RAPID TOOLING APPLICATION FOR THE EVALUATION OF A GREENSAND CASTING DEFECT

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DECLARATION
The research material in this paper, submitted to the '*South African Journal of Industrial Engineering'* has neither been published elsewhere nor is it being considered elsewhere for publication.

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ABSTRACT

The ability to produce production quality tooling, directly from CAD data, through additive manufacturing (AM) processes has obvious advantages with regards to the reduced lead time and labour costs. This, together with the ability to simulate the metal casting process, opens new doors for researchers in the field of metal casting. This paper reviews the suitability of tooling produced in PA 2200 polyamide material, for use in a research environment, where the failure of greensand, a mixture of silica sand, bentonite (clay) and water, is to be replicated as it would occur in an industrial setting.

OPSOMMING

Die aanleg deur middel van toevoegings vervaarding het duidelik voordele deur middel van die dierekte aanleg van CAD ten op sigte van die vermoe om produksie gehalte gereedskap te prodiseer, onder ander die verminderde tyd en arbeids kostes. Tesame met die vermoe om the metaal giet proses te kan simuleer, gee vir navorsers nuwe geleenthede in die gebied van metaal gietery. Hierdie artikel resenseer die geskiktheid van gereedskap wat in PA 2200 polyamide material gebruik word in die navorsingsomgewing, waar die mislukking van 'greensand', 'n mengsel van silica sand, bentonite (klei) en water, is, te herhaal as dit in 'n industriele omgewing sou plaasvind..

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1. INTRODUCTION

In order to evaluate the tendency of greensand moulding mixtures to experience scabbing, specially designed tooling for the manufacture of greensand moulds was proposed and developed by Boenisch and Patterson [1, 2]. The specially designed tooling provides suitable conditions to measure the resistance of a moulding mixture to failure by low wet tensile strength while the surface of the mould is experiencing expansion.

Scabbing occurs due to radiant heat from the liquid metal in the mould, rapidly driving moisture from the surface into cooler areas behind the mould wall, while expansion of the moulding aggregate on the surface introduces compressive forces which may result in mould wall failure and metal ingress into the resulting cavity.

Traditionally, foundry tooling is produced using subtractive manufacturing processes, where designs, either from 2D drawings or 3D data, are used to manufacture wooden replicas of the cast part to be produced. In many South African foundries, these replicas are used to produce prototype castings. These prototypes are used to determine the success of the design in terms of manufacturability, as well as to present to the customer for approval. This often takes place without the use of computer assisted simulation.

Depending on the moulding process, and required life, these wooden tools should often be replaced by metal, plastic (resin), or composite parts to serve as the tooling to be used in the production process. This is based on the required durability and environment in which the tooling is deployed.

An analysis of tooling produced in PA 2200 Polyamide material, for use in a research environment, where the failure of greensand, a mixture of silica sand, bentonite (clay) and water, is to be replicated as it would occur in an industrial setting, was required. The durability and functional aspects to tooling produced by additive manufacturing methods was compared with other common tooling materials, and the implications thereof are identified and discussed, the results of which show promise for additive manufacturing as a solution to complex tooling problems in the metal casting research environment.

2. THE GREENSAND MOULDING SYSTEM

Greensand is possibly the most widely used aggregate (or sand) moulding system used to produce metal castings. It consists mainly of aggregate, commonly a graded silica sand, clay and water, where the clay and water, form the binder for the moulding system.

The basic principle of greensand bonding supposes that once all of the aggregate is coated with a suitable layer of clay and water, if the moulding mix is compressed, it will form a mould that, while still plastic in nature, will have suitable strength with which to contain liquid metal for the purposes of metal casting.

The popularity of greensand is due to its low cost, environmentally friendly nature and its ease with which it can be reconstituted and reused. This is achieved with only minor additions of new additives to replace those lost or destroyed during the high temperature exposure of the casting processes, or mechanical breakdown thereafter.

