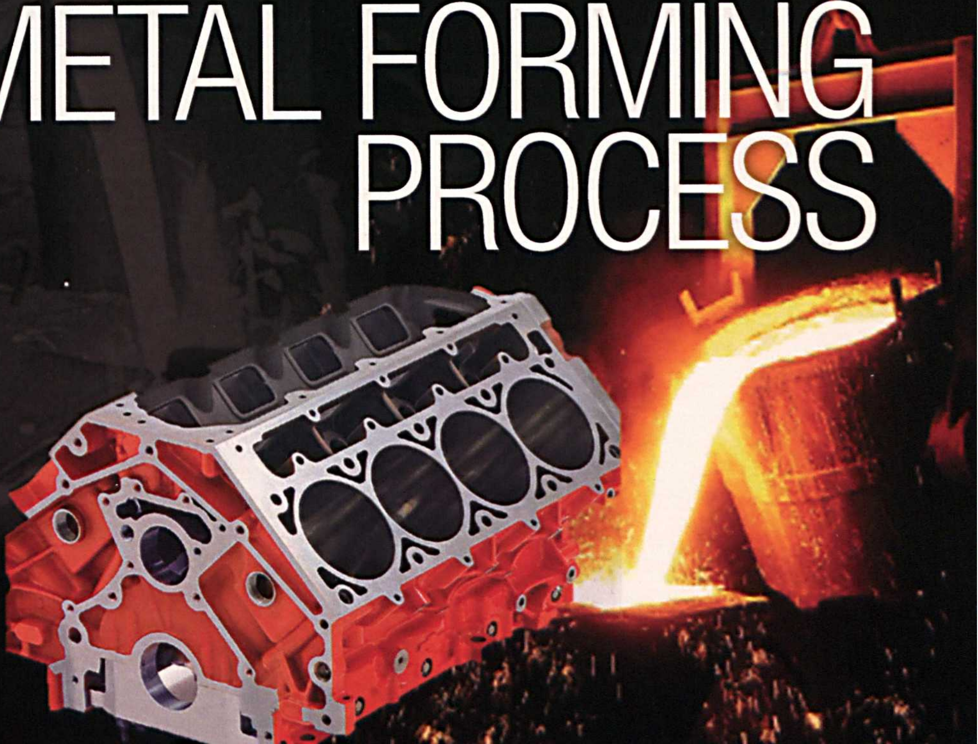
INAUGURAL LECTURE series

Prof. Dr. Shamsuddin Sulaiman

UPM
UNIVERSITI PUTRA MALAYSIA
BERILMU BERBAKTI

CASTING TECHNOLOGY
SUSTAINABLE METAL FORMING PROCESS



CASTING TECHNOLOGY

SUSTAINABLE METAL FORMING PROCESS

PROFESOR DR. SHAMSUDDIN SULAIMAN

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ABSTRACT

Metal casting is a process where molten metal is poured by gravity or injected with pressure into a mould cavity to produce the desired product. Most cast products are in finished goods form, which require minimal level of machining and surface finishing to achieve the desired tolerance and surface quality. Many industrial parts and components are produced by the method of casting, including engine blocks, crankshafts, automotive components, railroad equipment, plumbing fixtures, power tools, very large components for hydraulic turbines and so on. In terms of the theoretical application, two pertinent parameters, i.e. flow and thermal aspects, are explained in detail. The advancement from conventional to advanced materials has pushed casting technology into a competitive environment based on product requirements. Further, Computer Aided Design and Computer Aided Manufacturing (CAD/CAM) together with machine technology have also been introduced to the foundry or casting industry. This lecture will cover the development of Advanced Manufacturing Technology (AMT) applied in metal casting processes. Selected works on casting processes and technology for conventional and advanced materials are reviewed, and studies on metal matrix composites for engineering products are discussed. Other than process simulation technology, advances in mould and die design technology are also being applied in casting product development. With these technologies, the casting process will be maintained and sustained as an important and relevant component of the metal forming process.

INTRODUCTION

Casting is one of the oldest known processes used to produce metallic components. The first metal casting was done using stone and metal moulds during the 4000 -3000 B.C. period. The Mesopotamians were the first to cast bronze using forged moulds. Since then, various casting processes have been developed. In casting, the liquid material is poured into a cavity (die or mould) corresponding to the desired geometry. The shape adopted by the liquid material is stabilized, usually by solidification, and it can then be removed from the cavity as a solid component (Bruce et al., 1998).

Casting processes are important and extensively used manufacturing methods because they can be used to produce very intricate parts in nearly all types of metals at high production rates, can produce very large parts, with average to good tolerances, acceptable surface roughness and good material properties. The casting process reduces the need for expensive machining techniques which are often needed with other metal working techniques, thus reducing the overall cost of the products (Clegg, 1991). The competitiveness of the casting process is based primarily on the fact that casting allows the elimination of substantial amounts of expensive machining often required in alternative production methods.

In casting, the liquid material is poured into a cavity (die or mould) corresponding to the desired geometry. The shape adopted by the liquid material is stabilized, usually by solidification, and it can be removed from the cavity as a solid component. In principle, no limits exist with regards to the size or geometry of the parts that can be produced by casting. The limitations are set primarily by the material's properties, the melting temperatures, the properties of the mould material (mechanical, chemical and thermal) and the material's production characteristics, such as, whether it is to be used only once or many times (Bruce et al., 1998). Therefore, in terms of applications, various types and shapes of components could be produced. Figure 1 shows cast parts in typical automobile applications. Figure 2 shows different automotive cast parts produced with various types of metals. As the process generally involves the material being melted down and poured into a cast mould, it can virtually be applied to any type of material that is processed in the same way. Thus non-metallic materials such as plastics and composites can also be made by casting process (Kalpakjian and Schmid, 2010).

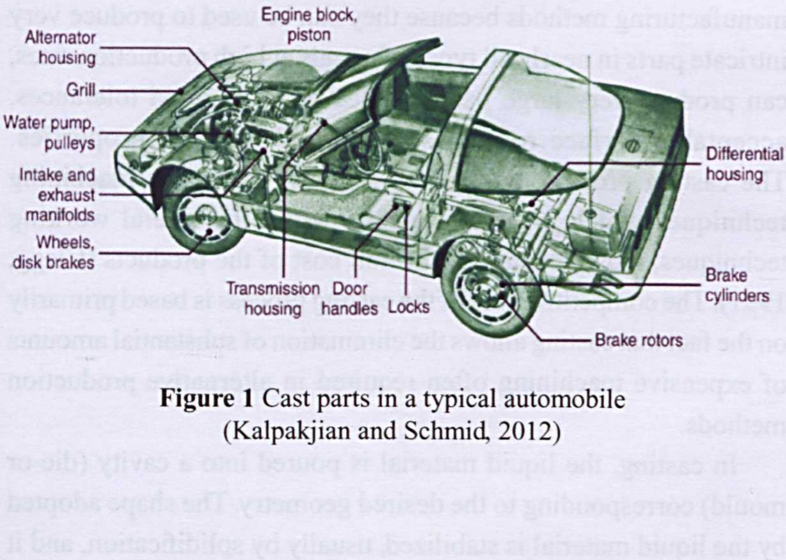


Figure 1 Cast parts in a typical automobile (Kalpakjian and Schmid, 2012)

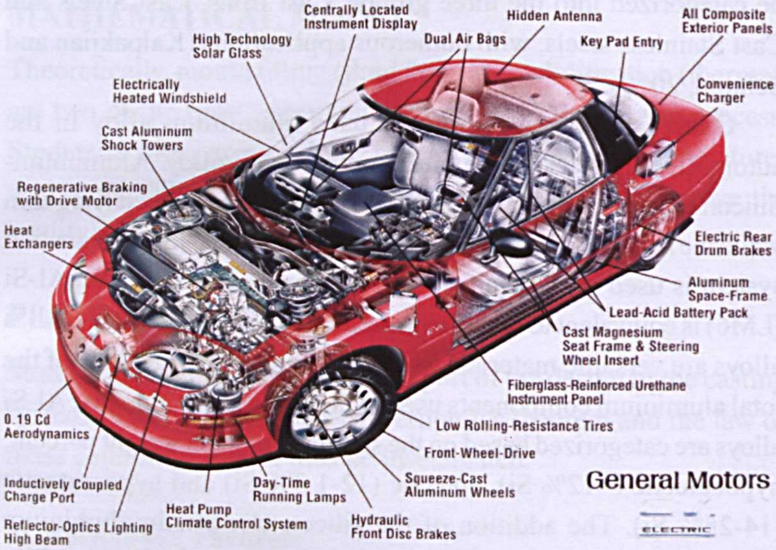


Figure 2 Some components of automotive parts (Groover, 2007)

In order to produce castings that are free from defects and meet requirements such as strength, dimensional accuracy and surface finish, factors that need to be controlled are the flow of the molten metal into the mould cavity and heat transfer during solidification and cooling of the metal in the mould. These parameters may influence the type of mould material and solidification of the metal from its molten state (Kalpakjian and Schmid, 2010).

