluminium.

5, 10, 32 and 42.5% aluminium were added.

The sample for the chemical analysis was taken from the alloy solidified in the sand reservoir after each experiment and Al, Fe and Si were determined. Results are shown in Table 4 and 5 and Fig. 12.

Table 4.
Chemical Composition of Magnesium Alloys with Aluminium.

| Al % added | No. of Experiment | Fe | Si | Al | Mg |
|------------|-------------------|------|------|-------|-------|
| 5 | 1 | 0.02 | 0.01 | 4.97 | 95.00 |
| | 2 | 0.04 | 0.01 | 4.94 | 95.10 |
| | 3 | 0.04 | 0.02 | 5.03 | 94.91 |
| | 4 | 0.04 | 0.04 | 5.14 | 94.78 |
| | 5 | 0.03 | 0.04 | 5.40 | 94.53 |
| | 6 | 0.04 | 0.03 | 5.40 | 94.53 |
| | 7 | 0.04 | 0.04 | 5.17 | 94.75 |
| | 8 | 0.08 | 0.03 | 4.85 | 95.04 |
| 10 | 1 | 0.06 | 0.02 | 9.92 | 90.00 |
| | 2 | 0.07 | 0.03 | 10.00 | 89.90 |
| | 3 | 0.07 | 0.03 | 9.92 | 89.98 |
| | 4 | 0.06 | 0.03 | 8.85 | 90.06 |
| | 5 | 0.05 | 0.03 | 10.07 | 89.85 |
| | 6 | 0.08 | 0.02 | 9.90 | 90.00 |
| | 7 | 0.06 | 0.02 | 10.03 | 89.89 |
| | 8 | 0.06 | 0.04 | 9.80 | 90.10 |
| 32 | 1 | | | 30.1 | |
| | 2 | | | 30.1 | |
| | 3 | | | 29.7 | |
| 42 | 4 | | | 40.7 | |

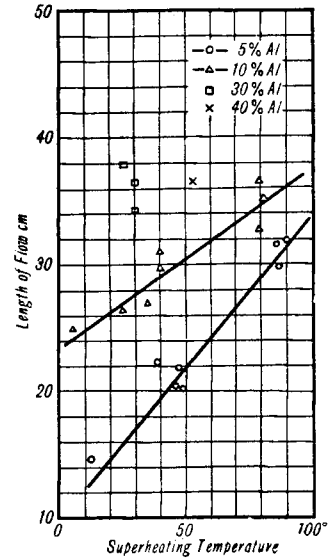


Fig. 12.

Relations between the Running Quality of the Magnesium Alloys containing 5%, 10%, 30% and 40% Aluminium and the Superheating Temperature, i. e. Temperature Difference between the Pouring Temperature and the Liquidus Temperature taken from Binary Equilibrium Diagram.

Table 5.
Results of Running Quality Measurement of Magnesium Alloys with Aluminium.