The only disadvantage of the greensand moulding process is the plastic nature of the mould, which can result in distortion of the mould and thus an inaccurate casting is produced.

2.1 Greensand Properties

Greensand mechanical properties are largely controlled by the binder material. That is to say, the content of both clay and water as individual constituents, and their content in combination, will affect all of the moulding material properties. The influence of clay and water contents are shown in figures 1, 2 and 3.

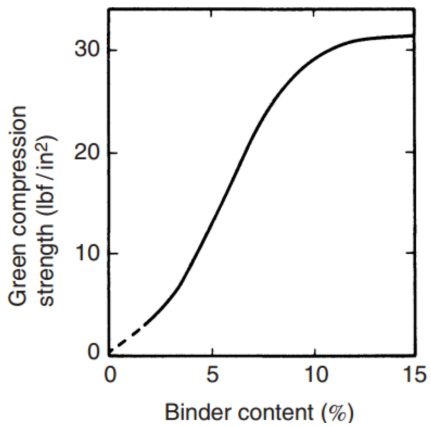

Figure 1 - Influence of binder (clay) content on green strength. [3]

Some of these properties include green compression strength, the property that determines the strength of the mould after compression of the aggregate mixture around the tooling and before casting, the dry compression strength, which is required during the casting process to maintain the shape of the mould while the liquid metal cools and solidifies, and flowability, the property which is required to ensure adequate movement of the unmoulded sand while it is filling the moulding box. If green compression strength increases, flowability typically decreases, and this could result in poor flow of sand around the tooling, which will cause a poor reproduction of the tool shape and detail in the mould surface as well as poor compaction of the moulding aggregate.

Wet tensile strength is another property controlled by the binder. It measures the ability of the mould to withstand mechanical forces while moisture content increases away from the mould surface due to evaporation at the mould surface.

In order to successfully produce moulds, the properties must be in balance, and these are commonly evaluated in the foundry laboratory prior to the moulding material being used to produce moulds.

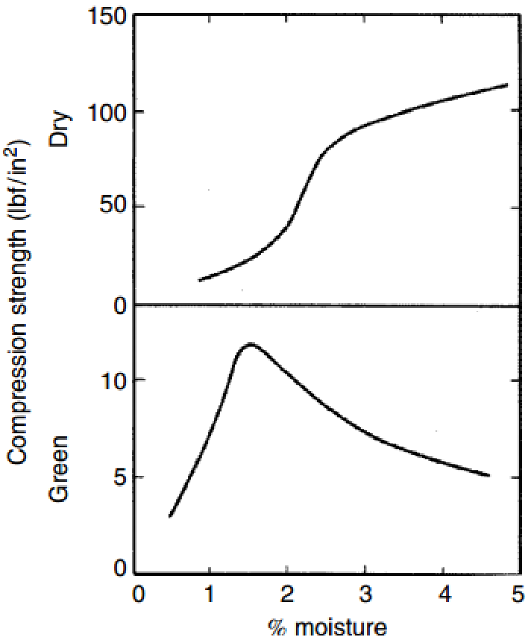

Figure 2 - Influence of moisture content dry and green compression strength. [3]

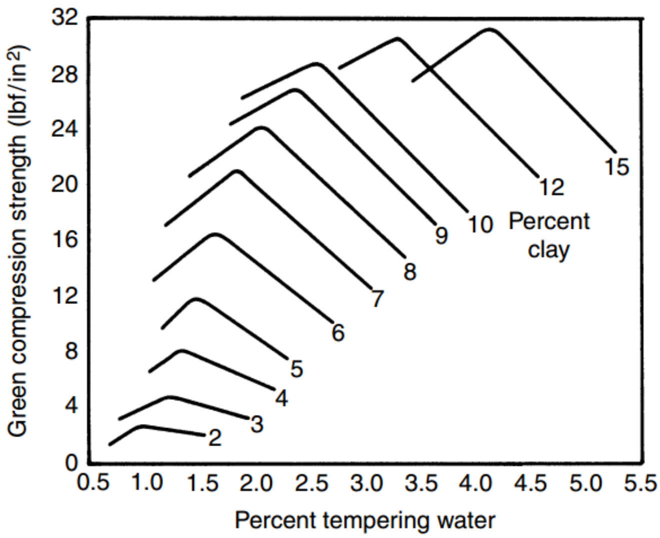

Figure 3 - The influence of both clay and water content on green compression strength. [3]

