Testing of liquid and solidification contraction of aluminium alloys

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THE shrinkage of metals in the mold can be divided into three distinctly different steps :

(a) liquid contraction during cooling of the metal from the pouring temperature to the solidification temperature, (b) solidification contraction as it passes from the liquid to the solid state, between the liquidus and solidus temperatures, and (c) solid contraction as the solid casting cools to room temperature.

The first two forms of contraction are mainly responsible for the formation of shrinkage cavities in casting and the solidification contraction is by far the most important in this respect. The solid contraction appears as the reduction of linear dimensions of the solidified casting as compared with the mold cavity and is responsible for warping, hot tearing of castings etc.

While there are sufficient data available in the literature regarding solid contraction and total contraction of metals, there are relatively few data available for liquid and solidification contraction of different alloys due to experimental difficulties involved in their determination.

It depends on the mechanism of solidification (crystallisation) of an alloy whether shrinkage cavities, which form as a result of liquid and solid contraction, will be concentrated in one place, distributed throughout the casting as shrinkage porosity, or whether external cavities will be formed. The mechanism of solidification in turn is affected by the chemical composition impurities, gases dissolved in the metal or alloy, heat content and temperature disiribution in the metal and in the mold during solidification, etc.

The knowledge of solidification contraction of different alloys is of a considerable practical value because it influences the size of risers necessary to compensate the contraction and diminate shrinkage cavities. Most technological tests used for determination of shrinkage tendency of foundry alloys as the tests after Bureau of Standards, Piwowarski, Pilling-Kihlgren, Schwarz, etc., are designed only for testing the total contraction of alloys. An attempt has been made to develop a simple test suitable for rapid and more accurate determination of liquid and solidification contraction of non-ferrous metals and alloys. The method has been checked with a series of aluminium alloys.

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SYNOPSIS

A method for testing liquid and solidification contraction of non-ferrous metals has been suggested. Cylindrical test specimens 75 mm diameter and 75mm high are cast in a 5-part steel permanent mold with controlled temperature. The permanent mold is designed so that the ingate can be closed immediately after casting to prevent the gating system from influencing the solidification of the test specimen. At the same time a small cylindrical specimen is being cast for checking the density and for dilatometric tests. Simple relations are given for calculating the liquid contraction, solidification contraction as well as the solid and total contraction, when knowing the weight of test specimens cast at two different temperatures. The method has been demonstrated in checking the contraction of a series of aluminium alloys. The effect of magnesium, copper and silicon on contraction of aluminium alloy castings is shown in the composition range up to 12% Mg, 11% Cu and 17% Si.

1. Derivation of correlations

The total volumetric contraction of a casting ($\triangle V$) is given by the sum of the volumetric contraction in liquid state ($\triangle V_3$), solidification contraction ($\triangle V_2$) and solid contraction ($\triangle V_1$)

$$\triangle V = \triangle V_1 + \triangle V_2 + \triangle V_3 .$$

or if expressed in percentage of the volume of the mold cavity V_0 :

$$e = e_1 + e_2 + e_3 \quad \ldots \quad \ldots \quad (1)$$

where

$$e_i = \frac{\triangle V_i}{V_0} \times 100\ (\%) \quad (i = 1,\ 2,\ 3)$$

The total contraction can be calculated from the difference between the theoretical weight of the cast specimen and its actual weight :

$$e = \frac{V_O.s - G_A}{V_O.s} \times 100\ (\%) \qquad \dots \qquad \dots \quad (2)$$

where

V_O=volume of the mold cavity (cm^3)
G_A=actual weight of the specimen (g)
s=theoretical density of the material (g/cm^3)

If the remaining conditions during casting and solidification are kept constant, it can be assumed that minor changes in casting temperature will not affect significantly the solidification and solid contraction of the alloy and only the liquid contraction will vary with temperature. It is therefore possible to calculate the liquid contraction of an alloy when knowing the total volumetric shrinkage e_A, e_B *at two* different casting temperatures t_A and t_B :

$$e_A = e_1 + e_2 + e_2^A$$
$$e_B = e_1 + e_2 + e_3^B$$

$$e_B - e_A = e_3^B - e_3^A \qquad \dots \qquad \dots \quad (3)$$

The total volumetric contraction at casting temperatures t_A and t_B can be determined by checking the respective values G_A and G_B and with the help of equation (2) :

$$e_A = \frac{V_O.s - G_A}{V_O.s} \times 100$$

$$e_B = \frac{V_O.s - G_B}{V_O.s} \times 100$$

Since :

$$e_3^A = b(t_A + t_L) \times 100 \qquad \dots \qquad \dots \quad (4)$$

and $e_3^B = b(t_B - t_L) \times 100$

where

b=coefficient of volumetric contraction of the melt ; and

t_L=liquidus temperature of the alloy,

it is possible to write equation (3) :

$$\frac{G_A - G_B}{V_O.s} = b(t_B - t_A)$$

Hence

$$b = \frac{G_A - G_B}{V_O.s(t_B - t_A)} \quad \text{and using (4) :}$$

$$e_3^A = \frac{G_A - G_B}{V_O.s} \times \frac{t_A - t_L}{t_B - t_A} \times 100 \qquad \dots \quad (5)$$

