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Casting Simulation and Effect of Gating System of an Automotive Wheel Rim

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ABSTRACT
Casting simulation is enhancing foundry engineering worldwide. Through this means, foundry engineers can model, simulate, visualise, analyse and modify casting process. SOLIDCast, an advance casting simulation software, is used in this paper to simulate the casting of a typical rim. Imported from a CAD program, the rim model has a diameter of 220mm, a width of 90mm and a thickness of 10mm. An initial simulation was run without any gating system and with the aid of design wizards a gate was added to the model. Then, a final simulation was run. The cooling curve at the end of the final simulation shows a full solidification time of 1.765 minutes. Both simulations were terminated at an ejection temperature of 200^{o}C. The results of both simulations are compared and validation is based on shrinkage porosity and mould temperature.

Keywords: *Casting; Simulation; SOLIDCast; Solidificatio; Rim.*

1 INTRODUCTION

One of the oldest methods of manufacturing is casting. It is a process in which a material is heated and melted, poured into a refractory mould cavity and allowed to solidify. Upon solidification, the product, known as casting, is ejected, cleaned, and any further finishing processes may be applied.

The automobile industry has benefitted from this age-old manufacturing process since many parts of an automobile are cast because of their intricate design. Some of these parts include: engine block, flywheel, wheel rims, gears and brake discs.

Through the years several methods have been used with the purpose of analyzing the solidification of foundry pieces. At the beginning, analytic methods were used. Later, researchers turned to the employment of numerical methods. Many mathematical models have been developed to predict the phenomena of solidification (Bala and Khan, 2013a) through analytical or computational simulations. At the present time the variety of methods used to simulate metal solidification is numerous, depending on the type of the outlined problem, the geometry, material types and thermal properties. Manjhi *et al* (1997) applied the method of control volume approximation to the simulation of the solidification and thermal treatment of steel ingots.

Recently (Bala and Khan, 2013b) has stated that the development of digital computer technology and applied numerical methods has provided a powerful means for simulating casting solidification. As computer-aided design and manufacture experience increasing use in industries, computer modelling of solidification process in foundry appears to be of great interest since it enables the microstructure, final shape, residual stresses, and defects to be predicted. Numerical simulation has become a fast indispensable tool in technological discovery and development and a strong driving force in the development of science and technology (Minkowycz et al, 2005).

The goal of simulation is to accurately capture solidification dynamics in pure and in alloy materials. To achieve this goal, numerical algorithm must accurately evolve the latent heat in an isothermal solidification process (Knoll et al, 2004); and it must also accurately couple the temperature and concentration fields in the non-isothermal solidification of multi-component alloys. Many researchers have used the numerical methods to model the casting process (Kron *et al*, 2004, Sakuragi, 2005, Mahmoudi, 2006). Also, both the finite difference method and the finite element method have been used to model casting and solidification process (Ogwuagwu, 2006).

Computer Aided Design (CAD), Computer Aided Manufacturing (CAM) and Casting Simulation software are enhancing and adding great value to casting technology worldwide. It is being used to enhance the manufacture of castings, thus reducing defects in castings and improving their quality. In addition, it has led to reduction in design-to-manufacture duration, better first-time and high quality castings, and lower costs of production.

Ega (2006) developed computer software using the java programming language, a high-level language to simulate the gating system of a casting.

Umekwe (2006) used Microsoft Visual Basic 6.0 to carry out computer simulation of the effects of mould thickness on solidification time and temperature. He focused on the use of numerical and computational models to investigate solidification parameters.

Many metal casting process analysis softwares are now available not only for thermal and flow modeling, but also for calculation of grain structure, porosity and mechanical property simulation. Some of these softwares include:

i. SOLIDCast
ii. SUTCast
iii. AUTOCast-x
iv. ProCast
v. Mavis Flow Simulation.
i. MAGMACast
vii AutoCAD
viii. SolidWorks
ix. Pro-Engineer
x. Catia

A rim is the metal edge of a wheel onto which the tyre is fixed. The type of automobile rims depends on the type of vehicle and tyre. Modern passenger vehicles and tubeless tires typically use one-piece rims. Heavy vehicles and trucks, on the other hand, may have a removable multi-piece rim assembly.