2.2 The Influence of Casting on Greensand Properties

The introduction of liquid metal into a greensand mould produces an inflow of heat from the metal at a temperature greatly above that of the boiling point of water. The surface of the mould quickly heats up and any water present will evaporate, condensing away from the mould surface; as heat continues to advance into the mould, the moisture is forced to migrate further, where it will again condense in cooler parts of the mould. According to Campbell [4] this is a continuous process, and dry and wet zones will move through the mould creating layers of varying properties.

Four zones can be distinguished:
1. The dry zone – all moisture has been evaporated from the binder due to the high temperature, the atmosphere within the zone remains fairly stagnant, with a composition of approximately 100% water vapour.
2. The vapour transport zone – with a near uniform temperature of 100°C, the water content is constant with steam migrating away from the casting.
3. The condensation zone – steam will recondense, producing an area of high moisture, which typically translates into a marked reduction in the greenstrength of the mould. Mechanical failure is most common in this area of the mould.
4. The external zone – temperature and moisture content in this part of the mould are yet to change.

The heat diffusing initially from the liquid metal and later the solidifying casting will cause the transformation zones to migrate deeper into the mould. Campbell [4] proposes that the progression of the zone advancement can be considered in terms of the distance, *d*, that an isotherm reaches as a function of time, *t*. This is a one dimensional heat flow (where *D* is the coefficient of diffusion) :

$$d = (Dt)^{1/2}$$

At an isotherm of 100°C, the value for *D* is approximately $1mm^2.s^{-1}$, after 1 second then, the evaporation front has moved 1mm, after 100 seconds, 10mm, and after 10 000 seconds (nearing 3 hours) the evaporation front is 100mm from the mould surface.
For the condensation zone, *D* is approximately $3mm^2.s^{-1}$, so that at the relevant time intervals, 1, 100 and 10 000 seconds, the front position will be at 1.7, 17 and 170mm respectively.

