

DEVELOPMENT OF FINITE ELEMENT MODEL FOR CONTROL OF SOLIDIFICATION SHRINKAGE IN AL-SI (A1200) CASTINGS

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Abstract

The objective of this work was to develop Finite Element model and experimentation of the control of solidification shrinkage in Al-Si (A1200) alloy castings. Finite Element method was used to discretize and solve the governing equations developed for the models using the commercial software, Comsol Multi-Physics. The models developed were validated from experimental data obtained using six samples. A comparison of the temperature profiles generated from the experiments and simulations showed that in 64% of the processes, there were no significant differences between the experimental and simulated values. Comparing the Niyama values obtained from experiments with those obtained from the simulations, there were no significant differences in 46% of the processes. Threshold Niyama values of $0.103 (^{\circ}\text{C-s})^{1/2}/\text{mm}$ for A1200 was established. Below these threshold values, shrinkage will occur in castings from these metals. Results showed that temperature gradients and cooling rates are important in predicting the occurrence of shrinkage in a casting. It was also revealed that alloy composition affects the threshold Niyama values. The Niyama value obtained for alloy A1200 was $0.103 (^{\circ}\text{C-s})^{1/2}/\text{mm}$ because of lower silicon content. The shapes of the castings did not have a significant effect on the Niyama values. However, the sizes of the castings affected their Niyama values since the smaller-sized castings had higher values than the bigger /mm while that with cast dimensions 150mm x 50mm ones. For alloy A1200 with cast dimension 200mm x 50mm, the Niyama value was $0.103 (^{\circ}\text{C-s})^{1/2}$ has a value of $0.129 (^{\circ}\text{C-s})^{1/2}/\text{mm}$.

Keywords: Aluminium alloy, Finite element, Solidification, Shrinkage, Al-Si (A1200), Casting

Introduction

Global trends and best practices in manufacturing processes combine technical details with the economics of the processes. Many researchers have opined that there are various manufacturing processes for the creation of products, the choice of which depends on specific parameters and

considerations (Stefanescu, 2002; Sinha and Goel, 2002; Khanna, 2006). Hsu and Yu (2006) stated that improving the quality of foundry products have been an issue for research in manufacturing. Brown and Spittle (1990) stated that, considerable international interest has been put in the

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development and improvement of near net-shape manufacturing methods in recent years. Extensive efforts have gone into developing computer models for the numerical simulation of the solidification process (Hui *et al.*, 2002; Barral *et al.*, 2003). These solidification simulation procedures involve the numerical analysis for heat transfer at the period of solidification using finite element method (FEM). The technique provides a description of temperature variation as a function of time at any position in a casting.

Barral *et al.* (2003) worked on numerical simulation of Aluminium casting problems while Bermudez and Otero, (2004) researched in numerical solution of Aluminium castings in the area of 3-dimensional solidification. Dacosta *et al.* (2019) developed an expert system for the control of solidification shrinkage in Aluminium alloys A1200. Some other worked were carried out in the area of numerical simulation on rapid melting and non-equilibrium solidification of pure and binary metals (Wang and Matthys, 1996; Vijayaram *et al.*, 2006; Komissarchuk *et al.*, 2017). Wiskel *et al.* (2002) did a solidification of Aluminium alloys using impulse atomization. A direct and experimentally acceptable way of predicting the occurrence of shrinkage in Al-Si alloys is required hence, the use of numerical analysis through the finite element method to obtain more accurate shrinkage prediction criteria for alloys A1200 has become imperative to achieve this, Abu-Dheir, (2007) worked on a numerical investigation of the solidification of Al-12.6% Si alloy during mold vibration.

FEM is a method for the numerical solution of field problems by dividing structures into several elements and connecting them at nodes (Seetharamu *et al.*, 2001; Si *et al.*, 2003). Many physical phenomena in engineering and science is best described in terms of partial differential equations Caillaud and El-Arem (2001). FEM is a function/basis-based approach to solve PDE and is widely used in diverse fields to solve static and dynamic problems, solid or fluid mechanics, electromagnetics, biometric and so on. FEM is an efficient design tool for performing parametric design studies by considering various design cases of different shapes, materials, loads, boundary conditions and analyze them, and thereafter choose the optimum design (Zeid, 2004; Akpobi and Lawani, 2006).

The mechanical properties of cast Al-Si alloys are significantly affected by the eutectic silicon shape in the structure (Skocovsky *et al.*, 2009; Zamani, 2017). Ye, (2003) stated that Al-Si binary alloy is a eutectic system with the eutectic composition at 12.6 wt.% Si. Silicon reduces the

thermal expansion coefficient, increase corrosion and wears resistance, and improves casting and machining characteristics of the alloy. In the view of Jigajinni *et al.* (2011) and, the properties of Al-Si alloys are mainly defined by individual physical properties, a volume fraction, distribution of its basic phases: α -Al solid solution and crystals of Si. In industrial Al-Si alloys the maintenance of silicon at a level of 5% up to 23% weights and as follows from the equilibrium diagram of a condition, the structure of these alloys can be pre-eutectic, eutectic or hypereutectic (Voort and Asensio-Lazano, 2009). The aim of the research is to develop a finite element model for the control of solidification shrinkage in Aluminium-Silicon Al-Si (A1200) alloy castings.

