# DEVELOPMENT OF AN EXPERT SYSTEM FOR THE CONTROL OF SOLIDIFICATION SHRINKAGE IN ALUMINIUM ALLOYS A1200 AND A8011

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**Abstract:** Solidification plays a critical role in the production of sound castings. Finite element method was used to discretize and solve the governing equations developed using Comsol Multi-Physics software. The models developed were validated from experimental data obtained from the foundry using twelve samples (six each of different dimensions, for Aluminium alloys A1200 and A8011). Threshold Niyama values of 0.103 °C-s$^{1/2}$/mm for A1200 and 0.143 °C-s$^{1/2}$/mm for A8011 were established. For alloy A1200 with cast dimension 200mm x 50mm, the Niyama value was 0.103(°C-s)$^{1/2}$ /mm while that with cast dimension 150 mm x 50 mm had a value of 0.129 °C-s$^{1/2}$/mm.

**Keywords:** Aluminium alloy, expert system, solidification, shrinkage

## 1. INTRODUCTION

The interaction between the liquid metal and moulding aggregate during casting solidification is responsible for a series of shrinkage induced defects generally termed shrinkage cavities and shrinkage porosities (Stefanescu, 2005). The mechanism of micro-porosity formation in aluminium alloys is complex and depends on actions of some phenomena (Seetharamu et al., 2001; Barral et al., 2003).

Mina (2005) reported that aluminium alloys are prone to porosity which forms when there is gas entrapment, solidification shrinkage due to failure of inter-dendritic feeding, and /or precipitation, reasoning, learning, communication and decision-making in order to arrive at a solution for the given problem. From the inception ES system, various developments have been done, which broaden its application to include

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pattern recognition, automation, computer vision, virtual reality, diagnosis, image processing, non- linear control, robotics, automated reasoning, data mining, process planning, intelligent agent and control, manufacturing (Xu, Wang, and Newman, 2011; Yusof and Latif, 2014)

Overfelt (1992) studied the manufacturing significance of solidification modelling. He asserted that typical manufacturing processes are too complex for complete analysis by simple model. Certain critical features of solidification can be modelled very accurately and used to predict casting result including defect. The simplest models according to Overfelt (1992), analysed the cooling of a casting assuming consuming heat flow only, and incorporated effect of the latent heat released using one of the several techniques. He emphasized that the implementation of solidification kinetics requires a balanced programme of experimental data coupled with computer simulations of heat transfer, nucleation and growth.

Similarly, Hui Xi-dong et al., (2002) worked on numerical simulation of rapid melting and non-equilibrium solidification of pure metals and binary alloys. In the work, a heat transfer model containing phase transformation dynamics was made for pure metals and binary alloys under pulsed laser processing. Droux (1991) also worked on three dimensional numerical simulation of solidification by an improved explicit scheme.

Wiskel et al., (2002) did a solidification study of Aluminium alloys using impulse atomization. In the study, heat transfer models of molten metal droplets moving in a gas stream were used to extensively understand and improve gas atomization systems. In particular, the solidification microstructure of the metal droplets produced during atomization is closely linked with heat flow conditions. Also, Brown and Spittle (1990), worked on the finite element simulation of solidification of Aluminium casting alloy (LM25). Here, a two dimensional axisymmetric finite element analysis was applied for the simulation of the solidification of the alloy.

Jumroonrut and Pitakthapanaphong (2005) worked on the filling and solidification simulation of Aluminium casting process. The work investigated the casting of Aluminium by finite difference simulation. Expert system (ES) in decision-making provides major application in intelligent decision-making for solving specific problem of interest and its applications are widespread due its unique domain independent characteristics (De-Weck and Kim, 2004; Ogbeide, 2010).

The structure and operation of an expert system are modeled after the human expert. Rules are used for representing knowledge in an expert system. Ogbeide (2010) has said that a rule is an IF/THEN type structure which relates some known information contained in the IF part to other information. This information can then be concluded to be contained in the THEN part. In this work, ES applications are categorised into three broad areas; execution of process planning activities, manufacturing planning, and diverse applications. CAPP and manufacturing applications are focused mainly on mechanical engineering domain.