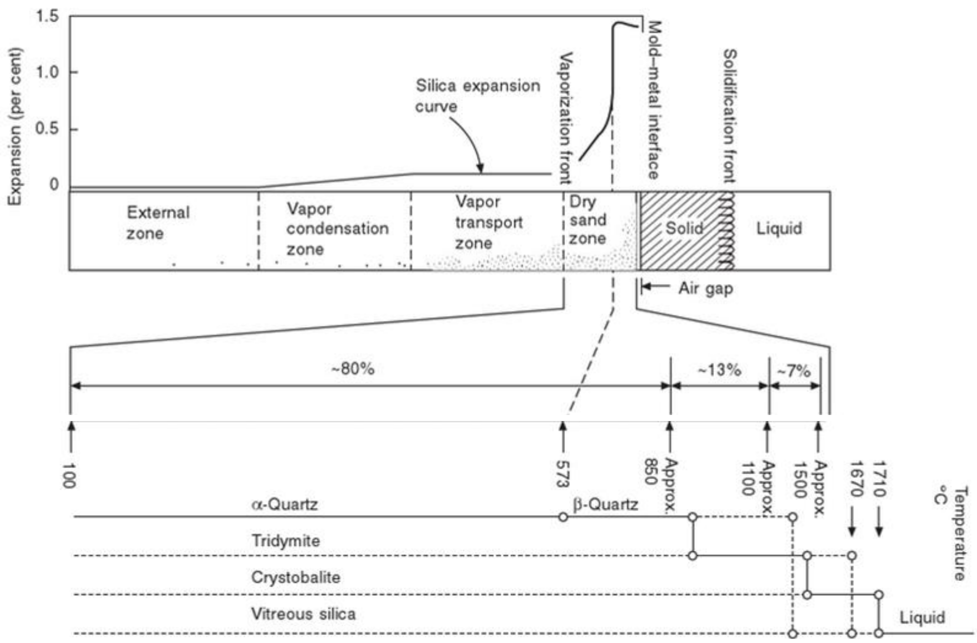

Figure 4 - Structure of the heated surface of a greensand mould against a steel casting; and the forms of silica (after Sosman 1927) with solid lines denoting stable states and broken lines denoting unstable states. [4]

2.3 Expansion of Silica Sand and Mould Weakness

The linear expansion of silica sand in the dry zone (Figure 4), can result in substantial stresses being experienced in the mould. This is as a result of the structural change within the silica at 573°C. With the development of the vapour condensation zone, an area behind the mould surface increases steadily in moisture content, the result being a lowering of the strength of the moulding mixture (Figure 2, 3). The ability to withstand the forces of the expanding silica aggregate, while an area of high moisture develops away from the mould surface will be determined by the wet tensile strength of the moulding mixture.

The development of expansion related defects is shown in figure 5. Upper mould surface weakness can be seen in a), constrained surface resulting in scabbing defects, and b), unrestrained and unsupported surface resulting in fillets and veining. Lower mould surfaces are also subject to weakness, with c), showing scabs and rat-tails, and d) showing scabbing occurrence.

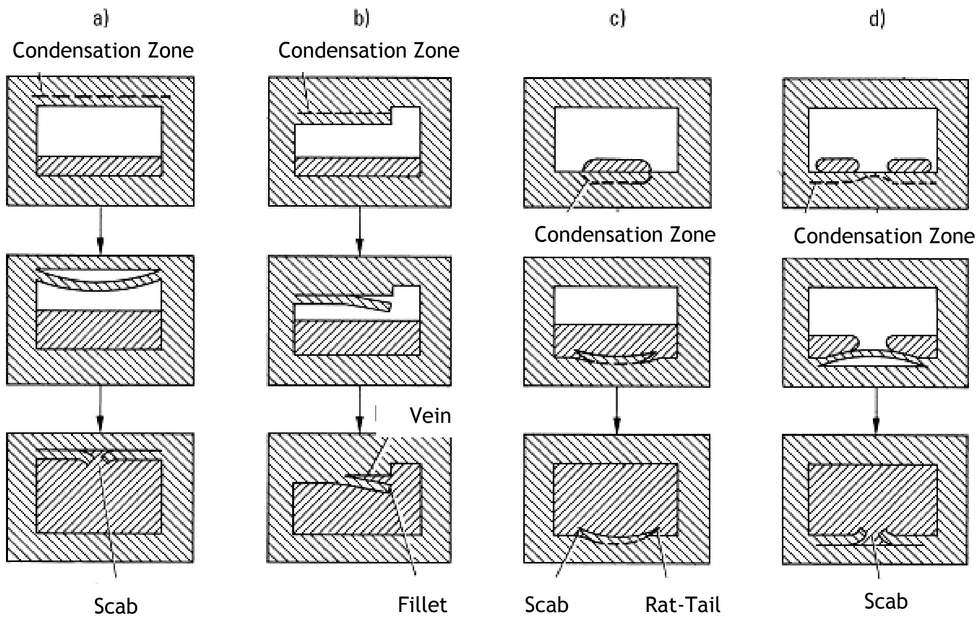

Figure 5 - Formation of the vapour condensation zone and resulting defects. [5]

The wet tensile strength of the binder can be measured in the laboratory using a standardised test. The moulding aggregate is shaped, heated to 300°C, allowing sufficient time for evaporation of moisture and subsequent condensation behind the surface, and then tensile forces are applied. This is shown schematically in figure 6.

