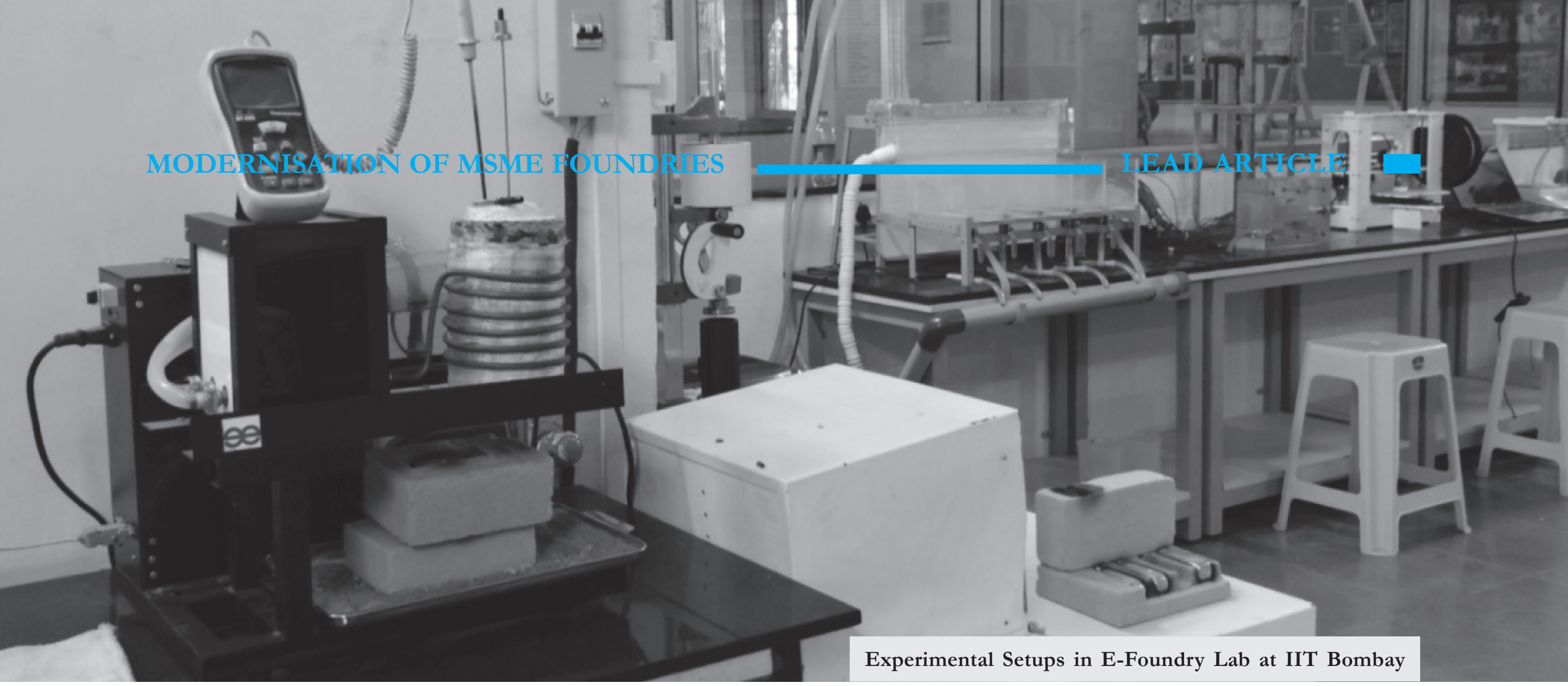

Experimental Setups in E-Foundry Lab at IIT Bombay

Tabletop Foundry for Training, Research and Small Enterprises +

Himanshu Khandelwal[1], B. Ravi[1] and Dipankar[2]
[1]Indian Institute of Technology Bombay, Mumbai [2] TREELabs Foundation, Mumbai

A tabletop casting system has been developed in the E-Foundry of IIT Bombay, which is useful for student lab experiments, research projects, and manufacturing a small number of small parts. It comprises four units: 3D printer for fabricating plastic patterns, clean no-bake (3-part) moulding, induction melter with direct pouring, and temperature data acquisition (DAQ). A laptop computer controls the 3D printer, melter and DAQ, all of them indigenously developed by faculty, students and alumni. The facility has been used for training students and for several research projects. The first project observed the metal flow rates through multiple gates connected to a single runner with sprue at one end. The second one studied the flowability of Al and Zn alloys in a small wheel casting with arms of different thickness (1-3 mm in steps of 0.5 mm). The third investigated cooling rates in different types of junctions ('L', 'T' and '+'). All these experiments could be done cleanly, quickly and safely by students. The system can also be used for producing a casting from its part CAD model within 1-2 days, at a fraction of the cost compared to metal rapid prototyping, which will be of interest to entrepreneurs.

