Int. J. Heat Mass Transfer. Vol. 24, No. 7, pp. 1089–1095, 1981
Printed in Great Britain

0017-9310/81/071089-07 $02.00/0
Pergamon Press Ltd.

AN INSTRUMENTATION SCHEME FOR MULTIPOINT MEASUREMENT OF MOULD–METAL GAP IN AN INGOT CASTING SYSTEM

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(*Received* 24 *March* 1980 *and in revised form* 20 *September* 1980)

Abstract—An instrumentation scheme is developed for simultaneous measurement of the time–gapwidth history at various locations of the mould–metal interface during solidification in an ingot casting system. Several casting experiments using this instrumentation show the variation of the time of inception of the gap and the variation of the gap size along the height and around the periphery of the ingot surface.

NOMENCLATURE

A,	surface area of the measuring probe;
$C_{ag}(t)$,	capacitance due to the airgap;
C_m,	capacitance due to the mica layer;
$C_{me}(t)$,	measured equivalent capacitance;
h,	distance of the measuring probe from the bottom of the mould wall;
H,	height of the mould wall;
K,	0.0884, conversion factor for e.s.u. to picofarad;
l,	distance of the measuring probe from the edge of the mould wall along the broader dimension;
L,	length of the broader dimension of the mould wall;
r,	radius of the measuring probe;
w,	distance of the measuring probe from the edge of the mould wall along the narrower dimensions;
W,	length of the narrower dimension of the mould wall.

Greek symbols

$\delta_{ag}(t)$,	width of the airgap;
ε_{ag},	permittivity of air in the gap.

1. INTRODUCTION

IN AN ingot-mould casting system the airgap formed at the mould–metal interface has got an important effect on the cooling time, casting quality and the mould life. The gap is normally observed to be formed a little later than the instant of pouring and the gapwidth is confirmed to be a function of time and to be different at different points on the casting surface. But due to the inherent complexity of this two-phase, high temperature transient system very few successful experimental techniques [1–4] to measure gapwidth have so far been reported. Moreover most of these experimental methods could only measure the inception time of gap formation and not the transient variation of the gapwidth. Oeters and Sardemann [5] have proposed an experimental technique which could measure the time of airgap formation and also the variation of gap size during solidification in an indirect manner from the relative motion of the solidified layer with respect to the mould outer wall using an inductive path recorder. Recently we [6] proposed a direct experimental technique for measuring the time–gapwidth history at a single point on the casting surface, based on the variation of the effective capacitance between the mould wall and the separated solidified cast surface. This method is capable of measuring both the inception time and also the time–gapwidth history of the gap.

The same concept of gauging the gapwidth from the gap-capacitance may further be utilised for simultaneous measurement of time–gapwidth history at more than one point on the casting surface if a suitable interface is developed between the sensing probes of the prime system and a multichannel recorder.

The present paper describes the essential features of a 12-channel interface developed for continuous, multipoint, in-process measurement of the gapwidth. The interface has been successfully employed for measurement of the time–gapwidth history during solidification at different points on the casting surface. Finally the experimental results obtained by the proposed measurement scheme are explained with physical reasoning and also compared with the results of other investigators wherever possible.

2. PRINCIPLE OF GAPWIDTH MEASUREMENT

The principle of gapwidth measurement is based on the variation of effective capacitance between two electrodes, one being the sensing probe fitted to the mould wall and the other is the solidifying and contracting wall of the casting.