Automobile rims can be produced using various materials which may be alloyed, gold or chrome plated. Various sizes which may range typically from 381mm to 711mm in diameter and various manufacturing processes including forming, forging and casting are used to produce it (Wikipedia, 2015).

This paper focus on the computer aided design and production of an automotive rim by casting with a consideration to the design of the gating system.

2 METHODOLOGY

2.1 MATERIALS, EQUIPMENT AND TOOLS

The following materials, equipment and tools were used:

2.1.1 SOLIDCast

SOLIDCast is a PC-based software tool that simulates the pouring of hot metal of virtually any casting alloy into sand, shell, investment or permanent moulds, and the subsequent solidification and cooling process. As explained by Finite Solutions Incorporated (2015), SOLIDCast uses the Finite Difference Method (FDM) of heat transfer calculation, combined with a unique tracking of volumetric changes in the metal, to predict the temperature and volume changes in a casting as it is poured, solidified and cooled. This results in an accurate method of predicting various casting problems, including micro- and macro-porosity, hot spots and other defects. SOLIDCast was developed and is being distributed by Finite Solutions Incorporated, a company based in the United States of America.

2.1.2 SOLIDWORKS 2013

The SolidWorks CAD software is a 3D design automation application that was developed by Dassault Systèmes SolidWorks Corporation, a Dassault Systèmes S.A. company, based in the United States of America. According to Dassault Systèmes SolidWorks Corporation (2015), SolidWorks lets designers quickly sketch ideas, experiment with features and dimensions, and produce models and detailed drawings.

2.1.3 ALUMINIUM ALLOY 6063

Aluminium alloy 6063 is a medium strength alloy. A datasheet from the Aalco Metals Limited (2015), describes the alloy as one with good surface finish, high corrosion resistance, weldability and formability. It also states some of the properties of aluminium alloy 6063 as:

i.	Density	2.68 g/cm^3
ii.	Ultimate Tensile Strength	241 MPa
iii.	Tensile Yield Strength	214 MPa
iv.	Specific Heat Capacity	900 J/kg^{o}C
v.	Modulus of Elasticity	68.9 GPa
vi.	Thermal Conductivity	200 W/mK
vii.	Solidus Temperature	616^{o}C
viii.	Liquidus Temperature	654^{o}C
ix.	Freezing Range	34^{o}C
x.	Latent heat of fusion	398 kJ/kg

The composition by weight of Al 6063 is:

i.	Silicon	0.2% - 0.6%
ii.	Iron	0.35%
iii.	Copper	0.1%
iv.	Manganese	0.1%
v.	Magnesium	0.45% - 0.9%
vi.	Chromium	0.1%
vii.	Zinc	0.1%
viii.	Titanium	0.1%
ix.	Others	0.15%
x.	Aluminium	Remainder

2.1.5 MOULDING SAND

Silica sand with the following properties was used for the casting process:

Thermal conductivity	-	0.59w/mK
Specific heat	-	1075.29J/kgK
Density	-	1521.71kg/m^3

2.2 METHODS

The process of producing the automobile rim was carried out by modelling and simulating the rim after which the actual casting was done using sand casting method.

The modelling of the casting process was done with the SOLIDCast software program, while SolodWorks program was employed to the design the rim SolidWorks program. Material specification was done in terms of type of material for both the cast and the mould thereby displaying their properties on an interface. It also allows the setting of initial mould (pouring) temperature and the ambient of the mould.

After successfully selecting the materials and their properties, the program saves the data and prepares for a part to be designed. The model rim casting was designed in and imported from the SolidWorks environment. The design process involves sketching of half of the rim due to symmetry as shown in Figure 1.

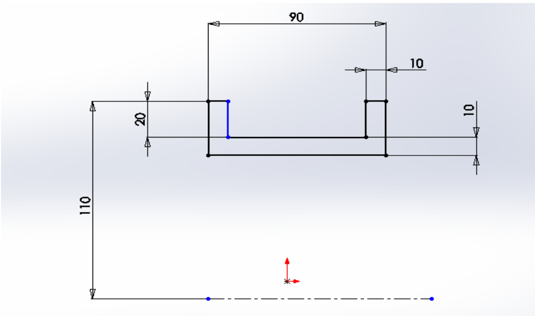


Figure1: The sketch of half rim

The sketch was then revolved about the centerline with the features in the SolidWorks through an angle of 360^{o} in the clockwise direction. Some features of fillets and chamfers were applied using the SolidWorks software. The internal edges of the model had fillets at a radius of 2mm and the external edges at a radius of 10mm.