TABLE I Chemical composition and corresponding solidus and liquidus temperatures

Designation	Type	Chemical composition	T_S (°C)	t_L (°C)
01	Al	Al 99·9%	660	660
02	Al Mg 3	2·69% Mg	620	650
03	Al Mg 7	6·94% Mg	565	630
04	Al Mg 9	9·14% Mg	535	620
05	Al Mg 12	12·13% Mg	500	607
06	Al Cu 3	2·95% Cu	600	655
07	Al Cu 5	5·30% Cu	548	645
08	Al Cu 9	9·02% Cu	548	635
09	Al Cu 11	10·80% Cu	548	630
10	Al Si 2	1·93% Si	577	635
11	Al Si 4	4·27% Si	577	620
12	Al Si 7	7·17% Si	577	610
13	Al Si 11	11·10% Si	577	577
14	Al Si 17	17·29% Si	577	670

Note : Solidus and liquidus temperatures after Smithells : Metals reference book I.

If the temperatures t_A and t_B are chosen so that $t_A = t_L + 100°C$ and $t_B = t_L + 200°C$, equation (5) is reduced to a simple expression :

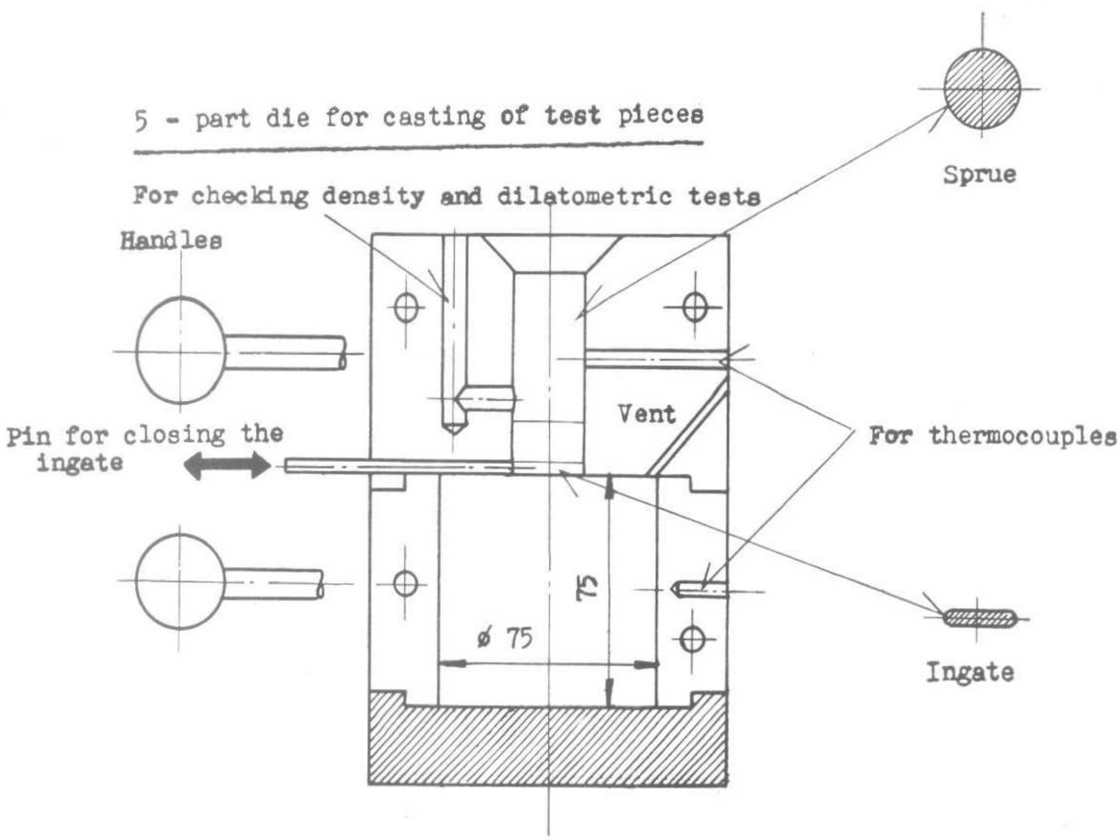
$$e_3^A = \frac{G_A - G_B}{V_O.s} \times 100 \qquad \dots \qquad \dots \quad (6)$$

Solid contraction can be easily determined with the help of the coefficient of linear expansion (a) in the temperature range between room temperature and the solidus temperature. Assuming that the coefficient of volumetric expansion in solid state is approximately 3a :