Keywords: Metal casting, foundry, tooling, induction melting, thermal analysis, training.

Introduction

"Tell me and I forget, teach me and I may remember, involve me and I learn," said Benjamin Franklin, a great scientist, inventor and statesman. This is certainly true for a complex manufacturing process like metal casting that involves many steps and multi-physics phenomena (flow, heat transfer, and stresses) inside intricate shapes[1]. It is difficult to learn the art, science and technology of metal casting from text books or black boards. Hands-on practice is essential. Metal casting facilities are also required by researchers for developing new alloys and for investigating the effect of geometric, material and process parameters on microstructure and mechanical properties.

Metal casting involves pattern making, sand moulding, metal melting, pouring, fettling, machining and testing. Researchers further require temperature sensing, data capture and analysis. Setting up a metal casting facility thus requires several equipment (compared to any other single manufacturing process), pushing up the cost and lab space. The need for trained personnel, safety issues, and cost of maintenance are additional

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hindrances. It is not surprising that most of the new Engineering and Polytechnic Institutes do not have casting facilities, and those who had in the past are closing them down. This is leading to a severe shortage of industry-ready technical manpower for foundries, tool rooms and original equipment manufacturers[2].

There is a need for a compact and low-cost metal casting facility that can be safely and easily operated by students, researchers and entrepreneurs. This however, gives rise to several technological challenges. The first is pattern making, which itself requires a comprehensive machining facility, preferably 4 or 5-axis CNC machining centre if the shapes are complex. Alternative routes, useful for producing plastic patterns, are available today based on rapid prototyping (RP) technologies. These systems require a 3D CAD model of the pattern, and fabricate the same in a suitable material using a layer-by-layer additive manufacturing technique[3]. Most of these are however, quite expensive. The second is mould making. Metal moulds are not economical for producing a small number of complex-shaped castings. Dispensable moulds made in green sand or ceramic shell require additional equipment and space, and are not clean enough for a lab environment.

The next challenge is metal melting in small quantities (say 1-2 kg). Induction furnaces are fast, clean, and easily controlled, but are quite large and expensive. Resistance furnaces are economical, but take a lot of time for melting. Cupola, gas/oil-fired furnaces are difficult to operate and not suitable for training or research purposes. Further, conventional ways of pouring by transferring liquid metal from furnace to ladle, taking the ladle to the mould, and pouring into the mold leads to temperature drop, oxidation and gas pickup, besides requiring skill and having safety issues. Direct pouring systems used in industry are too large and expensive for laboratory use.

It is clear that the equipment used in industrial foundries are neither suitable nor economical for training and research purposes. Production of small castings, especially those with thin walls poses other technological challenges, which also offer interesting research problems to investigate. One is related to metal fluidity, which affects the distribution of flow through the gating channels[4]. The second is flow and solidification of molten metal in different types of part features and junctions[5]. The third is rapid cooling, with resultant effect on microstructure and properties[6]. These investigations require innovative (yet economical) ways for visualising the flow and for measuring the temperatures within the casting as well as the mould.

In this paper, we describe a tabletop metal casting system that can be used by students and researchers. It is clean and easy to use, as well as economical to set up and maintain. The next section describes its major units, followed by some of the experimental castings produced by the facility.

Tabletop Integrated Casting System

The facility was developed and implemented in the E-Foundry lab at IIT Bombay, by a project team involving faculty, current students and alumni. The team envisioned an integrated system that could be accommodated on a tabletop. Plastic patterns would be fabricated automatically using an open-source low-cost 3D printer, and used to create a sand mould using a clean moulding process. The mould block would be inserted in a small induction furnace, from which metal would be directly poured into the mould under gravity. Thermocouples inserted into the mould would measure the temperatures, which would be acquired by a data acquisition unit, and stored in a computer for further analysis. The above-mentioned four units: pattern fabrication, mould-making, melting with direct pouring, and temperature data acquisition are described next.

