An Investigation of the Running Quality of Aluminium and Its Alloys.

By

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Introduction.

The running quality of molten metals and alloys is one of the most necessary properties to produce the sound castings. This property is indicated by its ability to flow into a mould and perfectly fill up all its spaces. As it is influenced by various factors; the condition of the mould, the casting method, physical and chemical properties of molten metals and alloys, etc., it is very difficult to determine in a scientific manner. Hitherto many measuring methods of this property have been studied by various investigators, but their results do not agree.

The running quality of aluminium was first studied in our country by Dr. D. Saitō and Mr. K. Hayashi(1), using a spiral, dry sand mould having a small rectangular cross section. Following their studies, A. Portevin and P. Bastien(2), A. Courty(3), A. von Zeerleder and R. Irmann(4), and T. Morinaga(5) measured this property, using a spiral, metallic mould having a small trapezoidal cross section; and C. M. Seager, Jr. and A. I. Krynitsky(6), and Y. Sakuma(7), using a spiral sand mould. L. Losana's study(8) was also reported.

The purity of the aluminium used in those studies varied: e.g. 99.3% Al by Courty, 99.4% by Morinaga or 99.8% by Saeger. Saeger reported that the running quality of pure aluminium was better than that of commercial aluminium having a purity of 99.2%, but Losana found that 98.32% aluminium had a better running quality than that of 99.26%. Although these results do not agree, it seems true that the running quality of aluminium is influenced by its purity.

Also, the relations between the running quality and the casting temperature obtained by the investigators mentioned above are different from each other. Saitō and Hayashi observed that the running quality of aluminium increased with a rise of temperature up to 750°C and showed no change between 750° and 880°C, but the others found only a linear relation.

Generally it is believed in the foundry that it is desirable to keep the maximum heating temperature of molten aluminium and its alloys as low as possible. Saeger and Krynitsky melted a commercial aluminium in the gas furnace, then heated it to maximum temperatures of 750°, 790° and 840°C, respectively, and poured it into the spiral test sand mould. After their results, in case of the dry sand mould aluminium has the best running quality at the maximum heating temperature 750°C and the worst at 840°C, and in case of the green sand mould it has the best at 750°C and the worst at 790°C. In further experiments, they melted aluminium ingots, whose purity are 99.8% and 99.2%, in the high frequency electric furnace or the gas furnace, heated them up to the maximum temperature of 750° and 850°C, held them at those temperatures, slowly cooled and poured them into the green sand test mould, whose moisture content was six to seven per cent. According to those results, the running quality of aluminium at the maximum heating temperature of 750°C averages ten per cent better than that at 850°C when the pouring temperature is given.

The running qualities of aluminium alloys were also measured by many investigators; 8% Cu alloy by Saeger and Krynitsky; Al—Fe, Al—Cu, Al—Si, Al—Mg, Al—Zn, Al—Cu—Si, Al—Si—Mg, Al—Cu—Mg and Al—Cu—Zn alloys by Losana; binary aluminium alloys with copper, zinc, silicon or nickel, alpax, the influence of addition of cadmium, magnesium, nickel, copper, zinc or manganese on alpax and the influence of magnesium on Cu 13.2% alloy by Courty; Cu 8% alloy, Lautal, Silumin, Zn 25% alloy, German alloy and Y-alloy by Morinaga; influences of silicon on Anticorrodal, of antimony on Silumin and manganese and magnesium on Magnalium by Zeerleder and Irmann; Lautal, Y-alloy and Silumin by Sakuma; and the influence of magnesium on Silumin by S. Kondō(9). L. W. Eastwood and L. W. Kempf(10) studied the running quality of 3.75% Mg, 3.75% Mg + 1.9% Si or 0.5% Sn, 4.3% Cu, 10% Cu and 5% Si alloys, Al—Mg—Mn—Ni alloy and the influence of iron on the secondary aluminium, by using a spiral sand mould having a flat rectangular cross section. These studies, except Curry's, are concerned with the relations between the running quality of the particular alloy and the temperature of mould, casting or melting.

The author studied the influence of repetition of melting on the running quality of pure aluminium, the relation between this quality and the maximum heating temperature or the superheating temperature, i.e. the difference between the pouring temperature and the melting or liquidus temperature, and the influence on the running quality of aluminium, of copper, silicon, zinc, manganese, magnesium, nickel or iron, which is contained within the limits of industrial addition, by using apparatus recently designed by himself.

Materials used.

The purity of aluminium ingot used in this investigation is 99.55%, excepting in the cases where the influences of the maximum heating temperature and an addition of iron on the running quality of 99.73% aluminium were studied. Chemical compositions of these ingots are shown in Table 1.

Table 1.

Chemical Composition of Aluminium Ingots.

	Si %	Fe %	Ti %	Cu %	Al (as balance) %
A	0.20	0.23	0.012	0.01	99.55
B	0.13	0.12	0.009	0.003	99.73

The author measured the running quality of ingot B at the superheating temperatures 12°, 30° and 50°C and at the maximum heating temperature 850°C. Table 2 shows these results as compared with values of ingot A determined from the temperature-running quality relation curve (Fig. 9) obtained under the same conditions.

Table 2.

Comparison between Running Qualities of Aluminium A and B.

Superheating Temperature °C	Length of Flow cm	
	99.73% Al	99.55% Al
12	23.3	26.5
30	31.3	32.0
50	42.5	41.3

As shown in Table 2, there is little difference between these results. Therefore, values of ingot A are adopted as the standards of the running quality of pure aluminium as a matter of convenience.

For alloying, an electrolytic iron was added as the plate of cathode deposit, pure zinc or pure magnesium as the ingot, and the other elements were added in the form of the hardeners, which were about 50% Cu, about 50% Si, about 18% Mn and about 20% Ni alloys, prepared by using electrolytic copper, metallic silicon with 0.4% Fe, electrolytic manganese and electrolytic nickel, respectively.

Experimental Apparatus and Procedure.

The same apparatus was employed as that used for measuring the running quality of molten magnesium and its alloys. This apparatus was designed by the author and consists of three parts, —a metallic mould having a straight measuring canal about 150 cm long, whose cross section is an inverted equilateral triangle, one 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 is equipped with a stopper, and a metallic mould having a down gate and a runner which leads to the measuring canal and acting as a part connecting the sand mould reservoir and the measuring canal. After filling the sand mould with the charge, the stopper was removed and the charge was poured into the test mould. The length of flow solidified in the measuring canal was taken as a measure of the running quality. The measuring canal was coated with very fine alundum cement uniformly on all surfaces. The temperature of the mould was kept at about 70°C. The details of the mould construction, its assembling method and the drying and heating method are omitted here as they were described in a previous paper(11)

The materials were melted in a graphite crucible, whose capacity was No. 6 to No. 8, by using an electric resistance furnace wound with nichrome wire. The aluminium ingot of 1.5 to 2 kg. was divided in some pieces and charged. Alloying materials, of the amounts calculated, were added after the aluminium was melted down. When all the charges were melted down, the bath was stirred quietly with a graphite rod to complete the mixing. It was then heated to the maximum temperature 850°C and the current cut off.

When the molten bath cooled down to a temperature of about 100°C above the pouring temperature predetermined, the crucible was taken out. An alumel-chromel thermocouple with steel protecting tube whose outer surface was coated with alundum cement, was fitted to the supporting stand and its hot junction was placed at the given position in the sand mould for reservoir, and then the molten metal was poured in. When the temperature of the melt in the reservoir lowered to the given temperature, the stopper was removed.