Materials and Methods

The study involved finite element modelling and software development for the control of solidification shrinkage in Aluminium-Silicon A1200 alloys. The finite element model was developed using the commercial software, Comsol Multi-physics (Soumyajit and Anand-Karthik, 2011), while the practical work for the validation of the developed model was carried out at the Engineering Materials Development Institute, Akure (EMDI), Nigeria. The research involved the use of finite element method to create numerical models, which would simulate the following aspects of the casting process: gating and risers, feeding/pouring; heat transfer and thermal contraction, and solidification.

Materials Properties of the Aluminium Alloy

Six samples of Al-Si alloys were used both for the simulation and foundry experiments. Relevant thermal properties of Aluminium alloy A1200 used as prepared by Tower Aluminium Rolling Mills Ota, Nigeria are as follows; percentage composition: 99.3% (Al, 0.20Si), melting point (645 °C), specific heat (893J/Kg. K), thermal conductivity (221 W/M. K), thermal expansivity (22.8 μ strain/ °C), and density (2680 Kg/m³).

Preparation of the test pieces

Green sand casting was used to produce 6 test pieces of Aluminum alloys A1200. The dimensions of the test pieces are shown in Table 1. The castings were careful produced based on conditions and parameters to facilitate directional solidification. In this experiment, the gating and feeding systems were designed to ensure that the risers solidify later than the hot spots. Also, the necessary shrinkage allowances were taken into consideration in constructing the patterns for the castings.

Table 1. Dimensions of test pieces and their gating systems

S/N	Casting size (mm)	Down sprue (mm)	Riser (mm)	Ingate (mm)	Runner bar (mm)	Vent (mm)
Dimensions for Cylindrical shape of Alloy A1200						
1.	200 × Ø50	70 × Ø25	70 × Ø20	30 × 69 × 17 (2 no)	0	70 × Ø5 (2 nos)
2.	150 × Ø50	70 × Ø25	70 × Ø20	30 × 69 × 17 (2 no)	0	70 × Ø5 (2 nos)
3.	200 × Ø25	70 × Ø20	70 × Ø10	30 × 42 × 7 (2 nos)	0	70 × Ø5 (2 nos)
Dimensions for Rectangular shape of Alloy A1200						
1.	200 × 50 × 39.4	70 × Ø25	70 × Ø25 (2 no)	24 × 42 × 7 (2 no)	150 × 25 × 20	70 × Ø5 (2 no)
2.	150 × 50 × 39.4	70 × Ø25	70 × Ø20	30 × 69 × 7 (2 no)	-	70 × Ø5 (2 no)
3.	200 × 25 × 19.7	70 × Ø20	70 × Ø10	24 × 42 × 7 (2 no)	-	70 × Ø5 (2 no)

Table 2. Thermal parameters based criteria for porosity prediction (Mina-Mi, 2005)

Author	Year	Criterion	Metal	Threshold value
Bishop <i>et al</i>	1951	G	Cast bar Cast steel plate	1.3 – 2.6 0 C/cm 0.2 - 0.4 0 C/cm
Davies	1975	G/Vs	NA	NA
Khan	1980	1/Vsn	NA	NA
Niyama.	1982	$G/(dT/dt)^{1/2}$	Steel	1
Lecomte – Beckers	1988	G/Vs	NA	NA
Lee <i>et al.</i> (LCC)	1990	$Gt_s^{2/3}/Vs$	Al alloy	1-3
S T Kao <i>et al.</i>	1994	$G^{0.38}/Vs^{1.62}$	NA	NA
Suri <i>et al.</i> (FRN)	1994	$FRN = \frac{n\mu\Delta T}{\rho_1 G V_3 \beta D^2}$	Al alloy	% porosity = $23.9 + 9.6 \times 10^{-6}(FRN) + 9.1 \times 10^{-13}(FRN)^2$
F. Chisea (FCC)	1998	$1/ts^m Vs^n$	Al alloy	1.52
Carlson <i>et al.</i> (Dimensionless Niyama)	2009	$N_y^* = \frac{G\lambda_2\sqrt{\Delta P_{cr}}}{\sqrt{\mu_1\beta\Delta T_f(\frac{dT}{dt})}}$	WCB steel Al A356 Mg alloy A Z91D	610 (0.01 pct) 137(0.1 pct) 211 (0.01 pct) 23 (0.1 pct) 776(0.01 pct) 99 (0.1 pct)

Nomenclature: G: Temperature gradient, Vs: Solidification velocity, ts: Local solidification time, Cλ: Material constant, dT/dt: Cooling rate, ΔPcr: Critical pressure drop, β: Total solidification shrinkage, ΔTf: freezing range, μl: Liquid dynamic viscosity

Mould Preparation

The moulds were prepared from green sand with bentonite as binder. The properties of the moulding sand includes, a permeability value of 150 cmWH, green strength of 78.4 KN/m2 and moisture content of 3.0% as measured at Engineering Materials Development Institute. Akure, Nigeria (EMDI, 2016).

The criterion for prediction of shrinkage

In Table 2, Mina-Mi (2005) gave existing thermal parameter criteria for porosity/shrinkage prediction as proposed in the literature. Some of these criteria can be reduced to the form of G^x/Vs^y (x varies over the range of 0~2 and y varies over the range of 0.25-1.0), among which the Niyama criterion that could be reduced to G/Vs is a representative one. The Niyama *et al.* (1982) criterion which is the most popular and frequently used of all the criteria was adopted for the prediction

of shrinkage. It was chosen because it provides a less complex way of predicting shrinkage in castings. Also, Foundries use the Niyama criterion primarily in a qualitative fashion, to identify regions in a casting that are likely to contain shrinkage porosity. The Niyama criterion is given by Eq. (1);

$$\frac{G_j}{\sqrt{R_{ij}}} \quad (1)$$

Where, G is the thermal gradient, given by Eq. (2);

$$G_{ij} = (T_j - T_i)/Ds \quad (2)$$

Where, (Tj – Ti) = difference in temperature between two points i and j in the casting

Ds = distance between these points.

