A temperature sensor based feedback system to ensure uniform microstructure in a cast product *

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ABSTRACT

Keywords:
Temperature Sensor,
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Heat Extraction,
Feedback Mechanism.

The mechanical properties of a metal casting are governed by grain size and microstructure in the metal, and isotropic microstructure leads to better mechanical properties. However, in practice, it is difficult to ensure cooling rates such that uniform microstructure in the cast occurs. In this paper, we propose a model for controlled cooling of the casting in order to achieve uniform microstructure and desired grain size throughout the cast product.

The main concept is that the microstructure of the casting depends on the rate of heat extraction. A faster rate of heat extraction leads to smaller grain size while a slower rate of heat extraction results in larger grain size. Generally, the geometry of the mould and the cast is such that the distance of cast from the external surface of the mould is continuously varying. This leads to variations in the rate of heat extraction which results in non-uniform grain development during the cooling process.

Since cooling rates are the primary concern, and this depends on the external temperature (T_e) of the mould, this temperature needs to be controlled. Our proposed model controls this temperature by using multiple variable speed fans to control T_e. The relevant heat transfer equations comprising of conduction and convection will be used to model the temperature throughout the mould. A feedback system will be incorporated which will consist of temperature sensors and a cooling system that will be integrated with a data processing unit. The temperature (T_e) so measured will be used to control the fan speeds such that heat extraction rates are controlled to achieve uniform grain size and arrangement in the cast product.

Although the present model has been developed for relatively simple geometries, the same can be extended for more complicated casting geometries. This will form the next phase of our work.

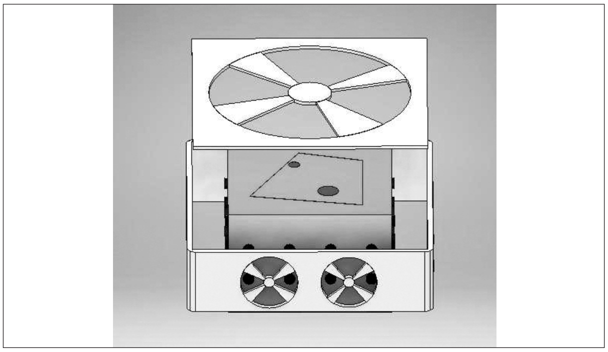

Fig.1. Side view of proposed model

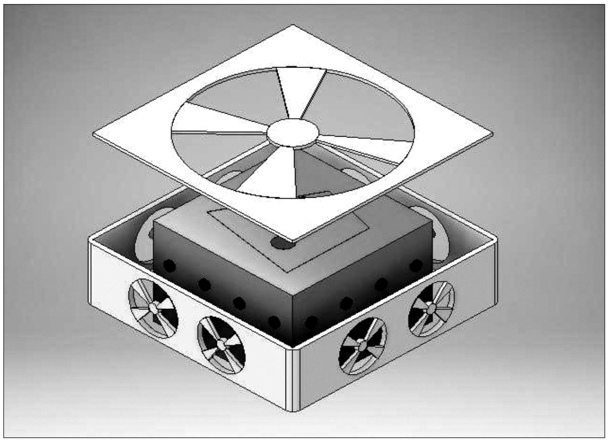

Fig. 2. Isometric view of proposed model

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1. Introduction

In the process of casting there is always a chance of development of non-uniform grain size or irregular grain arrangement. As the grain size and grain arrangement are a major factor behind various properties such as yield strength, tensile strength, impact strength, and all other mechanical properties, one should ensure uniform microstructure and small grain size in the casting by Hall Petch relationship. In the casting process, there is the formation of new grains that depends on how heat extraction is taking place in the recrystallization process.

This model works to eliminate the possibility of non-uniform grain formation due to geometry in the process of casting. Also, this model can tweak grain size according to need and application. For this process, a method of controlled cooling is used. This is done by temperature sensors, fans, and a data processing unit. It will maintain the same rate of heat extraction and give control to rate throughout the cast which will ensure arranged and small grain size for better performance of cast product.