| Al % added | No. of Experiment | Temperature of Mould °C | | | | Pouring Temperature °C | Liquidus Temp. determined from Equilibrium diagram °C | Superheating Temperature, i. e. Temperature Difference between Liquidus Temperature and Pouring Temperature °C | Length of Flow cm |
|------------|-------------------|-------------------------|-----------------|--------|------|------------------------|---|--|-------------------|
| | | Down Gate | Measuring Canal | | | | | | |
| | | | Entrance | Center | Mean | | | | |
| 5 | 7 | 69 | 70 | 70 | 70 | 635 | 623 | 12 | 14.7 |
| | 5 | 64 | 66 | 65 | 65.5 | 660 | 621 | 39 | 22.3 |
| | 2 | 65 | 70 | 70 | 70 | 670 | 624 | 46 | 18.4 |
| | 4 | 67 | 67 | 69 | 68 | 670 | 623 | 47 | 19.9 |
| | 6 | 65 | 65 | 67 | 66 | 670 | 621 | 49 | 18.2 |
| | 1 | 68 | 67 | 70 | 68.5 | 710 | 624 | 86 | 29.8 |
| | 3 | 67 | 67 | 68 | 67.5 | 710 | 624 | 86 | 31.6 |
| | 8 | 65 | 65 | 64 | 64.5 | 715 | 625 | 90 | 31.8 |
| 10 | 1 | 66 | 67 | 67 | 67 | 600 | 595 | 5 | 25 |
| | 2 | 60 | 60 | 60 | 60 | 620 | 595 | 25 | 26.4 |
| | 5 | 69 | 65 | 65 | 65 | 630 | 594 | 35 | 27.1 |
| | 3 | 65 | 62 | 64 | 63 | 635 | 595 | 40 | 29.7 |
| | 4 | 69 | 69 | 70 | 70 | 635 | 595 | 40 | 30.1 |
| | 6 | 63 | 61 | 65 | 63 | 675 | 596 | 79 | 32.7 |
| | 7 | 60 | 61 | 64 | 63 | 675 | 594 | 81 | 35.2 |
| | 8 | 55 | 59 | 58 | 59 | 675 | 596 | 79 | 36.5 |
| 32 | 1 | 69 | 55 | 55 | 55 | 481 | 451 | 30 | 36.5 |
| | 2 | 73 | 64 | 64 | 64 | 481 | 451 | 30 | 34.3 |
| | 3 | 73 | 63 | 58 | 60.5 | 481 | 456 | 26 | 37.9 |
| 42 | 4 | 63 | 54 | 52 | 53 | 505 | 452 | 53 | 36.5 |

The liquidus temperatures determined from the equilibrium diagram and the superheating temperatures are also shown in Table 5. Though alloys with the high aluminium content were prepared as to contain 32% and 42% Al corresponding to a eutectic composition and an intermetallic compound respectively, the appointed compositions could not be got as shown in the table. These experiments were not made in detail as the purpose for them was to find approximately the general tendency. The length of flow—the superheating temperature relation appears the straight line. The running

quality of 5% Al alloy is less than that of 10% Al alloy and the slope of the relation curve of the former is steeper than the latter. Alloys with high aluminium content have a superior running quality to the others.

C. Influence of Zinc.

1, 2 and 3% zinc were added. Zinc up to 2% gradually decreases the running quality of pure magnesium, but no further decrease is observable between 2% and 3%, as shown in Table 6 and Fig. 13.

Table 6.

Results of Running Quality Measurement of Magnesium Alloys with Zn, Mn and Cu.

| Alloying Element | No. of Experiment | Alloying (by Analysis) % | Temperature of Mould °C | | | | Pouring Temperature °C | Liquidus Temp. determined from Equilibrium diagram °C | Superheating Temperature, i. e. Temperature Difference between Liquidus and Pouring Temperature °C | Length of Flow cm |
|------------------|-------------------|--------------------------|-------------------------|-----------------|--------|------|------------------------|---|--|-------------------|
| | | | Down Gate | Measuring Canal | | | | | | |
| | | | | Entrance | Center | Mean | | | | |
| Zn | 1 | 0.92 | 69 | 69 | 70 | 69.5 | 700 | 648 | 52 | 29.1 |
| | 2 | 1.00 | 70 | 72 | 73 | 72.5 | 710 | 648 | 62 | 29.5 |
| | 3 | 1.87 | 65 | 71 | 72 | 71.5 | 690 | 646 | 44 | 26.3 |
| | 4 | 1.97 | 67 | 60 | 60 | 60 | 692 | 646 | 46 | 25.2 |
| | 5 | 2.04 | 65 | 55 | 55 | 55 | 690 | 645 | 45 | 26.2 |
| | 6 | 2.10 | 65 | 64 | 64 | 64 | 690 | 645 | 45 | 26.5 |
| | 7 | 3.20 | 65 | 67 | 65 | 66 | 695 | 641 | 54 | 27.0 |
| | 8 | 3.18 | 69 | 68 | 67 | 67.5 | 687 | 641 | 46 | 26.5 |
| | 9 | 3.14 | 71 | 66 | 65 | 65.5 | 686 | 642 | 44 | 27.3 |
| | 10 | 3.28 | 70 | 69 | 68 | 68.5 | 687 | 641 | 46 | 24.0 |
| | 11 | 3.12 | 72 | 65 | 65 | 65 | 687 | 642 | 45 | 25.5 |
| Mn | 1 | 0.48 | 65 | 60 | 60 | 60 | 705 | 650 | 55 | 34.0 |
| | 2 | 0.49 | 70 | 67 | 67 | 67 | 697 | 650 | 47 | 34.9 |
| | 3 | 0.45 | 65 | 67 | 67 | 67 | 688 | 650 | 38 | 30.6 |
| Cu | 1 | 0.50 | 65 | 62 | 63 | 62.5 | 698 | 648 | 50 | 32.5 |
| | 2 | 0.48 | 68 | 68 | 67 | 67.5 | 700 | 649 | 51 | 28 |
| | 3 | 0.51 | 68 | 65 | 65 | 65 | 698 | 648 | 50 | 31.6 |
| | 4 | 0.99 | 67 | 65 | 66 | 65.5 | 697 | 646 | 51 | 24.2 |
| | 5 | 1.01 | 65 | 60 | 60 | 60 | 697 | 646 | 51 | 23.6 |
| | 6 | 0.98 | 67 | 60 | 59 | 59.5 | 697 | 646 | 51 | 26.0 |