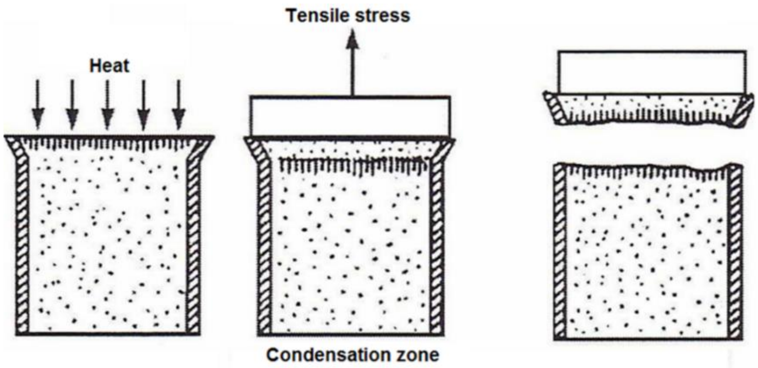

Figure 6 - Schematic representation of the wet tensile test.

The evaluation of the binder tensile strength does not account for expansion of the silica sand.

The prevalence of expansion defects is related to the wet tensile strength, and the occurrence of compressive stresses in the mould.
The wet tensile strength of a moulding mixture can be increased by increasing the binder content in the mixture, making use of alternative clay binders which exhibit higher wet tensile strengths, optimising binder ratios in the mixture (both clay and water), and using an more suitable silica aggregate with low surface area.

The steps taken in order to reduce the build-up of compressive stress in the mould can include the even and rapid filling of the mould, the reduction of moisture levels in the moulding material, and, increasing the content of additives which can dampen the expansion of silica aggregate.

2.4 Measuring the Effects of Prevention Methods

In order to evaluate the influence of both binder strength and compressive forces under varying conditions a special pattern is used for casting trials to be performed. The methodology employed resolved to vary the binder content, type, and optimisation of properties, as shown in figure 7.

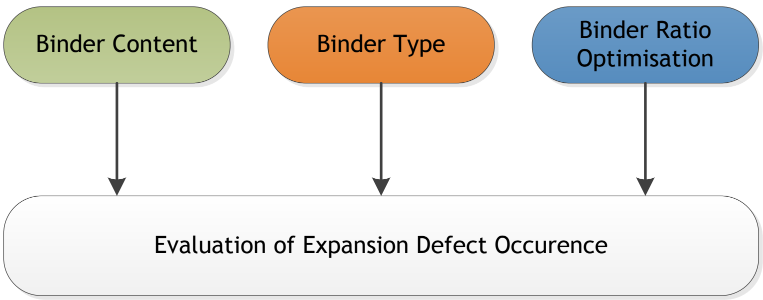

Figure 7 – Variables employed in the study methodology.

3. IMPLEMENTING AN ADDITIVE MANUFACTURING AND PROCESS SIMULATION SOLUTION

3.1 Foundry Patternmaking

The production of sand moulds for use with metal casting requires tooling to shape the cavity of the mould. The tooling allows moulding aggregate to be rammed or compacted around its shape, imparting an impression in the completed mould. The created cavity can then be filled with molten metal, and once solidified, the casting should be representative of the original design.

Traditional patternmaking is a labour intensive process, requiring great skill and years of experience. The pattern design originated from a two dimensional drawing or sketch of a measured artefact. The patternmaker, taking into consideration the moulding system to be employed, would then manually produce a wooden replica through subtractive processes and assembly.

Modern foundry patterns are now often produced using CAD data, rather than 2D drawings. The introduction of CAD and modern high speed CNC machining has allowed pattern shops to reduce the intensity of labour, and skills required to produce patterns. The rate at which CNC machining can produce tooling, as well as the improved accuracy of tool dimensions has obvious benefits, both economically and in terms of output quality.

CNC manufacturing, while offering these improvements and efficiencies, still is unable to produce single part patterns of a complex nature due to the limitations of the CNC process.