Figures 2 and 3 show the model just before and after the revolution respectively.

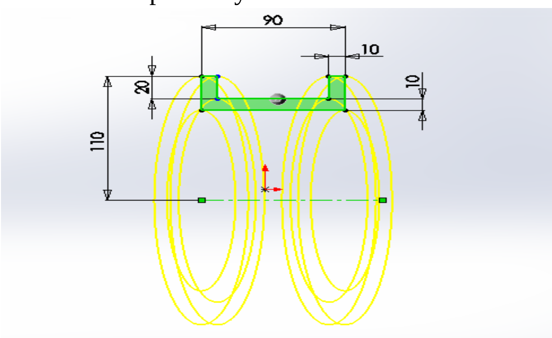


Figure 2: Showing a partially revolved sketched rim

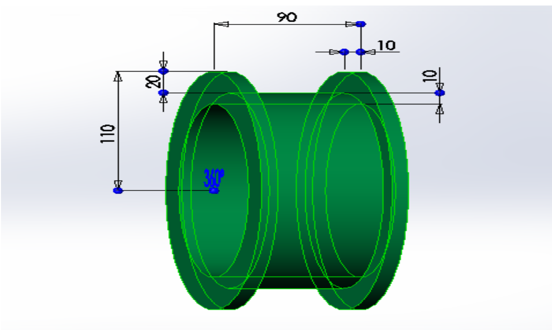


Figure3: Showing the fully revolved sketched rim

2.2.1 SIMULATION OF MODEL RIM

Usually, SOLIDCast runs a simulation on the part without any gating and risers this is called “freezing naked” (Finite Solutions Incorporated, 2015). During the simulation of the model rim casting, SOLIDCast assume the functions of a real foundry shop with a real rim mould, real molten metal, real temperatures and other real properties.

The idea of “freezing naked” is to determine the natural progression of solidification, based on the part geometry and process. SOLIDCast then feeds this information into the Riser Design and Gating Design Wizards, in order to determine feeding zones, riser sizes and locations, as well as to determine appropriate sized gating components designed to fill the casting in an appropriate time and manner (Finite Solutions Incorporated, 2015).

For the simulation to be successful, meshing (process of fitting together a modelled part with pre-defined materials) is carried out this allows program sees the model as a body made up of a series of connected cubes known as nodes. It is at these nodes that the already defined material properties are applied. This body is usually called a Mesh Model.

When the simulation was completed the gating and riser were added to complete the design after which SOLIDCast verifies the model by carrying out further simulation taking into consideration the filling and solidification time and pattern of the part from which investigations, analysis and modifications can be deducted. Figure 4 shows the sequence of the simulation process. Based on the results obtained from the simulations of the casting process, the actual casting was done following the procedure described in the flow chart of Figure 5.

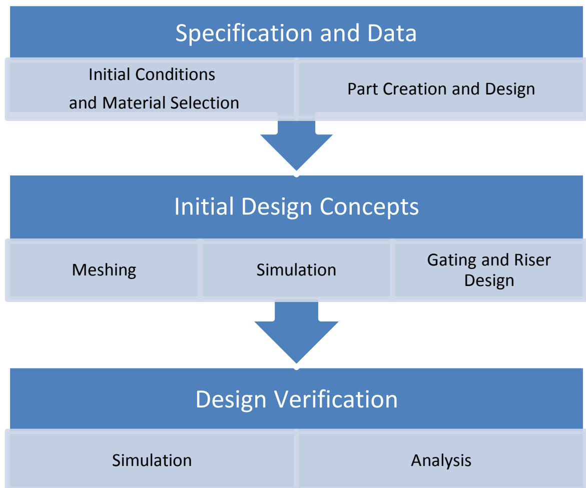


Figure 4: Sequence of the simulation process

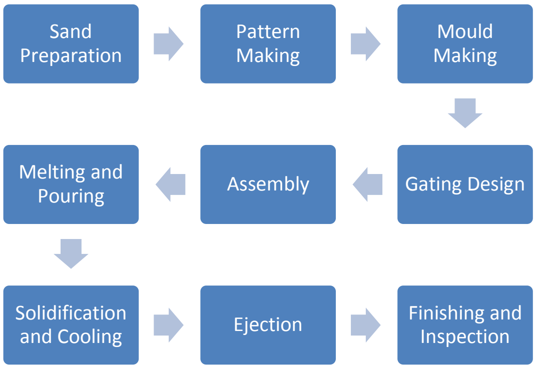


Figure 5: Flow Chart describing the actual casting process

3 RESULTS AND DISCUSSION

The results of the simulation of the cast wheel rim using SOLIDCast provided results in the following areas:

(i) Solidification time
(ii) Critical fraction solid time
(iii) Cooling rate
(iv) Material density function
(v) Hot spots
(vi) Casting temperature
(vii) Mould temperature

3.1 SOLIDIFICATION TIME

Solidification Time is the time, in minutes, for each part of the casting to become completely solid, i.e., to cool to the Solidus Point (Finite Solutions Incorporated, 2015).

Figure 6 shows the wheel rim without gating system and the first point solidified at 1.06 minutes (63.6 seconds) and the last point was at 2.08 minutes (124.8 seconds). Figure 7 indicates that the first point solidified at 1.04 minutes (62.4 seconds) and the last at 3.61 minutes (216.6 seconds). This increased time is due to increase in material volume due to the gating system.

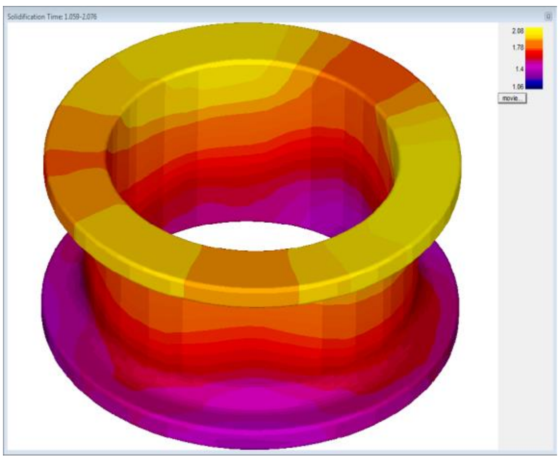


Figure 6: 3D plot of the solidification time for the initial simulation

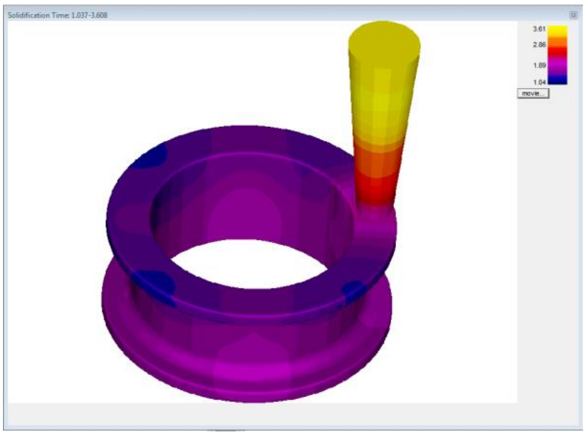


Figure 7: 3D plot of the solidification time for the final simulation

It is observed that in the initial simulation result, the areas around the top of the casting towards the centre solidify last. That could lead to defects in the casting, since there could be shortage of molten metal in those areas as it solidifies. However, the final simulation results show that the modified system allows molten metal to be fed to those regions so that there is no shortage. Solidification is seen to progressively take place from the bottom edges and some parts of the top edges to the top of the sprue and the pouring basin.

3.2 CRITICAL FRACTION SOLID TIME

Critical Fraction Solid Time is the time, in minutes, for each part of the casting to reach the Critical Fraction Solid Point. This is the point at which the alloy is solid enough that liquid feed metal can no longer flow (Finite Solutions Incorporated, 2015).

The minimum and maximum critical fraction solid time for the initial simulation of the rim was 0.23 and 0.6 minutes (i.e. 13 and 36 seconds) respectively as shown in the plot in Figure 8 and also indicates t the areas at the top of the casting solidify last. However, after the gate and risers had been added to the system, that situation was corrected as can be seen in Figure 9.