The author adopted a pouring temperature 50°C above the liquidus, which was determined corresponding to the addition from the binary equilibrium diagram hitherto published, as shown in Fig. 1 to Fig. 7. The correct superheating temperature was determined for the liquidus corresponding to the compositions obtained by the chemical analysis after the experiment. The sample for analysis was taken from the part solidified in the sand mould.

In studying the influence of the repetition of melting on the running quality of aluminium, at first a new aluminium ingot of about 2 kg., was

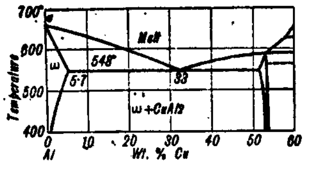


Fig. 1.

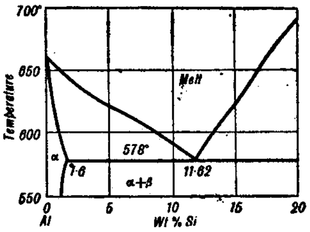


Fig. 2.

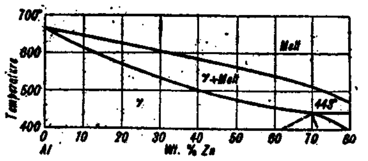


Fig. 3.

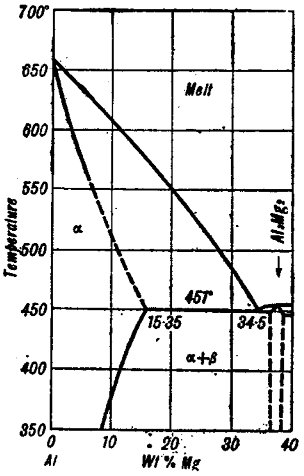


Fig. 4.

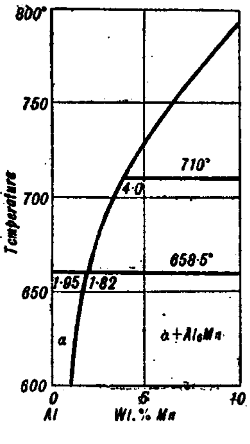


Fig. 5.

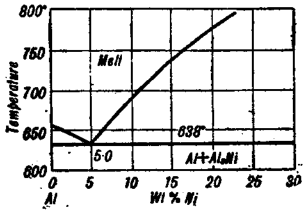


Fig. 6.

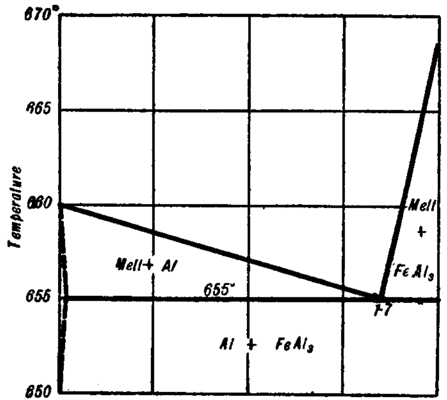


Fig. 7.

melted and poured into the test mould, and the molten metal in the sand mould was transferred into the crucible as quickly as possible before it began to solidify. New metal was added to the metal remaining in the crucible, to make up the deficit, and the melting and pouring operations were repeated as above mentioned. In such a manner the measurement was repeated several times.

The author adopted the maximum heating temperature 850°C in this investigation, excepting in studies of the temperatures themselves, in order to make the results comparable with values of magnesium and its alloys previously reported, and to make it easy to conduct experiments on aluminium at a superheating temperature over 100°C.

In studying the influence of the maximum heating temperature, after the aluminium ingot was melted down, the molten bath was heated up to maximum temperatures of 750°, 800° and 900°C, respectively, in the time of 30 to 60 minutes, and immediately the current was cut off. The crucible was held in the furnace for about five minutes at those maximum temperatures and then taken out. The foregoing operations were as above mentioned.

Results of Investigation and Their Considerations.

1. Pure aluminium.

(a) Influence of Repetition of Melting.

Results obtained at superheating temperatures of 25°, 50°, 75°, 100° and 125°C are shown in Table 3 and Fig. 8.

The amounts of new metal supplied are somewhat irregular and about 10 to 40% erratic, but it may be said that the irregularity gives no considerable error from the view point of the accuracy of this investigation.

In general, it appears that the running quality of the first melting is best and that of succeeding meltings is a little inferior to the first. For example, as shown on the parenthesized values in Table 3, the results obtained from the test at the superheating temperature purposely changed in the

Table 3.

Influence of Repeated Melting on Running Quality of Aluminium.

No. of Experiment	Temperature of Mould °C				Superheating Temperature, i. e. Difference between Melting Point of Metal and Pouring Temperature °C	No. of Melting	Length of Flow cm	Supply of New Metal g
	Down Gate	Measuring Canal						
		Entrance	Centre	Mean				
40	70	63	62	62.5	25	1	28.8	—
41	70	65	67	66	25	2	28.6	550
42	72	66	67	66.5	25	3	26.9	625
43	72	69	69.5	69.8	(125)	4	(53.8)	880
32	72	72	72.5	72.3	50	1	42.2	—
33	68	69	69.5	69.8	50	2	41.6	600
34	72	70	70	70	50	3	39.3	1,200
22	75	67	68	67.5	50	1	43.6	—
23	75	68	69	68.5	50	2	42.4	290
24	74	62.5	57	59.8	(75)	3	(47.1)	440
25	71	69	69	69	50	4	42.1	1,020
2	65	69	71	70	75	1	52.7	—
3	72	66	62	64	75	2	51.9	250
4	69	63	62	62.5	75	3	54.1	290
5	69	67.5	67	67	75	4	54.5	290
6	75	63.5	62	63	75	5	57.8	425
7	75	69	70	69.5	100	1	58.9	—
8	70	64	63	63.5	100	2	58.4	250
9	68	62	61	61.5	100	3	51.3	250
10	74	66	65	65.5	100	4	56.8	255
11	72	63	61	62	100	5	53.5	290
12	74	67	68	67.5	100	1	60.9	—
13	70	57	57	57	100	2	55.0	300
14	70	64	66	65	100	3	56.3	400
15	74	66	65	65.5	100	4	57.9	450
16	70	62	61	61.5	(125)	5	(57.0)	(375)
17	72	70	71	71.5	125	1	59.5	—
18	75	76	77	76.5	125	2	56.0	650
20	75	63	64	63.5	(50)	3	(43.0)	240
44	73	71	72	71.5	125	1	56.9	—
45	70	63	62	62.5	125	2	50.4	300
46	70	67	69	68	125	3	58.0	380

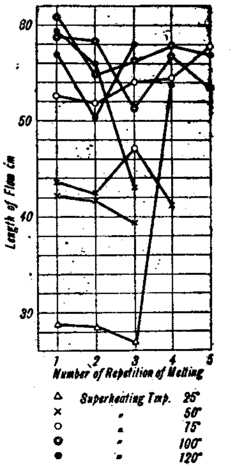


Fig. 8.

Influence of Remelting on the Running Quality of Aluminium at Various Superheating Temperatures.

process of that series, are a little inferior to the other values at the same superheating temperature series. The author thinks that this fact shows that the running quality of aluminium is slightly decreased by repetition of melting, but not seriously.

Accordingly new metal was used throughout this investigation.

(b) Influence of Superheating Temperature.

At first, the relation between a superheating temperature and a running quality of aluminium at a maximum heating temperature of 850°C was studied as the standard in this investigation. Results obtained are shown in Table 4 and Fig. 9.