3.2 Additive Manufacturing Technologies for Patternmaking

Rapid manufacturing technologies are used in casting production through a number of methods, and have been available to the metal casting industry for many years.

> *"The first use of RP models as a pattern started in the year 1989." [6]*

The evolution and stages of introduction of these is outlined in table 1, shown in the order in which they were introduced.

Table 1 - Application of additive manufacturing parts in metal casting and their typical uses.

Application Stage	***Typical Uses***
Consumable Patterns	Produced from materials such as wax and lost foam for use in the investment casting industry.
Consumable Moulds and/or Cores	Refractory moulds were produced using technologies such as selective laser sintering. These moulds were largely only suitable for non-ferrous castings.
Permanent Patterns	Through 3D printing, fused deposition modelling and solid ground curing, permanent tooling can now be grown in complex shapes.

Additive technologies allow for concurrent manufacturing, a process that reduces the period of time between part conception and part realization. The developments in the cast metals environment, centre on production of physical objects such as patterns, moulds and cores, from three dimensional computer data, which allows for the production of fully functional components.

> *"The emphasis is on the fully functional components, not look-like components, as the castings produced are of the metal desired for the component." [7]*

Table 2 outlines relevant properties of modern pattern materials. The traditional construction material of wood, while having favourable workability due to its low hardness and density, will not be as durable as metal or synthetic materials such as polyamide. Research by Malagi et al (2014), and Baligidad et al (2014), indicates that RP materials will typically last between 2.5 and 7.5 times longer (number of castings produced) than traditional wooden patterns. [6, 7]

Wooden patterns are also more prone to dimensional inaccuracies due to absorption of moisture, and the non-linear nature of the dimensional variations can result in poor simulation predictions.

Table 2 - Properties of Common Pattern Making Materials

Material	*Density*	*Hardness*	*Linear Thermal Expansion*
Wood (Jelutong)	0.36g/cm^3	2.46N/mm^2	N/A
Polyamide	0.93g/cm^3	78N/mm^2	1.09 x 10^{-4}/K
Metal (Aluminium)	2.7g/cm^3	540N/mm^2	22.2 x 10^{-6}/K

While aluminium patterns are more durable than polyamide, the process of producing master patterns (from wood) and then translating these into a permanent aluminium tool can result in similar dimension differences to that of the CAD model. This obstacle is obviated with simple shapes which can be manufactured by subtractive processes, but this is not a suitable alternative for complex casting shapes.

The use of RP tooling for research, in this case simulation of metal casting processes and resulting defects, requires the highest possible accuracy in terms of reproduction of dimensions. Dimensional variation of tooling, from CAD data, will reduce the accuracy of numerical methods of simulation which rely on accuracy of data to predict outcomes through finite element construction. The construction of a suitably high resolution mesh will ensure the highest possible accuracy of process predictions.

3.3 Simulation of Casting Process

Magma5 was used to simulate the metal casting process. Magma5 makes use of Finite Volume Method (FVM) to calculate the resulting volume change over a period of time. The software is able to predict amongst others, metal flow patterns, filling time, temperature of both metal and mould, and solidification of the metal making use of the calculated FV data changes.

Of particular interest for the current study were the metal flow, filling time and temperature evolution through the moulding material.

4. RESULTS

4.1 Pattern Production: EOSINT P Technology

The pattern was produced using the EOSINT P 385 machine, which employs selective laser sintering technology. The material chosen was the polyamide material PA 2200, with a grain size of 50µm. The growth of the pattern equipment took 18 hours, with a sintered layer thickness of 150µm.

The resulting pattern equipment, when measured for dimensional accuracy, has a maximum variation of ±50µm along both the x, y and z axes. This translates in to a negligible variation in terms of the moulds produced with the pattern equipment.

The resulting pattern equipment is shown in figure 8.