The air layer between the solidified casting and the probe fitted to the mould surface constitutes a dielectric; the thickness of this layer continually increases

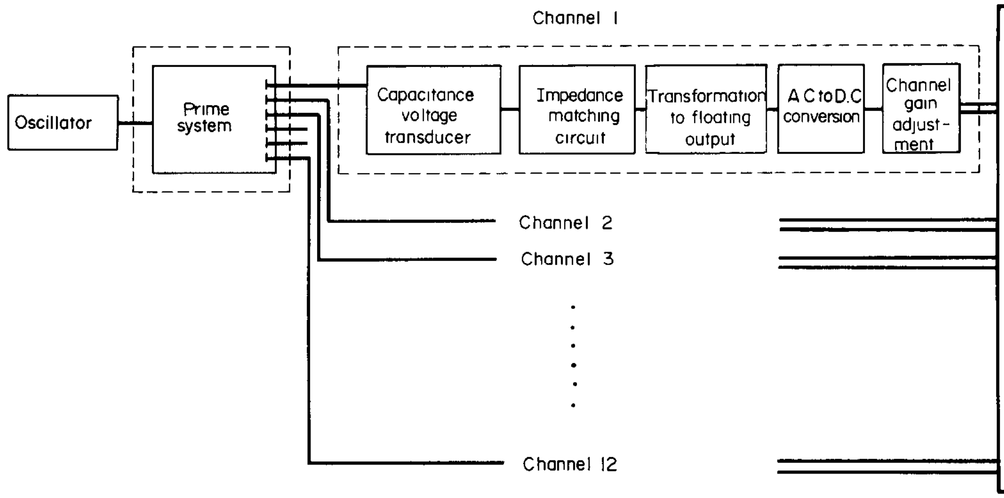

FIG. 1. Schematic diagram of the measuring circuit.

with time as the casting cools down and solidifies. A layer of mica insulation is pasted on the precisely machined surface of the sensing probe in order to prevent short-circuiting and sticking at the instant of pouring. The dielectric for which the capacitance is measured consists of a layer of mica, of a fixed thickness, in series with an air layer of thickness $\delta_{ag}(t)$ varying with time. The system is then assumed to behave like a series combination of two parallel plate capacitors neglecting the fringe effects. Such an assumption is justified because the area of the dielectric is very large compared to the total dielectric thickness.

The final expression for the measured equivalent capacitance $C_{me}(t)$ and the capacitance across the air gap may be written as

$$C_{me}(t) = \frac{C_m C_{ag}(t)}{C_m + C_{ag}(t)} \qquad (1)$$

and

$$C_{ag}(t) = \frac{K\varepsilon_{ag}A}{\delta_{ag}(t)}. \qquad (2)$$

Equations (1) and (2) may then be combined to result into the following expression for time dependent width of the airgap

$$\delta_{ag}(t) = \frac{K\varepsilon_{ag}A[C_{me}(t) - C_m]}{C_{me}(t)C_m}. \qquad (3)$$

The effect of stray capacitance and the minimization of the stray effect in this experimental method has been considered in detail in an earlier report of ours [6] on this subject.

3. THE INSTRUMENTATION

The instrumentation scheme that measures the transient variation of mould–metal gapwidth is shown in Fig. 1. The variable capacitance sensed at each of the measuring points of the prime system is connected to a resistance to form an R–C circuit which is fed by an oscillator to get an AC voltage output across the resistor at the desired frequency. This AC voltage is consequently transformed to a DC output which is recorded in the visicorder.

The entire measuring system may now be subdivided into the following parts:

(a) *The prime system*

The prime system consists of a metallic mould into which molten metal is solidified. The variation of gap-capacitance at the mould–metal interface is sensed with an arrangement shown in Fig. 2. The T-shaped measuring probes are introduced through holes and flushed with the inner mould wall. For measurement of airgap, the probes are electrically insulated from the mould wall by a suitable insulating material which remains non-conducting even when the mould gets heated up. In order to prevent short circuit and sticking, the initial contact between the measuring probe and the hot liquid metal is avoided by pasting a mica sheet of known thickness on the precisely machined surface of the probe. The oscillator supply path

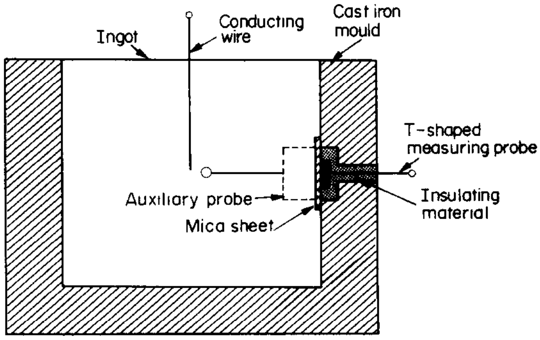

FIG. 2. The prime system.