The running quality of aluminium increases with a rise in the pouring temperature or superheating temperature, till about 100°C above its melting point, but at the superheating temperature 125°C it is rather inferior to the quality at 100°C. The slope of the curve showing the relation between the running quality of aluminium and the superheating temperature is somewhat steeper than that for magnesium obtained in the previous paper. It may be considered that this result is due to the fact that the latent heat of fusion of aluminium is about twice that of magnesium, and that their specific heats are almost the same; but the specific gravity of the former is about 1.6 times that of the latter.

Table 4.

Results of Running Quality Measurement of Aluminium at Various Pouring Temperatures.

No. of Experiment	Temperature of Mould °C				Pouring Temperature °C	Superheating Temperature, i.e. Difference between Melting Point of Metal* and Pouring Temperature °C	Length of Flow cm
	Down Gate	Measuring Canal					
		Entrance	Center	Mean			
19	75	65	65	65	677.5	19	30.7
37	69	66	68	67	683.5	25	32.0
40	70	63	62	62.5	683.5	25	28.8
22	75	67	68	67.5	708.5	50	43.6
32	72	72	72.5	72.3	708.5	50	42.2
35	68	63	64	63.5	708.5	50	38.4
2	65	69	71	70	734.5	76	52.7
7	75	69	70	69.5	758.5	100	58.9
12	74	67	68	67.5	758.5	100	60.9
17	72	70	71	70.5	783.5	125	59.5
44	73	71	72	71.5	783.5	125	56.9

* 658.5° is adopted as melting point of aluminium.

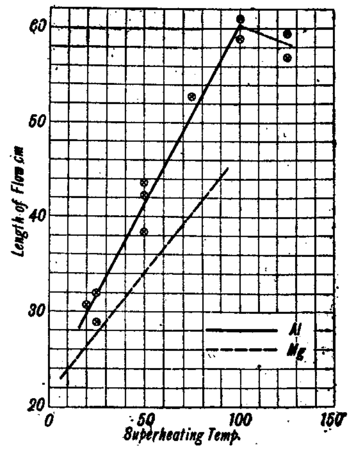


Fig. 9.

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

The running quality of aluminium increases linearly up to a pouring temperature of 800°C, according to Saeger and Krynitsky; from 658° to 800°C, according to Courty; from 730°C to 850°C, according to Portevin and Bastien; from 650° to 800°C, according to Morinaga; and from about 700° to 800°C, according to Sakuma. Contrary to the results obtained by these investigators, the author's results agree with these of Saitō and Hayashi mentioned above and also with results obtained by Matzukawa(15) which showed that the viscosity of molten aluminium, measured by a rotating cylinder method linearly decreases with a rise of temperature, although above 765°C the rate of decrease becomes slow. It may be thought that these phenomena are due to a formation of oxide and an absorption of hydrogen and other gases in molten aluminium. However, Saeger and Krynitsky have said that little or no effect in the quality of commercial aluminium (99.2%) resulting from treatment with oxygen, where oxygen was passed for 5 minutes through the molten aluminium at 850°C, and the lack of consistent improvement in quality from zinc chloride treatment made it doubtful that the effect of higher maximum heating was due to oxide formation or hydrogen absorption. But it should be noticed that there is a difference in experimental conditions between pouring at a maximum heating temperature and pouring at a lower temperature than the maximum.

(c) Influence of Maximum Heating Temperature.

Results obtained are shown in Table 5 and Figs. 10, 11 and 12. The relations between the running quality and the superheating temperature at the maximum heating temperatures of 750°, 800° and 900°C., are shown in similar straight lines of various slopes as in case of 850°C above mentioned. These four relations are summarized in Fig. 13.

In the case of a maximum heating temperature of 750°C, a measurement could not be conducted in a range of superheating temperature above 50°C. The relation between the running quality and the superheating temperature shows much the same slope as in the case of 850°C, and the values are slightly lower. This fact can be understood only by the usual conception and is contrary to Saeger's results. It may be considered that this phenomenon is attributable to there being no more time for the gas absorbed in molten aluminium to be thoroughly discharged than in the case of higher maximum heating temperatures, because of the shorter time for cooling from maximum heating to pouring temperature.

In the case of a maximum heating temperature of 800°C, a measurement was conducted up to the superheating temperature of 100°C. The rate of increase of the running quality with a rise of superheating temperature is the least of all in this case, and consequently the running quality value is the lowest in a range of higher superheating temperatures, but the reverse in a lower temperature range. It may also be considered that this fact results from the shorter time for cooling from maximum heating to pouring temperature.

In the case of a maximum heating temperature of 900°C, the running quality at the lower superheating temperature is better than in the case of 850° and 750°C, but at superheating temperatures of from 75° to 100°C, worse than in case of 850°C and better than in case of 800°C. In this case, the running quality at a superheating temperature

Table 5.

Influence of Maximum Heating Temperature on the Running Quality of Molten Aluminium.

No. of Experiment	Maximum Heating Temperature °C	Temperature of Mould °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		
25	761	70	71	71.5	71.3	23	29.7
18	761	66	72	71	71.5	26	30.5
20	761	70	70.5	70.5	70.5	26	31.5
8	761	70	71	69	70	37	34.7
9	751	72	70	70	70	38	37.3
7	764	65	72	66	69	51	41.4
26	761	72	69	68	68.5	51	38.6
6	802	70	70	68	69	51	43.0
29	800	72.5	70.5	69.5	70.0	51	42.4
17	810	66	70	71	70.5	77	46.5
16	805	69	73	71.5	72.3	76	50
10	810	71	72	70	71	101	49.9
35	810	71	70	69	69.5	101	51
21	906	69	67.5	67.5	67.5	26	33.7
31	904	69	69.5	68.5	69.0	51	43.0
14	900	69	70	65.5	67.8	76	45
15	895	72	69	67.5	68.3	76	47.5
34	899	72	71	71	71	82	53.0
12	899	72	69	67.5	68.3	101	54.0
32	900	72	72	71	71.5	101	55.0
33	899	66	70	69	69.5	101	56.2
22	898	71	69	70	69.5	126	53.0
23	901	67.5	68.5	69	69.8	126	54.1

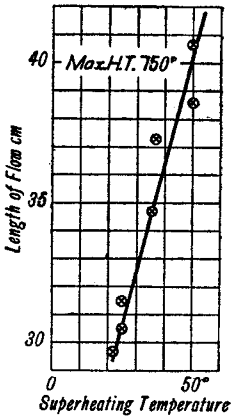


Fig. 10.

Relation between the Running Quality and the Superheating Temperature at the Maximum Heating Temperature 750°C.

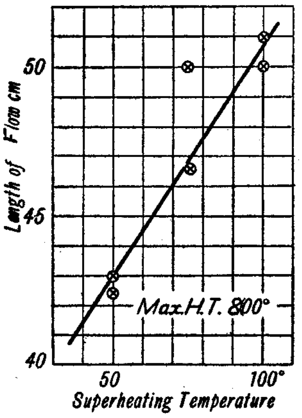


Fig. 11.

Relation between the Running Quality and the Superheating Temperature at the Maximum Heating Temperature 800°C.

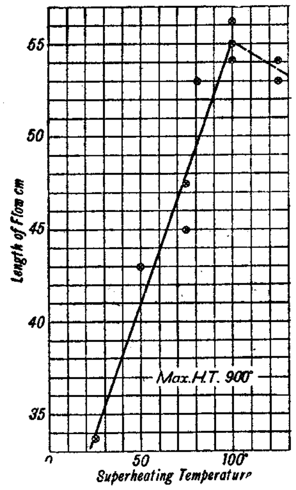


Fig. 12.

Relation between the Running Quality and the Superheating Temperature at the Maximum Heating Temperature 900°C.