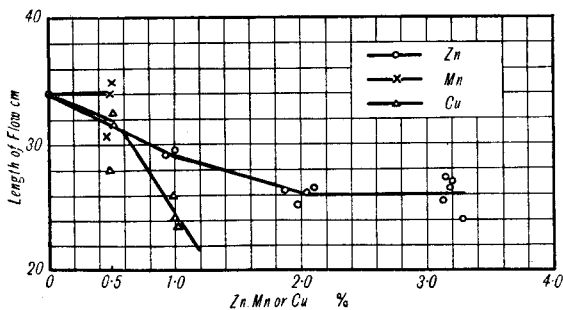


Fig. 13.

Influence of Zinc, Manganese or Copper Content on the Running Quality of Magnesium.

D. Influence of Manganese.

Only 0.5% manganese was added. Such a

small amount of manganese added to the industrial magnesium alloy has no influence, as shown in Table 6 and Fig. 13. The pouring temperature of experiment No. 3 is lowered because of the unexpected accident and therefore its superheating temperature is 38°C. The running quality of No. 3, 30.6 cm, is only 0.9 cm longer than that of pure magnesium at the same superheating temperature determined from Fig. 11.

E. Influence of Copper.

0.5 and 1.0% copper were added. An addition of copper up to 0.5% gradually decreases the running quality of pure magnesium, but 1% copper suddenly decreases it. These results are shown in Table 6 and Fig. 13.

F. Industrial Magnesium Alloys.

Results are shown in Table 7 and Fig. 14. Relations between the superheating temperatures

and the running qualities of Elektron A, B, C and D are summarized in Fig. 15. All of these relations are straight lines having almost equal slope.

Table 7.
Results of Running Quality Measurement of Elektron A, B, C and D.