## 2. MATERIALS AND METHODS

The knowledge based expert system was incorporated in this work to facilitate the automation of the shrinkage control processes through easy access to computer interfaces. The purpose is to integrate experimental results with the accuracy of the modeled results from the finite element modeling.The system is rule based and developed using an appropriate system software. The procedures flow chart for the development of the expert based system are input/prompt for material name, shape and dimensions, knowledge base, inference engine/rules, decision taking, and then report generation. The database created from the mass of information generated from the experiments were used to generate codes in Microsoft Visual Basic (see Appendix 3). The system has in its databank, thermal properties of selected two Aluminium alloys used in this work.

### 2.1. Properties of Alloys A1200 and A8011

Two varieties of Al-Si alloys were used both for the simulation and foundry experiments. Tower Aluminium Rolling Mills, Ota, Ogun State, Nigeria provided the following relevant thermal properties as shown in Table 1.

*Table 1* **Properties of Alloys A1200 and A8011**

| **Alloy** | **% Composition** | | **Melting Point ( $^{o}$C)** | **Specific Heat (J/KGK)** | **Thermal Conductivity (W/MK)** | **Thermal Expansivity (µstrain/ $^{o}$C)** | **Density Kg/M$^3$** |
|---|---|---|---|---|---|---|---|
| | **Al** | **Si** | | | | | |
| A1200 | 99.3 | 0.20 | 645 | 893 | 221 | 22.8 | 2680 |
| A8011 | 98.34 | 0.47 | 510 | 980 | 81 | 21.3 | 2890 |

### 2.2. Preparation of test pieces

Green sand casting was used to produce 12 test pieces (6 each) from two Aluminium alloys A1200 and A8011. The dimensions of the test pieces are shown in Table 2. The castings were careful produced based on conditions and parameters to facilitate directional solidification.

During casting, when the solidification progresses to the innermost region or hot spots, a lack of liquid metal leads to voids called shrinkage cavities. In these experiments, the gating and feeding systems were designed to ensure that the risers solidify later that the hot spots. Also, the necessary shrinkage allowances were taken into consideration in constructing the patterns for the castings.

Fig. 1. shows the two alloys plates before they were sent to furnace for melting and pouring.

*Table 2.* **The dimensions of the test pieces of both alloys A1200 and A8011**

| **CYLINDRICAL DIMENSIONS FOR BOTH ALLOYS A1200 AND A8011** | | | | | | |
|---|---|---|---|---|---|---|
| S/N | Casting Size (mm) | Down sprue (mm) | Riser (mm) | Ingate (mm) | Runner bar (mm) | Vent (mm) |
| 1 | 200 x $\phi$ 50 | 70 x $\phi$ 25 | 70 x $\phi$ 20 | 30 x 69 x 17 (2 nos) | 0 | 70 x $\phi$ 5 (2 nos) |
| 2 | 150 x $\phi$ 50 | 70 x $\phi$ 25 | 70 x $\phi$ 20 | 30 x 69 x 17 (2 nos) | 0 | 70 x $\phi$ 5 (2 nos) |
| 3 | 200 x $\phi$ 25 | 70 x $\phi$ 20 | 70 x $\phi$ 10 | 24 x 42 x 7 (2 nos) | 0 | 70 x $\phi$ 5 (2 nos) |
| **RECTANGULAR DIMENSIONS FOR BOTH ALLOYS A1200 AND A8011** | | | | | | |
| S/n | Casting size (mm) | Down sprue (mm) | Riser (mm) | Ingate (mm) | Runner bar (mm) | Vent (mm) |
| 1 | 200 x 50 x 39.4 | 70 x $\phi$ 25 | 70 x $\phi$ 15 (2 nos) | 24 x 42 x 7 (2 nos)<br>30 x 69 x 17 (2 nos) | 150 x 25 x 20 | 70 x $\phi$ 5 (2 nos) |
| 2 | 150 x 50 x 39.4 | 70 x $\phi$ 25 | 70 x $\phi$ 20 | 30 x 69 x 17 (2 nos) | | 70 x $\phi$ 5 (2 nos) |
| 3 | 200 x 25 x 19.8 | 70 x $\phi$ 20 | 70 x $\phi$ 10 | 24 x 42 x 7 (2 nos) | | 70 x $\phi$ 5 (2 nos) |


a b

**Fig. 1**. (a) Alloy A1200 plates before melting (b) Alloy 8011 plates before melting

## 2.3. Mould preaparation

The moulds were prepared from green sand with Bentonite as binder. Properties of the moulding sand are as shown in Table 3. The prepared moulds are shown in Figure 2.