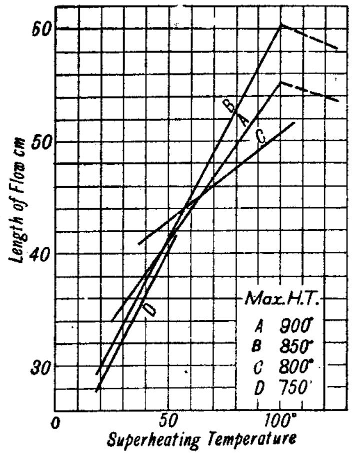


Fig. 13.

Composite of Superheating Temperature—Running Quality Diagrams at the Maximum Heating Temperatures 900°, 850°, 800° and 750°C.

of 125°C is worse than at 100°C, as in case of the maximum heating temperature of 850°C. It is supposed, in considering these phenomena, that when the heating temperature is too high, a formation of oxide and its occulusion, or an absorption of other gases, increases to a marked degree, and consequently the running quality is not so favourable at higher pouring temperatures; but that it does not markedly decrease at lower pouring temperatures because of easier discharge of dissolved gases, owing to the time required for lowering the temperature.

As shown in Fig. 13, in the vicinity of the superheating temperature 50°C, which has been adopted in this investigation by the author, the running quality of molten aluminium successively decreases, in the order of the maximum heating temperatures, 800°, 850°, 900° and 750°C, but the difference between them is not great. Consequently, the author considers that the influence of the maximum heating temperature is not very important in the range between the superheating temperatures 45° and 55°C, although it should not be neglected, and that the results obtained at the maximum heating temperature 850°C in this investigation, will not be appreciably influenced by the superheating temperature.

On the other hand, it should be noticed that the running quality of molten aluminium is best at the maximum heating temperature 800°C when the superheating temperature is below 50°C, and at the maximum heating temperature 850°C when the superheating temperature is above 50°C; while it is generally unfavourable at the maximum heating temperatures 900°C and 750°C. It may be supposed that the running quality of molten aluminium depends on a formation of oxide, its occulusion and an absorption of gases, etc., but it can not be absolutely said that the lower the maximum heating temperature, the better the running quality will be. It is necessary to take account of the relation between the pouring temperature and the maximum heating temperature in casting aluminium and its alloys.

2. *Influence of Alloying Elements.*

So far as the author has studied, the running quality of molten aluminium decreases with the small addition of an alloying element, without exception. Almost all test castings solidified in the measuring canal had an imperfect cross section in part. According to definition, the running quality of molten alloys should be determined only from a solidified part perfectly filling up the measuring canal. Therefore, it is meaningless in determining the running quality to measure only the total length of flow solidified in the measuring canal. The author has described a curve showing the relation between the content of an alloying element and the total length of flow and a curve showing the relation between the former and the length of flow perfectly filled up. The shorter the length of flow and the greater the interval between these two curves, the more unfavourable is the running quality. Nevertheless, it may be thought that this determination method is practically the same, in discussing the running quality of molten alloys, as a determination by only one of the two. Results obtained are shown en bloc in Table 6 and each of them in Figs. 15, 17, 19, 20, 21, 22 or 23. Fig. 14 represents running quality test castings of these alloys which show the flow of each alloy having a typical composition.

(a) Influence of Copper.

Additions of copper were 1, 2, 4, 8, 12 and 33%. As shown in Fig. 15, an addition of copper up to about 1% rapidly decreases the running quality of pure aluminium, then up to about 4% gradually decreases it and further additions almost linearly increase it till the eutectic point (Cu 32.5%), in the neighbourhood of which the quality becomes much better than pure aluminium. This result is entirely different from that obtained by L. Losana, which indicated that the running quality of aluminium rapidly increases by an addition of copper up to 2% and with further additions gradually increases. The author's result may be explained as follows: the running quality of aluminium decreases with increase of a solidification range, where a solid solution of aluminium with copper and a liquid coexist and therefore should take the minimum values at 5.7% Cu, which is a saturated solid solubility of copper at 548°C. But in the author's case, when the molten alloys were poured into the metallic mould, whose temperature was about 70°C, the crystal segregation should take place and a saturated solid solubility might apparently migrate somewhat to the aluminium side, and accordingly it may be thought that the running quality became the minimum value at about 4% copper. Some eutectic structure is noticed in Fig. 16 showing the microscopic structure of a cross section of the middle part of test castings of 4% Cu alloy.

Courty has found, in his study of this problem, that if the temperature of the metallic mould is 15°C and the pouring temperature is 750°C, the running quality of aluminium decreases with an addition of copper and, after reaching a minimum at 2.5% Cu, increases with further additions, and the running quality of the alloy with about 7% Cu takes the same value as pure aluminium, but the rate of increase in the range over 12% Cu is little. He was explained that these phenomena take place on account of increase in the density and the statical head with the addition of such a heavy component as copper.

Although it is unreasonable to compare the author's results with those of Courty because of very different pouring temperatures, there exists a common factor in that the running quality of aluminium with 2% Cu is minimum, so far as the total length of flow is concerned. But the

Table 6.

Influence of Copper, Silicon, Zinc, Magnesium, Manganese, Nickel or Iron on Running Quality of Aluminium.

Kind of Alloying Element	No. of Experiment	Content of Alloying Element %		Temperature of Mould °C				Pouring Temperature °C	Liquidus Temperature determined from Equilibrium Diagram °C	Superheating Temperature, i. e. Difference between Liquidus and Pouring Temperature °C	Length of Flow cm	
		Addition	Analysis	Down Gate	Measuring Canal						Total	Perfectly filled up
					Entrance	Center	Mean					
Cu	8	1	0.94	66	62	63	62.5	706	657	49	34.6	21.6
	10	1	0.94	73	66	66	66	706	657	49	33.3	26
	9	1	0.99	61	58	60	59	706	657	49	32.5	28
	18	2	1.91	73	69.5	72	60.8	704	655	49	36.3	24
	6	2	1.94	72	64	65	64.5	704	655	49	32.1	22.5
	5	2	1.98	73	67	68	67.5	704	655	49	34.0	25.3
	3	4	3.85	71	68	68	68	700	650	50	35.8	21.0
	2	4	3.91	71	66	67	67.5	700	650	50	34.9	22.2
	1	4	4.00	75	69	69.5	69.8	700	650	50	33.5	17
	23	8	7.88	76	68	68	68	688	638	50	37.3	37.3
	16	8	8.01	76	69	69.5	69.8	688	637	51	36.5	36.5
	14	8	8.05	66	62	63	62.5	688	637	51	35.1	29.7
	13	8	8.10	71	68	70	69	688	637	51	32.7	24.5
	22	12	11.65	68	64	64	64	674	625	49	39.1	34.4
	20	12	11.86	68.5	69	71	70	671	624	47	35.8	31.5
	21	12	11.88	80	71.5	71	71.3	674	624	50	39.9	33.3
	24	33	32.54	69	65	67	66	598	550	48	53.1	53.1
	25	33	32.81	74	69.5	70	69.8	598	549	49	49.7	49.7
	26	33	32.99	73	69.5	70	69.8	598	548	50	48.5	48.5
Si	1	1	0.99	65	60	57	58.5	702	650	52	33.0	19.5
	12	1	1.03	78	68	70	69	702	650	52	30.8	18.6
	2	1	1.13	71.5	70	70.5	70.3	702	649	53	36.2	23.0
	3	2	2.19	71	70	67	68.5	693	641	52	31.9	14.5
	4	2	2.21	73	70.5	71	70.8	680	641	39	33.5	17.1
	5	4	4.02	76	70.5	70	70.3	680	629	51	32.0	16.7
	6	4	4.53	75	67.5	67	67.3	680	625	55	33.9	13.0
	8	11.5	10.87	74	68	70	69	628	583	45	35.5	22.4
	7	11.5	11.19	73	70	69	69.5	628	581	47	35.1	25
	11	15	15.56	72	68	70	69	681	628	53	42.7	42.7
	10	15	15.62	70	68	70	69	667	629	38	40.7	40.7
	9	15	15.69	70	70	72	71	667	630	37	40.4	40.4
Modified	13	11	10.37	69	66	67	66.5	634	587	47	38.0	19.2
	16	11	11.08	75	70	72	71	634	582	52	39.6	15.5
	15	11	11.22	73	70	71	70.5	613	581	32	34.5	10.5
	18	13	12.29	69	65	62	63.5	610	588	22	25.0	25.0
	19	13	13.19	73	70	70	70	645	599	46	45.7	42.3
	17	13	13.73	71	69	70	69.5	631	605	26	38.8	33.5
Zn	7	1	1.00	76	72	72	72	709	657	52	39.2	39.2
	21	1	1.00	72	68	70	69	704	657	47	37.8	37.8
	4	2	1.98	75	72	71	71.5	708	656	52	35.1	29
	6	2	2.03	75	69	69	69	708	656	52	34.2	27.8
	28	3	3.07	70	68	69	68.5	707	655	52	32.4	32.4
	11	3	3.08	70	68	70	69	711	656	50	33.0	22.0
	32	5	4.93	74	69	72	70.5	701	651	50	33.2	24.0
	34	5	4.96	75	69	70	69.5	701	651	50	33.3	26.0
	13	5	5.01	70	69	70	69.5	701	651	50	35.0	21.5
	14	5	5.02	72	68	69	68.5	701	651	50	36.0	24.5
	15	10	9.80	71	69	71	70	692	642	50	35.4	19.0
	33	10	9.97	71	70	68	69	692	643	49	35.4	22.0
	16	10	10.24	70	69	70	69.5	688	642	46	38.5	24.0
	20	20	19.89	65	62	65	63.5	674	624	50	40.6	29.5
	19	20	—	73	67	59	63	674	624	50	36.2	25.0
	18	20	20.15	73	69	70	69.5	674	624	50	40.8	25.7