(a) Plastic Pattern Printer

Rapid prototyping systems work on the principle of layer-by-layer additive manufacturing. One of the most widely used technique to fabricate a layer is by passing plastic wire (taken from a spool) through a heated nozzle, and depositing the semi-solid plastic within a cross-section. The nozzle head is moved using a XY controller, whereas the platform on which the plastic is deposited is moved in vertical (Z) direction. The three (X,Y,Z) motions are controlled by a software programme, which takes the 3D CAD model of the part as input. The software slices the part CAD model to generate the cross-sections, and the cross-hatch motion path for each cross-section.

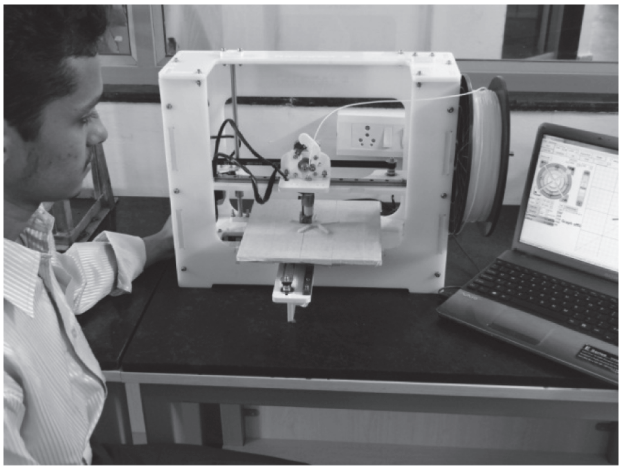

Fig. 1: Low-cost 3D Printer for automatic fabrication of plastic patterns.

The 3D printer implemented in E-Foundry lab is called RapidBot, which is a new generation of low-cost rapid prototyping machines built using open-source components (Fig. 1). It has an overall size of 400 mm x 250 mm x 350 mm, and can build a part with maximum overall dimensions of 200 mm x

150 mm x 150 mm. The machine uses a layer thickness of 0.15 mm, and gives overall dimensional accuracy of about 95% (10 mm error in part size of 200 mm). This is worse compared to mainstream RP systems (such as the Fused Deposition Modelling machines from Stratasys, Inc., USA), which have smaller layer thickness and better accuracy. The significantly lower cost of 3D printers, however, makes them very attractive for training and research purposes.

The 3D printer uses plastic wire composed of PLA (polyactic acid), a thermoplastic polyester derived from renewable resources such as corn starch, starch or sugarcane. It is strong enough to be used as a pattern for creating more than a dozen moulds before showing signs of wear.

(b) Sand Mould Block

The conventional green sand casting process uses silica sand mixed with clay (Bentonite), water and a few additives to improve the strength, permeability and collapsibility of the mixture. The sand mixture is packed around patterns placed in a metal mould box or flask, which provides the needed support around the sand mould. While it is a very economical process for industrial application, the geometric accuracy and surface finish of the castings produced by this route are not suitable for miniature and thin-wall parts. It is also difficult to maintain the cleanliness of a green sand foundry.

To overcome the above limitations, several alternative methods, usually used for core-making, were explored by the project team. One was silica sand mixed with sodium-silicate and hardened by passing CO_2 gas. These moulds however, required large grain sand (leading to poor surface finish) and proved to be too hard to break after casting. Another was oil-bonded silica sand moulds and heat-cured binder system but this requires a furnace to bake and harden the mould.

Then the project team explored 'no-bake' processes, which involves mixing the sand with suitable chemical binders, packing the sand mixture in mold box, allowing it to cure or harden at room temperature, and finally stripping the mould from the box. The 'three-part no-bake system' involves three chemicals: (a) alkyd oil resin, (b) liquid metallic catalyst and (c) polymeric methyl di-isocyanate hardener. The thermosetting resin and catalyst control the degree and time of binding, respectively. These two are first mixed, and are added to silica sand of suitable grain size. Then the hardener is mixed in, and the final mixture of sand and chemicals is poured around the pattern placed in a mould box. The hardener begins to crosslink with the resin at a rate controlled by catalyst.

