Chapter 13
Design and Fabrication of a Dip Immersion Probe for Melting and Pouring Practice in Casting Technology

Yap Tek Hong, Nadzri Che Kamis, and Choong Chee Guan

Abstract The accuracy of the molten aluminum temperature is essential to produce a good casting product. The solubility of hydrogen gas in molten aluminum is higher when the melting temperature increases. Over-exposure of hydrogen gas on molten aluminum immediately forms a skin of aluminum oxide, Al_2O_3 that causes drawbacks of mechanical properties in the final casting such as shrinkage, gas porosity, and oxide inclusions. Therefore, the melting temperature of aluminum should be kept as low as possible to minimize the hydrogen pick-up. Dip immersion probe (DIP) is designed to control the hydrogen gas solubility in aluminum by optimizing its melting temperature before the casting process. DIP consists of a couple of nickel chromium (NiCr) and nickel aluminum (NiAl) wires that are attached to a pyrometer and calibrated with a sensor of −270 °C to 1260 °C range and in a L-shape with 135° to ensure the ergonomic and safety of the user. Inconel 600 sheath material is used as an outer metal to provide good high-temperature strength, resists chloride-ion stress corrosion cracking, and minimizes oxidation at high temperatures. DIP is cost-effective, reliable, safe, and ergonomic especially for the teaching and learning process of small-scale casting activity in the foundry workshop, as well as technical and vocational education and training (TVET) in polytechnics in Malaysia.

Keywords Melting · Pouring · Casting · Temperature · Dip immersion probe

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Y. T. Hong (✉) · C. C. Guan
Mechanical Engineering Department, Politeknik Tuanku Syed Sirajuddin, Pauh Putra, 02600 Arau, Perlis, Malaysia
e-mail: yap@ptss.edu.my

C. C. Guan
e-mail: dr.choong@ptss.edu.my

N. C. Kamis
Mathematics, Science and Computer Department, Politeknik Sultan Mizan Zainal Abiddin, 23000 Kuala Dungun, Terengganu, Malaysia
e-mail: nadzri@psmza.edu.my

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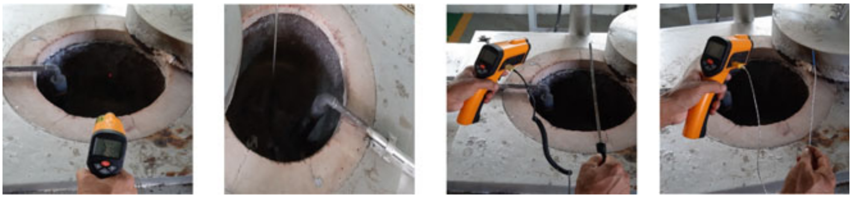
13.1 Introduction

A foundry workshop is a compulsory practical task to be completed by the students of the Mechanical Engineering Department, Polytechnic Malaysia. There are few activities to be carried out in the casting processes including pattern making, sand molding, melting, and pouring process. Casting revolved as one of the earliest metal shaping methods and is implemented by pouring the molten metal into a refractory mold containing the cavity of the shape, hence allowing the molten metal to solidify into the desired shape. In the end process, the object is taken out from the mold by breaking the mold apart (Rao 2001). In the breaking process, the molds are destroyed if sand molds are used, meanwhile, the molds are separated to remove the casting if a permanent mold is used (Sylvia 1999).

Aluminum is one of a large number of casting alloys in use worldwide in major industrial countries. It is notable as a ductile and low-density metal and has good corrosion resistance, and its melting point is about 660 °C. Generally, solubility of hydrogen in solid aluminum is very low, compared to liquid aluminum. However, the overheating of molten aluminum could cause high solubility of harmful hydrogen gas and consequently leads to the formation of the oxide layer (Khanna 2006). This may potentially cause defects such as shrinkage, gas porosity, and oxide inclusions which eventually contribute to drawbacks of mechanical properties in castings (Brown 2002).

Traditionally, the temperature of molten metal in the furnace is exhibited by its indicator device. However, it cannot be assumed as the exact temperature of the molten metal. Hence, the temperature is commonly measured by a probe known as the laser gun. The ability of the gun is limited, and the temperature of molten metal is inaccurate and always misinterpreted. This is caused by the difference between the temperature of the molten metal at immersion and surface of the furnace. As the alternative, an immersion-type probe was chosen to obtain an accurate molten metal temperature in the furnace. Figure 13.1 shows the constraints and comparatives of current measurement devices at the casting process which (a) laser gun thermometer, (b) built-in type ceramic sheath thermocouple, (c) iron chrome sheath thermocouple, and (d) un-sheath glass fiber-insulated thermocouple.