R_{ij}, = the rate of cooling rate from an instant of time τ₁ to τ₂ at a given location inside the casting is given by Eq. (3);

$$R_i = (T_j - T_i) / (\tau_2 - \tau_1) \quad (3) \quad u = g_l u_l + g_s u_s$$

Bailey *et al.* (1997) stated that if $\frac{G_j}{\sqrt{R_j}}$ is less than 1, then there is a high possibility of shrinkage occurring in steel castings.

Finite element model development for mould filling and solidification

The commercial software Comsol Multi-Physics was utilized to generate the nodes, element matrices and compute nodal values and derivatives. The same software was used to carry out analysis and compute the final solidification time, fraction of solid, temperature gradient, cooling rate, pressure, temperature and liquid metal velocity.

Temperature measurement

Two K-type thermocouples probes, 25mm apart were inserted into each of the moulds. The thermocouples were then connected to digital multi-meters from where temperature readings were taken at 20s intervals with a stopped clock.

Melting of the alloy specimens and pouring

The alloy specimens were melted in a diesel-fired crucible furnace and the pouring temperatures were read off from an optical pyrometer according to Ndaliman and Pius (2007).

Melting of the alloy specimens and pouring

In developing the models, the following assumptions were made as proposed by Dorin *et al.*, (2018); that,

the models were considered at the macro-scale level;

At the macro-scale level, the casting solidification system is treated as being in two phases, solid and liquid;

Nucleation and Growth of phases were not considered;

The solidification process is driven by the convection of mass and energy;

Two dimensionalities are assumed for cast height and length/radius;

The cast contains no impurities and the flow is radially and longitudinally laminar.

For the conservation equations for solidification and casting in shrinkage, the derived equations for the liquid phase and those for the solid phase were coupled using the mixture theory model proposed by Benon and Incropra (1987) where;

Conservation of mass:

$$\rho = g_l \rho_l + g_s \rho_s$$

$$v = g_l v_l + g_s v_s$$

$$H = g_l H_l + g_s H_s$$

$$K_{eff} = g_l K_l + g_s K_s$$

$$H = g_s c_s T + g_l (c_l T + (c_s - c_l) T_E + \Delta H_f)$$

$$H_s = c_s T$$

$$D_{eff} = g_l D_l + g_s D_s$$

$$H_l = c_l T + (c_s - c_l) T_E + \Delta H_f$$

Rectangular shape

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial z}(\rho v) = 0$$

Cylindrical Shape

$$\frac{\partial \rho}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r}(\rho u r) + \frac{\partial}{\partial z}(\rho v) = 0$$

Conservation of momentum:

Rectangular-Shape

x-direction

$$\frac{\partial}{\partial t}[u\rho] + \frac{\partial}{\partial x}(\rho u u) + \frac{\partial}{\partial z}(\rho u v) = -\frac{\partial p}{\partial x} + \mu \left[\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right]$$

z-direction

$$\frac{\partial}{\partial t}[v\rho] + \frac{\partial}{\partial x}(\rho v u) + \frac{\partial}{\partial z}(\rho v v) = -\frac{\partial p}{\partial z} + \mu \left[\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right]$$

Cylindrical-Shape

r-direction

$$\frac{\partial}{\partial t}[u\rho] + \frac{\partial}{\partial r}(\rho u u) + \frac{\partial}{\partial z}(\rho u v) = -\frac{\partial p}{\partial r} + \mu \left[\frac{\partial^2 u}{\partial r^2} + \frac{1}{r} \frac{\partial u}{\partial r} + \frac{\partial^2 u}{\partial z^2} \right]$$

z-direction

$$\frac{\partial}{\partial t}[v\rho] + \frac{\partial}{\partial r}(\rho v u) + \frac{\partial}{\partial z}(\rho v v) = -\frac{\partial p}{\partial z} + \mu \left[\frac{\partial^2 v}{\partial r^2} + \frac{1}{r} \frac{\partial v}{\partial r} + \frac{\partial^2 v}{\partial z^2} \right]$$

Conservation of species:

Rectangular shape

$$\frac{\partial}{\partial t}[\rho C] + \frac{\partial}{\partial x}(\rho u C) + \frac{\partial}{\partial z}(\rho v C) = \frac{\partial}{\partial x} \left(\rho D_{eff} \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial z} \left(\rho D_{eff} \frac{\partial C}{\partial z} \right) + S_c$$

Table 3. Meshing and Discretization Data from Comsol Multi-Physics

Alloy Shape	Tetrahedral Elements	Triangular Elements	Meshing Volume	Average Element	Alloy Shape
Cylinder 1 (200 × Ø50)	1615	872	4.973e-4m ³	0.6956	1.569
Cylinder 2 (150 × Ø50)	1655	910	4.038e-4m ³	0.6944	1.657
Cylinder 3 (200 × Ø25)	2783	1292	1.314e-4m ³	0.6986	1.699
Rectangular 1 (200 × 50 × 39.4 mm ³)	1619	1086	6.051e-4m ³	0.5584	2.125
Rectangular 2 (150 × 50 × 39.4 mm ³)	1231	812	4.171e-4m ³	0.6264	1.842
Rectangular 3 (200 × 25 × 19.4 mm ³)	1920	1030	1.365e-4m ³	0.6001	2.071

Cylindrical shape

$$\frac{\partial}{\partial t}[\rho C] + \frac{\partial}{\partial r}(\rho u C) + \frac{\partial}{\partial z}(\rho v C) = \frac{1}{r} \frac{\partial}{\partial r} \left(r \rho D_{eff} \frac{\partial C}{\partial r} \right) + \frac{\partial}{\partial z} \left(\rho D_{eff} \frac{\partial C}{\partial z} \right) + S_c$$

The source function was given by Benon and Incopera (1987).