The typical composition of the mixture used to prepare the no-bake moulds is as follows: resin (primary binder is) 2% of sand; catalyst is 3-10% of resin; and hardener is 20% of binder. The mixture sets within a few minutes, after which the pattern is removed from the mould. The entire operation including mixing, moulding and pattern stripping takes about 30 minutes. The relevant process parameters include the relative proportion of sand, resin, catalyst and hardener, sand grain size, ambient temperature and humidity. It was found that a higher amount of catalyst as well as higher ambient temperature increased the strength of mould, but reduced the bench life of the sand mixture.

For the experimental projects described later in this paper, a three screen, GFN 55-60 round grain silica sand was used. A commercial grade three-part no-bake chemical binder system was used, and cured with 5% liquid amine catalyst. After packing the sand mixture in the mould, it was allowed to harden for 2-4 hours before casting.

The above approach enabled superior mould hardness (compared to green sand moulds), collapsibility (compared to CO_2-hardened moulds), and clean workplace (comparable to die-casting). The mould box size was standardised to 8″x6″x6″ (200 mm x 150 mm x 150 mm). For producing the castings, the mould blocks were inserted under the crucible of the induction melter, described next.

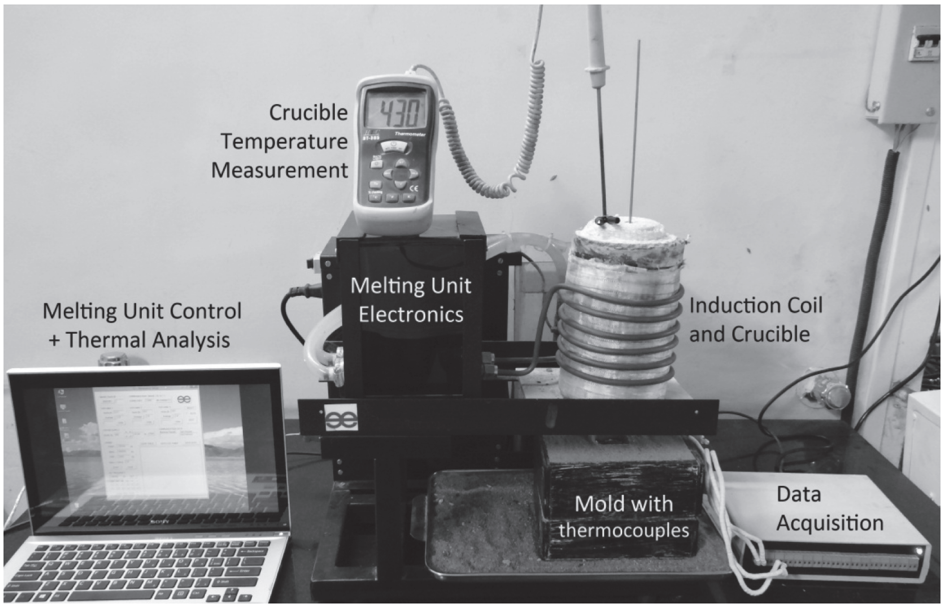

Fig. 2: Induction melter with direct pouring and data acquisition unit.

(c) Induction Melter with Direct Pouring

Induction furnaces use the heat produced by eddy currents generated by a high frequency alternating field. This provides a clean, fast and efficient means for melting metals for casting purpose. The industrial induction furnaces however, occupy considerable floor space and require dedicated 3-phase power supply. Further, the molten metal usually needs to be transferred to a separate ladle for pouring into the mould, which leads to heat loss, oxidation, and moisture pick-up.

To overcome the above limitations, it was decided to explore indigenous development of a compact and computer-controlled induction melting unit, with provision to place a mould block within the furnace for direct pouring into the mould cavity (Fig. 2). Table-1 lists down the specifications of the same. Metal charge is placed in a graphite crucible covered by suitable refractory material, surrounded by water-cooled copper coil. The alternating magnetic field produced by the high frequency current induces powerful eddy currents in the metal charge placed in the crucible, resulting in rapid heating and melting. A thermocouple provides a continuous measurement of internal temperature on a digital readout. The crucible has a hole at the bottom closed with a plug, which can be opened by pulling a connected graphite rod that protrudes from the top lid. The computerised control enables furnace starting, stopping and power optimisation. To minimise the overall size of the unit, several configurations of the induction circuit, coil and crucible, and cooling water container were explored. The unit was designed to be very energy-efficient. It incorporates various control strategies, algorithms and sub-systems, for delivering high quality metal melting conditions. The specifications are listed in Table 1, and three major design aspects are described here.