To reduce this problem, an exact temperature of the molten metal must be assumed to avoiding the potentially of casting defects such as gas porosity. Therefore, the objective of this work is to design and fabricate an immersion-type probe to meet the durability, user-friendly, and ergonomic factors, as well as to measure the temperature of molten aluminum accurately for the best quality of casting products. It is fabricated into L-shape (instead of a conventional probe with I-shape) to ensure the comfort of the user with a longer length for a safety factor, which is vital in the teaching and learning process.



(a) Laser gun thermometer

(b) Built-in type ceramic sheath thermocouple

(c) Iron chrome sheath thermocouple

(d) Un-sheath glass fibre insulated thermocouple

Fig. 13.1 Image of constraints and comparatives of current measurement devices at the casting process which **a** always misinterpreted and suitable for solid medium but not the liquid medium, **b** not durable at high temperature, easy crack, and unportable, **c** easy damage and not durable such as corrode, and **d** undurable, unsafe, not ergonomic and tend to melt at high temperature

13.2 Literature Review

In the twenty-first century, developments of new materials focused toward finding more importance for various engineering applications especially the lighter material namely aluminum (Karuppasamy et al. 2020). Aluminum and aluminum alloys are examples of non-ferrous metals used in engineering and construction fields. They are gaining huge industrial interest and are the most important of all non-ferrous alloys because of their excellent properties (Klemens et al. 2019). This is due to the significant combination of mechanical, physical, and tribological properties over the base alloys which have high strength, high wear, superior malleability, high stiffness, better high-temperature strength, good thermal and electrical conductivity, ease of machining, and improved damping capacity properties (Rana et al. 2012).

Aluminum alloys are used in sand casting work due to their strength-to-weight ratio, good corrosion resistance, and high ductility. These properties contain aluminum and trace amounts of metals such as copper, magnesium, silicon, and zinc (Zhang et al. 2019). One of the commonly used aluminum alloys is LM6 (Al-Si12) which contained strengthening elements and sufficient amounts of eutectic-forming elements (usually fluidity silicon) to make the metal flow through the cavities (Santhi et al. 2012). LM6 stays in the molten state longer than LM25 due to its greater fluidity, therefore helping the metal to reach the extremities of the mold cavities. This can also reduce the risk of defects such as misruns. However, LM6 is difficult to machine due to its high silicon content. LM6 can be used to add simple features (such as drilled holes); however, it is not suitable for intricate features (such as close tolerance holes). LM6 is also one of the most malleable aluminum alloys. This is an important characteristic for many marine applications, such as boat propellers, which must operate efficiently and have some malleability, without breaking, in harsh environments. Table 13.1 shows the chemical content composition of LM6 referring to BS 1490:1998 (Brown 2002).

Table 13.1 Chemical composition (weight percent) of LM6

Alloy	Cu	Mg	Si	Fe	Mn	Ni	Zn	Pb	Sn	Ti	Al
Weight percent	0.1	0.10	10.0 – 13.0	0.6	0.5	0.1	0.1	0.1	0.05	0.2	Remainder

The cast temperature is one of the important variables for the casting process. If the pouring temperature is too low, then the cavity in the mold will not be filled. Hence, this causes the inlet of the mold to freeze, where else if the pouring temperature is too high, it can cause shrinkage and loss of accuracy in the dimensions of the castings. Cast temperatures in aluminum alloys are usually found in between 675 °C and 790 °C and must be maintained at a pouring temperature at ± 800 °C (Klemens et al. 2019).

A thermocouple is a device for temperature measurement invented by Seebeck in 1822. In a thermocouple, small amount of electric currents flow in a closed circuit which consists of two different conductors. The flow is caused by a temperature difference between the junctions of the different conductors. The generated open-circuit voltages (electromotive force, e.m.f.) are the relative Seebeck voltages composed from the pair of conductors or thermoelements of the thermoelectric circuit. Therefore, a thermocouple is used to convert thermal energy into electrical energy due to the resultant of the temperature difference. Hence, it can be used as a source of electrical energy or for the means of temperature measurement (Pollock 1991).