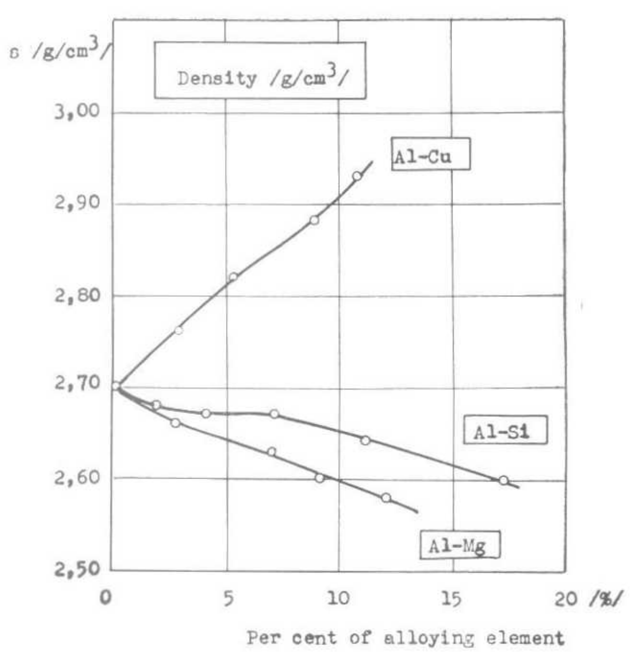
$$e_1 = \frac{V_s}{V_o} \times 3a(t_S - t_{20}) \times 100 \qquad \dots \qquad \dots \quad (7)$$

where

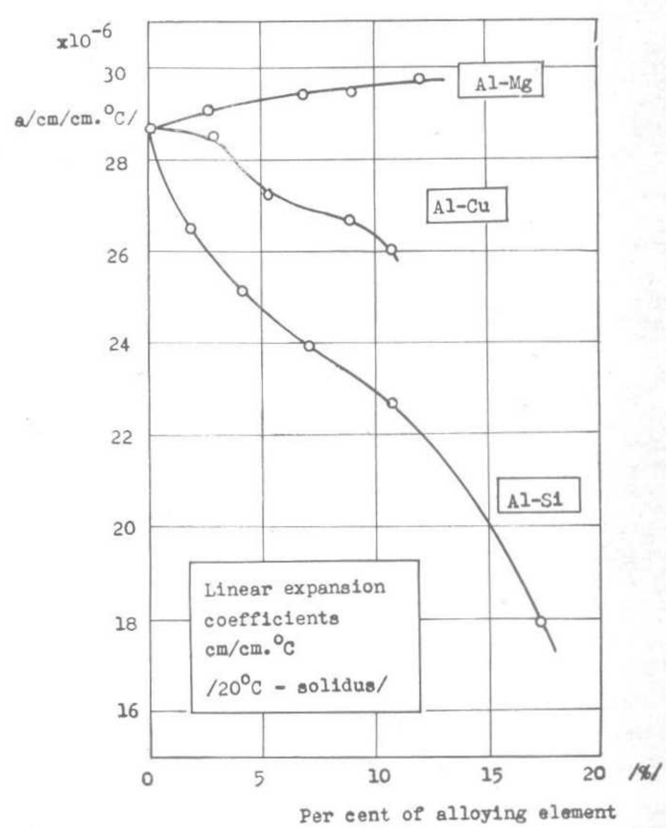
V_s=volume of specimen at solidus temperature t_S



1 *Steel permanent mold for contraction testing*



2 *Effect of chemical composition on density of cast aluminium alloys*



3 *Effect of chemical composition on linear expansion coefficients of cast aluminium alloys in temperature range 20°C to solidus*

Because

$$V_s = \frac{G_A}{s} \left[1 + 3a(t_S - t_{20}) \right]$$

$$e_1 = \frac{G_A}{V_O.s} \left[3a(t_S - t_{20}) \times 9a^2 (t_S - t_{20})^2 \right] \times 100$$

As the second term in brackets is negligible compared with the first one, it is possible to write :

$$e_1 = \frac{G_A}{V_O.s} \times 3a\ (t_S - t_{20}) \times 100 \quad \dots \quad \dots \quad (8)$$

Using equations 1, 2, 6 and 8 the solidification contraction can be calculated :