Table 1: Specifications of Induction Melter

Maximum Melting Temperature	1200 °C
Power Supply Frequency/Voltage	AC 230 V/50Hz
Crucible Material	Graphite
Crucible Dimensions	OD 8 cm, ID 6.5 cm, Depth 9 cm
Refractory Material	High Temperature Ceramic

Radio frequency induction heating is based on resonant amplification and creation of large currents (1000A) at high frequencies. It is very important to operate the resonant system at its peak frequency. Even 1-2 KHz deviation (for resonant frequency at say 500 KHz), can seriously impair energy coupling into the resonant system, resulting in poor efficiency. Furthermore, the resonant peak changes based on temperature, quantity of melt, state of melting, life-cycle of crucible, property of magnetic materials (paramagnetic / ferromagnetic), etc. The designed system employs special digital frequency synthesis strategies to create precise excitation frequencies, which are controlled with high crystal-based oscillators. The frequencies are changed using sophisticated control algorithms to precisely track the resonant peak and optimise it using digital frequency synthesis.

The second aspect incorporated in the induction melter design is creation of energy-efficient amplification schemes. Under normal operating conditions, nearly 500 KVA of reactive power may be created in the melting zone (real power drawn from mains remains around 1 KW / 1 KVA). The system employs energy-efficient high performance MOSFETs to reduce switching losses at high frequencies. The induction melting system also employs novel impedance matching and power-coupling schemes to couple power from the amplifiers to the furnace. Resonant-guaranteed series RLC topologies are used, with highly efficient magnetic couplings to the resonant tank-circuit. This ensures minimal losses in the coupling of power, hence cooler operation, thereby enhancing reliability of the electronic components.

The third aspect in the design ensures minimal energy loss from the hot zone. Various conduction, convection and radiation loss mechanisms are arrested, ensuring higher energy efficiencies. This again is important from points of view of safety, convenience and compact footprint of the apparatus.

Temperatures in excess of 1200 °C have been achieved in the induction melter, suitable for melting 1 kg of aluminium or zinc alloys in 15-20 minutes.

(d) Temperature Data Acquisition

A separate data acquisition (DAQ) unit is used for continuous measurement of temperatures in the casting and/or mould. The DAQ allows 16-channels of data to be acquired, and transferred to a computer through a RS232 port. The computer has a software programme to visualise and save the data.

For temperature measurement, K-type thermocouple wires are used, which are suitable for a wide range from -200 °C to 1350°C. They are embedded in the mold within ceramic sheaths, either stopping within the mould material, or protruding into the part cavity, to measure the temperature of the mould and casting, respectively. The measurements are recorded with a time interval of 0.1 seconds, providing sufficient accuracy to plot and interpret the cooling curves, while optimising the amount of data to be stored and analysed. The data is stored in a computer connected to the DAQ unit, and used for real-time visualisation as well as saving in an Excel file for subsequent analysis. The data can be post-processed for creating cooling curve plots for thermal analysis. The experimental castings produced using the above-mentioned system and related results are described next.

Casting Experiments and Results

The tabletop foundry was used for producing several experimental castings. The first project observed the metal flow rates through gating channels. The second project studied the flowability of Al and Zn alloys in a small wheel casting with arms of different thickness (1-3 mm in steps of 0.5 mm). The third project investigated cooling rates in different types of junctions ('L', 'T' and '+'). These are only representative projects to show the potential and versatility of the tabletop foundry, and are described here.

(a) Metal Flow Through Gating Channels

The purpose of this experiment was to study the nature of flow through multiple gates connected to a single runner, with the sprue at one end of the runner. Since it is not possible to visually observe the flow through the mould, a special cut-out mould was designed (Fig. 3). The sprue and runner are enclosed within the sand mold, but the top surfaces of the gates are open. The ends of the gates were closed with a quartz glass plate. This makes it possible to safely photograph and videograph the flow of metal as it emerges into the gating channels.