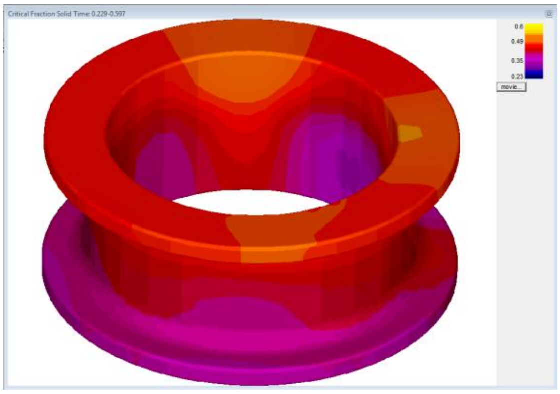


Figure 8: 3D plot of the Critical Fraction Solid Time for the initial simulation

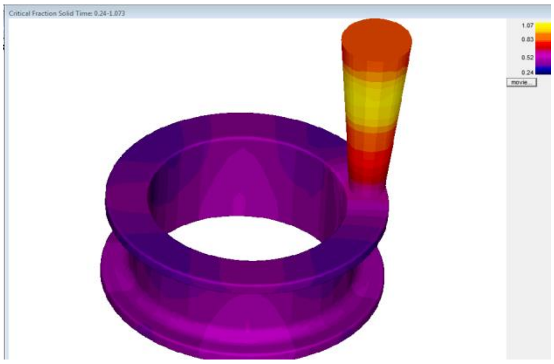


Figure 9: 3D plot of the Critical Fraction Solid Time for the final simulation

3.3 COOLING RATE

Cooling Rate is a measure of how quickly a casting is cooling down, in °C per minute (Finite Solutions Incorporated, 2015). Cooling Rate can be an indication of material quality. Areas of the casting that cool rapidly generally have a more favourable grain structure. Therefore, these areas tend to have better material properties such as strength and hardness. Those areas of the casting that cool more slowly generally tend to have poorer material properties (Finite Solutions Incorporated, 2015).

A careful consideration of the plots presented in Figures 10 and 11 show that the casting with the gating system cools faster with better material properties.

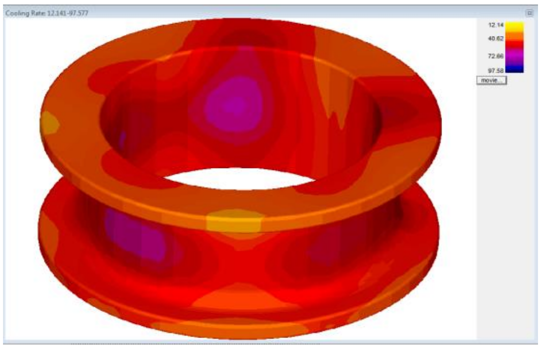


Figure 10: 3D plot of the cooling rate for the initial simulation

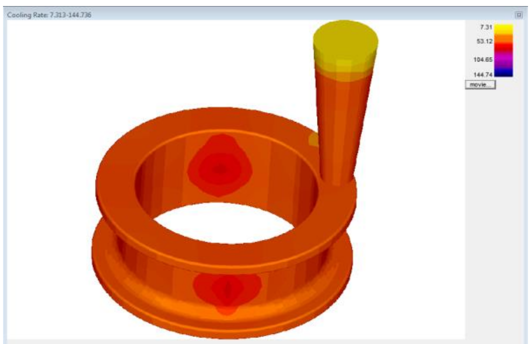


Figure 11: 3D plot of the cooling rate for the final simulation

3.4 MATERIAL DENSITY FUNCTION

This is the result of a calculation in which the contraction of the casting, and resulting flow of liquid feed metal, is taken into consideration during solidification (Finite Solutions Incorporated, 2015). Potential macro porosity can be predicted since material density function can indicate areas with low material density.

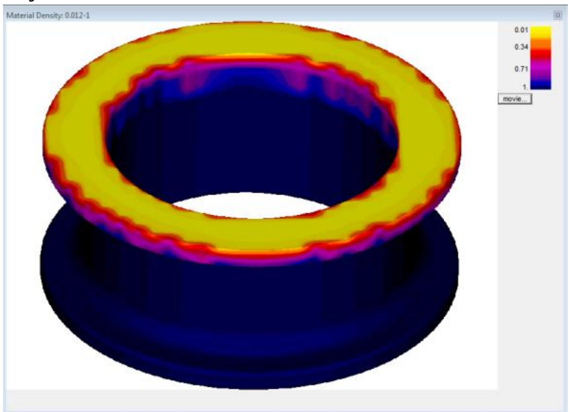


Figure 12: 3D plot of the material density for the initial simulation

Figure 12 predicts that there will be potential shrinkage at the top of the casting. The addition of a gating system eliminates this phenomemon as shown in Figure 13.