ADVANCES IN MATERIALS

Conventionally, the materials that are used for casting can be divided into two main categories, i.e non-ferrous alloys and ferrous alloys. A large and diverse group of alloys can be utilized in non-ferrous alloy castings. The most commonly used alloys are aluminium-based alloys. Other non-ferrous alloys which are often used are Magnesium, Copper, Zinc, Tin and Lead alloys. Ferrous alloys can be categorized into the three groups, Cast Irons, Cast Steels and Cast Stainless steels, with numerous applications (Kalpakjian and Schmid, 2010).

One of the most commonly used aluminium alloy in the automotive industry is the aluminium silicon alloy. Aluminium-Silicon designation with LM numbers is used in the United Kingdom while the American National Standards Institute (ANSI) designation system is used in the United State of America. Aluminium Al-Si (LM6) is equivalent to Aluminium association alloy: 356.0 [3]. Al-Si alloys are versatile materials which account for 85% to 90% of the total aluminium components used in the automotive industry. Al-Si alloys are categorized based on the silicon content in weight percent: hypoeutectic (<12% Si), eutectic (12-1 3% Si) and hypereutectic (14-25% Si). The addition of the silicon element in aluminium alloys will increase cast-ability by increasing mould filling ability and solidification of casting with absence of hot tearing or hot cracking issues [4]. Al-Si (LM6) alloys exhibit excellent resistance to corrosion under both atmospheric and marine conditions. It also has high fluidity which allows thinner and intricate sections to be cast as compared to any of other types of casting alloys (Apelian, 2009).

The advancement of materials has resulted in the introduction of composite materials and applications. For metal, Metal Matrix Composites (MMC) are considered as potential material candidates for a wide variety of structural applications in the transportation, automobile and sport goods manufacturing industries due to their superior range of mechanical properties(Hasyim et al., 2002). MMCs combine the metallic properties of matrix alloys (ductility and toughness) with the ceramic properties of reinforcements (high strength and high modulus), leading to greater strength in shear and compression and higher service-temperature capabilities (Clegg, 1991).

MATHEMATICAL MODEL

Theoretically, mould filling (fluid flow) and solidification (thermal) are two of the most important parameters in the casting process. Studies in these areas help to predict molten metal temperatures during the filling, the solidification patterns and to improve the quality and accuracy of the final products

FLOW ANALYSIS

Study of fluid flow is a very critical part of the design of the casting system. The two principles of Bernoulli's theorem and the law of mass continuity should thus be investigated.

a) Bernoulli's Theorem

This theory investigates the conservation of energy, pressure, velocity and the elevation of the fluid at any location in the specimen, as expressed in Eq. (1) (Kalpakjian and Schmid, 2010):

$$h + p/\rho g + v^2/2g = constant \tag{1}$$

In this equation h is the elevation above the reference level, p is the pressure at this level, ρ is the density of the fluid, g is the gravity constant and v is the velocity of the fluid at that level.

b) Mass Continuity

This law mentions that in the system with impermeable walls the rate of incompressible liquid flow is constant as is shown by Eq. (2) (Kalpakjian and Schmid, 2010):

$$Q = A_1 v_1 = A_2 v_2 \tag{2}$$

In Eq. (2) Q is volume rate of flow; A is the cross sectional area of the liquid stream and v is the velocity of the liquid at that cross section.

c) Solidification Time

Solidification time of the specimens depends on the volume of casting and its surface area as is clearly shown in Eq. (3) (Kalpakjian and Schmid, 2010).

$$\textit{Solidification time} = C\ (\textit{Volume / Surface area})^n \tag{3}$$

In this equation C is the constant, which relates to mould and metal properties, and n is taken as being between 1.5 to 2.

THERMAL ANALYSIS

For all transient casting heat transfer analysis, there is heat transfer by conduction and a temporal depletion of energy from the molten metal which causes its solidification. This physics must be expressed in mathematical form for the process.

The heat flow through the single homogeneous link (Figure 3) is given by:

$$q = -kA\frac{dT}{dx} \tag{4}$$

which can be converted into a matrix form as

$$\frac{kA}{L}\begin{bmatrix} 1 & 1 \\ -1 & -1 \end{bmatrix}\begin{Bmatrix} T_1 \\ T_2 \end{Bmatrix} = \begin{Bmatrix} Q_1 \\ Q_2 \end{Bmatrix} \tag{5}$$

Where there are different materials joined at an interface (Figure 5), the matrix equation becomes

$$\frac{1}{\dfrac{L_1}{K_1A_1}+\dfrac{L_2}{K_2A_2}+\dfrac{1}{h_iA_i}}\begin{bmatrix}1 & -1\\ -1 & 1\end{bmatrix}\begin{Bmatrix}T_1\\ T_2\end{Bmatrix}=\begin{Bmatrix}Q_1\\ Q_2\end{Bmatrix} \tag{6}$$

and with heat loss to a cooling surface it is expressed as (Figure 4),

$$\frac{1}{\dfrac{L_1}{A_1K_1}+\dfrac{1}{h_fA_f}}\begin{bmatrix}1 & -1\\ -1 & 1\end{bmatrix}\begin{Bmatrix}T_1\\ T_f\end{Bmatrix}=\begin{Bmatrix}Q_1\\ Q_f\end{Bmatrix} \tag{7}$$

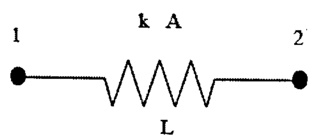


Figure 3 Single homogenous link

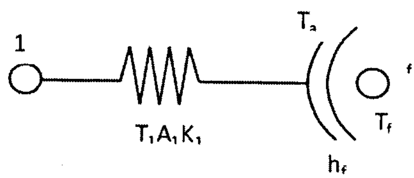


Figure 4 Heat loss to cooling surface

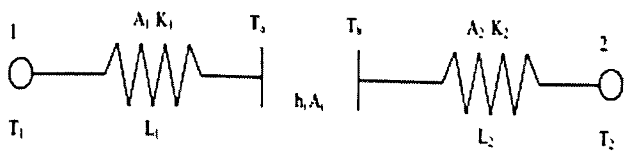


Figure 5 Different materials joined at an interface

In a transient analysis, energy is removed from the system by conduction, and this transient energy loss per unit volume can be expressed as:

$$\overset{\circ}{E} = \rho\, C \frac{dT}{dt} \tag{8}$$

or where phase change takes place over a finite temperature interval it is then expressed as:

$$\overset{\circ}{E} = \rho \frac{dH}{dT} \frac{dT}{dt} \tag{9}$$

In discretized form, at time step 'j' equation (9) can be expressed as

$$\overset{\circ}{E} = \rho \frac{dH}{dT} \left[\frac{T_i^{J+1} - T_i^j}{\Delta t} \right] \tag{10}$$

This can be combined with the conduction matrices (Equations 5, 6 or 7) to give an appropriate transient algorithm, which may be explicit, implicit or explicit-implicit (Crank-Nicolson). For example, for an implicit formulation and a homogeneous conduction link the equation is:

$$\rho\, V \frac{dH}{dT} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} - \frac{kA}{L} \Delta t \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \begin{Bmatrix} T_1^{j+1} \\ T_2^{j+1} \end{Bmatrix} = \rho\, V \frac{dH}{dT} \begin{Bmatrix} T_1^j \\ T_2^j \end{Bmatrix} \tag{11}$$

Similar equations may be derived by incorporating Equations 6 and 7 for the appropriate heat removal path, where in the die or mould the enthalpy gradient (dH/dT) is replaced by the material specific heat. Thus for an implicit formulation, the general form of the matrix equation can be written as:

$$[C]+\Delta t[K]\{T^{j+1}\}=[C]\{T^{j}\} \quad (12)$$

Using this basis, the heat capacity matrix (Sulaiman and Gethin, 1996) needs to be recalculated at each time step to account for phase change and where nonlinear thermal conductivity {k(T)} is present, the equation set needs to be solved iteratively within each step, with an update of the thermal conductivity at each iteration.

SIMULATION MODEL

Computer simulation is widely used to predict mould filling, solidification characteristics and to detect defects. This is very economical and saves a lot of time. Software such as MagmaSoft, EdStefan and AnyCasting are commonly used for casting simulation. For this study, mould filling and solidification times were estimated using AnyCasting and MAGMASoft softwares.

In this simulation and experimental work, mould filling and solidification time for both sand and permanent moulds are estimated. Further, the results include values of tensile test, hardness test and micro-structures obtained from the SEM test.