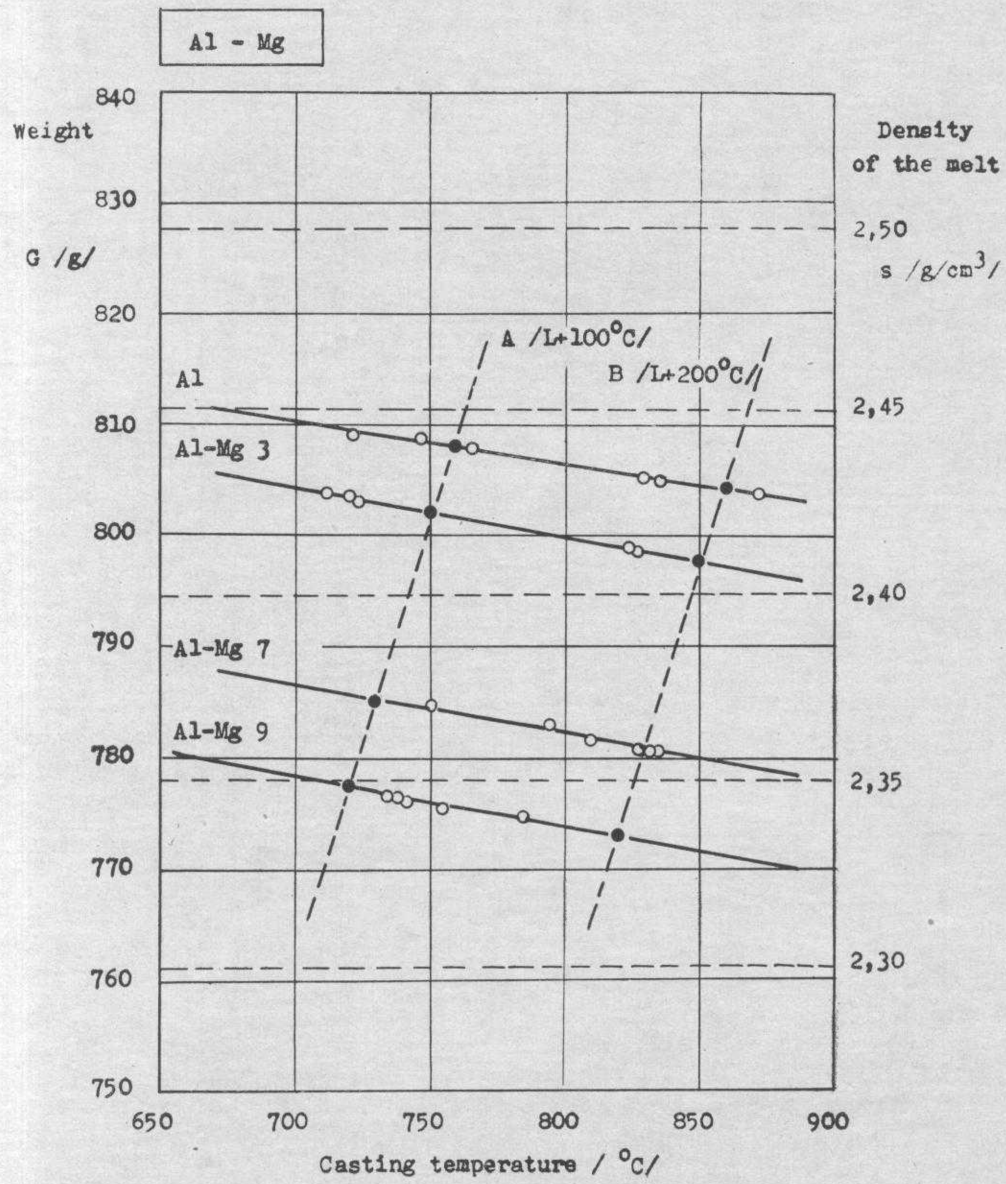
$$e_2 = e - e_1 - e_2 \quad \dots \quad \dots \quad (9)$$

or

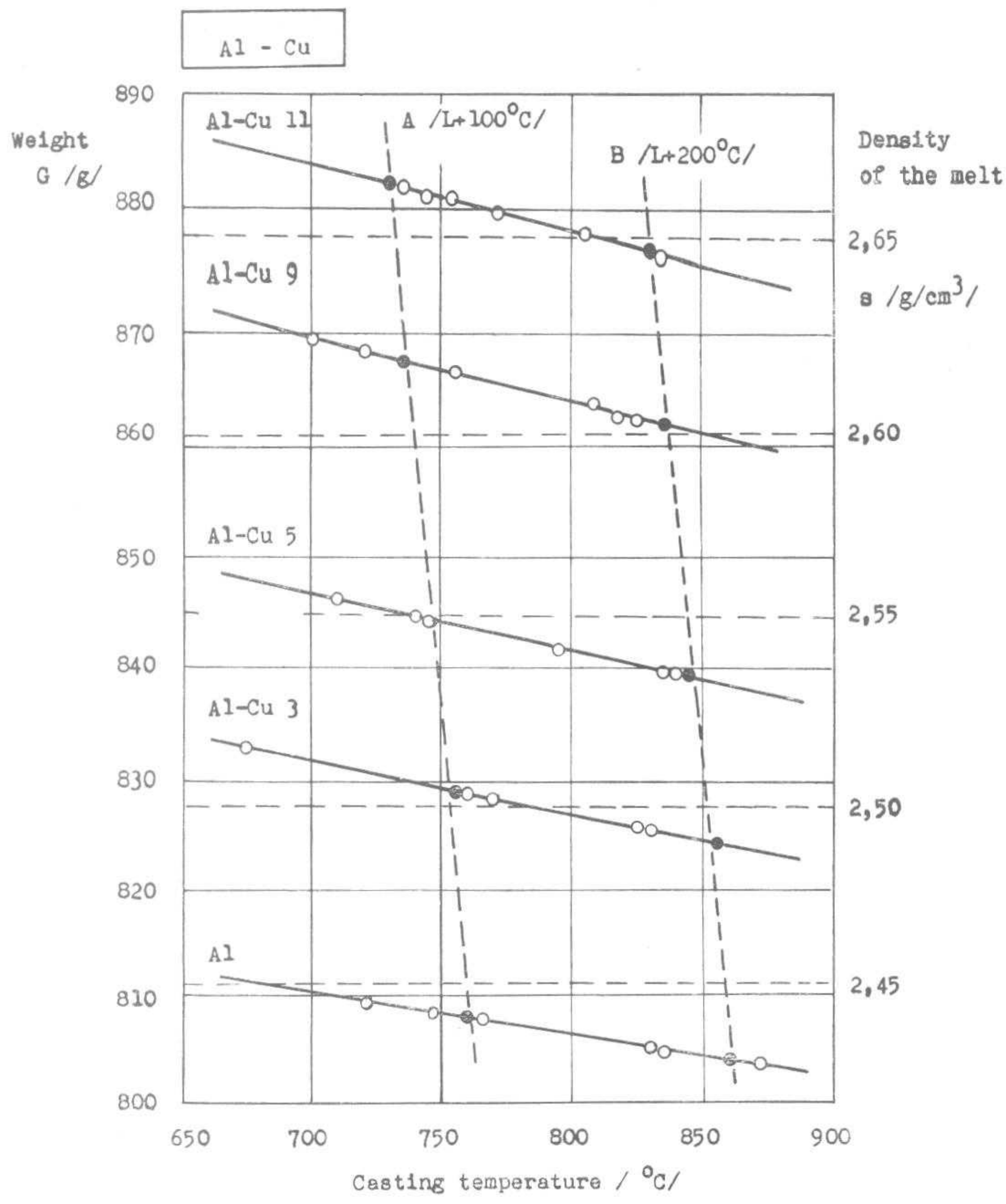
$$e_2 = \frac{100}{V_O.s} \{ V_O.s - G_A [2 + 3a(t_S - t_{20})] + G_B \} \quad (10)$$