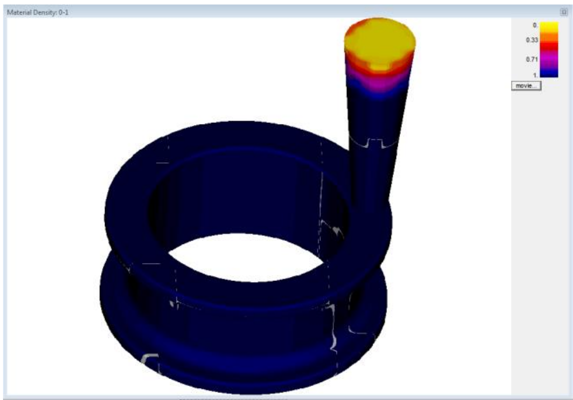
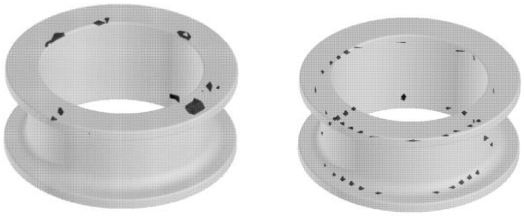


Figure 13: 3D plot of the material density for the final simulation

3.5 HOT SPOTS

Hot Spot plotting is a function in SOLIDCast that locates thermal centres or hot spots within the casting by comparing solidification times or critical fraction solid times of points within local areas (Finite Solutions Incorporated, 2015). The range of values is always 0 to 10. Hot Spots can be plotted based either on solidification time or based on critical fraction solid time. Both plots are shown in Figures 14 (a) & (b) and respectively at a value of 1.1.

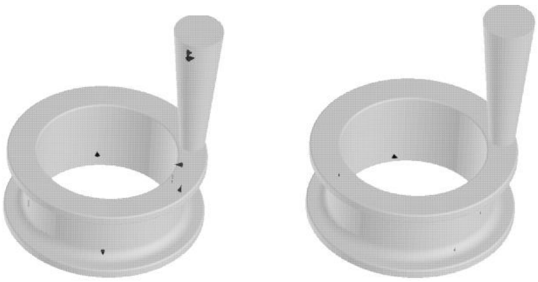


(a) (b)

Figure 14: 3D plot of hot spots based on (a) solidification time for the initial simulation, (b) Critical Fraction Solid Time for the initial simulation

The hot spot plot does not give an indication of the severity of the defect, as it does not take contraction or expansion into account. But it does give a good indication of what areas may have problems (Finite Solutions Incorporated, 2015).

Modification of the model by the addition of a gate helped to reduce the hot spots significantly as shown in Figures 15 (a) & (b). The plots were carried out at a value of 1.1.



(a) (b)

Figure 15: 3D plot of hot spots based on (a) solidification time for the initial simulation, (b) Critical Fraction Solid Time for the final simulation for the final simulation

3.6 CASTING TEMPERATURE

The temperature of the casting was recorded at different times during the simulation. The graph in Figure 16 was obtained from the final simulation. The graph is also the cooling curve of the casting.

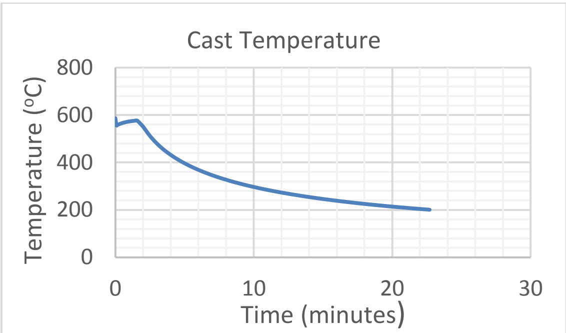


Figure 16: Graph showing casting temperature with time (cooling curve)

From a maximum temperature of 586.5°C, there is a steady drop in temperature until solidification begins at 559.4°C. Any further drop in temperature is minimal. In fact, it rises slowly to 566°C, the point when solidification is complete and cools rapidly to 200°C.