Results for the Sand Mould (AnyCasting)

The image of the center of the cylinder cavity produced by simulation model for a sand mould was captured and is presented in Figure 6. It shows the sequence of the solidification time for the LM6 alloy matrix without TiC as particulates. The legend shows the time and the colored regions represent the solidified casting parts. The model shows the pattern of the solidified casting which is of oval shape. The solidification time of the casting is clearly evident from the color regions. For the blue region solidification occurred within 78.08 to 161.92 seconds (Suraya, et al., 2011).

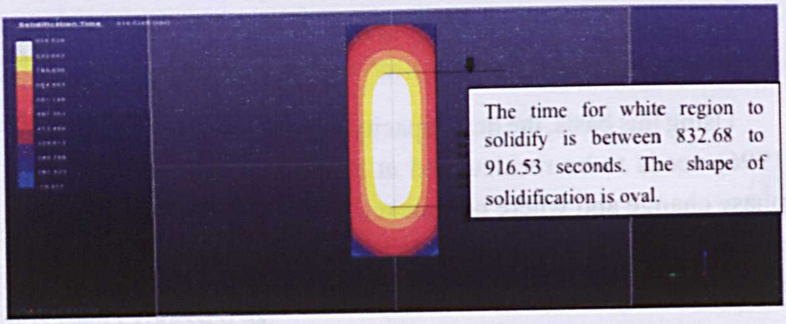


Figure 6 The sequence of solidification time

As can be seen in Figure 7, 2.81 seconds were needed for 25% filling with no solidification seen. The temperature distribution was between 627°C to 650°C. The mould filling visualizations for the LM6 alloy matrix, without TiC as particulates, are shown in Figures 8 to 10, respectively. Figure 8 shows molten metal fill 55% of the sand mould. The duration taken to fill the cavity was 6.19 seconds and the molten metal temperature was between 611°C to 642°C. The solidification percentage for the 55% mould filling was 0. Figure 9 shows the filling time for 75% cavity fill as 8.44 seconds with no solidification shown. 11.19 seconds were needed for the molten metal to completely fill the mould cavity, as shown in Figure 10. The temperature distribution was maintained at around 627°C to 650°C. The results, show that temperature distribution during mould filling was between 619°C to 650°C and no solidified area could be seen throughout this process.

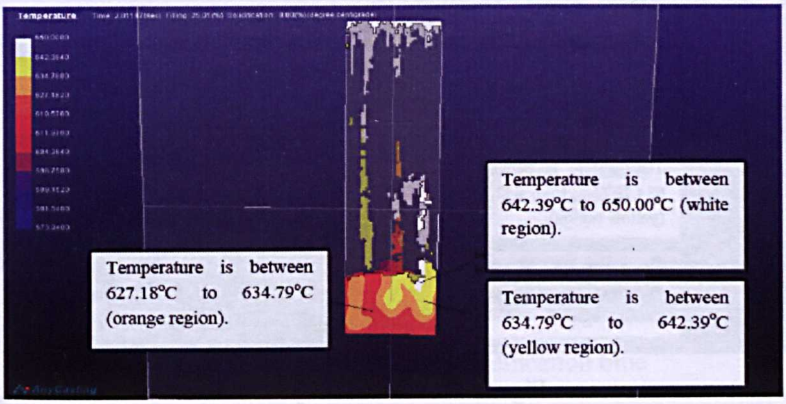


Figure 7 25% cavity fill

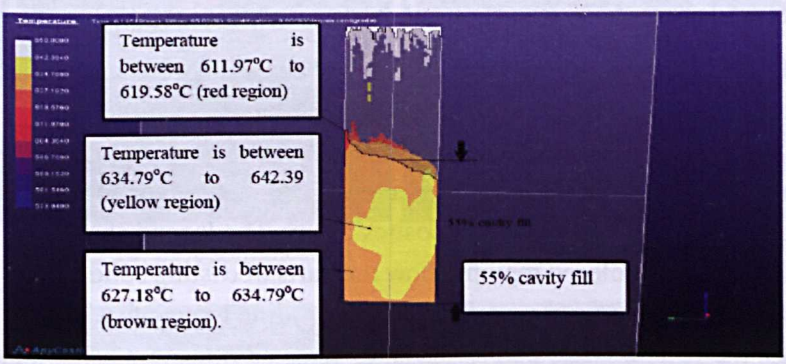


Figure 8 55% cavity fill

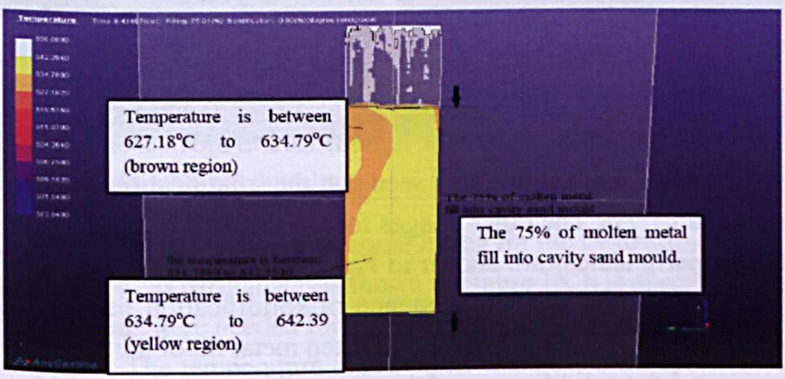
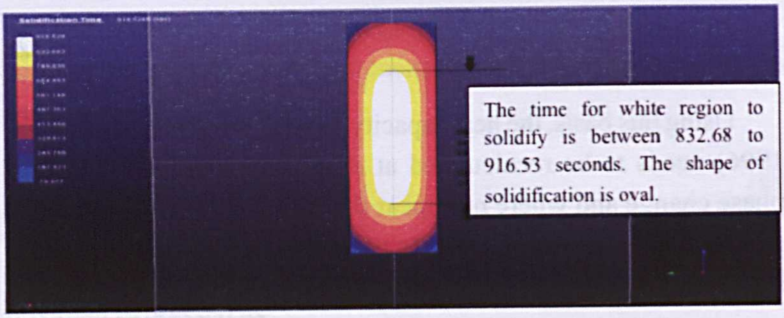


Figure 9 75% cavity fill



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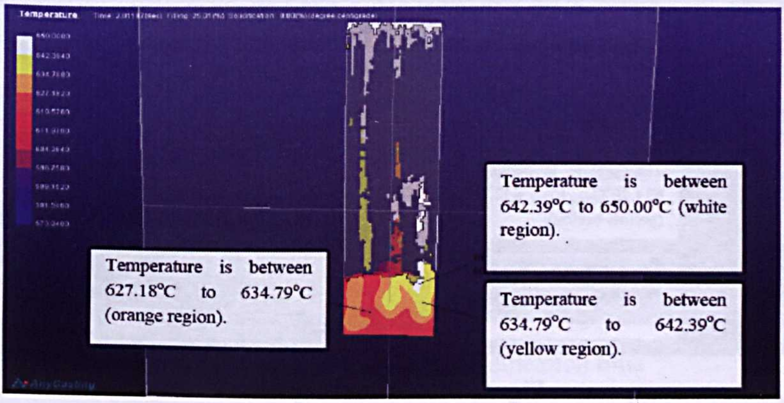


Figure 7 25% cavity fill

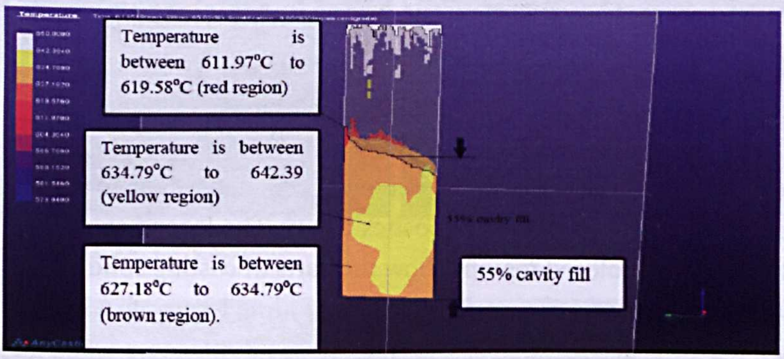


Figure 8 55% cavity fill

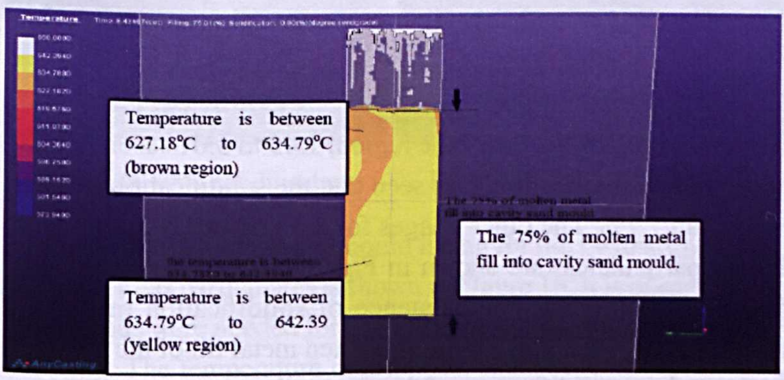


Figure 9 75% cavity fill

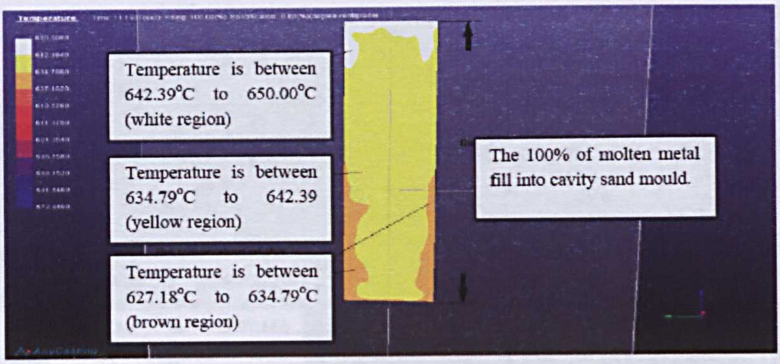


Figure 10 100% cavity fill

Results for the Permanent Mould (AnyCasting)