Where for rectangular shape

$$S_c = \frac{\partial}{\partial x} \left(\rho D_{eff} \frac{\partial (C_l - C)}{\partial x} \right) + \frac{\partial}{\partial z} \left(\rho D_{eff} \frac{\partial (C_l - C)}{\partial z} \right) - \frac{\partial [\rho f_s (u - u_s)(C_l - C_s)]}{\partial x} - \frac{\partial [\rho f_s (v - v_s)(C_l - C_s)]}{\partial y}$$

for cylindrical shape,

$$S_c = \frac{1}{r} \frac{\partial}{\partial r} \left(r \rho D_{eff} \frac{\partial (C_l - C)}{\partial r} \right) + \frac{\partial}{\partial z} \left(\rho D_{eff} \frac{\partial (C_l - C)}{\partial z} \right) - \frac{\partial [\rho f_s (u - u_s)(C_l - C_s)]}{\partial r} - \frac{\partial [\rho f_s (v - v_s)(C_l - C_s)]}{\partial z}$$

Conservation of energy:

Rectangular shape

$$\frac{\partial}{\partial t}[\rho H] + \frac{\partial}{\partial x}(\rho u H) + \frac{\partial}{\partial z}(\rho v H) = \frac{\partial}{\partial x} \left(K_{eff} \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial z} \left(K_{eff} \frac{\partial T}{\partial z} \right) + S_c$$

Cylindrical shape

$$\frac{\partial}{\partial t}[\rho H] + \frac{\partial}{\partial r}(\rho u H) + \frac{\partial}{\partial z}(\rho v H) = \frac{1}{r} \frac{\partial}{\partial r} \left(r K_{eff} \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left(K_{eff} \frac{\partial T}{\partial z} \right) + S_c$$

Where for rectangular shape

$$S_c = \frac{\partial}{\partial x} \left(\frac{K_{eff}}{c_s} \frac{\partial (H_s - H)}{\partial x} \right) + \frac{\partial}{\partial z} \left(\frac{K_{eff}}{c_s} \frac{\partial (H_s - H)}{\partial z} \right) - \frac{\partial [\rho f_s (u - u_s)(H_l - H_s)]}{\partial x} - \frac{\partial [\rho f_s (v - v_s)(H_l - H_s)]}{\partial y}$$

For cylindrical shape

$$S_c = \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{K_{eff}}{c_s} \frac{\partial (H_s - H)}{\partial r} \right) + \frac{\partial}{\partial z} \left(\frac{K_{eff}}{c_s} \frac{\partial (H_s - H)}{\partial z} \right) - \frac{\partial [\rho f_s (u - u_s)(H_l - H_s)]}{\partial r} - \frac{\partial [\rho f_s (v - v_s)(H_l - H_s)]}{\partial z}$$

Where according to Stefanescu, (2002),

$$\rho = g_l \rho_l + g_s \rho_s$$

$$u = g_l u_l + g_s u_s$$

$$v = g_l v_l + g_s v_s$$

$$D_{eff} = g_l D_l + g_s D_s$$

$$H = g_l H_l + g_s H_s$$

$$K_{eff} = g_l K_l + g_s K_s$$

$$H_l = c_l T + (c_s - c_l) T_E + \Delta H_f$$

$$S_c = - \frac{\partial (\Delta H_l \rho_l g_l)}{\partial t} - \frac{\partial (\Delta H_l \rho g_s (u - u_s) + \Delta H_l \rho_l g_l u)}{\partial x} - \frac{\partial (\Delta H_l \rho g_s (v - v_s) + \Delta H_l \rho_l g_l v)}{\partial y}$$

$$g_l + g_s = 1$$

$$H_s = c_s T$$

$$H = g_s c_s T + g_l (c_l T + (c_s - c_l) T_E + \Delta H_f)$$

$$\text{Solidification contraction, } \beta = \frac{V_l - V_s}{V_s} = \frac{\rho_l - \rho_s}{\rho_l}$$

$$\beta = 0 \text{ for no shrinkage}$$

Discretization of numerical model

Two shapes, rectangular and cylindrical were used in the simulation. The choice of the two shapes was to reduce the complexity of the equations to be solved. Also, the cost of validating the models experimentally for three shapes was taken into consideration. Three sizes were simulated (Table 1.) for each of the shapes. In all, six different geometries were developed and discretized for the simulations.

Results and Discussions

For the Aluminum alloy A1200, cylindrical shape 1, the temperature profiles at the two probes are similar in trend (Figure 1a). However, the graph of the experimental and simulated Niyama values (Figure 1b.) shows a similar trend below 110 second as shown.