2. Concept Involved

Uniform heat extraction rate which ensures uniform microstructure must be equal at every point of cast. For this, the application of Fourier's Law at all the fan locations based on the data received from the temperature sensors. This law generates a new value of temperature which is desired for the same rate of heat extraction throughout the cast. These values of new temperatures are required to be maintained by the cooling system.

3. Methodology

Fig. 3 shows a typical schematic of a casting. $T_m(t)$ is the uniform time-varying temperature of the casting. $T_m(t)$ is uniform since the thermal conductivity of the casting is much higher than the thermal conductivity of the mould. In the schematic, BD is the surface of the mould. The fastest rate of conduction will take place from the location where the distance of cast is nearest to the boundary of themould. Hence the temperature is highest at point B and continuously decreases till point D.

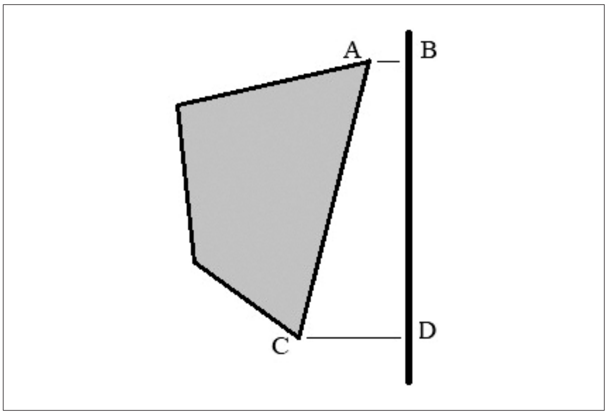

Fig.3. Sample schematic

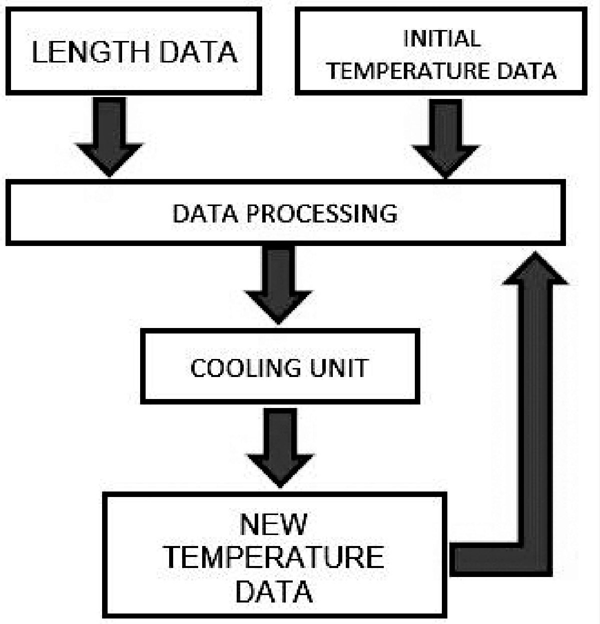

Fig. 4. Process flow chart

Temperature sensors are mounted at the walls of the mould. Multiple fans are used to blow air perpendicular to the surface of the mould. A single fan caters to a finite region of the mould surface. The initial wall temperature (T_o) is highest at point B due to the highest rate of heat conduction.

3.1. Data collection for governing the cooling system

The distance of the cast product from the mould wall is first collected. This data is fed into a table and the mean length for a single fan is calculated.

Values of temperature are recorded at various locations with the help of temperature sensors. These temperature values are fed into a table and the mean temperature for a single fan is calculated.

Table 1 is to be made for all the length data in front of every sensor.

Table 1.
Data Sheet for Length Data.

Sheet for Length Data				
d_1	d_2	d_3	d_4	Mean Length for Fan
				= SUM(d_1:d_4)/4

Table 2.
Data Sheet for Temperature Data.

Sheet for Temperature Data				
S_1	S_2	S_3	S_4	Mean Temperature for Fan
				= SUM(S_1:S_4)/4

Table 2 is to be made for all the temperature datain front of every sensor.