3.7 MOULD TEMPERATURE

Mould temperature is a very important factor to consider during casting as it affects the quality of the casting. The following result was obtained from the final simulation as shown in the graph in Figure 17.

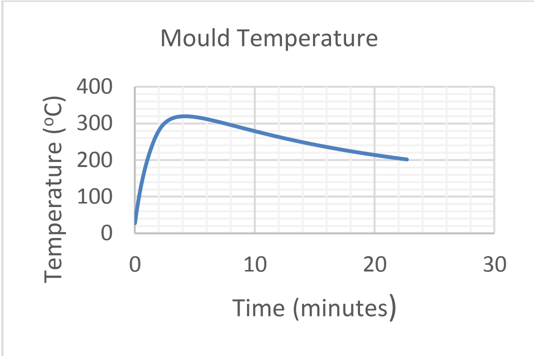


Figure 17: Graph showing mould temperature with time

A careful consideration of the casting and mould temperatures presented shows that there is transfer of heat from the casting to the mould. As the temperature of the casting drops progressively, that of the mould rises until a point when they both are decreasing this is shown in Figure 18. Series 1 is the cooling curve of the casting, while Series 2 is heating curve of the mould.

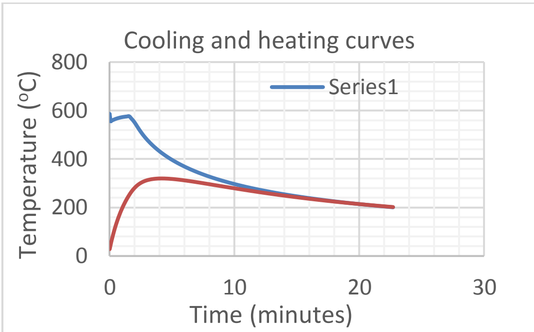


Figure 18: Comparison of the cast and mould temperatures

3.8 RESULTS VALIDATION

To validate the results from the SOLIDCast program, a real rim was cast based on those results. The validation was based on the following two conditions:

i. *Macro Porosity*: This is a defect predicted by material density function. At the end of the actual casting based on the results from the final simulation, it was observed by sight and touch that no such defect was present in the casting.

ii. *Mould Temperature:* In order to validate the results of the mould temperature from the simulation, a thermocouple was placed in the mould during the actual casting and the result obtained (series 2) is compared with the simulation result (series 1) as shown in in Figure 19.

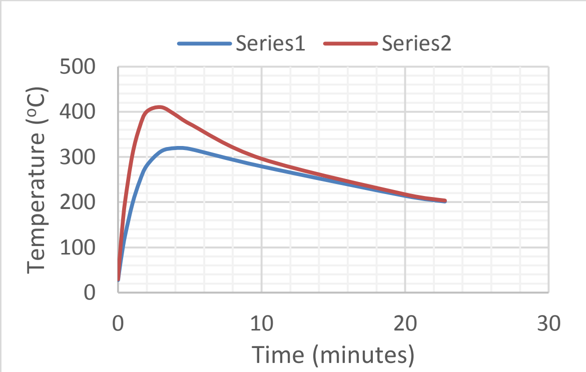


Figure 19: Graph comparing the measured and the simulated mould temperatures

A comparison of the mould temperature from the simulation and the measured values indicates a slight variation. This can be attributed to the fact that the simulation software records the mould temperatures from any point(s) around the mould, taking the maximum values for the point(s). But the measured values were from a thermocouple placed at one position throughout the duration of the casting. However, it is very interesting to note that the increase and decrease of the mould temperatures from both results are very similar.

4.0 CONCLUSION

The use of simulation software SOLIDCast in conjunction with SolidWorks enhances casting of automobile wheel rim by considering solidification parameters for sound cast was achieved making it a useful tool for the foundry. The introduction of gating system during the simulation ensure the a better and sound automobile wheel rim production.The results obtained include cooling curves showing the temperature of the casting and mould at different times; a full solidification time of 1.765 minutes; a cooling rate of 144.74°C/min; a cooling time of 22.7 minutes at a temperature of 200°C and predicting defects like shrinkage porosity and hot spots associated with the pouring of molten metal, solidification and cooling.

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