The metal used in these experiments is zinc aluminium alloy ZA8 poured at 455°C. The flow of the metal from the gates into the rectangular cavities is captured through high speed video (for observing in slow motion later). The total volume of metal flowing through each gate and the time taken for the same are recorded. It was observed that the flow starts first from the gate nearest to the sprue, followed by the last gate (farthest from the sprue). Then flow appears in the second gate, and finally through the third gate. It can also be observed that over the total duration, the flow rate through the furthest gate is the highest, and nearly twice as much as from the first gate. The next highest flow rate is observed in the gate which is third from the sprue, followed by the second and the first gate. Figure 4 shows the state of flow at two instants of time.

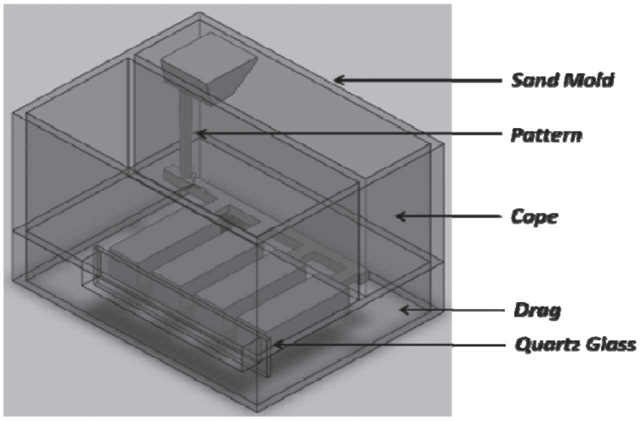

Fig. 3: CAD model of mould arrangement to visualise metal flow in gating channels.

These results compare well with those from experiments in which a similar setup was fabricated in transparent plastic, and the flow of coloured water was observed[4]. Students and researchers can explore variations of this experiment, which include different gating configurations (vertical or horizontal); the number, position, shape and size of sprue, runner and gates; alloy composition; and process parameters including filling temperature and flow rate.

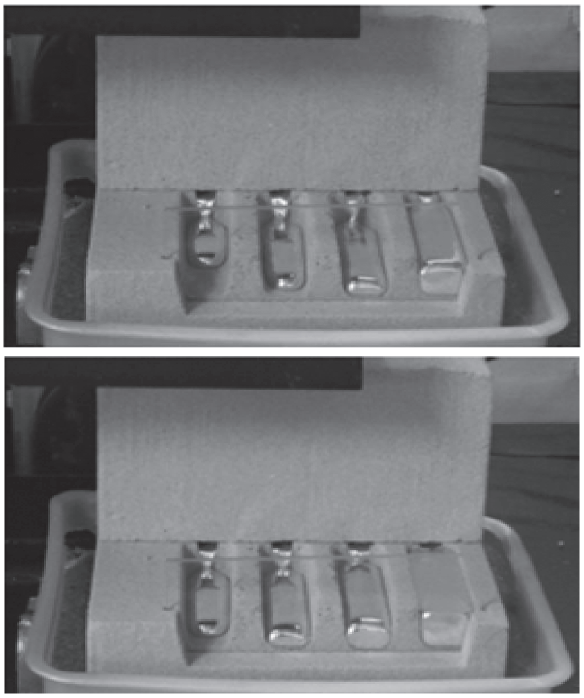

Fig. 4: Flow through the last gate is nearly twice as through the first gate.

(b) Metal Flow Through Thin Sections

The purpose of this experiment is to study the flowability of different metals through thin sections to understand the manufacturability limits for a particular combination of geometric, material and process parameters. A wheel casting was designed, with spokes of different thickness values (1, 1.5, 2, 2.5 and 3 mm), as seen in Fig. 5. Two different alloys were investigated. The first was zinc aluminium alloy ZA 8, which was poured at 455 °C. The second was aluminium alloy LM6, which was poured at 680°C. While all spoke sections completely filled in the ZA8 alloy casting, the LM6 alloy was unable to flow through the thinnest section of 1 mm.