where G_A and G_B are weights of specimen cast at temperatures $t_A = t_L + 100°C$ and $t_B = t_L + 200°C$ respectively.

In all equations when calculating V_O, the thermal expansion of the mold must be taken in account.



4 *Effect of casting temperature on weight of specimens and on liquid density (Al-Mg alloys)*



5 *Effect of casting temperature on weight of specimens and on liquid density (Al-Cu alloys)*

2. *Experimental procedure*

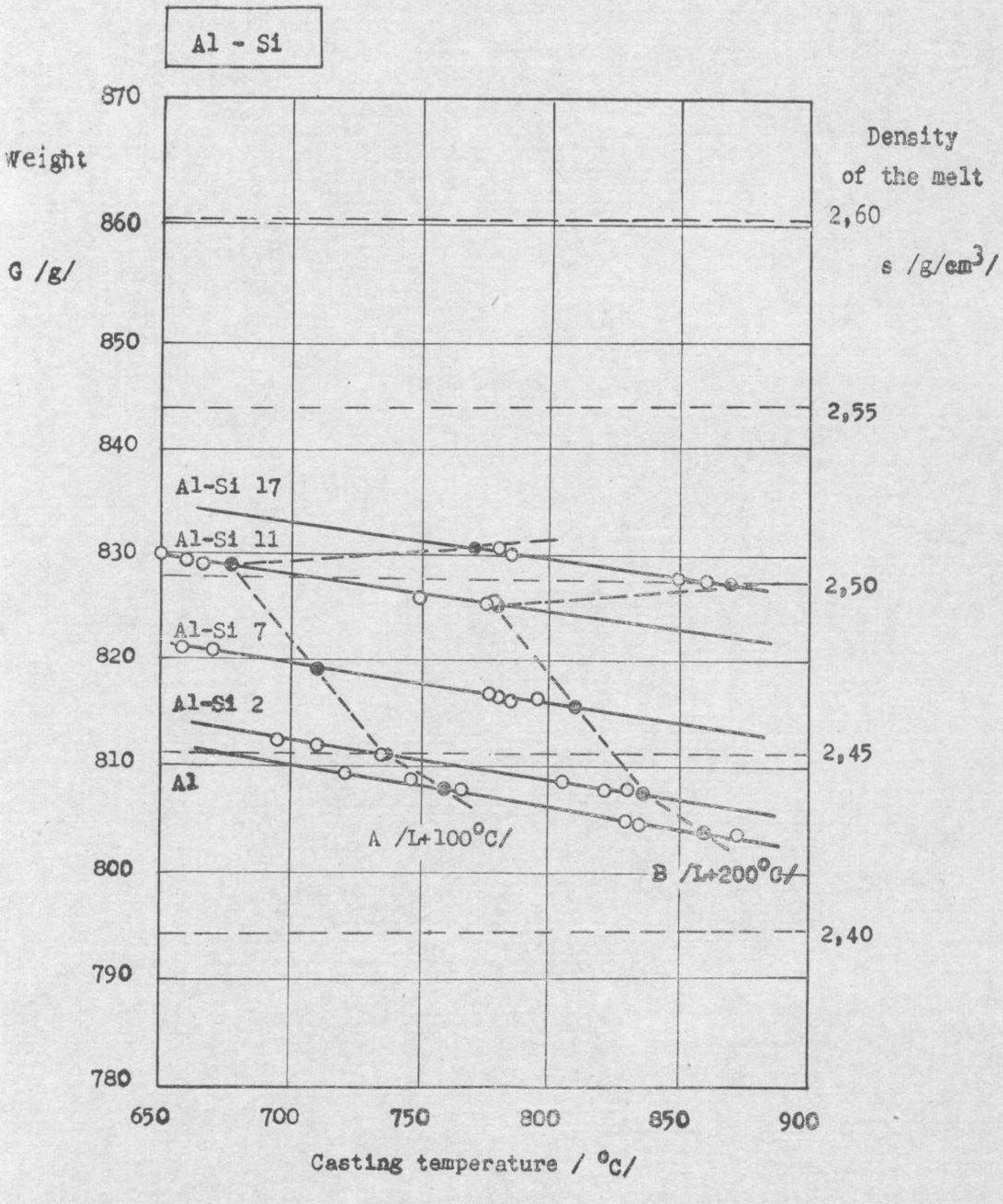
A steel permanent mold (Fig. 1) has been used for casting cylindrical test specimens 75 mm diameter and 75 mm high.