This data fed into a data processing unit that relates this data with laws of heat transfer and gives results to the cooling system for control of heatextraction.

The lowest temperature from the temperature datasheet is denoted by T_o. We already know the temperature of the melted metal which is denoted by T_m and considering it to be the same throughout the molten metal.

Now we apply **Fourier's law:**

$$\frac{\Delta Q}{\Delta t} = -kA\frac{\Delta T}{\Delta x} \quad .....(1)$$

And make conduction rate of every point equal to the lowest conduction rate for uniform heat extraction.

Consider T_d to be the temperature for which best grain size, as well as microstructure, will be obtained for cast product. T_d is the value which can be obtained experimentally. This setup can also be used with T_o value but to get the best results T_d is preferred over T_o.

Set: $T_o = T_d$: Condition applied for best Microstructure condition. (Ref. Fig. 5)

To set the fan speed accordingly at the lowest temperature point to obtain the desired temperature i.e. T_d.

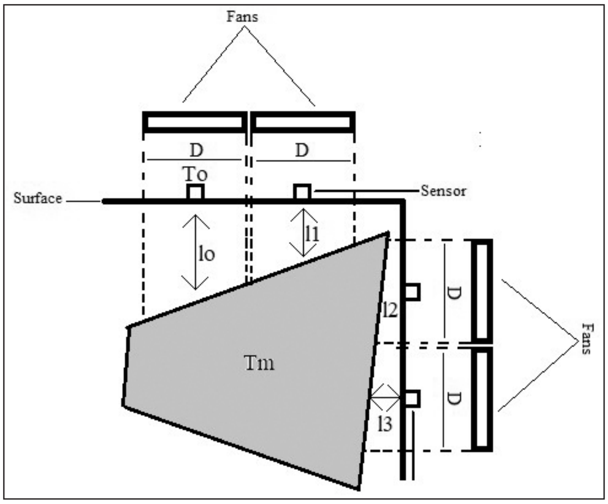

Fig. 5. Sample Drawing

Equating heat flux equations at the initial condition at two different positions i.e. location of distance l_o and location of distance l_1 we get

T_m : Temperature of cast

$$-k\frac{(T_m - T_d)}{l_o} = -k\frac{(T_m - T_1')}{l_1}$$

On solving we get

$$T_1' = T_m - \frac{(T_m - T_d)l_1}{l_o} \quad .....(2)$$

Here is temperature required at location 1 to maintain equal heat flux at both fan locations.

Similarly, for other locations we will get equations:

$$T_2' = T_m - \frac{(T_m - T_d)l_2}{l_o} \quad .....(3)$$

$$T_3' = T_m - \frac{(T_m - T_d)l_3}{l_o} \quad .....(4)$$

Fan speed will be changed in accordance with the temperature at a location.

Results for the above conditions:

Initial conditions:

$$T_o < T_1 < T_3 < T_2$$

Due to different length for heat conduction from cast to mold

$$l_2 < l_3 < l_1 < l_o$$

Finally, the desired conditions:

$T_o = T_d$: Condition applied for best microstructure condition

$T_d < T'_1 < T'_3 < T'_2$: By conditions of equal heat extraction

Fan speed relation:

$$F_o < F_1 < F_3 < F_2$$

T'_1, T'_2, T'_3 Are calculated with equations fed into the cooling system to get these temperatures at the corresponding location. At these locations, temperature sensors are already placed which will ensure that fans are able to achieve the calculated temperature or not.

In other words, all sensors will work as a calibration system for controlled cooling in this model.

4. Analysis of Heat Extraction as a Function of Time

Analysis of heat extraction with continuous data capturing and processing gives more accurate results as it is acting on small changes to the heat extraction rate at different locations in real-time.

This fast data processing unit is used, as the temperature data from the sensors can generate a high quantity of readings in a very short time. Also, the cooling unit must adjust according to the new cooling condition required for a uniform microstructure.