*Table 3.* **Sand properties.** Source: EMDI, Akure

| **Property** | **Value** |
|---|---|
| **Permeability** | 150 cmWH |
| **Green Strength** | 78.4KN/m$^2$ |
| **Moisture Content** | 3.0% |

**Fig. 2.** Prepared mould for one of the cylindrical shapes

### 2.4. 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 stop clock.

### 2.5. Criterion for prediction of shrinkage

In Table 4, Mina (2005) gave existing thermal criteria for prediction of shrinkage as proposed in literature.

*Table 4.* **Existing thermal criteria for prediction of shrinkage.** Source: Mina (2005)

| Criterion | Author | Year proposed |
|---|---|---|
| $G$ | Bishop et al | 1951 |
| $\frac{G}{V_s}$ | Davies | 1975 |
| $\frac{1}{V_{sn}}$ | Khan | 1980 |
| $\frac{G}{\sqrt{R}}$ | Niyama et al | 1982 |
| $\frac{G}{V_s}$ | Lacomte- Beckers | 1988 |
| $\frac{G_{0.33}}{V_{s1.67}}$ | Lee et al | 1990 |
| $\frac{G_{0.38}}{V_{s1.62}}$ | Kao et al | 1994 |
| $\frac{1}{t_{sm}V_{sn}}$ | Chiesa | 1998 |

Where, $G$ = Temperature gradient
$R$ = Cooling rate
$V_s$= Solidification velocity
$t_s$ = Local solidification time

The Niyama criterion which is the most popular and frequently used of all the criteria was adapted for the prediction of shrinkage. It was chosen because it provides a less complex way of predicting shrinkage in castings. The Niyama criterion is given by:

$$\frac{G_{ij}}{\sqrt{R_{ij}}} \tag{1}$$

Where G is the thermal gradient given by:

$$G_{ij} = \frac{(T_j - T_i)}{\Delta s} \tag{2}$$

Where $(T_j - T_i)$ is the difference in temperature between two points $i$ and $j$ in the casting and $\Delta s$ is the distance between these points. $R_{ij}$, the rate of cooling rate from an instant of time $\tau_i$ to $\tau_j$ at a given location inside the casting is given by:

$$R_{ij} = \frac{(T_i - T_j)}{(\tau_j - \tau_i)} \tag{2}$$

Bailey (1997) stated that, if $\frac{G_{ij}}{\sqrt{R_{ij}}}$ is less than 1, then there is a high possibility of shrinkage occurring in Steel castings.

### 2.6. Harmonization of results and statistics

In order to make statistical comparison between the results obtained from experiments and simulations, the following hypotheses wee formulated and subjected to T-tests.

For temperature and Niyama values, the processes (simulation and experiment) were subjected to the following hypotheses: The null hypothesis ($H_O$): $\mu_{experiment} = \mu_{simulation}$ while the alternative hypothesis ($H_1$): $\mu_{experiment} \neq \mu_{simulation}$. $P < 0.05$, it implies that the result is SIGNIFICANT, which means the REJECTION of Meaning that there is a significant difference between the experimental and simulated result)**.** $P > 0.05$, it implies that the result is NOT SIGNIFICANT, which means the NON REJECTION of the Null Hypothesis ($H_O$): $\mu_{experiment} = \mu_{simulation}$**.** (Meaning that there is no significant difference between the experimental and simulated result).

## 3. RESULTS AND DISCUSSION

In The interface, outputs and reports that were generated from the developed knwledge base are presented below. Figures 3-11 show reports that were generated from the knowledge base expert system software developed. Data that could be generated from these include the following:

- Gating system dimension
- Metal composition;
- Thermal properties of metals;
- Pattern and mould box sizes with the appropriate tolerances;
- Sketch of the shape to be cast;
- Sprue and riser calculations;
- Shrinkage prediction at specified time intervals.