The permanent mold is divided horizontally and vertically into 5 parts. In the upper part the gating system is placed consisting of a cylindrical sprue 25 mm diameter and ending with a flat ingate 25×5 mm. The main feature of the test die is that the ingate can be closed immediately after casting by a pin 5 mm diameter to prevent the gating system from influencing the solidification of the test specimen. Another cylindrical specimen 8 mm diameter is attached to the sprue and cast simultaneously, for checking the density of the alloy and for dilatometric tests.

Before casting, the permanent mold was preheated and kept at constant temperature 250°C±10°C using a combination of gas heater and air cooling. Built-in thermocouples have been used to check the mold temperature in three different places.

An induction melting furnace 20 kg capacity was used for melting the experimental alloys. The casting temperature was checked by an immersion pyrometer in the ladle immediately before casting and during casting using a NiCr-Ni thermocouple placed in the gating system and attached to a potentiometric recorder.

Six specimens were cast of each alloy at different



6 *Effect of casting temperature on weight of specimens and on liquid density (Al-Si alloys)*

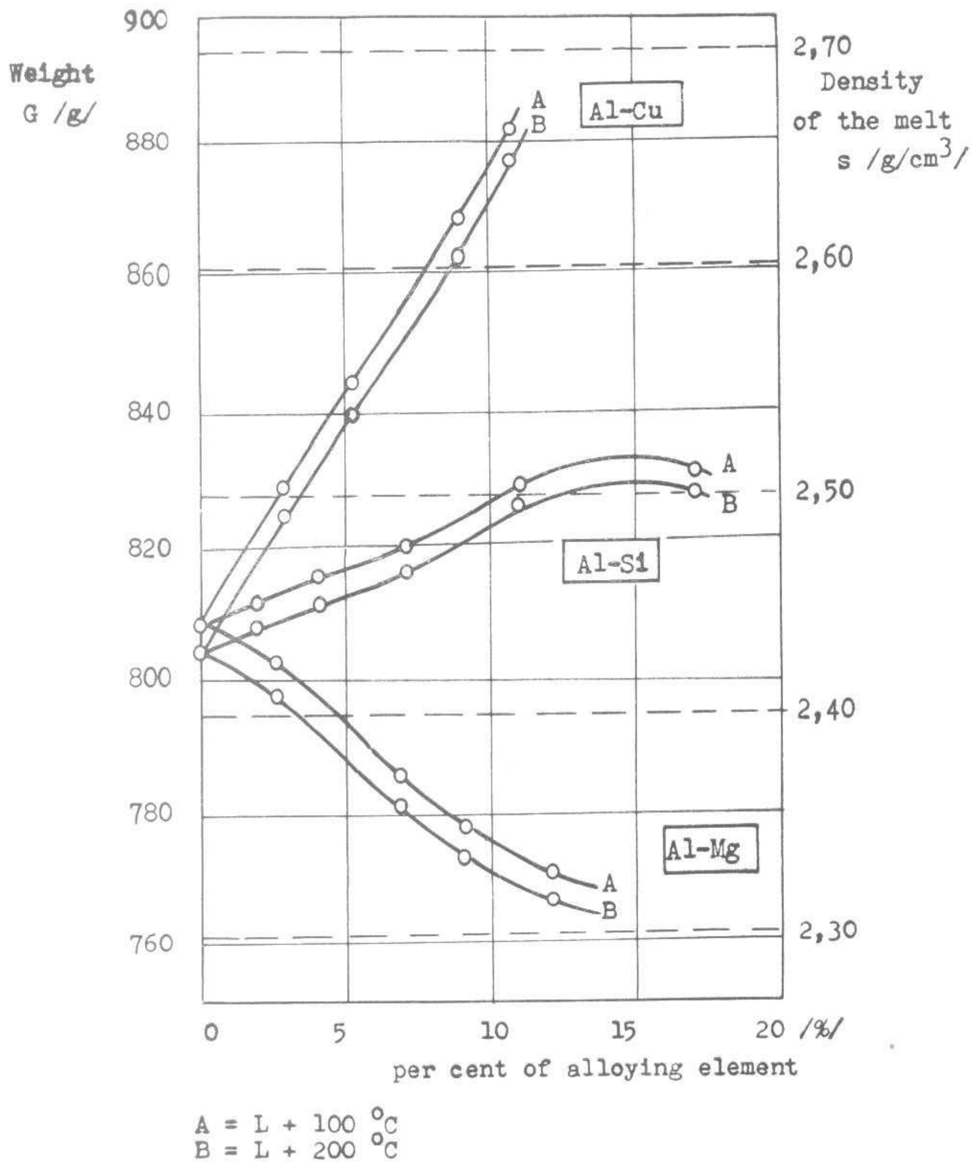
casting temperatures, approximately 100°C and 200°C over the liquidus temperature. The density of the alloys was determined by weighing the cast and machined cylindrical specimens 7 mm diameter in air and in water. The values thus obtained were found sufficiently close to the theoretical density.