| Elektron | No. of Experiment | Temperature of Mould °C | | | Pouring Temperature °C | Superheating Temperature, i. e. Temperature Difference between Liquidus ⁽¹⁾ and Pouring Temperature °C | Length of Flow cm | |
|----------|-------------------|-------------------------|-----------------|--------|------------------------|---|-------------------|------|
| | | Down Gate | Measuring Canal | | | | | |
| | | | Entrance | Center | | | | Mean |
| A | 21 | 71 | 70 | 71 | 70.5 | 664 | 33 | 20.8 |
| | 23 | 68 | 70 | 70 | 70 | 664 | 33 | 21.8 |
| | 9 | 68 | 70 | 70 | 70 | 670 | 39 | 21.4 |
| | 4 | 70 | 70 | 70 | 70 | 674 | 43 | 23.4 |
| | 12 | 72 | 70 | 70 | 70 | 704 | 73 | 28 |
| | 15 | 67 | 69 | 70 | 69.5 | 704 | 73 | 26.8 |
| | 22 | 67 | 68 | 69 | 68.5 | 708 | 77 | 30.6 |
| | 17 | 68 | 70 | 71 | 70.5 | 751 | 120 | 34 |
| | 18 | 70 | 70 | 70 | 70 | 751 | 120 | 34.5 |
| | 19 | 66 | 68 | 68 | 68 | 751 | 120 | 32 |
| 24 | 70 | 70 | 70 | 70 | 761 | 130 | 33.5 | |
| B | 1 | 66 | 70 | 70 | 70 | 680 | 50 | 20 |
| | 2 | 68 | 69 | 70 | 69.5 | 680 | 50 | 19.2 |
| | 4 | 70 | 68 | 69 | 68.5 | 680 | 50 | 21.9 |
| | 5 | 70 | 69 | 68 | 68.5 | 680 | 50 | 20.1 |
| | 8 | 66 | 68 | 66 | 67 | 705 | 75 | 22.8 |
| | 10 | 68 | 67 | 67 | 67 | 710 | 80 | 27.9 |
| | 6 | 70 | 68 | 68 | 68 | 720 | 90 | 25.0 |
| | 9 | 67 | 69 | 69 | 69 | 720 | 90 | 25.4 |
| | 7 | 70 | 68 | 70 | 69 | 724 | 94 | 26.0 |
| | 11 | 70 | 70 | 70 | 70 | 745 | 115 | 34.4 |
| | 12 | 70 | 70 | 69 | 69.5 | 765 | 135 | 35.7 |
| | C | 14 | 70 | 70 | 70 | 70 | 644 | 18 |
| 15 | | 70 | 67 | 67 | 67 | 680 | 54 | 26.7 |
| 16 | | 70 | 70 | 70 | 70 | 680 | 54 | 26.0 |
| 2 | | 72 | 69 | 70 | 69.5 | 720 | 94 | 33.7 |
| 5 | | 71 | 71 | 70 | 70 | 720 | 94 | 33.7 |
| 11 | | 70 | 70 | 70 | 70 | 720 | 94 | 32.4 |
| 12 | | 70 | 70 | 70 | 70 | 720 | 94 | 30.9 |
| 1 | | 75 | 66 | 67 | 66.5 | 770 | 144 | 39.9 |
| 9 | | 69 | 69 | 69 | 69 | 770 | 144 | 40.1 |
| 10 | | 70 | 68 | 68 | 68 | 770 | 144 | 39.9 |
| D | 1 | 69 | 70 | 68 | 69 | 680 | 78 | 35.1 |
| | 2 | 69 | 70 | 69 | 69.5 | 680 | 78 | 35.1 |
| | 3 | 70 | 69 | 68 | 68.5 | 680 | 78 | 36.9 |
| | 4 | 68 | 70 | 70 | 70 | 680 | 78 | 37.8 |
| | 8 | 67 | 70 | 70 | 70 | 680 | 78 | 36.9 |
| | 9 | 69 | 71 | 69 | 70 | 680 | 78 | 35.7 |
| | 12 | 72 | 70 | 70 | 70 | 680 | 78 | 36 |
| | 5 | 72 | 70 | 69 | 69.5 | 720 | 118 | 42.0 |
| | 6 | 69 | 71 | 69 | 70 | 720 | 118 | 42.0 |
| | 7 | 69 | 70 | 69 | 69.5 | 720 | 118 | 41.9 |
| | 10 | 68 | 70 | 70 | 70 | 735 | 133 | 43.4 |
| 11 | 69 | 69 | 69 | 69 | 735 | 133 | 44.0 | |