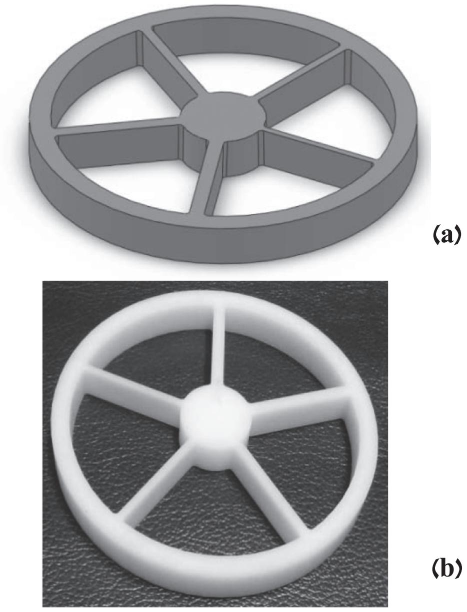

Fig. 5: Wheel part: (a) CAD model and (b) 3D printed plastic pattern.

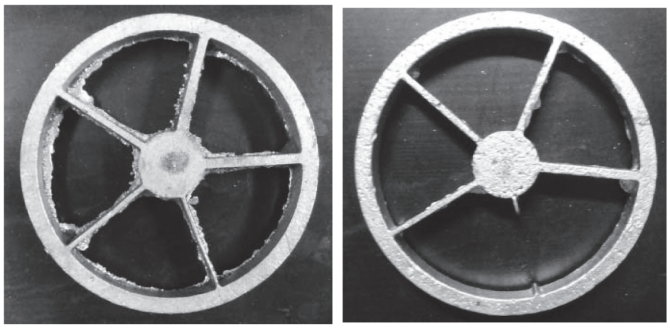

Fig. 6: Wheel casting: left- ZA8 alloy, and right- LM6 alloy.

The variations of this experiment can include different shapes (straight and curved flow paths, thickness and length combinations); materials (alloy composition, treatments, mould material); and process parameters (mould-making, pouring temperature and rate). This will help build a knowledge base of casting process capabilities, which can be used by product engineers to design more foundry-friendly parts.

(c) Cooling Rates in Different Junctions

The goal of the third experiment was to study the cooling rates during solidification of different types of junctions ('L', 'T' and '+'), since it is well-known that the cooling rates affect the microstructure and mechanical properties of the cast part. For this purpose, a multi-junction part was designed (Fig. 7). Its pattern was fabricated, and used to create a sand mould by the no-bake process described earlier. Two K-type thermocouples were inserted during moulding itself, so that their tips were at the centre of the 'L' and '+' junctions. The other end of each thermocouple was inserted into the data acquisition system, connected to a laptop computer. The cooling curves (temperature vs. time) obtained from the two thermocouples are shown in Fig. 8. These can be correlated with the experimentally measured values of microstructure (grain size, phase distribution), and further with mechanical properties (strength, hardness).

The experiment can be varied by changing the type of junction (ex. 'V', 'Y', 'X', '*'), wall thickness, angle between the walls, and distance between the junctions. The effect of alloy composition, mould material, and various process parameters can be investigated on the cooling rate, and resultant effect on the mechanical properties of the casting.

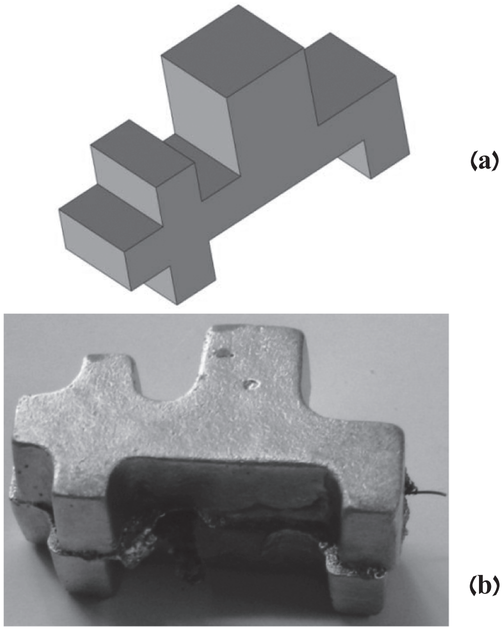

Fig. 7: Multi-junction part, (a) CAD model, (b) casting with thermocouples.