Dilatometric tests have been made using cast and machined specimens 5·5 mm dia. and 30 mm long with built-in thermocouples. Linear expansion coefficients have been determined for different temperature ranges up to approx. 50°C below the solidus temperature and, by extrapolation of these values, up to the solidus temperature.

3. Results and discussion

A series of aluminium-magnesium, aluminium-copper and aluminium-silicon alloys has been tested, with Mg content up to 12%, Cu content up to 11% and Si content up to 17% approximately. The experimental alloys have been prepared out of pure metals (Al 99·9% containing 0·03% Fe, 0·06% Si, traces of Zn, Mn, Cu, Mg 99·9%, electrolytic copper and metallic silicon). Chemical composition and the corresponding solidus and liquidus temperatures are given in Table I.

The densities of experimental alloys are shown in Fig. 2. The extrapolated values of linear expansion



7 *Effect of chemical composition on G_A and G_B and on liquid density at temperature $t_A = t_L + 100°C$ and $t_B = t_L = 200°C$*

coefficients in temperature ranges up to solidus temperature are shown in Fig. 3.

The effect of casting temperature on the weight of cast specimens is shown in Figs. 4, 5 and 6. The values obtained have been used for calculating the liquid densities at different temperatures shown in the same diagrams.

In diagrams 4, 5 and 6, temperatures $t_A = t_L + 100°C$ and $t_B = t_L + 200°C$ are marked, giving the values G_A and G_B.

The effect of chemical composition on values G_A and G_B and on liquid density of experimental alloys at temperatures t_A and t_B is shown in Fig. 7.

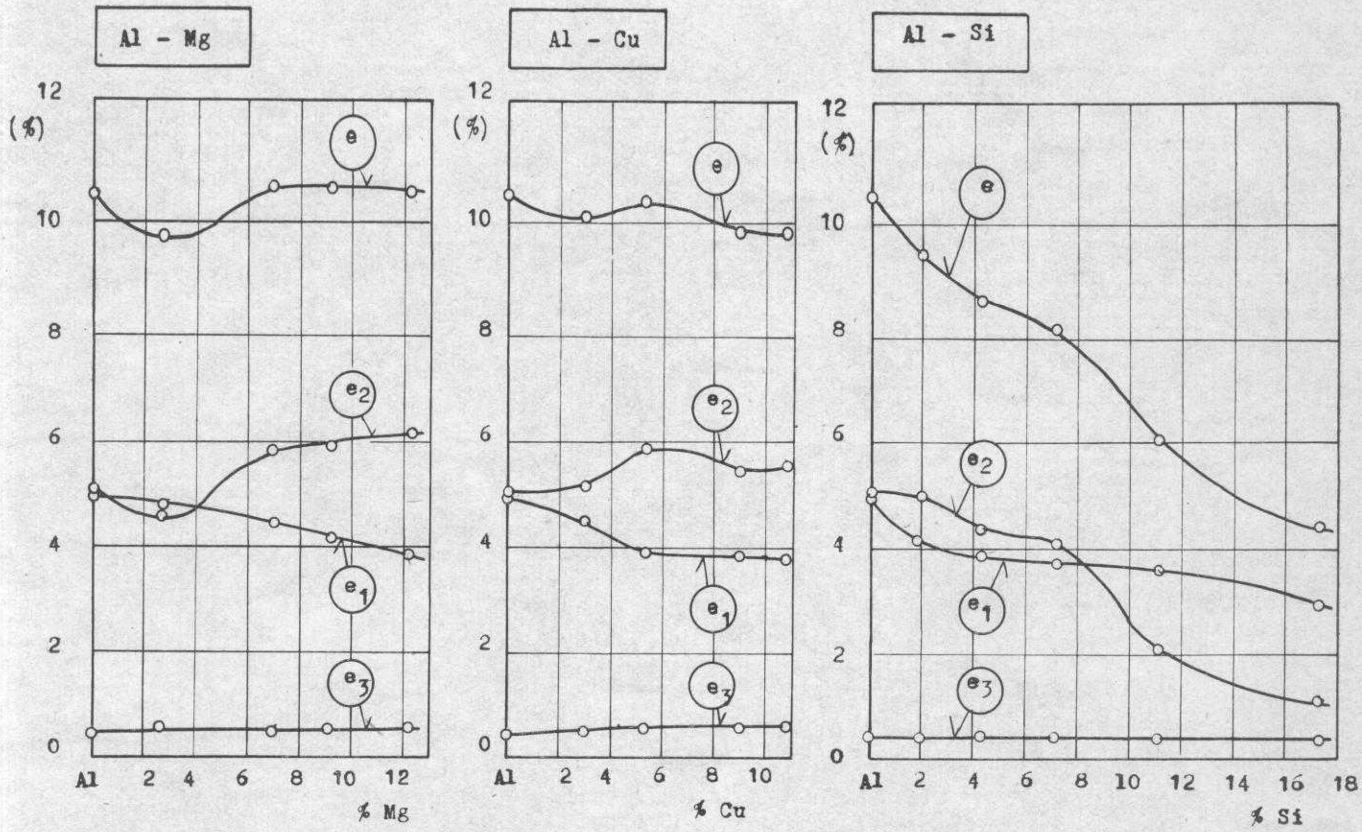
Using the values from Figs. 2, 3 and 7 and equations 2, 5, 8, 9 and 10, the liquid contraction, solidification contraction as well as solid and total contraction of the experimental alloys can be calculated. The main experimental data and results calculated are given in Table. II.