Equational analysis of heat flux with respect to time at two different positions. For this model, we are considering the cast as a lumped body. We get

$T_m(t)$: Temperature of the cast with respect to time

dT_m/dt = constant throughout the body: Due to the fact that we are assuring heat extraction from every part to be the same.

$T_d(t)$: Temperature of the outer point at the farthest distance from the cast. It is calculated with experiment.

Here we are equating heat flux at the location of distance l_o and location of distance l_1.
Fourier's Law,

$$\frac{\Delta Q}{\Delta t} = -kA\frac{\Delta T}{\Delta x}$$

$$-k\frac{(T_m(t)-T_d(t))}{l_o} = -k\frac{(T_m(t)-T'_1(t))}{l_1} \qquad ......(5)$$

On solving we get

$$T'_1(t) = T_m(t) - \frac{(T_m(t)-T_d(t))l_1}{l_o} \qquad ....(6)$$

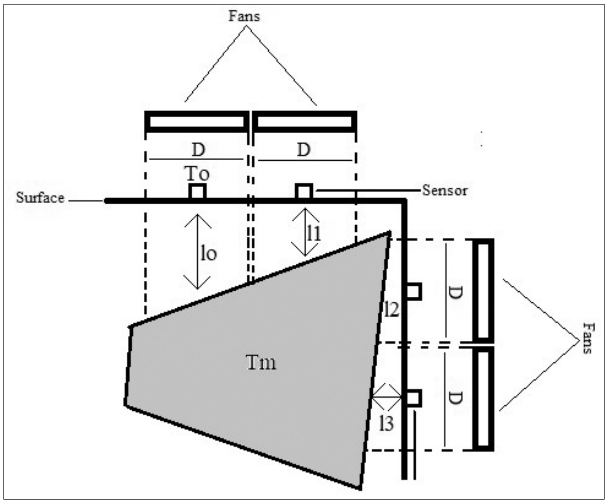

Fig. 6. Sample drawing

Here,
T'_1 is the temperature required at location 1 with respect to time to maintain equal heat flux at both the fan locations.

Similarly, for other locations we will get equations:

$$T_2'(t) = T_m(t) - \frac{(T_m(t)-T_d(t))l_2}{l_o} \qquad .....(7)$$

$$T'_3(t) = T_m(t) - \frac{(T_m(t)-T_d(t))l_3}{l_o} \qquad ......(8)$$

Finally, the desired conditions:

$T_o(t) = T_d(t)$:Condition applied for best microstructure condition

$T_d(t) < T'_1(t) < T'_3(t) < T'_2(t)$: By conditions of equal heat extraction.

Fans speed will be changed accordingly and the relation for this case is:

$$F_o < F_1 < F_3 < F_2$$

With this data, the model presents the idea of fan speed at which the heat extraction from the cast is uniform everywhere which will result in the uniform microstructure in a cast product.

$T'_1(t), T'_2(t), T'_3(t)$ are calculated with equations that are fed into the cooling system to get these temperatures at the corresponding location.

At these locations, temperature sensors are already placed which will ensure that fans are able to achieve the desired temperature or not. In other words, all sensors will work as a calibration system for controlled cooling in this model.

5. Equational Analysis for 1D Model

Here we are doing complete equational analysis for 1 D model. To show heat extraction exclusively for this model only.

In the figure below, there is a casting material surrounded by a mould. All mould surfaces surrounding the casting material are perfectly insulated except for the left and right ends.

Considering the following conditions hold:

To have uniform grain-size we need to have a uniform rate of cooling of the castingmaterial, i.e.

$dT_c/dt = -\beta$ = constant. Here $\beta > 0$ and

The temperature at a location.