Also for cylindrical shape 2 (150 x Ø50), the temperature profiles at the two probes are similar in trend (Figure 2a.). However, the graph of the experimental and simulated Niyama values (Figure 2b) do not show any similar trend. The experimental results peaked at a Niyama value of about $2.5 \text{ (}^\circ\text{C-s)}^{1/2} / \text{mm}$ whereas the simulated values are below $0.50 \text{ (}^\circ\text{C-s)}^{1/2} / \text{mm}$. The experimental results peaked at a Niyama value of above $4.0 \text{ (}^\circ\text{C-s)}^{1/2} / \text{mm}$ whereas the simulated values are below $1.0 \text{ (}^\circ\text{C-s)}^{1/2} / \text{mm}$. In the case of alloy cylinder 3, the temperature profiles at the two probes are similar in trend (Figure 3a). The graph of the experimental and simulated Niyama values (Figure 3b) shows a similar trend also. The experimental results peaked at a Niyama value of above $0.80 \text{ (}^\circ\text{C-s)}^{1/2} / \text{mm}$ whereas the simulated values are below $0.20 \text{ (}^\circ\text{C-s)}^{1/2} / \text{mm}$.

A look at the profiles of alloy A1200 with rectangular shapes; rectangular shape 1 ($200 \times 50 \times 39.4 \text{ mm}^3$) shows that the temperature profiles (Figure 4a) at the two probes are similar in trend. However, the graph of the experimental and simulated Niyama values (Figure 4b.) do not show any similar trend. The experimental results peaked at a Niyama value of about $1.4 \text{ (}^\circ\text{C-s)}^{1/2} / \text{mm}$ whereas the simulated values are below $0.20 \text{ (}^\circ\text{C-s)}^{1/2} / \text{mm}$.

Also, for rectangular shape 2, the temperature profiles (Figure 5a.) at the two probes are similar in trend. However, the graph of the experimental and simulated Niyama values (Figure 5b.) do not show any similar trend. The experimental results peaked at a Niyama value of about $3.5 \text{ (}^\circ\text{C-s)}^{1/2} / \text{mm}$ whereas the simulated values are below $0.50 \text{ (}^\circ\text{C-s)}^{1/2} / \text{mm}$.

The temperature profiles for rectangular sample 3 (Figure 6a.) at the two probes are similar in trend. However, the graph of the experimental and simulated Niyama values (Figure 6b.) do not show any similar trend. The experimental results peaked at a Niyama value of about $6.5 \text{ (}^\circ\text{C-s)}^{1/2} / \text{mm}$ whereas the simulated values are below $0.50 \text{ (}^\circ\text{C-s)}^{1/2} / \text{mm}$. The meshing and discretization was done using Comsol Multi-Physics software. Meshes are used for rendering to a computer screen and for physical simulation such as finite element analysis or computational fluid dynamics. The

details of the elements generated are shown in Table 3. It indicated the collection of nodes and elements that form the finite element mesh.

Figure 7. shows the replacement of each of the three cylindrical shapes by a set of nodes to produce Tetrahedral and triangular elements using Comsol Multi-Physics software. While Figure 8. shows the replacement of each of the three rectangular shapes.

Outputs from Finite Element simulations using Comsol Multi-Physics

Figure 9a. shows the 3D view of the simulated casting for alloy A1200 cylinder 1. In Figure 9b, a section velocity of the melt is presented showing a relative stability in the motion of the melt 6s after pouring. The centre region of the casting indicated higher magnitude of motion. At 840s after pouring, there is virtually no motion as shown in Figure 9c. meaning that solidification is almost complete except for some few areas. This shows that the metal has cooled to about 300°C except for the Sprue area. The low liquid fraction shows that the metal is completely solidified except for the small part of the Sprue where there exists a high liquid fraction.

Figure 10a shows the 3D view of the simulated casting for alloy A1200 cylindrical shape 2. In Figure 10b. section velocity of the melt is presented showing a relative stability in the motion of the melt 4s after pouring. The centre region of the casting indicated low magnitude of motion while a high level of motion is shown in fractions of the sprue and runner. At 140s, after pouring, there exists some motion as shown in Figure 10c meaning that solidification is incomplete in the middle region while the metal in the sprue and runner are solidified. This shows that the metal is still liquid in most parts of the casting.

Figure 11a. shows the 3D view of the simulated casting for alloy A1200 cylinder 3. In Figure 11b, the volume fraction at 9s is presented. The high liquid fraction shows that the metal is liquid except in parts of the sprue and runner where there exists low liquid fraction. It shows a high level of motion in the melt 9s after pouring. At 480s after pouring, there was some motions as shown in Figure 11c meaning that solidification is incomplete except for some few areas. The low liquid fraction shows that the metal is completely solidified except for the small part of the Sprue where there exists a relatively high liquid fraction.

Figure 12a. shows the 3D view of the simulated casting for alloy A1200 rectangular 1. In Figure 12b, a section velocity of the melt shows that the metal has cooled to about 500 showing a

high level of motion in the casting 12s after pouring. Some sections of the casting indicated high magnitude of motion. In the same vein, Figure 12c. shows motion in the casting 840s after pouring.

From the Statistical analysis results, there were significant differences in the Niyama values obtained for Alloy A1200 Cylinders 1 and 3. However, for Cylinder 2, there was no significant difference. There were significant differences in the Niyama values obtained for Alloy A1200 Rectangular shapes 1 and 3. However, for Rectangular shape 2, there was no significant difference. A comparison of the temperature profiles generated from the experiments and simulations shows that in 64% of the processes, there were no significant differences between the experimental and simulated values. However, in comparing the Niyama values from the experiments and simulations, there were no significant differences in 46% of the processes. Figure 13. shows Some of the castings from the experiments before the removal of flashes and cleaning.