Figure 11 is an image of the center of the cylinder cavity from the simulation model using a permanent copper metallic mould. The figure shows the sequence of solidification times and the visualizations of molten metal percentage fill in the cylinder cavity and solidification of the composites cavity. The legend shows the time and the colored regions show the parts of casting solidifying. The model shows the pattern of the solidified casting which is similar to a half oval shape. The patterns of solidification using the permanent copper mould are different from those observed with the sand mould whereby with the sand mould the pattern appears to be oval whereas a conical shape is observed for the permanent mould. The solidification time for the casting is clearly seen in the colored region. For the blue region, 1.45 to 5.01 seconds were needed for solidification. It is seen that the solidification was not more than 7.7%. The other images for the LM6 alloy matrix with TiC as particulates are shown in Figures 12 to 15, respectively. The figures illustrate the sequence of solidification times and visualization of the percentage of molten metal fill of the cylinder cavity and the solidification of the composite.

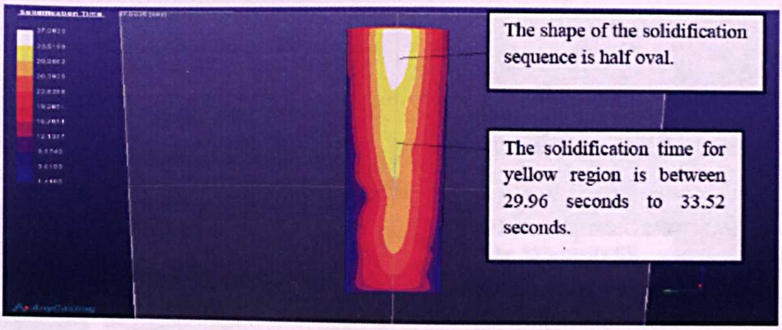


Figure 11 The sequence of solidification time

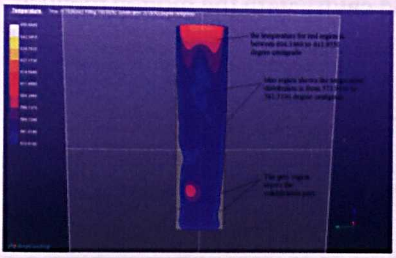


Figure 12 25% solidification

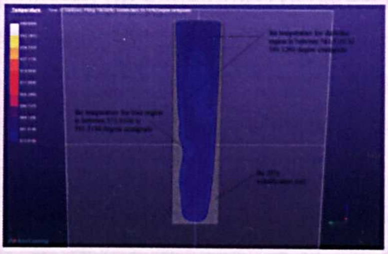


Figure 13 55% solidification

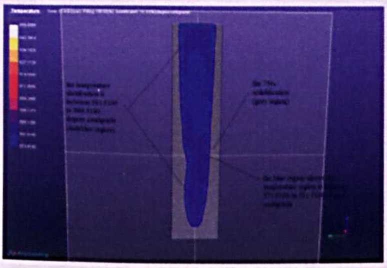


Figure 14 75% solidification

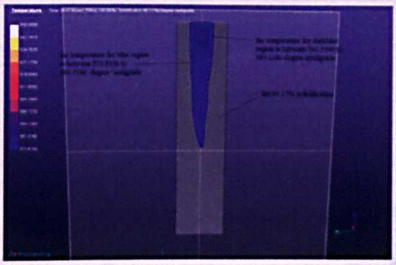


Figure 15 95% solidification

The visualization of the mould filling for the LM6 alloy matrix without TiC as particulates is shown in Figure 16. It is observed that 2.8 seconds were needed for 25% filling with 4.20% solidification occuring. The temperature distribution was between 573.91°C to

650°C. The other images for the LM6 alloy matrix with 5-20 wt% of TiC as particulates are shown in Figures 17 to 19. The legend shows the temperature and the colored regions show the percentage of mould filling. Figure 17 shows 55% fill of molten metal into the sand mould. The duration to fill the cavity was 6.1 seconds and the molten metal temperature was between 573.91°C to 604.35°C. The solidification percentage of this 55% mould filling was 10.44%. Figure 18 shows that a duration of 8.4 seconds was needed for molten metal to fill 75% of the cavity and 14.73% solidification can be seen throughout this figure. A duration of 11.2 seconds were needed to completely fill the mould cavity with the molten metal as shown in Figure 19. The temperature distribution was maintained at around 574°C to 650°C and 23.39% solidified area was seen throughout this process.

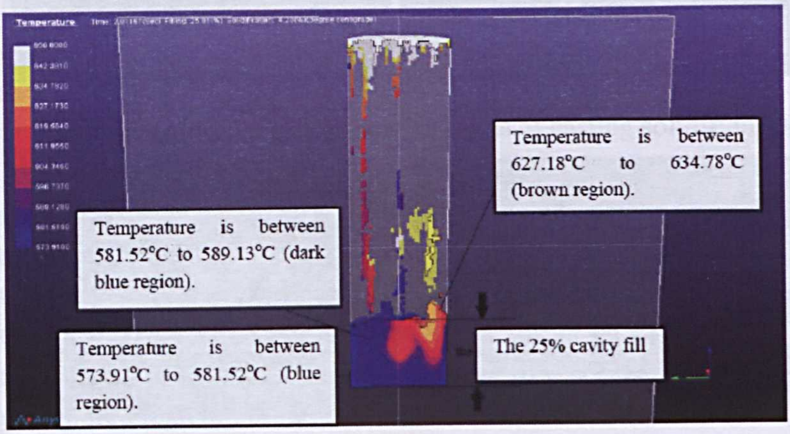


Figure 16 25% cavity fill

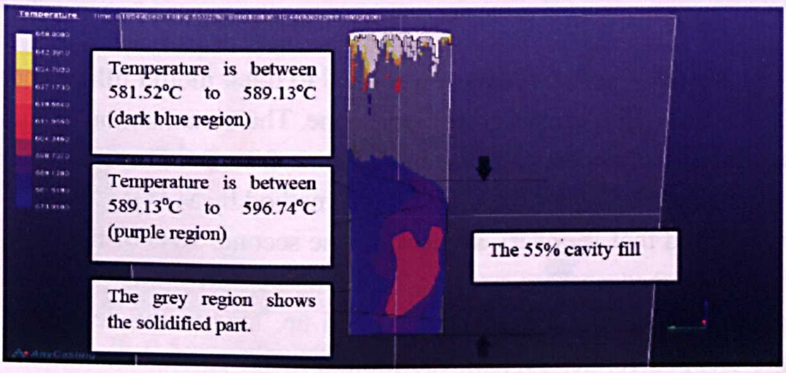


Figure 17 55% cavity fill

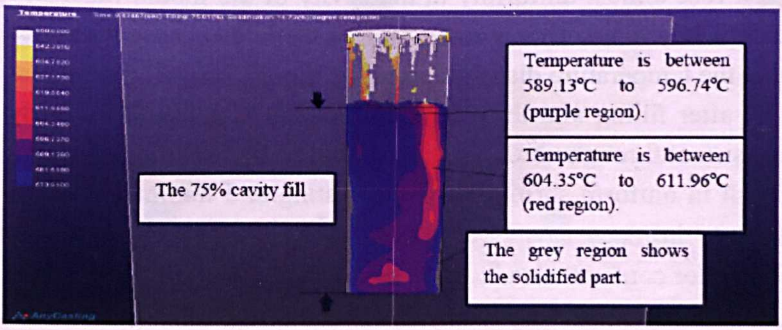


Figure 18 75% cavity fill

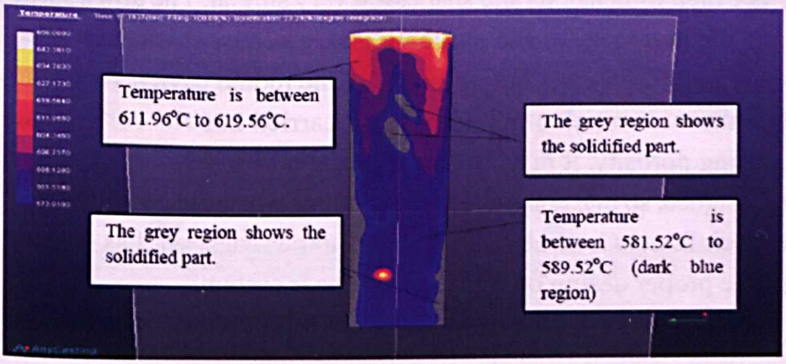


Figure 19 100% cavity fill

Mould filling (MAGMAsoft)