T_m (t): temperature of the casting material.

$$l_{ml} \times l_{cl} = l_{ml} \times l_{cr}$$

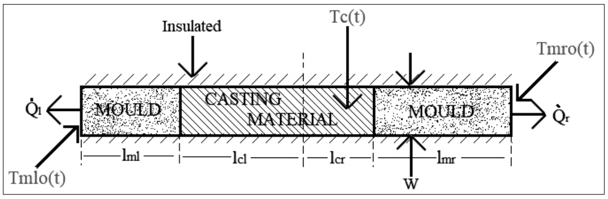

Fig. 7. Model for 1D analysis

Since all the surfaces are insulated except right and left it can be assumed as a 1-D heat transfer model.

If $\frac{k_m}{k_c} \ll 1$ $(k_m$: thermal conductivity of the mould, k_c: thermal conductivity of the casting material). Here since the casting product conducts heat much more easily than the mould, we can safely assume that the casting behaves like a lumped body.

Condition of heat transfer

$$0 \leq x \leq l_{cr} + l_{mr}$$

$$\rho_c c_{pc}[l_{cr}(wd)] \frac{dT_c}{dt} = \frac{-k_m[T_c(t) - T_{mro}(t)]}{l_{mr}} \quad .....(9)$$

$$-(l_{cr} + l_{mr}) \leq x \leq 0$$

$$\rho_c c_{pc}[l_{cl}(wd)] \frac{dT_c}{dt} = \frac{-k_m[T_c(t) - T_{mlo}(t)]}{l_{ml}} \quad .....(10)$$

p_c: Density

C_{pc}: Heat capacity

l_r : Length

wd: Area of cross-section

Assumptions:

i) No contact resistance between casting and mould.

ii) Given that

$$l_{ml} \times l_{cl} = l_{ml} \times l_{cr}$$

on $x > o$ side only l_{cr} region of the cast takes part in the heat transfer and on the $x < o$ side only ι_{cl} region of the cast takes part in the heat transfer.

From equations (9) and (10) we get

$$T_c(t) = T_{mro}(t) - \frac{1}{k_m}\rho_c c_{pc}[l_{cr} l_{mr}(wd)] \frac{dT_c}{dt} \quad .....(11)$$

$$T_c(t) = T_{mlo}(t) - \frac{1}{k_m}\rho_c c_{pc}[l_{cl} l_{ml}(wd)] \frac{dT_c}{dt} \quad .....(12)$$

Since we know the value of $T_{mro}(t)$ and $T_{mlo}(t)$ from sensors by using the above equations we can get the temperature of the cast as a function of time.

We are setting the value of $T_{mro}(t)$ and $T_{mlo}(t)$ such that same heat extraction from both right and left side with the help of fans. Since the heat extraction is same it will give $T_c(t)$ value to be equal at both right side and left side. This can be related as uniform cooling in this 1 D experimental model.

6. Ongoing Improvements

Model improvement can be done by using small diameter fans and a greater number of fans so that temperature control is more precise for maintains the uniform microstructure irrespective of geometry is of the cast.

By increasing the number of sensors will also give a more precise value of temperature that also increases the effectiveness of the model.

A more responsive cooling system will give the best result on integration with fast data processing unit. Fans used are with a large spectrum of speed for various temperature ranges.

Continuous temperature sensing will be the best option for better optimization of the model. High Capacity data processing unit should be used for faster processing and delivering the data to the cooling system as the temperature is a continuous varying in this model.

7. Limitations

At this stage, this model will not be able to give effective results for the irregular shape of the cast product.

Highly irregular means its geometry change significantly in short distance.

Temperature sensors must have high temperature working range so that they do not melt on the application of the model surface.

8. Conclusion

This model helps in the Controlled Cooling which ensures similar heat extraction rate throughout the cast. This similar heat extraction will ensure uniform grain arrangement.As faster heat extraction creates a smaller grain size. Variable fan speed help to control the rate of heat extraction which allows varying the grain size. This model is developed to get better Mechanical Properties for the casted product.

Currently, we are working on the analysis of convection outside the mold in between the mold and fans. For which we are developing an equational analysis of convection coefficient with temperature. We are developing an equational relation between the conduction, convection and fan speed (cooling).

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