Thermocouples operate according to the Seebeck principle. As mentioned earlier, a thermocouple can produce an electromotive force (e.m.f.) by converting thermal energy into electrical energy. The e.m.f. is measured as electric potential (voltage) produced by the temperature difference and is known as the Seebeck effect. The constant is proportionate to the Seebeck coefficient (S) and is also known as thermopower in Eq. (13.1):

$$\Delta \mathrm{V} = -\mathrm{S}\Delta \mathrm{T} \tag{13.1}$$

where ΔV and ΔT are the voltage and temperature differences, respectively. The temperature at the junctions of a thermocouple is the function of voltage produced (Hadi et al. 2021).

Thermocouples are widely used in tribological studies for temperature data collections. The applications of thermocouples (in data collections) are (i) to measure the bulk temperature of lubricant or process fluid, (ii) to determine air or atmospheric temperature during tests, and (iii) to measure the temperature rise in specimens tested (Starchowiak et al. 2004). At present, thermocouples are being used in industrial, scientific, and OEM applications (original equipment manufacturer).

There are multiple types of thermocouples, with its own unique characteristics in terms of temperature range, durability, vibration resistance, chemical resistance, and application compatibility. However, types J, K, T, and E are the base metal thermocouples and are commonly used. As for type R, S, and B thermocouples which

Table 13.2 Specifications of the dip immersion probe

No	Parameter	Specification
a	Temperature range	0–1260 °C
b	Accuracy	± 1.1 °C
c	Probe diameter	8 mm
d	Probe length	L-Shape: 915 mm
e	Sheath material	Inconel 600

are noble metal thermocouples used in high-temperature applications. Thermocouples are also widely used in research and development to characterize the material properties (Hadi et al. 2021; Yordanov et al. 2018).

13.3 Methodology

In this project, a K-type thermocouple was used in the measurement of the molten temperature and the preparation of aluminum casting alloy (LM6) samples under different temperature conditions.

13.3.1 Specification of DIP Immersion Probe for a Measurement Probe of Casting Process

The dip immersion probe must be designed according to the cast temperatures in aluminum alloys in the range of 675–800 °C with the following specification as shown in Table 13.2.

13.3.2 Conceptual, Design, and Fabrication of the Dip Immersion Probe

The main function of a dip immersion probe is to provide the intended temperature of the 675–800 °C range to the molten aluminum alloy (LM6) in order to obtain the molten metal casting. Sand mold is used in the pouring process, where a higher molten temperature is estimated in the corresponding pouring temperature at the range between 50 and 100 °C higher than the melting temperature of 660 °C. The ergonomics of the user in their casting environment is the main consideration for the design concept. More specifically, the probe was designed or modifies to 135 degrees over the working area to fit the user, not which to eliminate discomfort and

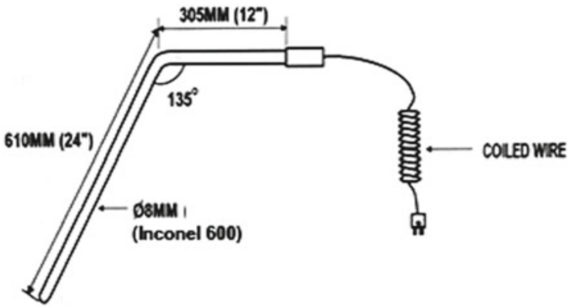


Fig. 13.2 The schematic diagram for DIP immersion probe

risk of injury due to casting work, besides to ensure a certain safety of the user at the measuring process in Fig. 13.2.

The material used in this project was LM6 with the chemical compositions of alloys as shown in Table 13.1. LM6 alloys ingot were being melted at the melting temperature using the crucible furnace. The molten metal is then melted at the silicon carbide crucible at different pouring temperatures. The melting temperatures selected for this project were 650, 700, 750, and 800 °C.

13.3.3 Pouring Temperature Measurement

The pouring temperature was measured by (a) built-in type ceramic sheath thermocouple (CST), (b) laser gun thermometer (LG), and (c) dip immersion probe (DIP). The built-in type of ceramic thermocouple that was attached to the crucible furnace and the pouring temperatures were read at the temperature panel meter gauge. For the laser gun thermometer, the laser beam that was focused on the molten metal was to be measured, and the reading was displayed on the laser infrared thermometer screen. For DIP, the thermocouple tip was inserted into the molten metal, and the reading will display on the thermometer screen (see Fig. 13.3).