The MAGMAsoft simulation was used to track mould filling and solidification processes at the same time. The visualization of the mould filling process can be seen in Figures 20 to 26. The flow front was tracked by VOF (volume of fluid) method by MAGMAsoft. It was found that for every successive one second, 10% of the total volume (encompasses pouring basin, sprue and runner system, gatings, casting and feeder) was filled up. Due to the design of the stepped runner system, the molten metal entered the mould through all gates at the same time, as shown in Figure 21. The melt rose almost uniformly in the cavity of the mould till it was completely filled. This is a good filling method because it ensures that the temperature distribution in the mould is equal throughout just after filling and thust he solidification rate would be fairly consistent throughout the casting. Equal rate of solidification will result in uniform shrinkage of the casting and minimize defects such as shrinkage cavities as a result of non-uniform cooling rates. The color contours also indicate that during mould filling, cooling had actually started especially at the end of the runner. It can be seen that the down sprue and feeder were filled up simultaneously since their dimensions and shapes are very similar. The down sprue was the entrance for the molten metal, whereby it was not filled up or completely wet during filling of the mould cavity. To ensure that there is no risk of air entrapment carried into the casting and causing porosity, it may be best if the down sprue dimensions are redesigned, so that complete wetting of its wall occurs during initial mould filling. Generally, the mould filling is successful as a result of the proper design of the stepped runner system.

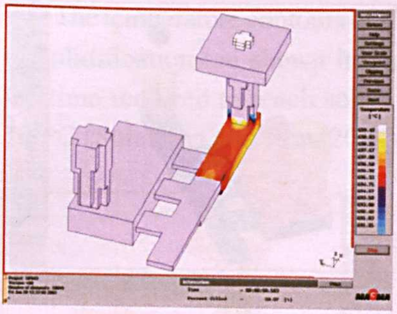


Figure 20 0.5 sec. 10% filled up

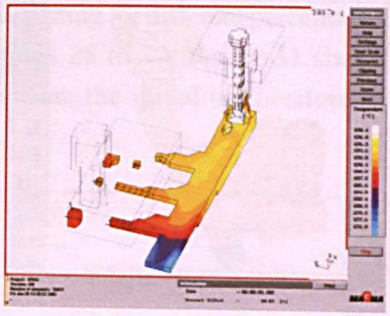


Figure 21 1.0 sec. 20% filled up

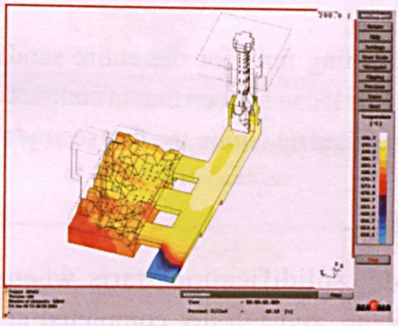


Figure 22 2.0 sec. 40% filled up

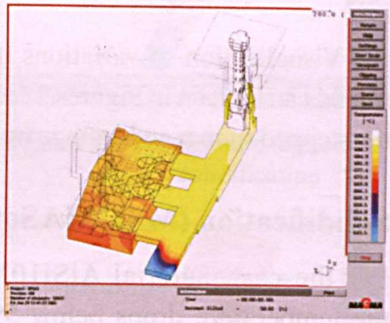


Figure 23 2.5 sec. 50% filled up

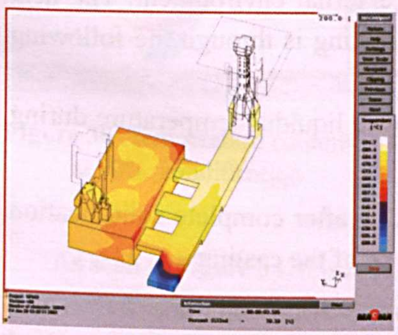


Figure 24 3.5 sec. 70% filled up

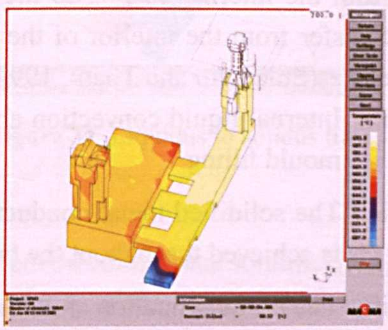


Figure 25 4.0 sec. 80% filled up

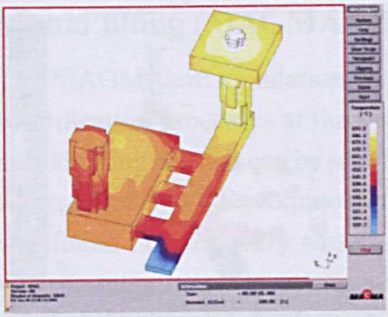


Figure 26 5.0 sec. 100% filled up

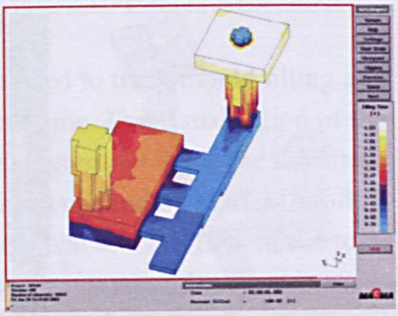


Figure 27 Mould filling time

Visualization of variations in filling time for the entire sand mould can be seen in Figures 22 to 27. It can be seen that in contrast the stepped runner and gatings were filled up within the first second.

Solidification (MAGMASoft)

For the cast material AlSi10Mg, solidification starts when the temperature drops below 595°C, and is fully completed at temperatures below 555°C. Solidification is a result of heat transfer from the internal casting to the external environment. The heat transfer from the interior of the casting is through the following routes(Sulaiman and Tham, 1997):

i. Internal liquid convection above liquidus temperature during mould filling
ii. The solidified metal conduction after complete solidification is achieved throughout the bulk of the casting
iii. The heat conduction at the metal-mould interface
iv. Heat conduction within the green sand mould
v. Convection and radiation from mould surface to the surroundings

The temperature contours of the casting for different percentages of solidification are shown in Figures 28 to 30. Figure 31 shows the time required to reach solidus from the initial temperature of 700°C (Sulaiman and Lim, 2004).

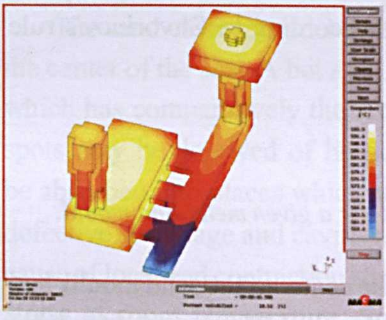


Figure 28 Temperature contour at 10% solidification

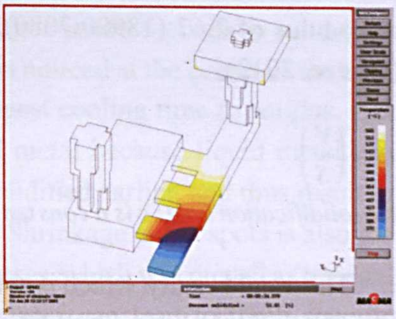


Figure 29 Temperature contour at 51% solidification

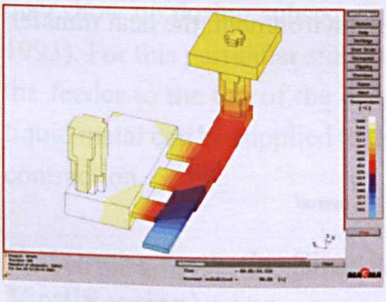


Figure 30 Temperature contour at 90% solidification

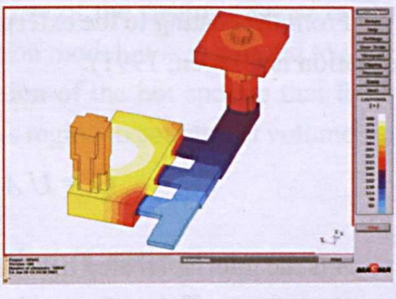


Figure 31 Liquidus to solidus time

As seen in Figure 31, it is apparent that directional solidification is achieved in the runner system. The tip of the runner, which has the lowest thickness, resulted in faster solidification than in other places. After about 60 seconds, the molten metal in the runner tip had completely solidified. Solidification time is proportional to the volume to surface area ratio (modulus of casting) (Sulaiman and Hamouda, 2004), therefore the faster solidification rate at the runner tip is expected. The solidification front propagates towards the sprue base from the runner tip. It can be calculated that the mould cavity has a modulus of 10.56 (432000/40920) while the runner tip has a modulus of 2.67 (18900/7080). According to Chvorinov's rule (Grieve, 2012),

$$t = c\left(\frac{V}{S}\right)^2$$

t = solidification time ; c is a constant for a given metal and mould.