	22	30	28.54	74	70	71	70.5	655	608	47	38.5	26.8
	25	30	29.49	75	69	70	69.5	655	606	49	37.2	24.5
	26	30	29.72	70	64	63	63.5	655	606	49	37.2	23.5
	24	30	30.78	73	71	72	71.5	655	604	51	40.5	32.5
	29	30	37.72	74	73	74	73.5	655	602	53	39.6	24.9
Mg	2	1	1.00	71	71	70	70.5	704	655	49	39.7	39.7
	10	1	1.12	70	63	64	63.5	704	654	50	34.0	34.0
	3	1	1.22	74	72	72	72	704	653	51	35.1	35.1
	4	3	3.00	71	70	67	68.5	693	643	50	37.2	28.5
	5	3	3.09	73	71	71	71	693	642	51	30.1	30.1
	14	5	4.96	73	69.5	72	70.8	682	632	50	34.7	29.7
	7	5	4.97	74	70	72	71	682	632	50	37.8	29.7
	9	10	8.36	68	63	64	63.5	654	613	41	33.3	21.9
	15	10	10.43	68	69	69	69	654	601	53	34.7	21.6
	13	15	12.03	70	70	71	70.5	622	592	30	32.8	21.0
	12	15	16.09	70	66	67	66.5	622	568	54	30.7	19.2
Mn	1	0.5	0.56	70	71	74	72.5	710	658	52	42.6	42.6
	6	0.5	0.59	70	72	74	73	710	658	52	36.0	36.0
	7	1	1.10	72	70	70	70	710	658	52	38.4	38.4
	3	1	1.18	75	71	74	72.5	710	658	52	39.7	39.7
	9	1.5	1.80	70	70	70	70	709	657	53	41.9	41.9
	18	1.95	2.16	70	70	70.5	70.3	708	660	39	43.2	43.2
	16	1.95	2.25	74	71	68	69.5	708	672	36	43.1	43.1
	17	1.95	2.49	72	70	71	70.5	708	680	28	41.1	41.1
	12	3	3.00	70	73	74	73.5	742	692	50	48.8	48.8
	13	3	3.81	75	70	70	70	742	707	35	48.6	48.6
	15	5	5.21	74	72	73	72.5	780	733	47	34.8	20.5
	14	5	5.49	75	73	72	72.5	780	737	43	31.1	22
Ni	21	1	0.85	70	70	70	70	702	653	49	38.3	26.0
	13	1	0.95	71	71	71	71	702	652	50	38.6	29.0
	14	1	0.97	72	66	65	65.5	702	652	50	37.3	29.0
	12	2	1.96	72	66	66	66	698	648	50	39.5	27.2
	7	2	2.00	70	70	70	70	702	648	54	40.2	32.0
	11	2	2.09	70	69	71	70	698	647	51	38.9	27.5
	19	3	2.86	75	72	72	72	693	644	49	39.0	24.0
	18	3	2.95	72	73	72	72.5	693	644	49	37.2	25.0
	16	3	3.00	68	68	68	68	690	644	46	36.8	26.0
	4	3	3.06	70	70	70	70	693	644	49	34.3	25.0
	3	3	3.17	71	69	71	70	693	644	49	34.0	18.0
	10	4	3.94	69	68	67	67.5	690	641	49	38.5	24.0
	9	4	3.99	73	67	68	67.5	690	641	49	37.0	26.5
	32	4	3.99	74	69	70	69.5	688	641	47	38.3	18
	26	5	4.69	70	72	73	72.5	688	638	50	35.6	24.5
	5	5	4.94	71	70	70	70	688	638	50	36.2	20.0
	6	5.7	5.55	73	73	73	73	688	643	45	35.3	30.3
	17	5.7	5.61	75	68	69	68.5	690	644	46	36.2	24.5
Fe	4	0.5	0.43	66	69	63	66	708	658.8	49.2	35.7	35.7
	5	0.5	0.51	69	69	70	69.5	708	658.5	49.5	37.0	31
	2	1	0.95	71	69	67	68	707	673	44	44.4	31.4
	3	1	0.97	69	68.7	68	68.4	707	652.2	47.8	44	34.2
	15	1	1.02	69	68.5	68	68.3	707	657	50	43.8	33.3
	10	1.5	1.44	71	70	68	69	705	655.8	49.2	40	24.7
	8	1.5	1.47	71	71	68	69.5	705	655.7	49.3	42.2	23.6
	6	1.5	1.51	68	70.5	65.5	68	705	655.6	49.4	38.2	28.8
	9	1.5	1.51	72	69	69	69	705	655.6	49.4	44.7	23.7
	13	1.7	1.81	69	69	68.5	68.8	705	660	45	40.3	40.3
	14	1.7	1.82	68.5	70	69.5	69.8	705	660.4	39.6	39.2	32.3
	12	1.9	1.94	71.5	69.5	69.5	69.5	704	666	38	40.2	34.3
	11	1.9	1.98	73.5	69	69	69	704	667.2	36.8	37.8	30.5