Conclusion

Finite Element Analysis were carried out using data from six samples for a better insight into the temperature profiles and nature of the solidification of the alloys. The models developed were validated using experimental data. From the finite element analysis, a helpful insight has been given to the nature of liquid metal velocity during mould filling, pressure contours that develop during solidification and temperature distribution as the metal cools. A comparison of the temperature profiles generated from the experiments and simulations show that in 64% of the processes, there were no significant differences between the experimental and simulated values. However, in comparing the Niyama values from the experiments and simulations, there were no significant differences in 46% of the processes. This work has been able to establish experimentally and analytically, threshold Niyama values of $0.103 (^{\circ}\text{C-s})^{1/2}/\text{mm}$ for A1200. Below these threshold values, it is expected that shrinkage will occur in castings from these metals. With this conclusion, the presence of shrinkage in these alloys can be controlled.

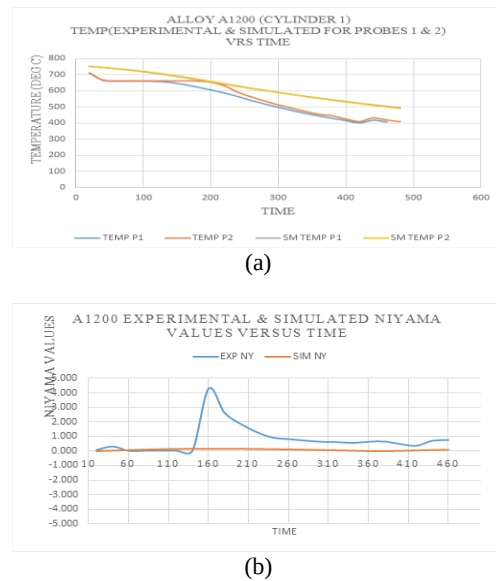


Figure 1. Temperature profile for Cylindrical shape 1 ($200 \times \phi 50$) (a) Probes 1 and 2 (b) Values of the Niyama criteria

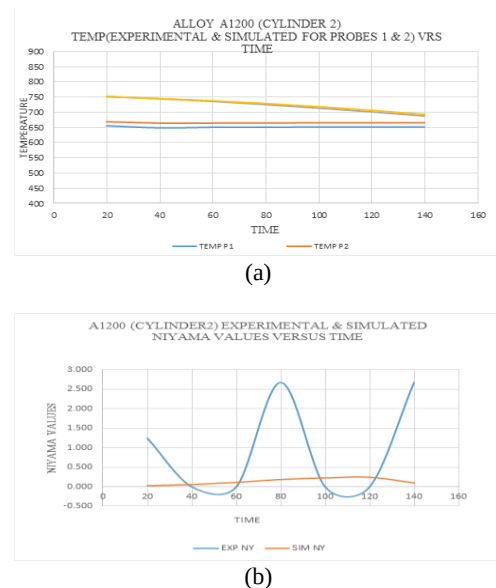
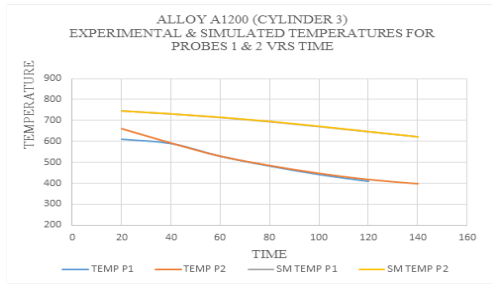
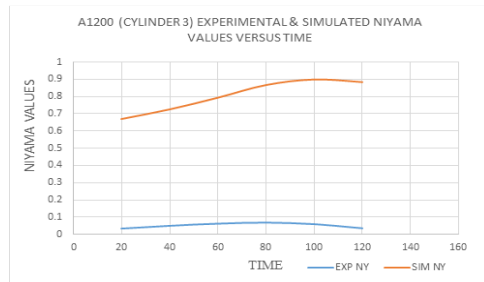


Figure 2. Temperature profile for Cylindrical shape 2 ($150 \times \phi 50$) (a) Probes 1 and 2 (Experimental and Simulate (b) Values of the Niyama criteria

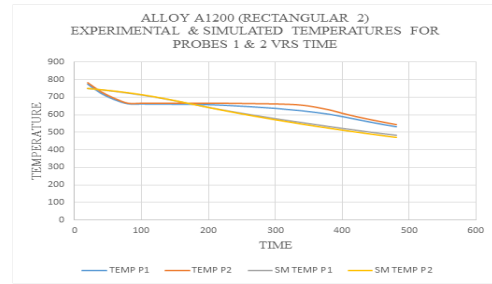


(a)

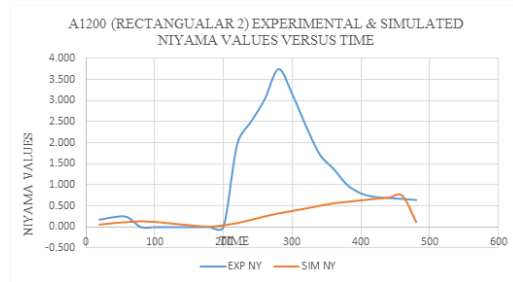


(b)