The mould cavity, which is at the center of the sand mould, had comparatively the longest solidification time. This is understandable because according to Fourier's law of conduction, thermal resistance increases with the thickness across which heat is to be conducted.

From the casting to the external environment, the heat transfer equation is (Hagen, 1991):

$$Q = UA\,\Delta T_{overall}$$

A is the interfacial area between two media and *U* is the overall heat-transfer coefficient (or conductance), which has the unit of W/ m^2.K.

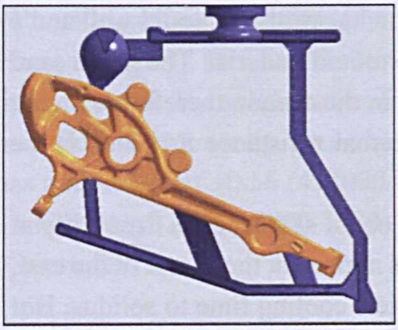
$$U = \frac{1}{\frac{1}{h_1} + \sum\frac{\Delta x}{k} + \frac{1}{h_2}}$$

For the casting, h_1 is the interfacial heat transfer coefficient between mould and cast, h_2 is the heat transfer coefficient between the mould and the surroundings. Δx is the thickness of the mould wall and k is the thermal conductivity of the mould material. The green sand layer in the cavity is thicker than in the runner, therefore a higher Δx will reduce U or increase thermal resistance R, which is the reciprocal of U.

The sand casting model took about 400 seconds to solidify at the center of the cast. A hot spot is noticed at the center of the cast, which has comparatively the longest cooling time to solidus. Hot spots may be deprived of liquid metal because liquid metal can be absorbed into places which solidified earlier, and thus result in defective shrinkage and cavities. Shrinkage at hot spots is also the cause of localized contraction stresses, which will prevail as residual stress at room temperature. Stresses can lead to three specific phenomena in castings, namely the appearance of cracks, warping of the casting shape and the presence of locked-up stresses which may show up during subsequent use of the casting (Roosz et al., 1993). For this particular simulation model, it is suggested to shift the feeder to the top of the location of the hot spot so that fresh liquid metal can be supplied to this region to counteract volumetric contraction.

Outcomes from the Simulation (Casting Modification)

The simulation and experimental results make it evident that some modification of the casting components should be carried out. This includes the gating and runner system of the whole casting components. Some typical modifications are shown in Figures 32 and 33.



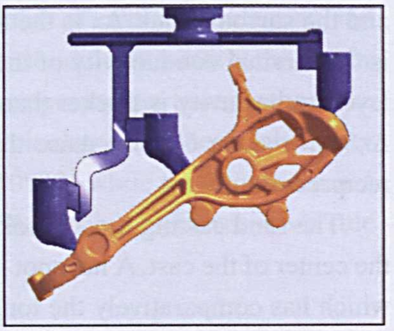


Figure 32 Before simulation **Figure 33** After simulation

EXPERIMENTAL WORKS

The equipment required for this experiment covers 3 categories: a) thermocouple for temperature measurement; b) equipment for melting and pouring metal; and c) computer hardware and software for execution of the instruction program and real-time data collection. Be:

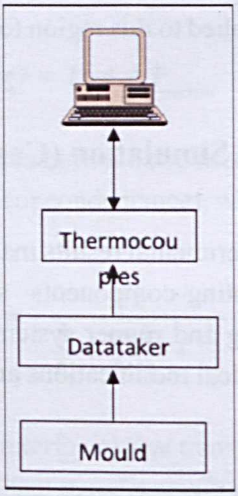


Figure 34 Components used in Temperature Measurement

As illustrated in Figure 34, the sand mould was connected to thermocouple wires placed at the various predetermined points in the sand mould. Datataker was used to compile the qualitative information in numerical format. This numerical data will then be sent to the computer for display and recording (Sulaiman and Tham, 1997).

In the experiment, the host computer continuously retrieved data from the datataker at specified time intervals until a stop command was issued from the computer. Thermocouple wires were used to measure the temperature of the mould at various points because of its sensitivity to temperature changes.

The input parameters for the simulation were based on experimental observations. The input parameters are shown in Table 1.

Table 1 Tensile strength and modulus young without and with 5 to 20% weight percentages of titanium carbide particulates

Weight percentage (%wt.)	Sand casting		Permanent metallic mould	
	Tensile Strength, σ (Mpa)	Modulus Young, E (Mpa)	Tensile Strength, σ (Mpa)	Modulus Young, E (Mpa)
0	82.29	8023.32	121.81	8762.04
5	107.52	9493.18	140.34	8393.39
10	103.94	9022.05	139.33	8409.78
15	84.50	10485.62	132.55	7760.79
20	82.71	8382.71	123.83	13278.85

Experiment Results

These results include the values from the tensile test, hardness test and microstructures obtained from the SEM test. For every reinforced particulate, explanations based on the results are discussed. Further, a comparison approach is used to identify the processed particulate composite castings which are superior in all aspects of properties and microstructural features (Sulaiman and Tham, 1997).

Mould and Casting Temperature

Temperature measurement was a very important step in this research study where the temperature history of the casting was acquired by using K-type thermocouples inserted into each section of the mould and connected to a data-logger called DATATAKER 605. The data-logger was connected to a computer running the Delogger program to capture the thermal data into an Excel file. The cooling curves data of the solidification process, for each section of different thicknesses, were obtained by DATATAKER.

From Figure 35 and Figure 36, it can be seen that the cooling rates were different for the two different moulds. The thermocouples readings were used to find the temperature profiles as a function of time corresponding to the liquidus front passing by each thermocouple. The average data were taken to plot the cooling curves. The temperature profile of the composite using the sand mould showed slow freezing rates as compared to the temperature profile of the composite using the permanent metallic moulds (copper). These results can be explained by the influence of several factors.

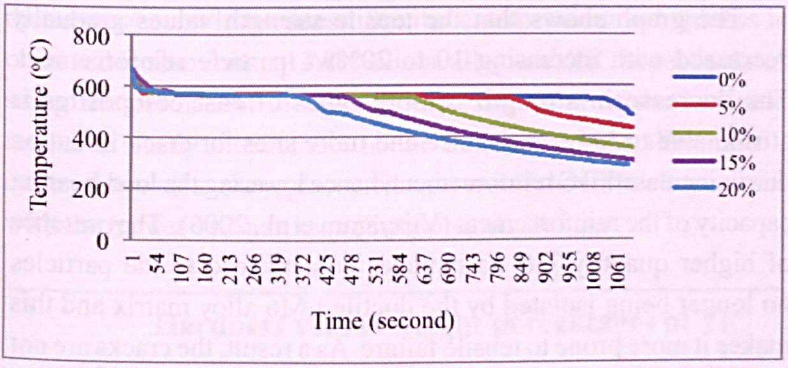


Figure 35 Cooling curve for sand casting mould

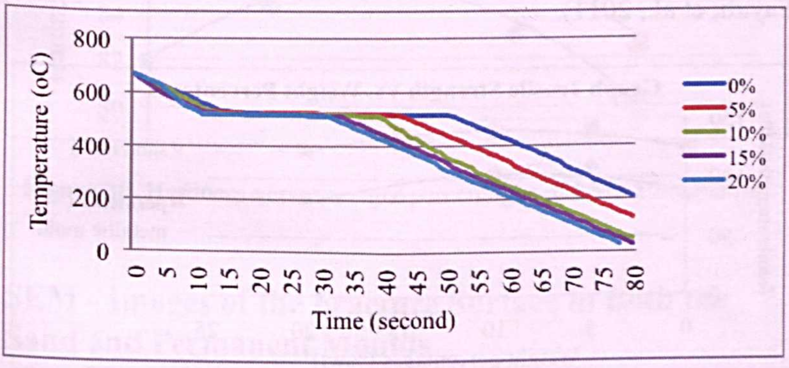


Figure 36 Cooling curve for copper permanent metallic moulds

Tensile Test

The objective of this experiment was to investigate the behavior of the specimen in two types of moulds under a tensile test. Through performance of the tensile test the properties determined were tensile strength and young's modulus. This experiment which was used to determine the material's properties is used in a wide range of industries. Average tensile strength versus weight percentages of TiC is shown in Figure 37 (Lim et al., 2005).

