ABSTRACT

The cooling rate of molten cast iron can make or mar it. The cooling rate plays a significant role in the resulting mechanical properties of cast iron. It determines the grain growth and size. The mechanical properties of cast iron variation along its length are achieved either with the use of different mold materials or by sectioning to ensure varied cooling rates. Mechanical properties can, however, also be varied along its length without any of these adopted methods by the incorporation of cooling channels in the mould. This study seeks to expand the frontier of this concept with the use of different cooling fluids and fluid flow rate, and numerically investigate the impact on the cooling rate of gray cast iron (class 40). The cooling curve for the cast iron was impacted by the use of different cooling fluids with the attainment of the desired mechanical properties with the selection of an appropriate cooling fluid. Also, the flow rate of the cooling fluid has an impact on the cast iron cooling rate.

Keywords: Cast Iron; cooling channels; cooling fluids; grain size.

1. INTRODUCTION

It is not an understatement that a correlation exists between the cooling rate and the resulting mechanical properties and structure of cast iron, hence controlling the cooling curve is crucial to good solidifying. The solidification involves nucleation, which is the formation of crystals and
their subsequent growth [1]. The huge demand for cast iron in the automobile, machinery, and construction industries has placed a premium on its production. The grain size of cast iron is an influencer of its mechanical properties [1-6]. The grain size is dependent on the cooling rate [7]. Fast cooling results in grain refinement, while slow cooling produces coarse grain. The microstructural features of iron-based materials are refined with higher cooling rates [8] and this has an attendant positive impact on the mechanical properties [9-11]. It is, however, important to ensure even cooling as uneven cooling produces low-quality cast. Coarse grain structure is a recipe for cracking and surface defects, and better properties come with grain refinement. The phase constitution of ferrous alloys is unchanged with grain refinement [1].

The process of casting iron is achieved through the pouring of the molten metal into the mould designed to produce the desired shape and size. A cast of uniform mechanical properties across its structure evolves because of uniform cooling rates. Cast iron with non-uniform mechanical properties can, however, be produced either by using different mould materials or by segmenting the mould [3-4,12]. This is the usual practice besides heat treating processes employed in improving the cast iron properties [6,13]. A novel concept of using cooling tubes incorporated in the mould has, however, showed the possibility of varying the mechanical properties of casted iron without sectioning and employing different mould materials [7]. This study seeks to expand the frontier of this concept by determining the impact of different cooling fluids and fluid flow rate on the cooling rate of cast iron using COMSOL Multiphysics 5.5 as the modelling tool.

2. MATERIALS AND METHODS

The numerical method of study was employed by modelling the temperature distribution in the cast to determine the cooling rate using COMSOL Multiphysics 5.5 and incorporating the non-isothermal pipe flow and heat transfer in solids interfaces. The mould material is moulded green sand with the cooling channels placed 30 mm from the intended cast surface on both sides. The cooling channels span half of the cast iron length. The cast iron dimensions are 400x400x200 mm.

The cross-sectional area of the cooling channels used for the study was 78.54 mm² with a circular geometry because of its high volume to surface area ratio. The three-dimensional view of the model assembly is depicted in Fig. 1.

The impact of the cooling fluid type was investigated with the use of water, seawater, vegetable oil, ethylene glycol, and air at a flow rate of 10 l/min. The properties of the cooling fluids and cast iron are depicted in Table 1.

The contribution of the cooling fluids flow rate to the cooling rate was also investigated with the use of varying flow rates. Flow rates of water at 2 l/min, 4 l/min, 6 l/min, 8 l/min, and 10 l/min were investigated to determine the impact on the cooling curve.

The mass and momentum equations govern the fluid flow in the cooling channels. The energy equation governs the heat transfer due to the cooling. The selected friction model was the Churchill friction model. The expressions are as documented in previous studies [7]. The transfer of heat from the cast iron to the mold is by conduction according to the relation;

\[ \rho C_p \frac{\partial T_{sol}}{\partial t} = \nabla \cdot (k \nabla T_{sol}) \]  

(1)

Where

- \( T_{sol} \) is the temperature of the solids
- \( \rho \) is the density
- \( C_p \) is the specific heat capacity at constant pressure
- \( k \) is the thermal conductivity.