**Fig. 3.** Interface that enables input of fresh data into the data base and generate reports

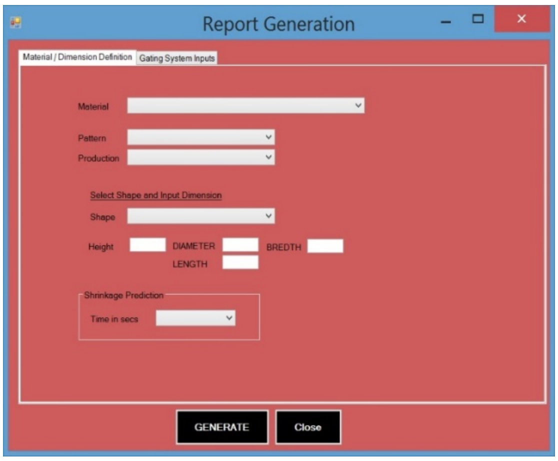



**Fig. 4.** Interface for the input of casting dimension and report generation

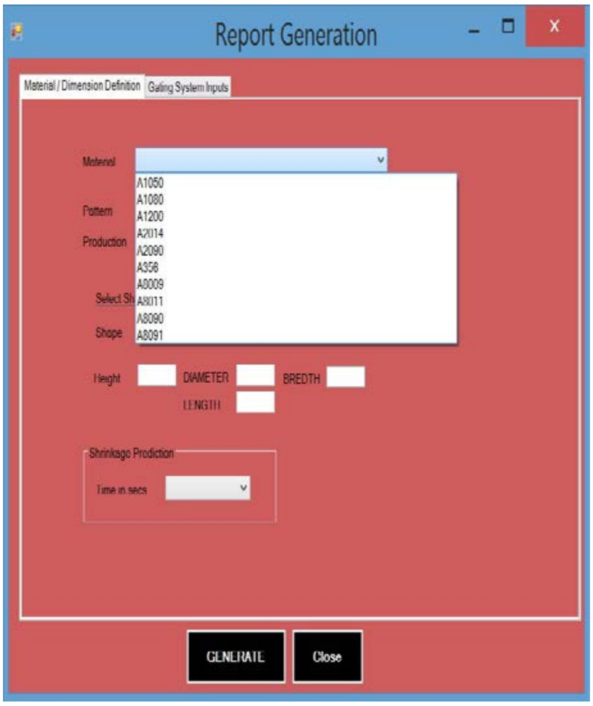



**Fig. 5.** Draw down dialog box for the selection of material from the data base

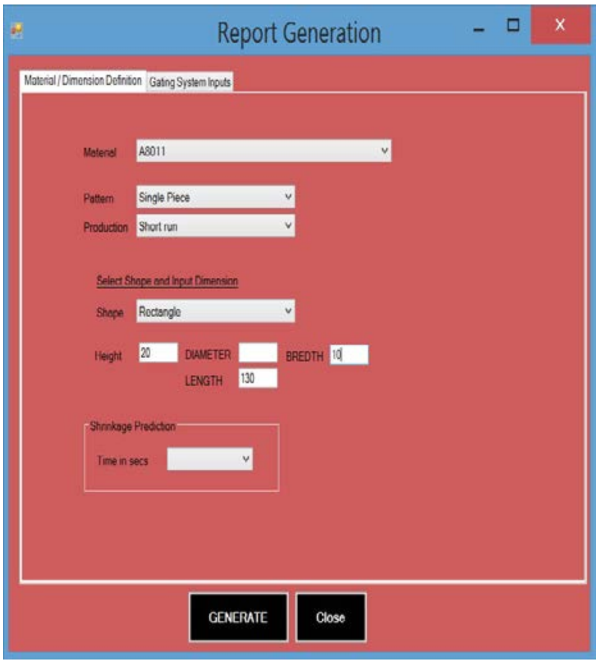



**Fig. 6.** Interface for inputs for report generation from the expert system

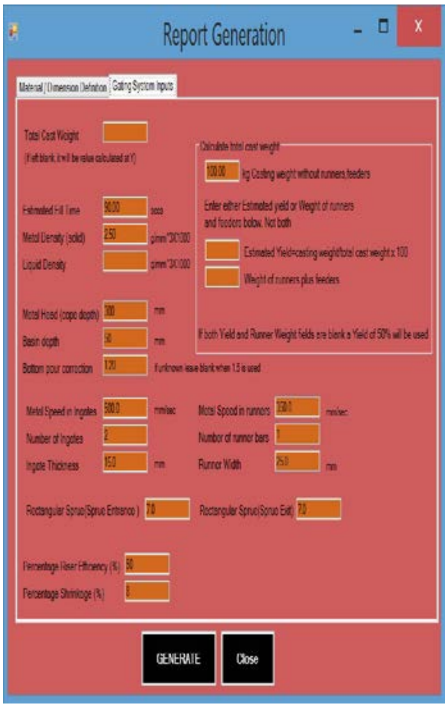



**Fig. 7.** Generation of gating information from expert system

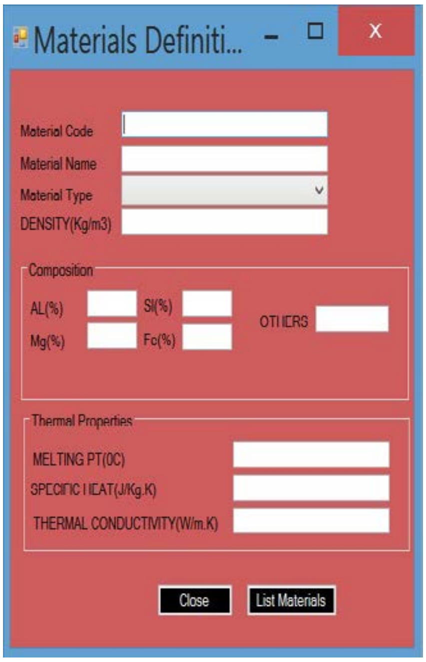
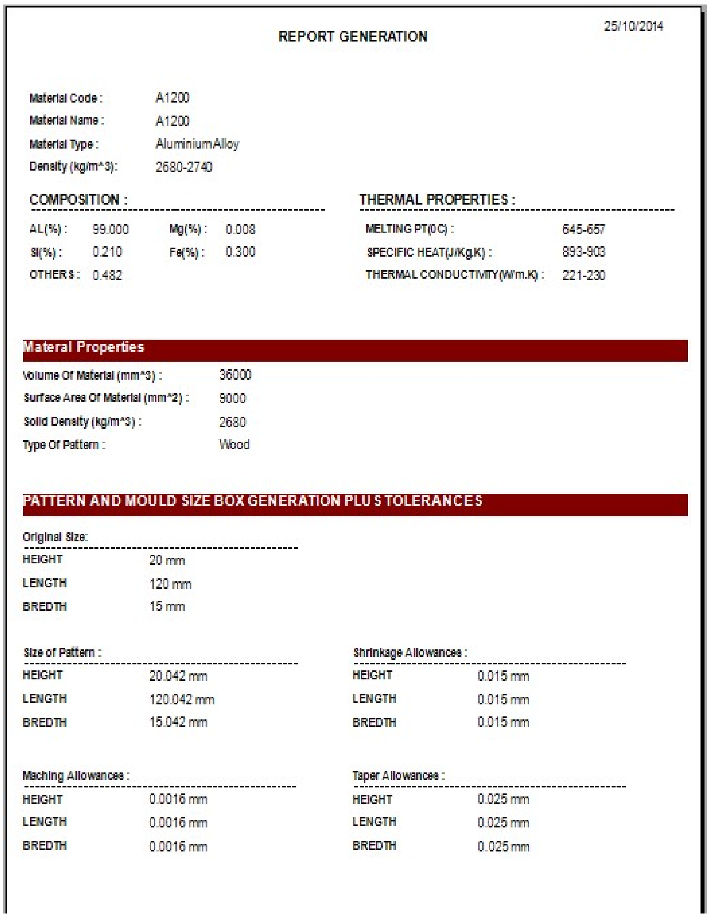



**Fig. 8.** Interface for inputing new information to the data base



REPORT GENERATION 25/10/2014

Material Code : A1200
Material Name : A1200
Material Type : AluminiumAlloy
Density (kg/m^3): 2680-2740

COMPOSITION :

| | | | |
|---|---|---|---|
| AL(%) : | 99.000 | Mg(%) : | 0.008 |
| SI(%) : | 0.210 | Fe(%) : | 0.300 |
| OTHERS : | 0.482 | | |

THERMAL PROPERTIES :

| | |
|---|---|
| MELTING PT(0C) : | 645-657 |
| SPECIFIC HEAT(J/KgK) : | 893-903 |
| THERMAL CONDUCTIVITY(W/m.K) : | 221-230 |

Materal Properties

| | |
|---|---|
| Volume Of Material (mm^3) : | 36000 |
| Surface Area Of Material (mm^2) : | 9000 |
| Solid Density (kg/m^3) : | 2680 |
| Type Of Pattern : | Wood |

PATTERN AND MOULD SIZE BOX GENERATION PLUS TOLERANCES

Original Size:

| | |
|---|---|
| HEIGHT | 20 mm |
| LENGTH | 120 mm |
| BREDTH | 15 mm |

Size of Pattern :

| | |
|---|---|
| HEIGHT | 20.042 mm |
| LENGTH | 120.042 mm |
| BREDTH | 15.042 mm |