The graph shows that the tensile strength values gradually decreased with increasing 10 to 20%wt. particle reinforcement. The decrease in strength of both types of cast composites is attributable to lower resistance and more sites for crack initiation due to increased TiC reinforcement, hence lowering the load-bearing capacity of the reinforcement (Vijayaram et al., 2006). The presence of higher quantity TiC particulates content lead to the particles no longer being isolated by the ductile LM6 alloy matrix and this makes it more prone to tensile failure. As a result, the cracks are not arrested by the ductile matrix and would propagate easily between the titanium carbide particulates (Fatchurrohman, et al., 2012; Sayuti, et al., 2011).

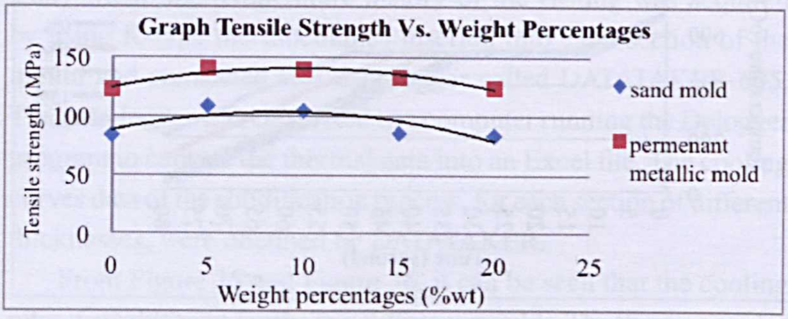


Figure 37 Average tensile strength versus weight percentages of TiC.

Hardness Test

Ten readings were taken for each weight percentage and the mean hardness value used to plot the graph as shown in Figure 38. From the graph it clearly seen that the hardness value increased gradually from 0 to 10% wt. and after 10% wt. the hardness value started to decrease. The maximum hardness value obtained was 85.82 for 10 percentage. The effect of the TiC particulate is apparent from the improvement in hardness. Similar enhancement in hardness is observed in aluminium-11.8% silicon alloy with TiC as particulates using the permanent metallic mould. The trend of the hardness results is partly attributable to the constrained metallic matrix material as well as the replacement of some of the LM6 alloy matrix with the harder TiC particles (Suraya et al., 2011).

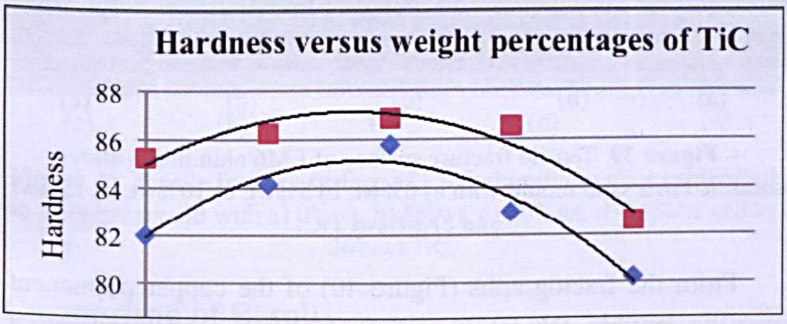
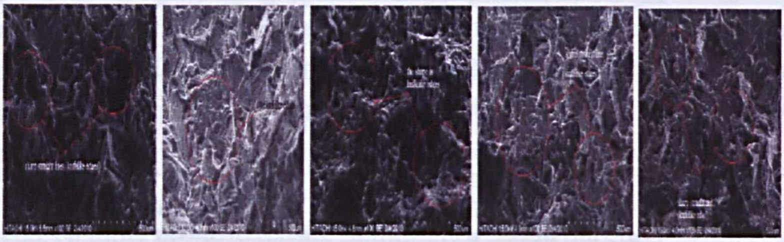


Figure 38 Hardness versus weight percentages of LM6 alloy matrix.

SEM - Images of the Fracture Surface in Both the Sand and Permanent Moulds

A scanning electron microscope (SEM) was used to obtain highly magnified images of the fracture surface to help determine the failure mode. In order to assess the nature of failure and the bonding of the TiC particles with the matrix, fractured surfaces of tensile specimens were examined under a SEM machine. The microstructures shown in Figure 39 illustrate aluminium 11.8% Si alloy without particulates and with 5, 10, 15, 20 %wt (Sayuti et al., 2011).

The features show the sharp straight lines of high-hardness materials after they fail. The crystallographic planes are cleaved, in theory, to the weakest direction, leaving the material with knifelike edges. However, the embrittled zone was observed to be larger at the fracture surface of the specimen having higher TiC content.



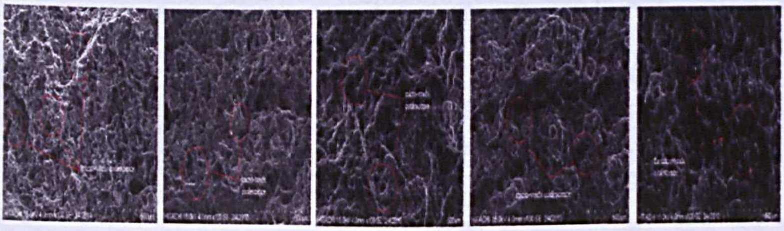
(a) (b) (c) (d) (e)

Figure 39 Tensile fracture surface of LM6 aluminium alloys solidified in a sand mould with a) 0%wt, b) 5%wt, c) 10%wt, d) 15%wt and e) 20%wt TiC.

From the fractographs (Figure 40) of the copper permanent metallic moulds, the fracture surface of composites indicate a ductile dimple structure. It shows micro-void coalescence, which basically looks like clay that has been ripped apart. The voids were formed mainly at the particle-matrix interface. However, growth of the voids was limited by the competing and synergistic influences of the brittleness of the reinforcing TiC particles and cyclic ductility of the matrix material (Suraya et al., 2011).

The factor that influenced this failure is the load transfer between the soft LM6 alloy matrix and the hard brittle TiC particles reinforcement. The presence of the hard, brittle TiC particulates caused the pre-existing high dislocation density in the LM6 alloy matrix. Residual stresses generated in the LM6 alloy matrix and dislocations arose from the mismatch in the thermal expansion coefficient between the soft matrix and the hard reinforcement TiC particulates (Fridlyander, 1995).

During cyclic deformation it seems possible that the mismatch that exists between the brittle reinforcing particles and the ductile matrix favors concentration of stress near the particle-matrix interface, causing the matrix in the immediate vicinity to permanently fail or the particles to separate from the matrix.



(a) (b) (c) (d) (e)

Figure 40 Tensile fracture surface of LM6 aluminium alloys solidified in a copper mould with a) 0%wt, b) 5%wt, c) 10%wt, d) 15%wt and e) 20%wt TiC.

Comparison of Results

For this research, cylindrical moulds were used and the pattern flows of the mould filling were not very complex. This type of experimental study is suitable to find a new composition of new materials. By using the data, AnyCasting can simulate the behavior of other complex moulds to predict the flow of the molten metal meeting in the cavity, to predict molten metal temperatures during filling and the solidification patterns which can be used to enhance and improve the quality and accuracy of the final products. Tables 2 and 3 show the comparison of the simulation and experimental results for both the sand and permanent moulds (Taufik et al., 2011).

Table 2 Comparison of simulation experimental study results for the permanent mould

(wt%)	**Solidification Time (seconds)**	
	Experimental	**Simulation**
0	971.50	1285.50
5	770.00	947.54
10	575.50	665.54
15	377.00	430.74
20	260.00	233.23

Table 3 The comparison of simulation and and experimental study results for the sand mould

(wt%)	Solidification Time (seconds)	
	Experimental	Simulation
0	32.19	37.22
5	29.10	28.35
10	27.9	27.23
15	14.9	13.78
20	12.1	11.76

ADVANCED TECHNOLOGY APPLICATION

With the increased need for quality manufacturing along with the factors of short lead times and short product lives, as well as the increasing consumer awareness regarding the quality of products, it is becoming increasingly important for manufactures to initiate steps to fulfill all of these requirements. View this against the fact that developments in microelectronics in the recent past have made higher computational ability available at low costs. It is thu imperative that manufacturing takes advantage of the availability of these low cost yet more powerful computers. Hence, the use of Computer Aided Engineering, particularly for mechanical industries, should now be a realizable goal (Rao, 2004).

CAD / CAM (computer-aided design and computer-aided manufacturing) is a term that refers to computer systems that are used to both design and manufacture products. While CAD is the use of computer technology for the process of design and design documentation, CAD / CAM systems are used both for designing a product and for controlling manufacturing processes. The geometries in the CAD drawings are used by the CAM portion of the program to control the machine that creates the exact shapes that were drawn. The total components can be assumed to consist of a number of inter-linked domains, as shown in Figure 41.