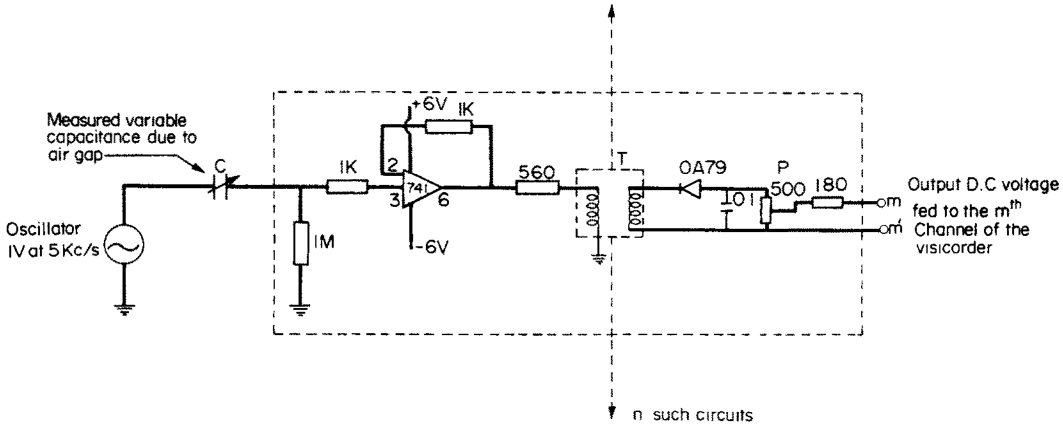

FIG. 3. Circuit diagram for *m*th channel of the interface.

to each of the probes through its respective capacitor–resistor circuit is established by means of a conducting wire dipped in the centre of the casting. The return path of all the circuits is the common ground.

(b) *Interface for capacitance measurment*

The probe terminals at the measuring points and the ground, lead to the input of a multichannel interface. The interface accepts through the sensing probes, the variation of capacitance at its input and produces at its output a continuous variation of DC voltage matching the input of a data logger. For the present test set-up, the interface has been developed for continuous record of output at 12 different channels of a Honeywell visicorder Model 906T. Figure 3 shows the circuit diagram of one of the channels of the interface.

In the first part of the interface a resistor is provided in series to each of the variable capacitance to be measured. The oscillator supply connected to the prime system produces an AC voltage proportional to the capacitance variation across the resistor. The purpose of the remaining part of the interface is two fold, viz. (1) to transform the AC voltage signal to a measurable DC output; (2) to ensure impedance matching with the recording device.

A unity gain buffer amplifier 741C is used for impedance matching. The input impedance of the buffer amplifier is very high relative to the source impedance. A signal isolating (1:1) transformer T is used to facilitate measurement in a visicorder which requires floating input for each of its channels. The secondary signal is rectified and filtered by a conventional diode and capacitance combination. The potentiometer P adjusts the overall gain of each channel.

(c) *Recording of output signal*

The output signal is recorded in a visicorder which is a multichannel general purpose oscillograph. The instrument is a direct-reading type and uses galvanometers with magnet assembly for recording the output signal on photographic paper. The galvanometers used for recording are highly sensitive electromagnetically damped type. A specified external damping resistor is installed in the shunt position with each galvanometer. The value of the series resistance is adjusted depending on the sensitivity requirement.