13.4 Results and Discussion

The temperatures of molten metal (LM6) were measured by (a) built-in type ceramic sheath thermocouple (CST), (b) laser gun thermometer (LG), and (c) dip immersion probe (DIP) and recorded as shown in Table 13.3.

The results in Table 13.3 can be used to conduct the melting and pouring practice of a typical aluminum alloy, especially for LM6 (Al-Si12) in the casting process. It can be observed that for the measurements by equipment (a) and (b), the reading obtained becomes different with the testing temperature as per set through the reading by the built-in type of ceramic sheath thermocouple at the furnace. The results showed a

Fig. 13.3 Temperature measurement by DIP

Table 13.3 Temperature measurement by (a) built-in type ceramic sheath thermocouple, (b) laser gun thermometer, and (c) DIP immersion probe (DIP)

Testing temperature, (°C) by equipment			Reading 1 (°C)	Reading 2 (°C)	Reading 3 (°C)	Average reading (°C)	Different reading (°C)
650	a	CST	650	651	652	651.0	
	b	LG	645	645	646	645.5	− 5.7
	c	DIP	653	653	654	655.3	+ 4.3
700	a	CST	700	700	701	700.0	
	b	LG	688	690	692	690.0	− 10.0
	c	DIP	702	704	703	703.0	+ 3.0
750	a	CST	750	751	751	750.6	
	b	LG	745	745	746	745.5	− 5.3
	c	DIP	752	752	753	752.3	+ 1.7
800	a	CST	800	800	801	800.5	
	b	LG	785	789	790	788.0	− 12.5
	c	DIP	802	803	805	803.5	+ 2.8

series of different readings of temperature with molten aluminum alloys at different temperatures of 650, 700, 750, and 800 °C between (a) built-in type ceramic sheath thermocouple, (b) laser gun thermometer, and (c) dip immersion probe (DIP).

In the measuring using the built-in type ceramic sheath thermocouple and DIP, which shows the differences temperatures of 4.3 °C for 650 °C, 3 °C for 700 °C, 1.7 °C for 750 °C, and 2.8 °C for 800 °C, respectively. This signified that the different methods of temperature between these two measuring methods were not much affected by the value of the molten aluminum temperatures. The differences between are varying but narrow and in between 0.2 and 0.7%. This different value is still under the accuracy of the accuracy (typical values) for the thermocouple sensor. This value does not affect the accuracy of the molten aluminum alloy temperature within the limits for pouring purposes. This indicated that the value measured by the current probe and DIP is acceptable and has no effect on the pouring temperatures of the molten aluminum alloy.

For the measuring by built-in type ceramic sheath thermocouple and laser gun thermometer, the differences in temperature are 5.7 °C for 650 °C, 10 °C for 700 °C, 5.3 °C for 750 °C, and 12.5 °C for 800 °C, respectively. This indicated that the different method of temperature between these two measurement methods has higher values and affected the value of the molten aluminum temperatures. The differences between are varying and quite large and in between 0.7 and 1.6%. This value affected the accuracy of the molten aluminum alloy temperature within the limits for the pouring purposes. This signified that the value measured by the laser gun thermometer is not acceptable and influences the pouring temperatures of molten aluminum alloy. The large difference in the molten temperatures caused overheating of the molten aluminum which can lead to entrapped gas in the molten metal during the melting and pouring process (Brown 2002). These gases can form trapped air and hydrogen in molten aluminum which may lead to gas porosity. Hence, high melting temperatures can initiate the formation of hot cracks in the mold and form porosity defects in the casting (Sylvia 1999; Khanna 2006; Rana et al. 2012).

13.5 Conclusion

Dip immersion probe (DIP) was successfully designed and fabricated as a device to measure the melting temperature of metals and to ensure the quality of the casting. DIP was provided with the temperature of the molten metal especially aluminum alloys when placed on the furnace. This information can be useful in the melting and pouring process. By using this probe, the temperature can be obtained easily, and the temperature of the molten metal can reduce the overheating of molten metal. DIP is practical and can be used by moving the probe into or out of the process from time to time, with minimal adjustments. It is able to display any apparent change of indicated temperatures. The probe shows a wider temperature range, more prone to drift, more sensitive, and relatively cost-effective with a longer lifespan. It is also more ergonomic designated and safer to handle as compared to conventional probes for small-scale casting activity in foundry workshop.

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