Figure 3. Temperature profile for Cylindrical shape 3 ($200 \times \text{Ø}25$) (a) Probes 1 and 2 (b) Values of the Niyama criteria

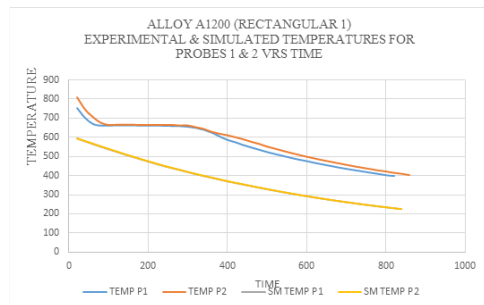


(a)

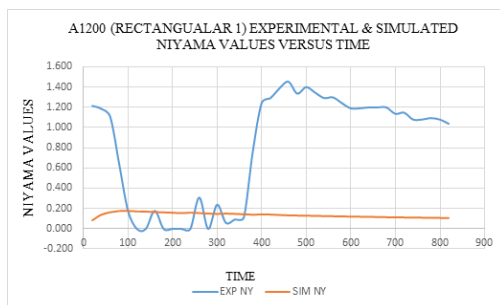


(b)

Figure 5. Temperature profile for Rectangular shape 2 ($150 \times 50 \times 39.4 \text{ mm}^3$) (a) Probes 1 and 2 (b) Values of the Niyama criteria

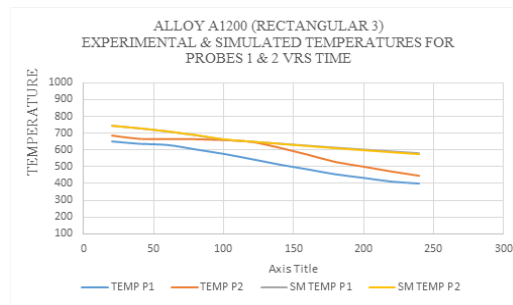


(a)

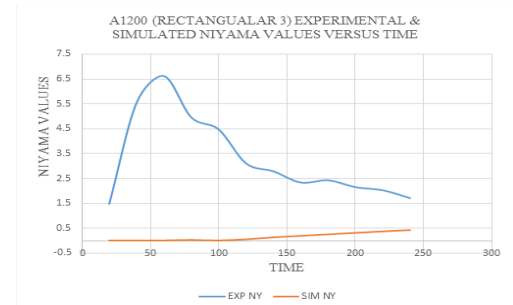


(b)

Figure 4. Temperature profile for Rectangular shape 1 ($200 \times 50 \times 39.4 \text{ mm}^3$) (a) Probes 1 and 2 (b) Values of the Niyama criteria

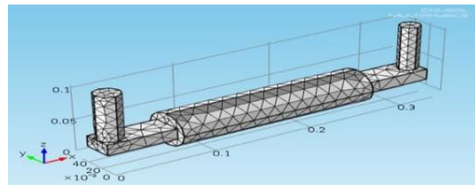


(a)

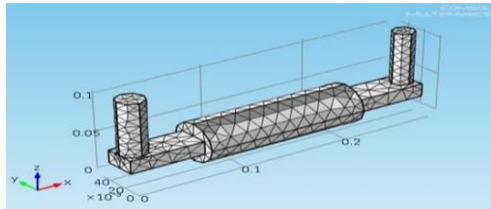


(b)

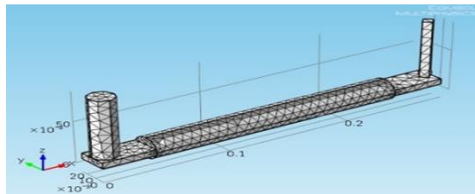
Figure 6. Temperature profile for Rectangular shape 3 ($200 \times 25 \times 19.4 \text{ mm}^3$) (a) Probes 1 and 2 (b) Values of the Niyama criteria



(a)

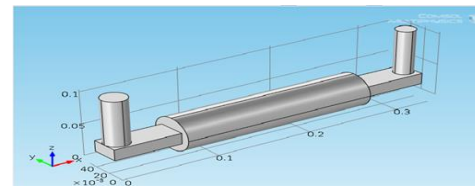


(b)

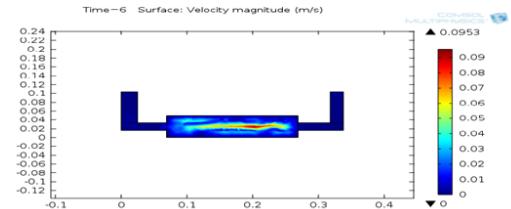


(c)

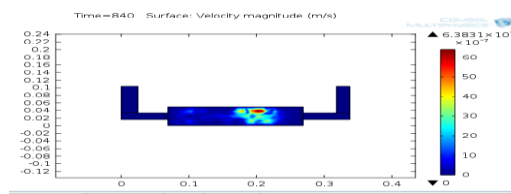
Figure 7. Alloy A1200 Cylindrical shapes (a) Cylindrical shape 1 (b) Cylindrical shape 2 (c) Cylindrical shape 3



(a)

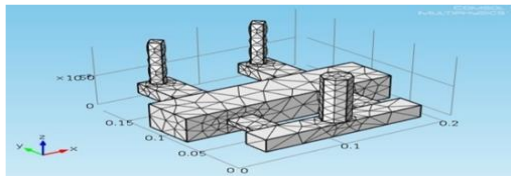


(b)