4. MEASUREMENT PROCEDURE

The first step in the measurement procedure is an accurate calibration of different measuring channels by recording the deflection of the galvanometer spot in the visicorder for standard value of capacitances. Deflection of the galvanometer spot at a particular channel immediately after pouring indicates the parallel plate capacitance between the molten metal and the connecting probe with the mica sheet as the dielectric in between. This initial capacitance due to the mica sheet is also measured separately at each of the measuring point before pouring by means of an auxiliary probe as shown in Fig. 2. A drop in capacitance from this initial value indicates the inception of an airgap. Normally as the solidification progresses, the gapwidth increases, leading to a reduction of the recorded deflection at the visicorder which is in turn proportional to gap-capacitance.

5. EXPERIMENTAL

With the above set-up, measurements have been carried out in a rectangular cast iron mould of dimension 114.3 × 76.2 × 152.4 mm and a mould-wall thickness of 12.7 mm. The location of measuring probes at mould walls I, II, III and IV are shown in Fig. 4. Test castings are made from a low melting-point metal, lead 99.9% pure. Cast metal is melted on a fire brick bath using an oil-fired furnace. Molten metal is transferred to the pouring ladle made of natural clay and poured into the metallic mould kept at a temperature of 40°C. The mould box is placed on a thick layer of sand and fire bricks. Temperature of the molten metal before pouring is measured with a

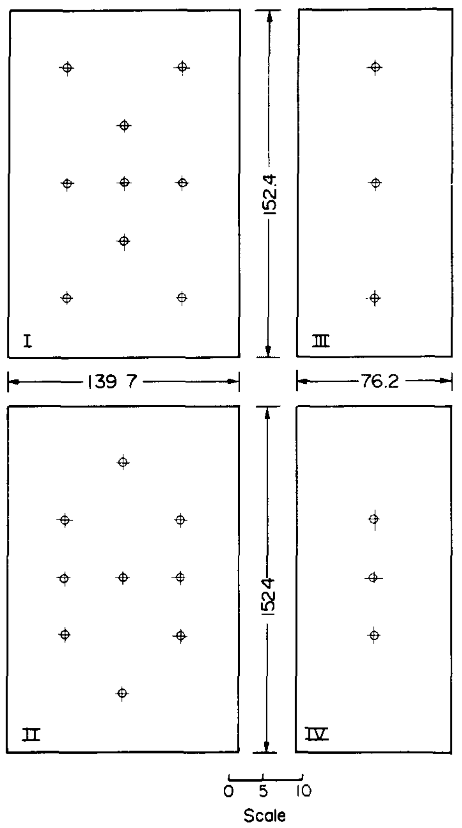

Fig. 4. Location of measuring probes on the mould wall.

chrome–alumel thermocouple. In all the experiments, molten metal is poured at a constant temperature of 520°C.

6. RESULTS AND DISCUSSION

A large number of casting experiments were carried out using the above instrumentation scheme. The continuous transient variation of the gapwidth simultaneously for 12 different points on the mould inner wall are recorded as direct results of the present experiments. The records indicate the instant of gap-formation for the measuring points as well as the gapwidth at those points at any instant of time after pouring. Some of the interesting results are given below to show the usefulness and versatility of the measurement scheme.

The measured variation of gapwidth with time for the probes fitted at the centre of broader and narrower dimension of the mould are plotted in Fig. 5. The gapwidth increases with time for both the walls as expected. The results also indicate that the gap forms comparatively earlier at the narrower dimension of the mould wall and at any instant of time during solidification the size of the gap is more at the narrower dimension of the casting than at the broader one. These results are in conformity with the observation of the earlier investigators [4, 5] for rectangular casting.

Figure 6 shows the variation of airgap inception time along the height of casting on the broader dimension of the mould wall. The result shows a steady lengthening of the time of inception of airgap formation from ingot-top to ingot-bottom. Similar variation is also observed on the narrower dimension of the mould wall. The observed delay in separation at the bottom of the ingot relative to the top may be attributed mainly to the comparatively higher value of the ferrostatic pressure near the bottom.