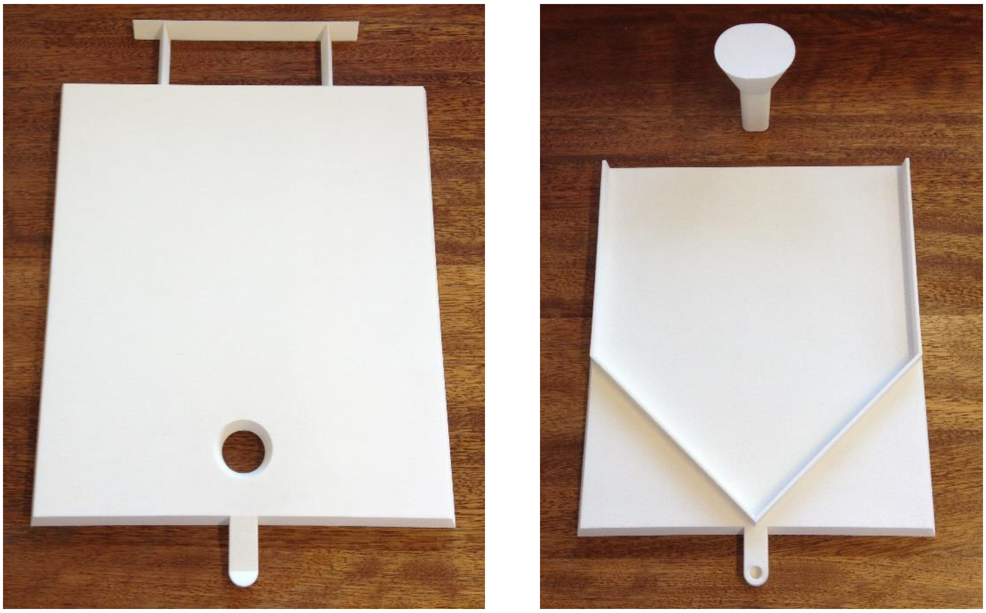

Figure 8 – Polyamide pattern in four parts: Left – drag pattern half and running system, Right – cope pattern half and down-sprue.

4.2 Simulation Data

The simulation data generated from the CAD model was used to predict the outcomes of the investigation into expansion related casting defects.

The heat radiated onto the top surface of the mould, from the advancing molten metal is shown in figure 8. The increase in temperature of the moulding material reaches in excess of 200°C before 50% of the casting is filled. This prediction would indicate that the development of a dry zone, vapour transport zone and vapour condensation zone are all likely to have taken place by this time. Any area of mould surface which is expanding at a rapid rate will be experiencing linear expansion of up to 1.5%, causing compression forces in the mould surface.

From the work of Sosman, presented by Campbell [4], we can estimate that with a mould accuracy of 0.05mm, the 100°C isotherm is likely to move into the mould wall ±3.2mm after 10 seconds, with the condensation zone moving ±5.5mm in the same period.