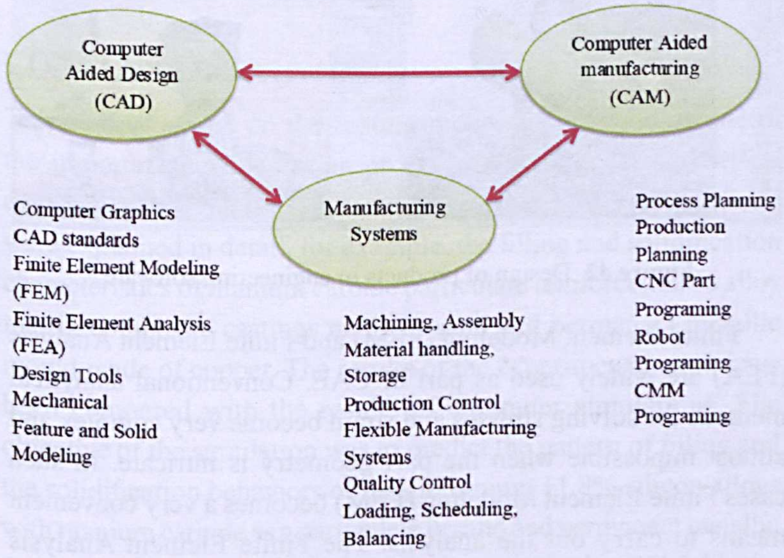


Figure 41 The influence of computers used in the Manufacturing Environment (Rao, 2004)

Computer Aided Design (CAD) and Computer Aided Engineering (CAE)

Computer Aided design (CAD) involves the use of computers to create design drawings and product models. Computer aided design is usually associated with interactive computer graphics, known as a CAD system. There are several powerful commercially available programs to aid designers in geometry description and engineering analysis, such as CATIA, AutoCAD, SolidWorks, ProEngineering, Solid Edges and VectorWorks. The software can help identify potential problems, such as excessive loads, deflections or interface at mating surfaces (Kalpakjian and Schmid, 2010). Figure 42 shows the outcomes of product design using CAD and engineering software.

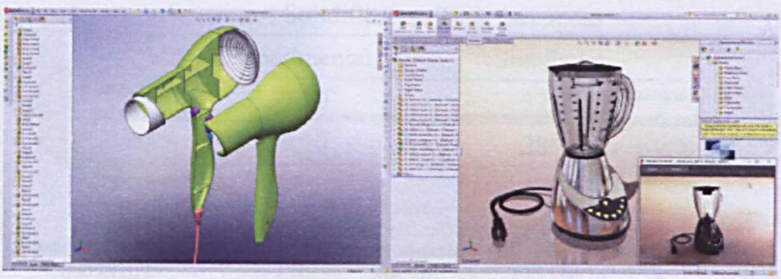


Figure 42 Design of products in engineering software

Finite Element Modeling (FEM) and Finite Element Analysis (FEA) are widely used as part of CAE. Conventional analytical methods for solving stresses and strain become very complex and almost impossible when the part geometry is intricate. In such cases Finite Element Modeling (FEM) becomes a very convenient means to carry out the analysis. The Finite Element Analysis (FEA) is a very powerful analysis tool, which can be applied to a range of engineering problems, such as, stress analysis, dynamic analysis, deformation studies, fluid flow analysis and heat flow analysis. Various related sophisticated software packages are now available, such as, ABAQUS, ANSYS, NASTRAN, LS-DYNA, MARQ, ALGOR and DEFORM (Rao, 2004). Figure 43 shows the outcomes of FEA of a product.

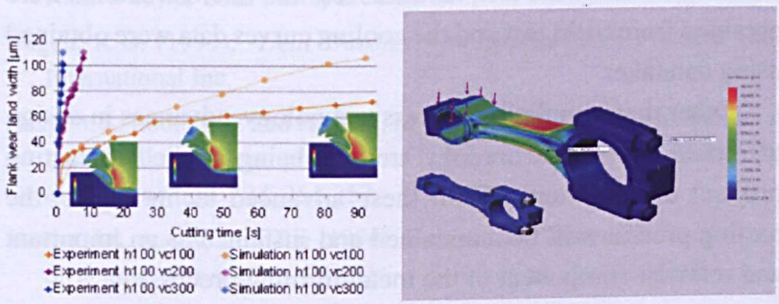


Figure 43 Finite element analysis of a product.

CONCLUSIONS

This study focused on the casting process application as one of the important metal forming processes. In terms of theoretical application, two pertinent parameters i.e. flow and thermal aspects were explained in detail, for example, the filling and solidification characteristics of titanium carbide particulate reinforced LM6 alloy matrix composite castings made in sand and permanent metallic mould made of copper. The results of the experimental work have been compared with the results of computer simulations. The objective of the simulation was to predict the pattern of filling and the solidification behaviors of the aluminium 11.8% silicon alloys with titanium carbide as a particulate in sand and permanent metallic casting moulds. Simulation of temperature versus time helped in the visualization of the temperature contours and the distribution inside the solidifying composites. The solidification rate is influenced by the thermal properties of the mixture of LM6 alloys matrix with particles and it is dependent on the solid weight percentages. The presence of the TiC particles in the LM6 alloy matrix caused shortening of the solidification rates because of the diminishing latent heat released during solidification. During the experimental work values of tensile test, hardness test and microstructures were obtained from SEM test and the cooling curves data were obtained using datataker.

Other than simulation process technology, advances in design of mould and die technology are also being applied in casting product development. With these advanced technologies, the casting process will be maintained and sustained as an important and relevant component of the metal forming processes.

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BIOGRAPHY

Professor Shamsuddin was born on 4 January 1963, in Kampong Parit Hj Adnan, Pontian, Johor. He obtained his B.Eng degree in Agricultural Engineering from Universiti Pertanian Malaysia (now called Universiti Putra Malaysia) in 1986. He then joined UPM as a Tutor in the Department of Mechanical and Manufacturing Engineering. Subsequently, he continued his studies and obtained his MSc in Mechanical Engineering (specialising in Product Design and Economic Manufacture) from the University of Swansea, Wales, United Kingdom, in 1989, and finally his Ph.D in 1992, in the area of metal casting process, from the same university. Professor Shamsuddin has been a Professor in the Department of Mechanical and Manufacturing Engineering since September 2007. Currently he is the research coordinator and programme coordinator for the Master of Manufacturing System Engineering (MSE) programme at the Department of Mechanical and Manufacturing Engineering. He has also held other posts, including Deputy Dean of School of Graduate Studies (April 2008-March 2011), Senate Member (July 2011- June 2014), Deputy Dean of Faculty of Engineering (Sept 2003-Aug 2006), Deputy Director of University Agricultural Park (TPU) (Feb 2001-Nov 2011), Head of Department of Mechanical and Manufacturing Engineering (Jan 1995-Aug 1998) and Lecturer and Associate Professor, Department of Mechanical and Manufacturing Engineering (Feb 1992-Aug 1998).

Professor Shamsuddin has taught more than 5 subjects at Postgraduate, Bachelor and Diploma levels. He has been contributing continuously to the development of various engineering programmes, curricula and syllabi during his 20 years of service as tutor, lecturer, associate professor and professor, at the Faculty of Engineering. He was one of the key persons in developing the

Master of Engineering programme, in the area of Manufacturing System Engineering and Engineering Management, at the department.

Professor Shamsuddin has been the leader in acquiring and completing several major research projects with total funding of more than RM3 million from the Ministry of Science, Technology and Innovation (MOSTI). Consequently, hundreds of his works have been recognized and published extensively in renowned journals and conference proceedings. He has also been invited to be a speaker and panelist at various international conferences. In tandem with his expertise, he has also supervised and co-supervised 38 MS students, 62 MEng students and 27 PhD students. He is also an external examiner for students from other higher learning institutions, both local and international, for their MS/PhD degrees.

ACKNOWLEDGEMENTS

Professor Shamsuddin would like to thank his late father Haji Sulaiman Haji Abdullah, late mother Hajjah Mariam Sadiran, his wife, Pn Salmah Sahudin, his sons Ashraf and Arief and his daughter, Aisyah, for their understanding and prayers.

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CASTING TECHNOLOGY

SUSTAINABLE METAL FORMING PROCESS

THE INAUGURAL LECTURES are given by honored faculty members within the University who have obtained the rank of full professor. This event gives the honoree the opportunity to deliver a lecture to fellow faculty and other university guests concerning their work and research interests.

The context of the lecture itself typically includes a summary of the evolution and nature of the honoree's specialized field, highlights of some of the general issues of that particular field, and a description of how the honoree situates his/her work within their field.

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