The variation of the gapwidth along the height of the casting for the narrower dimension of the mould wall is shown in Fig. 7 for different instant of time after pouring. Results show that at any instant of time during solidification, gapwidth is maximum at the top and gradually decreases towards the bottom. The slower rate of gap formation near the ingot bottom appears to be due to the presence of a ferrostatic pressure higher than at the top. The variation of air-gap inception time along the broader dimension of the

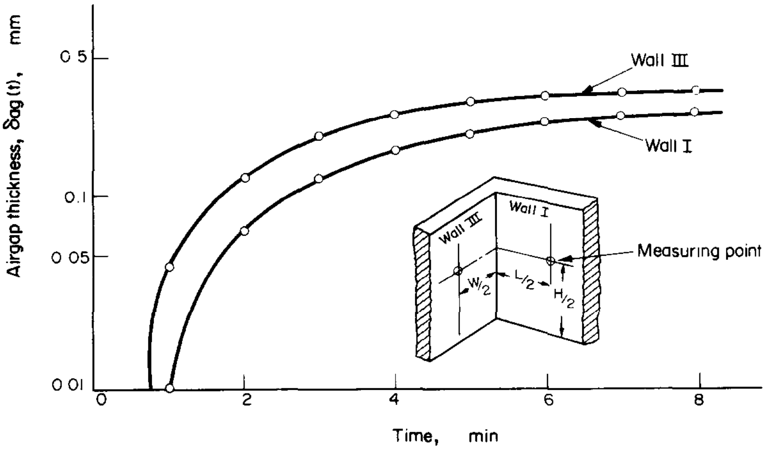

Fig. 5. Variation of gapwidth with time at the centre of broader and narrower dimension of mould wall.

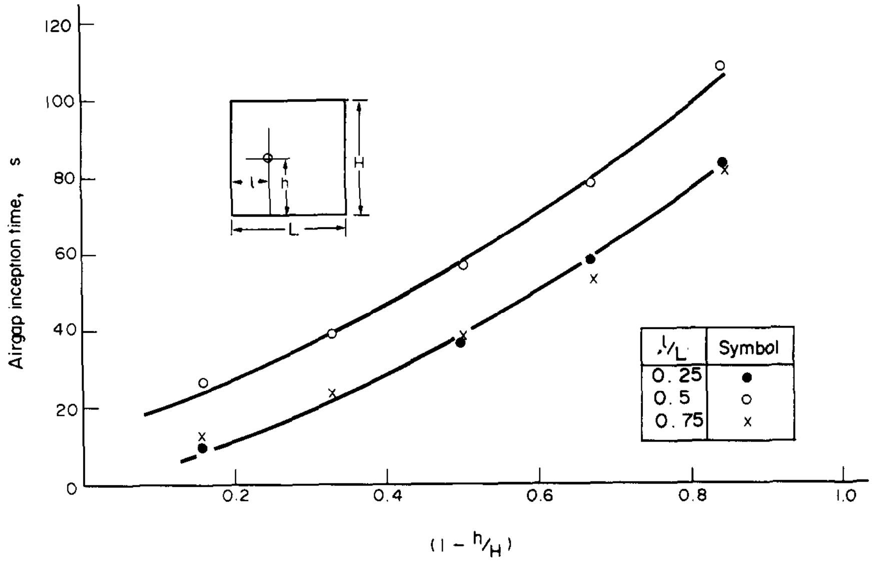

Fig. 6. Variation of airgap inception time along the height of casting.

ingot at different heights shown in Fig. 8 indicate that at a particular height of the casting, airgap formation time is maximum at the middle and reduces towards the edge. The reason for this may be the comparatively quicker solidification at the corners.

The trend of variation of the airgap inception time and also the positional variation of the gapwidth along the mould height and at different points around the mould perimeter for a particular height as observed in Figs. 5, 6, 7 and 8 in the present experiments compare favourably well with the findings of Diener, Drastik and Haumann [4] and Oeters and Sardemann [5] for rectangular casting.