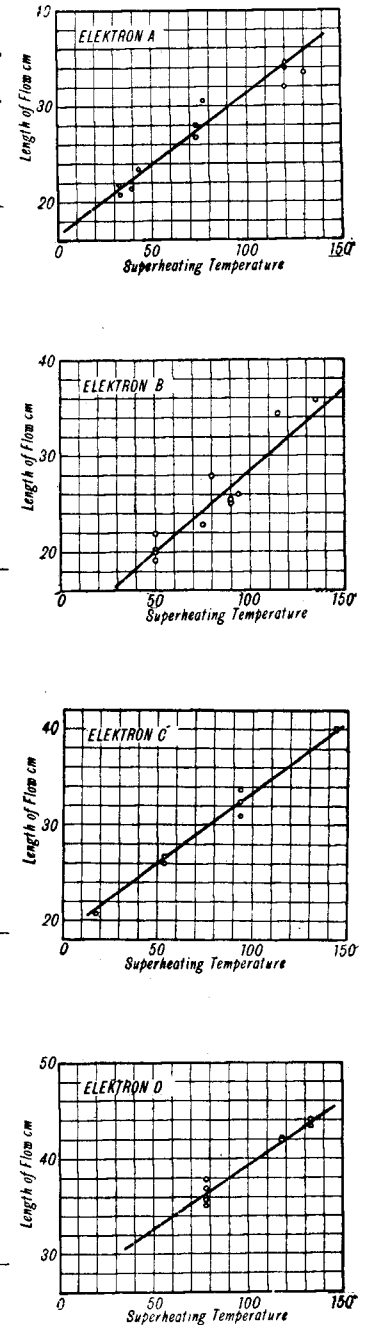


Fig. 14.

Length of Flow - Superheating Temperature Diagrams for Elektrons A, B, C and D. The Superheating Temperature is defined as the Temperature Difference between the Pouring Temperature and the Liquidus Temperature of these Magnesium Alloys determined by Differential Thermal Analysis.

(1) Liquidus temperatures were determined by thermal analysis.

The running quality at the same superheating temperature is the best at D, followed by C, A and B respectively. Fig. 16 represents some running quality test castings of Elektron D.

G. Consideration of Experimental Results.

Fig. 17 represents the relations between the aluminium content of magnesium and its running quality at the superheating temperatures 20°, 50° and 90°C. Comparing these results with those of Portvin, Bastien and others, it is remarked that the running quality values of pure magnesium obtained by the author are considerably better

than theirs; and that the running quality of pure magnesium decreases by an addition of 5% Al and increases by 10% addition, but is less than pure magnesium. It should be possible that the running quality of magnesium decreases with an addition of aluminium according to the theoretical consideration that the running quality of an alloy decreases with the increase of its solidification range. As the temperature of the mould is about 70°C and therefore the cooling velocity of alloy is very high in the author's investigation, we may conclude that the crystal segregation occurs because of the super cooling. Therefore, it may be

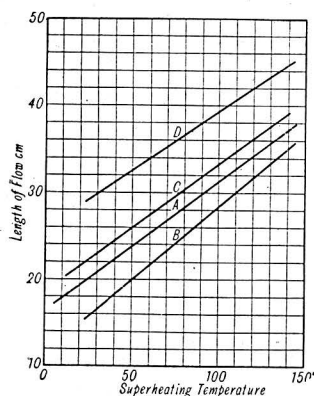


Fig. 15.
Composite of Superheating Temperature-Length of Flow Diagrams for Elektrons A, B, C and D.

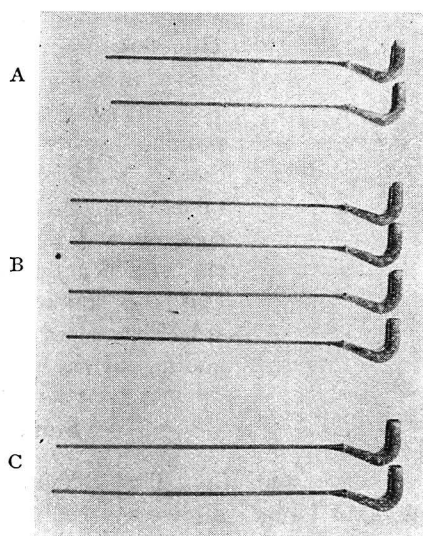


Fig. 16.
Representative "Running Quality" Test Castings of Elektron D. Pouring Temperature: (A) 680°, (B) 720°, (C) 735°.