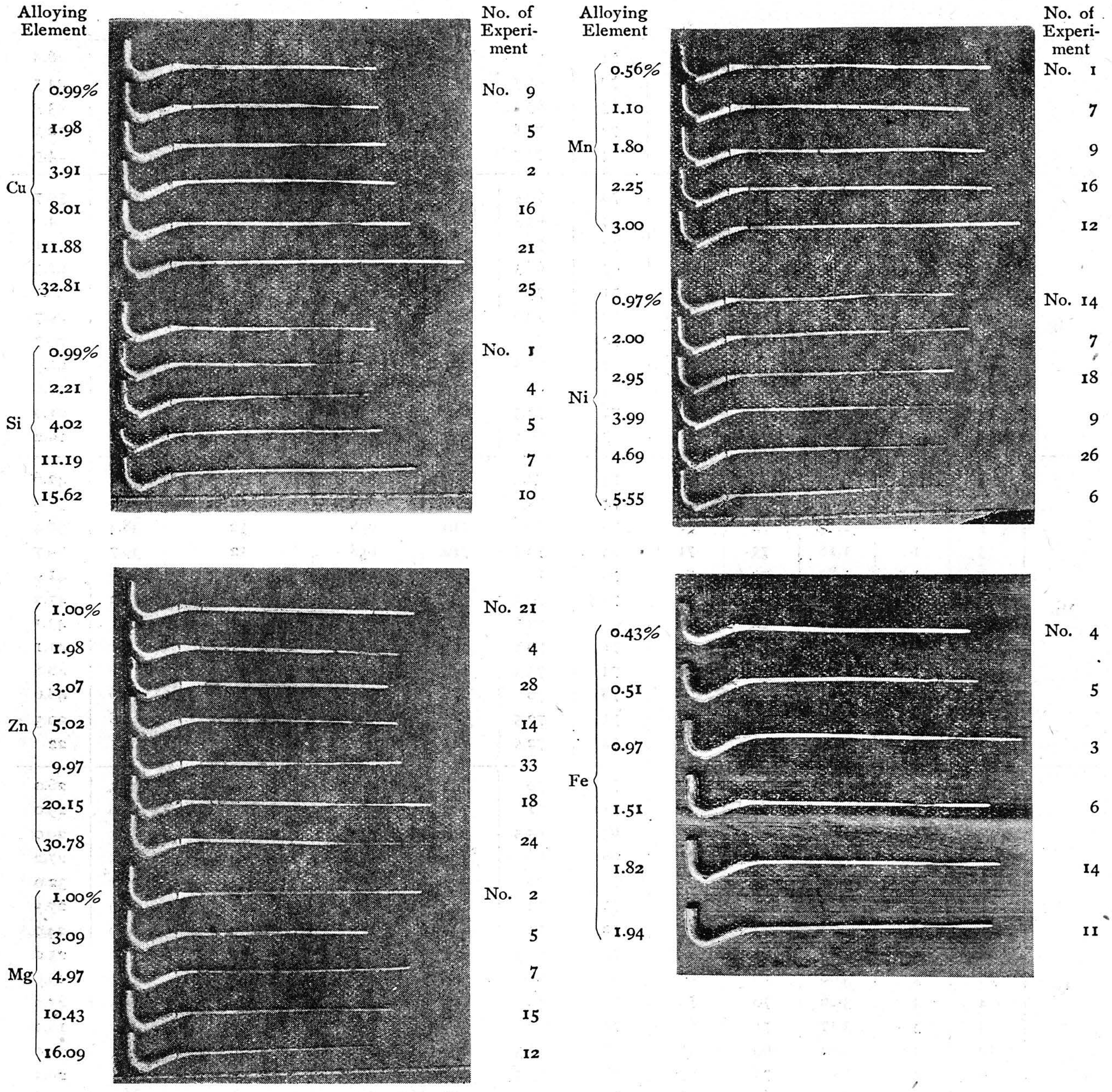


Fig. 14.

Representative " Running Quality " Test Castings of Binary Aluminium Alloys with Copper, Silicon, Zinc, Magnesium, Manganese, Nickel or Iron. Superheating Temperature : about 50°C.

disagreement in these results found in the range above 12% Cu cannot be explained by the density and the statical head, as above mentioned. It appeares that this difference is attributable to the superheating temperature and, in the author's case, the running quality of the alloy linearly increases with decrease of solidification range, because of the constant superheating temperature, while in Courty's case the influence of greater superheating temperature on this quality overbalances that of the decrease of solidification range, because of the constant pouring temperature.

(b) Influence of Silicon.

Additions of silicon were 1, 2, 4, 11, 11.5, 13 and 15%. As shown in Fig. 17, the running quality of pure aluminium suddenly decreases by an addition of silicon up to about 1% and then gradually increases with further additions of silicon, when only the total length of flow is considered; while it suddenly decreases by an addition of silicon up to about 2%, takes the minimum value at about 3% Si and then gradually increases with further additions of silicon up to about 11%, from which it considerably increases until it takes the same value as pure aluminium at about 15.5% Si, if the length of flow perfectly filled up is considered.

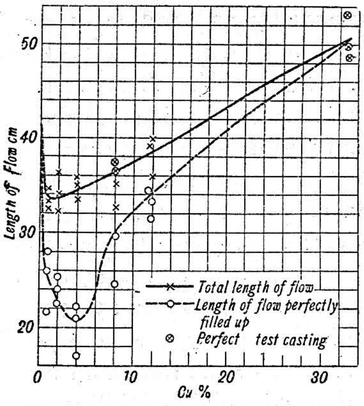


Fig. 15.

Influence of Copper Content on the Running Quality of Aluminium. Superheating Temperature, about 50°C.

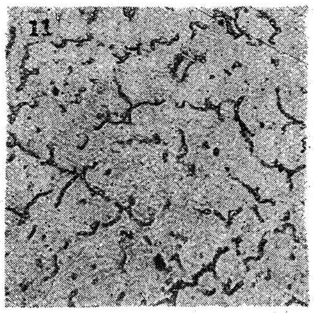


Fig. 16.

Microscopic Structure of Cross Section of A Middle Part of Test Casting of Aluminium with 4% of Cu. (×300)

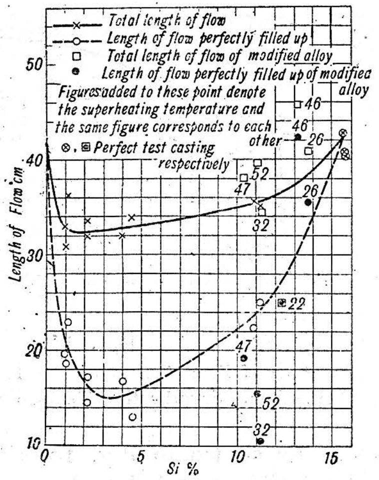


Fig. 17.

Influence of Silicon Content on the Running Quality of Aluminium. Superheating Temperature, about 50°C.

The inclination of these relation curves and the silicon content of the minimum value are somewhat similar to Courty's results.

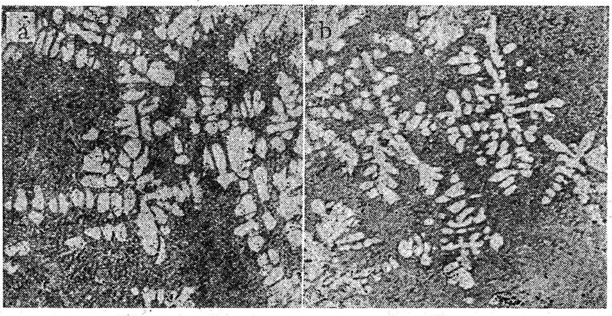
It is noticeable that the alloy with the lighter density and the higher liquidus temperature than the eutectic alloy has the better running quality. This phenomenon can not be explained by only the solidification range of the equilibrium diagram, as before, because the saturated solid solubility of silicon into aluminium is about 1.6% at 578°C and the eutectic composition is 11.7% Si. Courty has explained it by the lighter density of higher silicon alloy, but the author believes that it should be far more fundamentally studied.