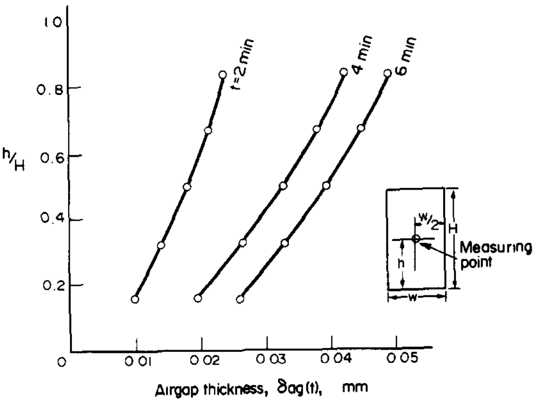

Fig. 7. Variation of gapwidth along the height of casting.

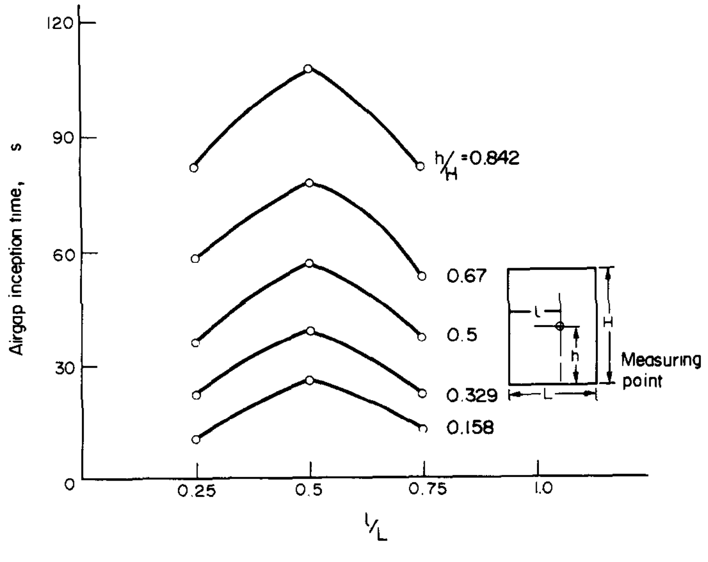

Fig. 8. Peripheral variation of airgap inception time.

But the experimental method of Diener, Drastik and Haumann [4] was limited to the measurements of airgap inception time only. The method of Oeters and Sardemann [5] has the disadvantages of fixing the measuring probe under pressure to the newly formed solid skin for which a prior knowledge of the time of gap formation is necessary. Further the presence of the probe pressing the ingot skin may considerably interfere the solidification process itself.

As far as the correctness of the measurement is concerned it may be worthwhile to note that in the present method, the additional thermal resistance of the mica sheet pasted on the mould inner wall alters the local heat transfer rate which in turn affects the phenomenon of airgap formation. But a simple calculation of the different thermal resistances from the measured temperature distribution [7] of the mould at different instant of time shows that the additional conductive resistance due to the mica sheet is always less than 5% of the overall thermal resistance. Specially after the inception of the airgap, the gap itself forms the largest resistance compared to which the mica sheet resistance is almost negligible. The effect of the mica sheet at the probe interface on the phenomenon of gap formation may therefore be reduced by making the mica sheet thickness as small as practicable.

Regarding the applicability of this instrument for industrial purpose, it is apparent from equation (3) that for a given probe diameter, large gap size required to be measured for industrial casting may give rise to a very small capacitance beyond the resolution of the present instrument. In order to use the present instrument for measurement of large mould–metal gap the probe size is therefore to be changed accordingly to equation (4)

$$r = \sqrt{\left(\frac{\delta_{ag}(t) C_m C_{me}(t)}{0.0884\pi\,[C_m - C_{me}(t)]}\right)} \qquad (4)$$

where the values of C_m and $C_{me}(t)$ may be assumed to be 100 pF and 20 pF respectively for the present instrument.

Figure 9 shows the variation of the probe dimension to be chosen to gauge a given maximum gap width using the present instrument. From a practical viewpoint, the surface area of the castings used in steel industry are also proportionally large to accommodate the big probes without any appreciable sacrifice of the accuracy of measurement.