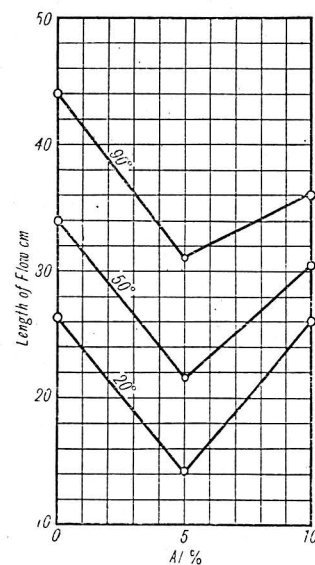


Fig. 17.
Influence of Aluminium 10% on the Running Quality of Magnesium, when the Superheating Temperature, i. e. Temperature Difference between the Pouring Temperature and the Liquidus Temperature determined by Binary Equilibrium Diagram, is 20°, 50° and 90°.

supposed that in case of the alloy of the unsaturated solid solution, the molten metal begins to solidify on the inner surface of the measuring canal and forms a pipe. A composition of the alloy near the pipe approaches to the saturated solution from the original composition. A structural photomicrograph of a cross section polished and etched by a 0.5% HNO₃-alcoholic solution of an alloy solidified in the canal is given in Fig. 18, which shows the existence of a eutectic structure by 5% Al. Therefore it may be thought that the solidus line in the equilibrium diagram migrates to the aluminium side, and the running quality of the alloy decreases at the neighbourhood of 5% Al and increases at 10% Al because of the formation of more eutectic mixture than at 5%.

The fact that the running quality of the alloys containing about 30% Al is better than that of

pure magnesium is due, perhaps, to the fact that the temperature difference between liquidus and the mould is about 67% of that between the melting point of magnesium and the mould. Therefore the heat absorbed by the mould in unit time at the former is less than the latter, although inherent physical properties of a eutectic alloy, for example the form of crystal, governed them. The same fact may be supposed also in case of 40% Al. The decrease of the running quality with the increase of the solidification range is noticed also in case of the zinc addition; but the fact observed by L. Losana⁽³⁾ that zinc is more effective to magnesium than aluminium was not observed. It is supposed that the cessation of the decrease of the running quality at the relatively low zinc content resulted from inherent properties of zinc.

Alloys containing 0.5% Mn appear nearly

similar to pure magnesium, for its solidification range is very narrow and the variation of its thermal properties is so little.

It is supposed that the effect of a copper addition on one side resulted from the greater thermal conductivity and the lower specific heat as compared with pure magnesium; and on the other side from little solubility of copper in magnesium and greater range of the co-existence of liquid and magnesium solid solution with approach to pure magnesium.

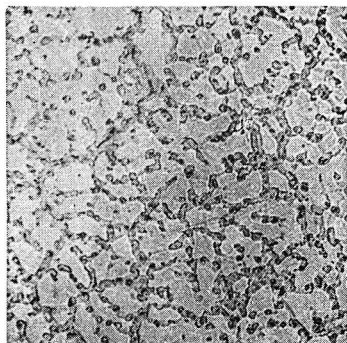


Fig. 18.

Microscopic Structure of Cross Section of A Middle Part of Test Casting of Magnesium with 5% of Al.

So it may be said that the running quality of the binary alloy of magnesium and an element, whose solid solubility in magnesium is little and which itself or whose intermetallic compound forms a eutectic alloy with magnesium, at first suddenly decreases and then increases towards the eutectic composition with addition of an alloying element. The fact observed by Bastien and others that the running quality of magnesium increases successively with the addition of copper may be caused by their very smaller value of the running quality of magnesium and the constant pouring temperature.

The influence of the various kinds of the flux and the various ways of melting on the running quality of Elektron is unavoidable, but it will be not so very important, if the refining can be satisfactorily operated.

Assuming that each result of investigations for influences of the simple addition of an alloying element on magnesium may be individually applied to industrial magnesium alloys, the following consideration may be allowed. At the zinc contents of Elektron A, B and C as shown in Table I their running quality are almost equal as shown in Fig. 13. To their contents of copper, the running quality of magnesium relatively decreases, but their mutual differences are not very noticeable. Manganese contents are about similar to each other. But aluminium contents of Elektron A, B, C and D are 3.57, 3.95, 4.69 and 9.95% respectively and even

if the difference of aluminium is relatively low, considerable differences of the running quality develop as shown in Fig. 17. The phenomenon that the running quality of Elektron D is far better than the others shows the same relation as above mentioned for the influence of a simple addition.