A study of the influence of a modification on the running quality of this alloy was conducted with two ratios of alloy, 11% and 13% Si. After preparing the molten alloy, the crucible was taken out of the furnace, about one gram of metallic sodium (corresponding to 0.05% Na) was thrown into the molten bath at about 800°C and stirred in with a graphite rod on the end of which was a perforated container (made of a small graphite crucible), which contained metallic sodium. Then the bath was refined with a small amount of sodium fluoride and poured into the test mould, after allowing the bath to settle and removing the slag. As the temperature of the bath dropped during this refining process, the required superheating temperature could not be maintained.

Results obtained are shown in Table 5 and Fig. 17. Numerical figures added to experimental points of modified alloys in Fig. 17 denote the superheating temperature and these figures correspond with the total length of flow and the length of flow perfectly filled up, respectively.

According to these results, it may be estimated that the running quality of the modified alloy is much the same as that of the normal alloy with 11% Si addition, but with 13% addition the modified is somewhat superior to the normal alloy.

Fig. 18 represents the microscopic structure of cross sections of middle parts of test castings of 10.37% Si and 13.73% Si alloys, modified with metallic sodium and sodium fluoride, showing the effect of the modification.



a. Si 10.37% b. Si 13.73%

Fig. 18.

Microscopic Structure of Cross Section of A Middle Part of Test Castings of Aluminium with 10.37% and 13.73% of Silicon modified with metallic Sodium and Sodium Fluoride. (×150)

According to Saitō and Matsukawa, the viscosity of silumin containing 12.77% Si, measured by the rotating cylinder method, increases with repetitions of modification, and in each case does so suddenly in the vicinity of the liquidus temperature. It may be considered that the running quality of the molten alloy will not be greatly influenced by viscosity in the narrow temperature range just above the liquidus, when it is poured into a metallic mould whose temperature is 70°C and rapidly cools.

(c) Influence of Zinc.

Additions of zinc were 1, 2, 3, 5, 10, 20 and

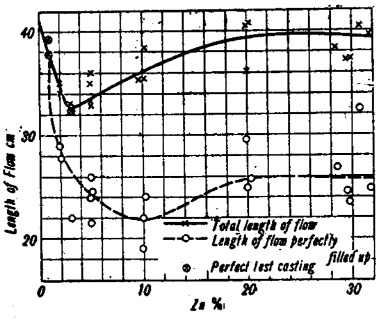


Fig. 19.

Influence of Zinc Content on the Running Quality of Aluminium. Superheating Temperature, about 50°C.

30%. As shown in Fig. 19, the running quality of aluminium remarkably decreases by the addition of zinc up to about 3% and gradually increases with further additions of zinc, when the total length of flow is considered; while it considerably decreases up to about 10% Zn and increases to nearly parallel with the total length curve, when the length of flow perfectly filled up is considered. In both cases, there is no observable change of the quality between 20% and 30% Zn. These results agree with Courty's in finding the running quality of the alloy of this series to have a minimum value at about 11% Zn.

Zinc is soluble in solid aluminium over a wide range. The liquidus temperature of aluminium alloy containing zinc lowers very slowly with additions of zinc, and even at 30% Zn is only about 50°C lower than the melting point of aluminium; and at that zinc content the solidification range is only about 70°C. All the alloys tested in this study belong to the range of solid solutions. Therefore, it may be considered that there is no observable change at the high zinc content because of the facts above mentioned.

It should be noticed that the running quality of the alloy containing 30% Zn is less than that of pure aluminium, despite the considerable increase of density.

(d) Influence of Magnesium.

1, 3, 5, 10 and 15% magnesium were added.

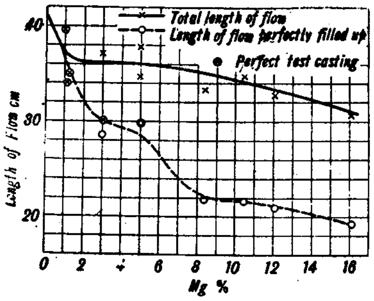


Fig. 20.

Influence of Magnesium Content on the Running Quality of Aluminium. Superheating Temperature, about 50°C.

As shown in Fig. 20, the running quality of aluminium suddenly decreases by an addition of magnesium up to about 2% and with further additions gradually decreases. As all the alloys tested in this experiment have the compositions of the solid solutions of aluminium with magnesium, these results may be considered as reasonable from the author's point of view previously mentioned, because the solidification ranges of the alloys of this system on the aluminium side increase with additions of magnesium and become maximum at 15.35% Mg. But it should be noticed that there is no migration of the magnesium content of the minimum running quality from the saturated solid solubility to the aluminium side according to the supercooling and the crystal segregation, as observed on the magnesium side in a previous investigation.

On the other hand, Portevin and Bastien have observed that the running quality of aluminium gradually increases with an addition of magnesium. As their results were obtained at the constant pouring temperature of 700°C, it may be thought that the influence of the superheating temperature overbalances that of the solidification range at higher magnesium contents, as in the case of copper. For instance, the liquidus temperature of 15.35% Mg alloy is 572°C, and consequently the superheating temperature is 128°C and the solidification range is 120°C. In the author's case, it may be considered that the influence of supercooling on the aluminium side is not so remarkable as on the magnesium side, because of the greater latent heat and heat content of aluminium, as the superheating temperature is constantly 50°C.

(e) Influence of Manganese.

0.5, 1, 1.5, 1.95, 3 and 5% manganese were added. As shown in Fig. 21, the running quality of aluminium slightly decreases by an addition of manganese up to about 1% and then considerably increases from this content and between 3% and

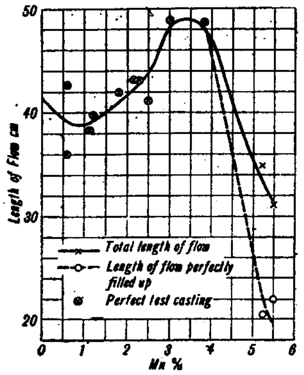


Fig. 21.

Influence of Manganese Content on the Running Quality of Aluminium. Superheating Temperature, about 50°C.

4% Mn takes the maximum value, but it suddenly decreases by an addition of 5% Mn. It should be noticed that the running quality of a hyper-eutectic alloy is much superior to the eutectic alloy. It may be thought as reasonable that the running quality of the alloy of this system suddenly decreases at about 5% Mn, as the liquidus temperature is very high and the solidification range considerably increases by this manganese content.

(f) Influence of Nickel.

1, 2, 3, 4, 5 and 5.7% nickel were added. As shown in Fig. 22, the running quality of aluminium suddenly decreases by an addition of 1% Ni and then gradually decreases with the further additions. This result agrees with Courty. It should be noticed that the running quality of this alloy decreases with the diminution of the solidification range, in which nickel is hardly soluble in solid aluminium and the eutectic point of this alloy is about 5% Ni at 638°C.

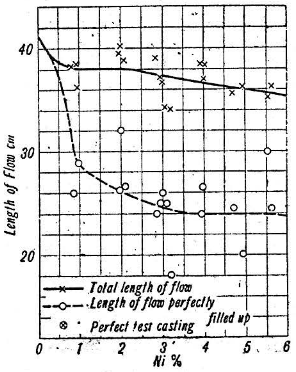


Fig. 22.

Influence of Nickel Content on the Running Quality of Aluminium. Superheating Temperature, about 50°C.

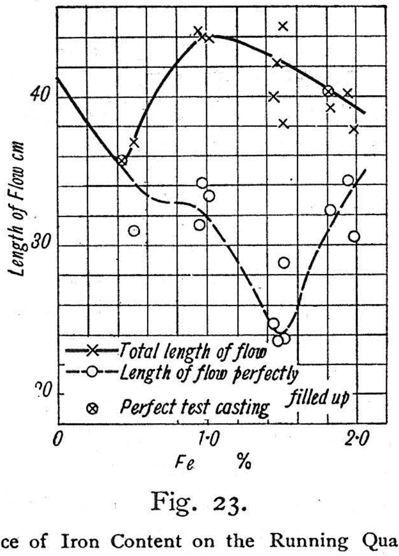


Fig. 23.