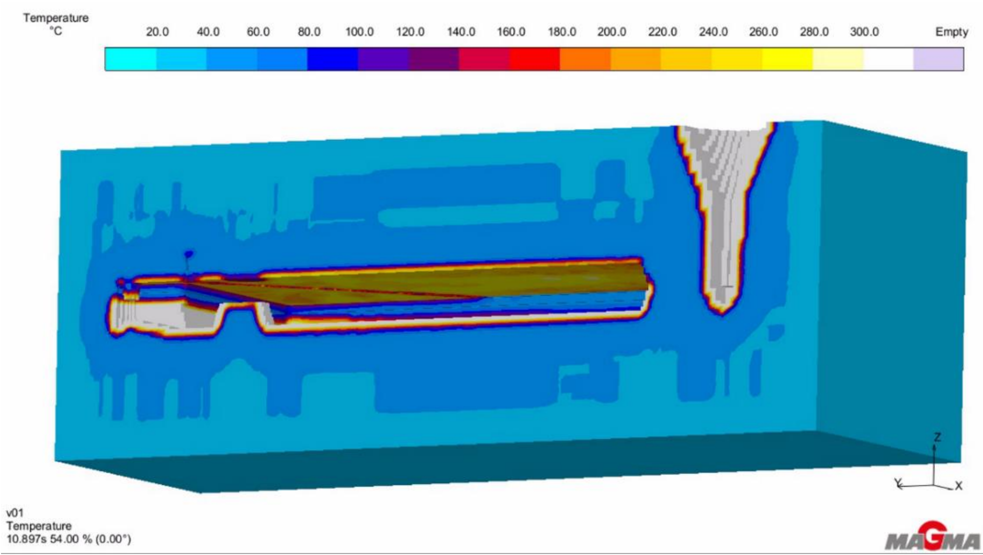

Figure 9 – Simulation data: mould temperature during filling (8-10s).

If the compression forces experienced in the dry zone of the mould are higher than the wet tensile strength of the binder in the condensation zone, defects will develop as a result of mould weakness and failure.

The development of the expansion defects will be a time dependant process. If mould filling can be achieved before the mould surface can fail, casting defects can be avoided. Figure 9 shows details of the filling time for various sections of the mould based on metal flow data.

Any interruption in the casting process will allow the radiated heat to penetrate deeper into the mould before filling, and possibly increasing the risk of expansion related defects.

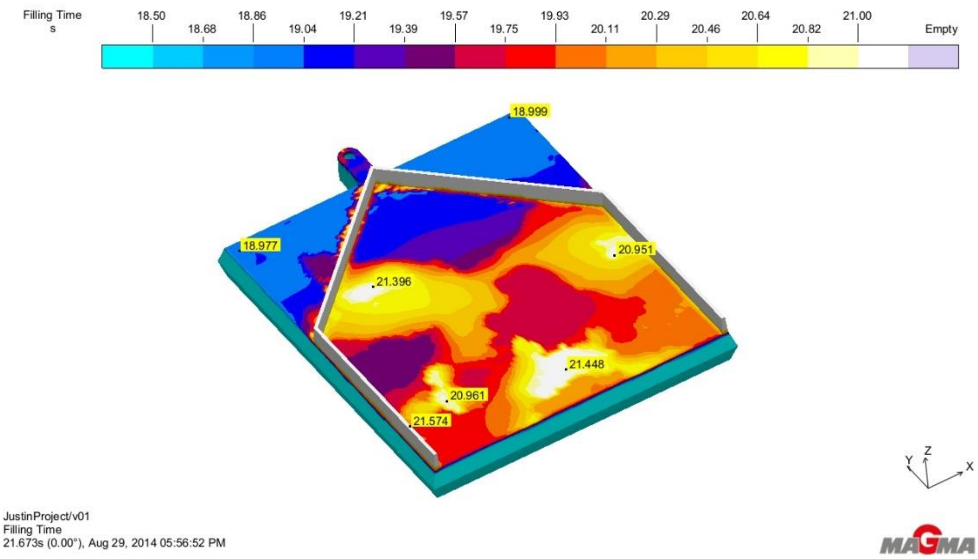

Figure 10 - Simulation data: filling time.

5. CONCLUSION

The selection of polyamide PA2200 material was evaluated with regards to its suitability for pattern equipment required during the evaluation of greensand moulding mixtures. The polyamide material performed substantially better than wooden tooling, and only marginally poorer than metal tools. This is in agreement with the expected durability and dimensional stability based on hardness, density and linear expansion values.

The effects of small variations in dimensions of moulds is clear, and the ability to simulate the process, and make meaningful evaluation and predictions from the simulation data relies on accurate duplication of the defined simulation parameters in the production of moulds. These factors were suitably satisfied by the PA 2200 material in the patterns produced.

Due to the ability of the additive manufacturing process to produce tools of greater complexity than subtractive processes, and suitable dimensional stability of the polyamide material for the requirements of this study, such tooling is of great value in the research environment.

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