Supporting Facilities and Lab Utilisation

The metal casting facilities described earlier, for carrying out the above experiments are housed in the E-Foundry Lab in IIT Bombay (picture in the beginning). They supplement other experimental setups, including a transparent mould setup for observing the flow of coloured water in multi-gate gating system. Another transparent mould setup with an H-shaped cavity allows observing the impingement of water inside the cavity, turbulence, and air entrapment. Other equipment include machines for testing sand grain size, mould hardness and permeability. All these equipment also are made in India.

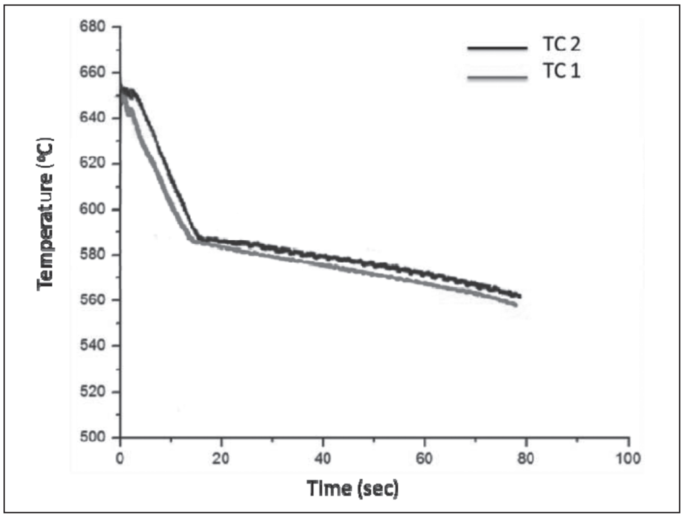

Fig. 8: Cooling curves obtained from thermocouple 1 and 2.

The transparent mould setups are used for undergraduate (B.Tech.) lab courses. The melting facilities are used by post-graduate (M.Tech.) students. Doctoral (Ph.D.) scholars also use these facilities for their research experiments.

The E-Foundry Lab also houses a mini-library stocked with books related to metal casting, materials, manufacturing, and CAD/CAM. A video conference facility enables reaching out to students and teachers in other Institutes.

Conclusion

An indigenous tabletop foundry has been successfully developed, and demonstrated for different types of student laboratory and research projects. The compact size has been achieved by miniaturising each unit (pattern-making, moulding, melting, pouring, and temperature data acquisition), and integrating them to a large extent. The use of standard power supply (220V, 5 A) and laptop computer for controlling the 3D printer, induction melter and DAQ enabled easy installation and use anywhere. We have also developed three experimental projects that enhance the interest of students in metal casting, and also produce research results that are useful to the industry. All these experiments can be done cleanly, quickly and at a cost which can be affordable by Academic Institutes as well as small business units. The project team would be happy to share information regarding the tabletop system, and the drawings of the patterns used for the three experiments, so that they can be replicated by teachers and researchers in other Institutes. It is hoped that this will lead to a renewed interest in metal casting, and resurgence of qualified technical manpower in foundry industry.

Acknowledgements

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References

1. B. Ravi, Metal Casting: Computer-Aided Design and Analysis, PHI India, ISBN: 81-203-2726-8, 7th Print, 2013.
2. B. Ravi, Technical Manpower Training for Foundries: NKN E-Foundry Mission, *Proceedings of the 60th Indian Foundry Congress*, Bangalore, The Institute of Indian Foundrymen, 2-4 Mar, 2012.
3. D.K. Pal, B. Ravi, and L.S. Bhargava, Rapid Tooling Route Selection for Metal Casting using QFD-ANP Methodology, International Journal of Computer Integrated Manufacturing, Vol. 20(4), 2007, p. 338-354.
4. K.H. Renukananda, Udit Chheda, and B. Ravi, Flow through Multi-Gate Gating System: Experimental and Simulation Studies, Proceedings of ASME International Mechanical Engineering Congress & Exposition, 15-21 Nov. 2013, San Diego, CA, USA.
5. D. Joshi and B. Ravi, Classification and Simulation Based Design of 3D Junctions in Castings, Transactions of American Foundry Society, Vol. 117, 2009, p. 7-22.
6. Vasudev Shinde, B. Ravi and K. Narasimhan, Solidification Behaviour and Mechanical Properties of Ductile Iron Castings with Varying Thickness, International Journal of Cast Metals Research, Vol. 25 (6), 2012, p. 364-373.