Influence of Iron Content on the Running Quality of Aluminium. Superheating Temperature, about 50°C.

(g) Influence of Iron.

0.5, 1, 1.5, 1.7 and 1.9% iron were added. As shown in Fig. 23, the running quality of aluminium considerably decreases by an addition of iron up to about 0.5%, and then considerably increases from 0.5% to 1.0% Fe and with the further addition of iron gradually decreases again when the total length of flow is considered, while it slightly decreases from 0.5% to 1% Fe and markedly decreases from 1% to 1.5%, but it increases from 1.5% to 2% Fe, when only the length of flow perfectly filled up is concerned. The difference between these two relation curves considerably increases from 1% to 1.5% Fe and gradually diminishes from 1.5% to 2% Fe.

These phenomena may also be explained by the binary equilibrium diagram of aluminium-iron system and the solidification theory; the running quality of aluminium decreases by a small addition of iron because of the formation of the solidification range and increases with the further addition of iron because of the diminution of the solidification range toward the eutectic point. The author thinks that the great difference between the total length of flow and the length of flow perfectly filled up at the iron content from 1% to 1.5% and the approach between these curves with the further addition of iron may be caused by the increase of the eutectic constituent.

According to I. Ōbinata and S. Terazawa, the eutectic composition of this binary alloy migrates toward the iron side and the eutectic temperature lowers because of considerable supercooling in case of such rapid cooling as in the author's study. Consequently, in these results, this alloy does not have the maximum running quality at 1.7% Fe, the eutectic composition in the equilibrium state, but gives the appearance of having its solidification range there. Although the decrease of the total length of flow in the vicinity of 2% Fe might be caused by the superheating temperature being about

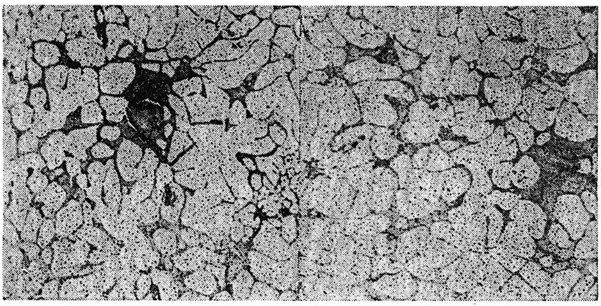

a b

Fig. 24.

Microscopic Structure of Cross Section of A Middle Part of Test Castings of Aluminium with 1.94% Fe; (a) the Part about 24 cm from the Starting Point of Measuring, (b) the Part about 5 cm from the Front Head. ×150

10°C lower than the others, it may be thought that such a temperature difference will not produce so considerable an influence on the running quality because there is in fact a supercooling.

Fig. 24 represents microscopic structures of middle parts of test casting No. 12 of the alloy containing 1.94% Fe; a is the part about 24 cm from the starting point of measuring and b is the part about 5 cm from the front head. Both photomicrographs show that aluminium primarily separates out.

Summary and Conclusion.

The running qualities of molten aluminium and its alloys were measured by means of the same metallic mould as was used in a previous investigation for magnesium and its alloys, having an inverted equilateral triangular cross-section, each side of which is 7 mm. The temperature of the mould was 70°C. The author determined the influences of the repetitions of melting, the superheating temperature, the maximum heating temperature, and of a limited content of copper, silicon, zinc, magnesium, manganese, nickel or iron on the running quality of aluminium. The maximum heating temperature of the melts was 850°C, except in case of the study of the influence of maximum heating temperature itself. The superheating temperature, i.e. the difference between the pouring temperature and the melting point of metal, or the liquidus temperature of alloy, was 50°C, except in case of the study of its own influence. The purity of alminium used was 99.55%, except in case of studies of the influence of maximum heating temperature and of iron on the running quality, when the purity is 99.73%. There is so little difference between these two that they may be considered as the same.

The results obtained are as the follows.

(1) The repetition of melting does not give any favourable effect on the running quality of aluminium, but there is no marked diminution of this quality.

(2) The running quality of alminium linearly increases with a rise of the superheating temperature up to about 100°C, and decreases at a further rise of this temperature; for instance in the neighbourhood of 125°C.

(3) The influence of the maximum heating temperature on the running quality of aluminium depends on the pouring temperature. When the superheating temperature is over 65°C, the running quality is superior in the following order of maximum heating temperatures: 850°, 900° and 800°C, but when the superheating temperature is below 45°C, the running quality is superior in the following order: 800°, 900°, 850° and 750°C. In the neighbourhood of a superheating temperature of 50°C, the influence of the maximum heating temperature is small.

(4) Generally, the running quality of aluminium is initially decreased by a small addition of a simple alloying element, and with a further addition it decreases or increases according to the inherent properties of the element added. Most of the test castings of the alloy have an imperfect reproduction of the measuring canal at its front head or in the neighbourhood of the front head. The author thinks that the formation of imperfect test castings may be caused more or less by the solidification range.

In summarizing these results, the influences of alloying elements are as follows:

(5) Copper up to about 4% decreases the running quality of aluminium, but it generally increases linearly by 4% to 33% additions.

(6) Silicon up to about 2% suddenly decreases the running quality of aluminium, but considerably increases it by 2% to 15% additions.

(7) The modification with metallic sodium and sodium fluoride has no influence on the running quality of 11% Si alloy, but it slightly increases the running quality of 13% Si alloy.

(8) Zinc up to about 3% suddenly decreases the running quality of aluminium, and from 3% to 10% slightly decreases it, but no further decrease is observable between 20% and 30%.

(9) Magnesium up to about 3% suddenly decreases the running quality of aluminium, but from 3% to about 16% gradually decreases it.

(10) Manganese up to 1% slightly decreases the running quality of aluminium, but from 1% to 4%, considerably increases it, while 5% manganese rapidly decreases it again.

(11) Nickel up to about 1% suddenly decreases the running quality of aluminium and from 1% to about 5% gradually decreases it.

(12) Iron up to about 0.5% suddenly decreases the running quality of aluminium, from 0.5% to 1.0% slightly decreases it and by 1.5% addition considerably decreases it, but from 1.5% to 2% gradually increases it.

These results for alloys may be explained by the equilibrium diagram and the solidification theory, as mentioned in a previous paper, except in the cases of silicon, manganese and nickel. It will need a more minute study of the relations between running quality and the inherent properties of various alloys and alloying elements, in order to explain why the running quality of a hyper-eutectic alloy containing silicon or manganese is superior to a eutectic alloy, and the running quality of an alloy containing nickel decreases with the diminution of the solidification range.

Acknowledgement.

This investigation was accomplished as one of the research projects of the 24th (Castings) Sub-committee of the Nippon Gakujutsu Shinkōkai.

The author wishes to express his appreciation to Prof. Dr. Hiroshi Sawamura, under whose cordial guidance these experiments were carried out. The author also wishes to express his thanks to Prof. Dr. Hideo Nishimura, for his valuable suggestions in the microscopical study, to Assistant Prof. Kiyokado Nishihara, for electrolytic manganese used in this investigation and to the Nippon Denki Yakin K.K. for metallic silicon.

Sincere appreciation is likewise given to Mr. Sachio Matsuda, for his assistance in conducting the experiments, and to Mr. Rikichi Kawabata for the chemical analyses.

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