Shrinkage Allowances :

| | |
|---|---|
| HEIGHT | 0.015 mm |
| LENGTH | 0.015 mm |
| BREDTH | 0.015 mm |

Maching Allowances :

| | |
|---|---|
| HEIGHT | 0.0016 mm |
| LENGTH | 0.0016 mm |
| BREDTH | 0.0016 mm |

Taper Allowances :

| | |
|---|---|
| HEIGHT | 0.025 mm |
| LENGTH | 0.025 mm |
| BREDTH | 0.025 mm |

**Fig. 9.** Report generated page

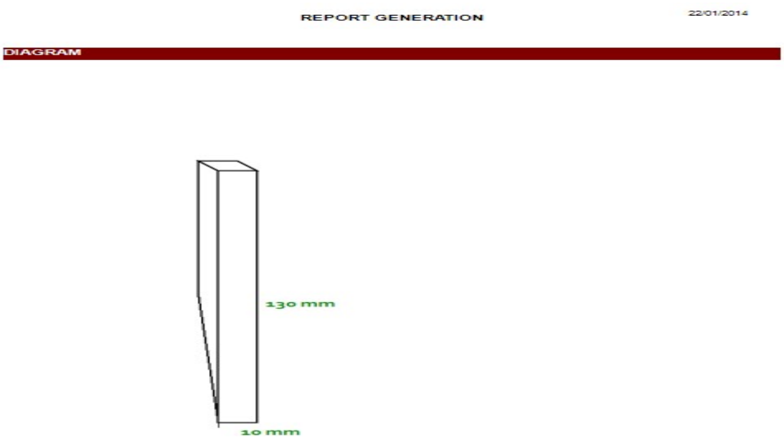



**Fig. 10.** Generating of casting shape

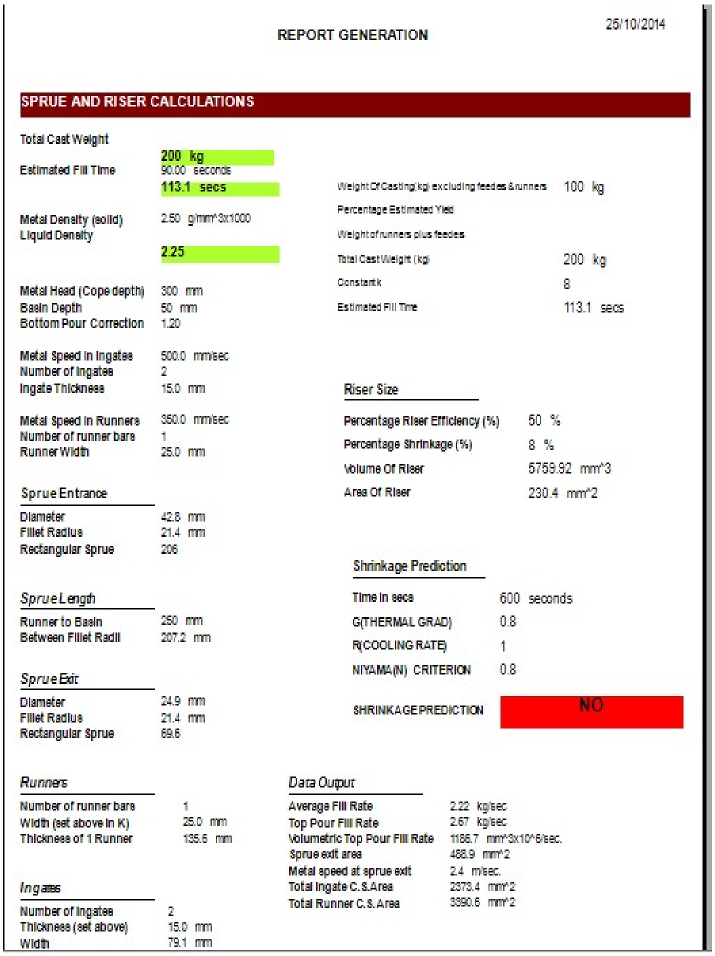



Fig. 11. Shrinkage prediction and other outputs

## 4. CONCLUSION

The knowledge base of the expert system is limited by the information generated from the experiments and simulations for the two alloys used in this work. Further work can be carried out through experiments and simulations on other alloys to expand the knowledge database.

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