In view of the above facts the present method which gives a direct record of the time–gapwidth history at different locations on the mould wall simultaneously appears to be relatively simple but reasonably accurate [6] when compared to the other existing techniques of gapwidth measurement.

7. CONCLUSION

The instrumentation scheme proposed in this paper for multipoint measurement of mould–metal gap in an ingot casting system is established through experiments on laboratory scale castings. Further, the present instrument may directly be used even for industrial application with some minor alteration of the probe dimension and selecting a suitable heat resistant electric insulation around the probe specially for high temperature alloys.

Acknowledgements—This work was conducted at the Central Mechanical Engineering Research Institute, Durgapur, India. The authors wish to thank Director of the Institute for his kind permission to publish the paper.

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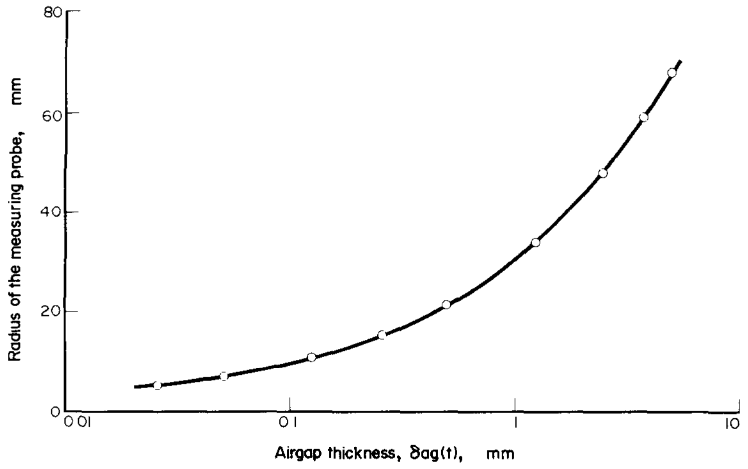

FIG. 9. Curve for selection of probe size for a given maximum airgap thickness.

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UN ENSEMBLE DE MESURE EN PLUSIEURS POINTS D'UN ESPACE MOULE–METAL POUR UN MOULE DE FONDERIE

Résumé—On développe un ensemble expérimental pour la mesure simultanée à plusieurs époque et en plusieurs points de l'interface moule–métal pendant la solidification d'un métal en fonderie. Plusieurs expériences montrent la variation du temps d'apparition de l'espace libre et la variation de l'épaisseur de cet espace suivant la hauteur et la périphérie du moule.

EIN INSTRUMENTIERUNGSPLAN FÜR DIE MESSUNG DES SPALTS ZWISCHEN FORM UND METALL AN MEHREREN STELLEN BEIM BARRENGIESSEN

Zusammenfassung — Es wird ein Instrumentierungsplan für die gleichzeitige Messung des Zusammenhangs zwischen Spaltweite und Zeit an verschiedenen Stellen der Trennfläche zwischen Form und Metall während der Erstarrung beim Barrengießen entwickelt. Mehrere Gießexperimente mit Verwendung dieser Instrumentierung zeigen die Variation der Zeit für die Spaltentstehung und den Verlauf der Spaltweite über der Höhe und am Umfang der Barrenoberfläche.

СИСТЕМА КОНТРОЛЬНО-ИЗМЕРИТЕЛЬНОЙ АППАРАТУРЫ ДЛЯ ИЗМЕРЕНИЯ ЗАЗОРА МЕЖДУ ИЗЛОЖНИЦЕЙ И МЕТАЛЛОМ ПРИ ЛИТЬЕ СЛИТКОВ

Аннотация — Разработана измерительная аппаратура для определения зависимости ширины зазора вдоль границы раздела изложница-металл при затвердевании металла в слитке. Несколько экспериментальных отливок с использованием данной аппаратуры продемонстрировали различия во временах образования промежутка и изменения его размера по высоте и периферии поверхности слитка.