### Table 1. Material properties

| Material                     | Density (kg/m³) | Specific Heat Capacity (kJ/kg.K) | Heat Capacity-Cp | Thermal Conductivity (W/mK) | Conductivity |
|------------------------------|----------------|---------------------------------|------------------|-----------------------------|--------------|
| Water                        | 1000           | 4.182                           |                  |                             | 0.609        |
| Seawater (S = 35 g/kg)       | 1027           | 3.85                            |                  |                             | 0.6          |
| Vegetable oil                | 918.5          | 1.67                            |                  |                             | 0.168        |
| Ethylene glycol              | 1137           | 2.36                            |                  |                             | 0.258        |
| Air                          | 1.225          | 1                               |                  |                             | 0.0255       |
| Gray cast iron (Class 40)    | 7000           | 0.42                            |                  |                             | 50           |
Heat transfers through the cooling tubes are by convention according to the relation:

\[ Q_c = hC(T_{ext} - T) \]  \hspace{1cm} (2)

\( C \) is the pipe circumference and \( T_{ext} \) is the temperature external to the pipe. \( h \) is the coefficient of heat transfer given by the expression:

\[ h = Nu \frac{k}{d_{hyd}} \]  \hspace{1cm} (3)

Where the Nusselt number is Nu, and \( d_{hyd} \) is the hydraulic diameter of the pipe.

The cooling fluid entry temperature was set at 150°C and cast iron injection temperature was 1200°C.

The cooling rates were obtained using the relation:

\[ \text{Cooling rate} = \frac{dT}{dt} \]  \hspace{1cm} (4)

\( dT \) is the temperature change for every 100 minutes of time interval (dt)

3. RESULTS AND DISCUSSION

Fig. 2 depicts the cooling curves for the utilized cooling fluids based on the average cast temperature.

The cooling curves of the gray cast iron are similar for water and seawater \((S = 35 \text{ g/kg})\) except at the tail end of the curve due to their similar properties: thermal conductivity. The cooling rate of the cast iron is positively influenced by the cooling fluid of higher thermal conductivity as is visible in Fig. 2. Air offered the least cooling rate. The cooling curves of the gray cast iron were also observed to be steepest at the start period of cooling for the cooling fluids considered except for air which maintained a uniform gradient.

The cooling rates for the utilized fluids at every consecutive one hundred (100) minutes interval is as depicted in Table 2.

The use of seawater as a cooling fluid resulted in the best cooling rate of the gray cast iron for the first two consecutive 100 minutes and followed closely by water. This can be attributed to the good thermal properties of water in comparison.
to the other utilized fluids. The cooling rate of the other fluids; air, vegetable oil, and ethylene increased over the first three consecutive 100 minutes of cooling before experiencing a decline.

Fig. 3 depicts the temperature state of the cast iron after cooling for twelve (12) hours with the use of the investigated fluids.

Fig. 3 depicts that the cast iron also has a lower temperature at the section of the cooling channels for all the considered cooling fluids. This is the basis of varied mechanical properties along the cast iron length. The grain size will differ because of different cooling rates.

Fig. 4 depicts the cooling curves for the cast iron at varying water flow rates through the cooling channel.

The effect of the cooling fluid flow rate on the cooling curve of the cast iron is minimal. An increase in the flow rate by a multiple of five (5) resulted in a slight change in the cooling curve.

Table 2. Cooling rate of the cast iron

| Fluid       | 100  | 100  | 100  | 100  | 100  | 100  | 100  |
|-------------|------|------|------|------|------|------|------|
| Air         | 0.73 | 1.21 | 1.32 | 1.22 | 1.20 | 1.01 | 0.70 |
| Vegetable oil| 1.73 | 2.51 | 2.01 | 1.61 | 1.10 | 0.71 | 0.51 |
| Ethylene    | 2.13 | 2.61 | 1.90 | 1.41 | 1.22 | 0.82 | 0.60 |
| Seawater    | 2.93 | 3.00 | 1.81 | 1.40 | 1.01 | 0.62 | 0.21 |
| Water       | 2.91 | 2.99 | 1.80 | 1.40 | 1.00 | 0.83 | 0.30 |
Fig. 3. Cast iron temperature condition after twelve hours of cooling
4. CONCLUSION

The study led to the following deductions;

- The cast iron cooling curve was affected by the use of different cooling fluids.
- A cast of the desired mechanical properties will evolve with the selection of an appropriate cooling fluid.
- The cast iron cooling rate is minimally affected by the flow rate of the cooling fluid.
- The thermal conductivity of the cooling fluid is a contributor to the impact it has on the cooling rate of the cast iron.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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