Effect of copper, magnesium and silicon on contraction of aluminium alloys is shown in Fig. 8. All values are given for casting temperatures 100°C over the liquidus temperature.

The calculated liquid contraction is relatively low (0·4 to 0·5%/100°C). Only with the aluminium-copper alloys can any marked influence of chemical composition be seen.

Solid contraction is lower at higher Cu, Mg and Si contents due to lower expansion coefficients (Cu and Si alloys) and due to decrease in the solidus temperature.

The solidification contraction of Al-Mg and Al-Cu alloys first decreases slightly and then increases with increased content of alloying elements and varies bet-



8 *Effect of Mg, Cu and Si on contraction of aluminium castings*
e=total volumetric contraction, e_1=solid contraction, e_2=solidification contraction, e_3=liquid contraction

TABLE II Main experimental data and results

Designation	Alloy	s (g/cm³)	a.10⁻⁶ (cm/cm.°C)	G_A (g)	G_B (g)	V_o.s (g)	e_A (%)	e_1 (%)	e_2 (%)	e_3 (%)
01	Al	2·70	28·7	808	804	902	10·42	4·94	5·04	0·44
02	Al Mg 3	2·66	29·1	802	797·5	888·7	9·74	4·74	4·51	0·51
03	Al Mg 7	2·63	29·4	785	781	878	10·60	4·31	5·83	0·46
04	Al Mg 9	2·60	29·5	777·5	773	869	10·52	4·08	5·92	0·52
05	Al Mg 12	2·58	29·7	771·4	767	862	10·50	3·83	6·15	0·52
06	Al Cu 3	2·76	28·5	829	824·4	922	10·10	4·46	5·14	0·50
07	Al Cu 5	2·82	27·2	844·5	839·2	942	10·04	3·86	5·91	0·57
08	Al Cu 9	2·88	26·7	867·5	862	962	9·83	3·82	5·43	0·58
09	Al Cu 11	2·93	26·0	882	876·5	978	9·82	3·71	5·54	0·57
10	Al Si 2	2·68	26·5	811	807·5	896	9·49	4·01	5·09	0·39
11	Al Si 4	2·67	25·1	815	811	892	8·64	3·87	4·32	0·45
12	Al Si 7	2·67	23·9	819·1	815·5	892	8·17	3·68	4·10	0·41
13	Al Si 11	2·64	22·7	829	825·5	882	6·01	3·56	2·05	0·40
14	Al Si 17	2·60	17·9	830·7	827·5	869	4·41	2·86	1·18	0·37

Contractions are expressed as percentages of the volume of the mold cavity and are related to casting temperature $t_A = t_L + 100°C$.

ween 4·5 and 6·15%. Silicon decreases the solidification to only 2% at 12% Si and 1·2% at 17% Si.

4. Conclusion

The results obtained are in good accordance with the literature and experience, and the suggested method seems to provide a relatively simple way of testing the contraction of non-ferrous metals.

As a metallic mold is used, the results can slightly differ from results obtained in sand molds, but the difference will apparently not be significant.

Discussions

Dr **R. T. Parker** (Alcan Research and Development Ltd., England) : Did the author control the hydrogen contents of the alloys and the sodium contents of the Al-Si alloys, as these are known to affect apparent shrinkage values ?

Dr **N. Samek** (Author) : The hydrogen content of the alloys was not checked but the melting conditions of all alloys were very closely controlled to ensure possibly uniform and comparable results.

A Speaker : Why is there no linearity in the expansion coefficient/composition curves ?

Dr **N. Samek** : I do not see any reason for such a linearity. The diagram shows values for temperature ranges always up to the solidus temperature which changes with chemical composition. There could be linearity only when comparing values for constant temperature ranges.