The relation between the running quality and the composition of the many-component alloys should not be explained only by the relation as in case of the simple addition of each alloying element, but it may be thought that as each element above mentioned is dissolved in the solid magnesium within the limited addition to Elektron and the aluminium content is far more than the others, aluminium is the most important element. Therefore it may be estimated that the relation above mentioned for the binary alloy is possible also in case of the many-component alloy; the running quality of the many-component alloy decreases with the increase of the solidification range, takes the minimum value at a saturated solid solution and then increases with the reduction of the solidification range. But it may be considered that the solidus line migrates to the magnesium side because of the crystal segregation from supercooling of the alloy in the mould.

Summary and Conclusion.

The running quality of molten metals and alloys has been defined as the property indicated by an ability to flow into the mould and perfectly fill up its inner part.

A new apparatus for measuring the running quality has been designed. This apparatus consists of three parts; a metallic mould having a straight measuring canal about 150 cm long whose cross section is an inverted equilateral triangle a side of which is 7 mm, a sand mould of an inverted circular cone type which acts as a reservoir for the molten metal and a metallic mould having a downgate and a runner which leads to the measuring canal and acting as a part connecting the sand mould reservoir and the measuring canal.

To equalize the statical head of the molten metal charge throughout the test, a stopper is used in the sand mould. After filling the sand mould with the charge, this is removed and the charge is poured into the test mould. Assuming that the metal completely fills the measuring canal, the height difference in the reservoir is only about 2 mm. The measuring canal is made by assembling two steel angles and one flat steel, and are coated with very fine alundum cement on their inner surfaces to prevent the metal from flowing in spherical drops because of extreme smoothness of the inner surfaces. The temperature of the mould is

measured by inserting mercury thermometers into holes in the moulds, which are maintained at 70°C. The pouring temperature is measured by an alumel-chromel thermocouple placed in the steel protecting tube.

The length of metallic flow solidified in the measuring canal is taken as a measure of the running quality.

By using this apparatus, the running quality of pure magnesium and the influence of a limited content of aluminium, zinc, manganese or copper on magnesium, and also the running quality of four kinds of industrial magnesium alloy, Elektron are studied.

The results obtained are as follows:

The running quality of pure magnesium decreases by an addition of 5% aluminium, but increases by 10% addition. The increasing effect of 30% aluminium is very marked. Zinc up to 2% gradually decreases the running quality of pure magnesium, but no further decrease is observable between 2% and 3%. A small amount of manganese within the extent added to the industrial magnesium alloy has no influence. An addition of copper up to 0.5% gradually decreases the running quality of pure magnesium, but 1% copper suddenly decreases it. These phenomena should be attributed to many factors, such as casting conditions and inherent properties of alloying elements and others, but should be explained by the solidification theory and the equilibrium diagram as follows: the running quality of magnesium gradually decreases as an alloying element dissolves in magnesium and consequently the solidification range increases, showing a minimum value at the composition of a saturated solid solution and then gradually increases as the solidification range decreases, showing a maximum value at a composition corresponding to a eutectic, an intermetallic compound or others which have a constant temperature of solidification as does a pure metal, but as the equilibrium condition practically does not exist, the effect of supercooling and crystal segregation should

be taken into account in considering the experimental results.

The measurements of running qualities of industrial magnesium alloys, three about 4% Al alloys and one about 10% Al alloy, were performed under the practical condition and it is found that the influence of aluminium is far more important than the others. The author believes that the same relation as in case of binary alloys may be possible also in the many-component alloys.

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References.

- (1) A. Portevin & P. Bastien, *Comptes Rend.*, **194** (1932), 850.
- (2) P. Bastien, *Rev. Metallurg.*, **31** (1934), 270 & 324.
- (3) L. Losana, *Alluminio*, **1** (1932), 237; *Chem. Abstr.*, **27** (1933), 4510.
- (4) K. Achenbach, H. A. Nipper & E. Piwowarsky, *Die Giesserei*, **26** (1939), 597.
- (5) L. W. Eastwood & L. W. Kempf, *Trans. A. F. A.*, **47** (1939/40), 571.
- (6) D. Saito & K. Hayashi, *Memoirs of the College of Engineering, Kyoto Imperial University*, **2** (1918-22), 83.
- (7) W. Ruff, *The Iron & Steel Inst., Carnegie Scholarship Memoirs*, **25** (1936), 1.