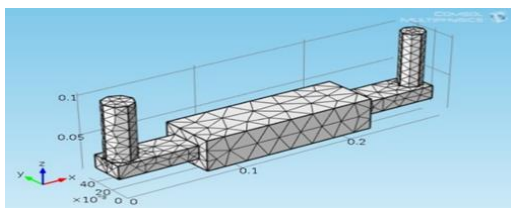


(c)

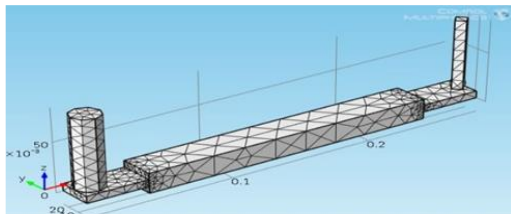
Figure 9. 3D view of the simulated casting for alloy A1200 cylindrical shape 1 (a) 3D View of simulated casting (b) section velocity at 6s (c) velocity at 8400s



(a)

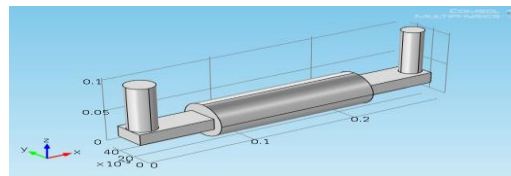


(b)

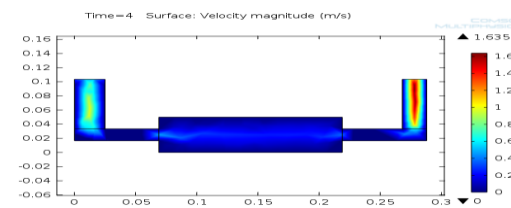


(c)

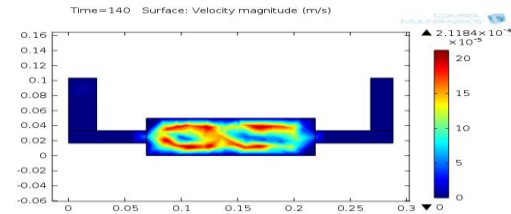
Figure 8. Alloy A1200 Rectangular shapes (a) Rectangular shape 1 (b) Rectangular shape 2 (c) Rectangular shape 3



(a)



(b)



(c)

Figure 10. The 3D view of the simulated casting for alloy A1200 cylindrical shape 2 (a) 3D View of simulated casting (b) section velocity at 4s (c) velocity at 140s

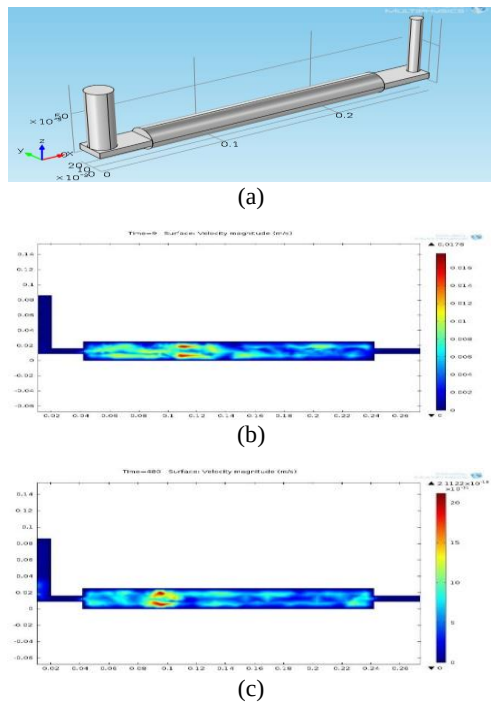


Figure 11. 3D view of the simulated casting for alloy A1200 cylindrical shape 3 (a) 3D View of simulated casting (b) section velocity at 9s (c) section velocity at 8400s

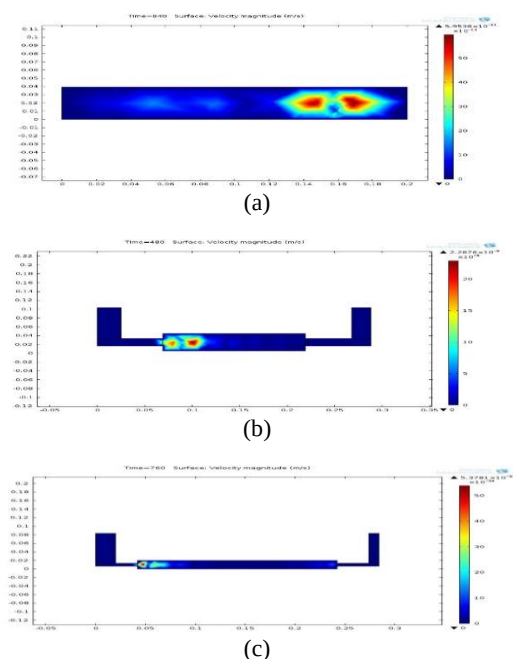


Figure 12. 3D view of the simulated casting for alloy A1200 rectangular 1 (a) Shape 1 (200 × 50 × 39.4 mm³) section velocity at 840s (b) Shape 2 (150 × 50 × 39.4mm³) section velocity at 480s © Shape 3 (200 × 25 × 19.7mm³) section velocity at 760s.



Figure 13. Some of the castings from the experimental procedures and measurements before the removal of flashes and cleaning

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