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REDESIGN OF AN INDUSTRY TEST FOR HOT TEARING OF HIGH PERFORMANCE ALUMINIUM CASTING ALLOYS USING CASTING SIMULATION SOFTWARE

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Abstract

Hot tearing propensity in aluminium alloys is commonly measured using dog-bone and ring tests. Hot tearing occurs as a result of a number of factors including; level of stress and strain, hot spots and nucleation sites. This paper presents the results of a study to redesign a dog-bone type hot tear test using casting simulation software to ensure that the location of the tearing was always in the same location.

In the simulation of the original five fingered die both the stress and strain were sufficiently high for hot tearing but there was no defined hot spot implying that the random hot tear locations would result depending upon suitable nucleation sites. A number of design iterations were carried out to produce more focussed hot spots and to ensure that the die was easy to manufacture and use, and was economically viable.

Introduction

Hot tearing is a phenomenon that occurs during the solidification of a cast material when the stress created generated by the thermal contractions (both solidification and linear) become greater than the inherent strength of the material. There is a tendency for them to occur in hot spots within the geometry as this will be the weakest material. Hot tear tests have been developed over the years so that engineers can determine the susceptibility of alloys to hot tearing and to investigate the effect of trace elements for example. Despite much work on hot tearing over the last several decades there is still no consensus on the mechanism of the nucleation of hot tears. There is almost no doubt that they are initiated on pre-existing defects but there have been a number of mechanisms proposed for the growth of the crack. Pellini [1] proposed a theory of hot tearing based on the accumulation of strain which must fulfill the following criteria: cracking occurs in the hot spot, hot tearing is controlled by the level of strain occurring within the hot spot and finally that the accumulated strain in this region depends upon the strain rate and a time factor. This has been further developed by Clyne and Davies [2].

Rapaz [3] and previously Prokhorov [4] have suggested that it is the strain rate which is the critical factor for controlling hot tearing. This is justified by the assuming the strain rate during solidification is limited to the rate at which fracture can occur. A third approach assumes that failure occurs at a critical stress with the remaining liquid around the solidifying grains acting as a stress raiser.

The final theory is that hot tearing occurs because there is not enough feed metal to supply the hot tearing region [5,6]. Foundries will often grain refine their alloys in order to promote better feeding so that hot tearing doesn't occur. Katgerman has summarised these mechanisms as presented in Table I.

Table I: Possible hot tearing mechanisms [7]

Temperature range fraction of solid	Nucleation of crack	Propagation of crack	Fracture Mode
$T_{rigidity} < T < T_{coherency}$ F_s = 50-80%	Grain boundary covered with liquid; shrinkage or gas pore	Liquid film rupture Filled gap	Brittle, intergranular Healed crack
$T < T_{rigidity}$ F_s – 80-99%	Pore, surface of particle or inclusion, liquid film or pool, vacancy clusters	Plastic deformation of bridges Liquid film rupture, liquid metal embrittlement of solid bridges	Brittle, intergranular Plastic deformation of bridges possible
Close to solidus F_s = 98=100%	Pore, particle or inclusion, segregates at grain boundary, liquid at stress concentration point, vacancy clusters.	liquid metal embrittlement Plastic deformation of bridges, creep	Brittle transgranular propagation possible Macroscopically brittle or ductile, transgranular propagation possible

Hot tear test methods

A number of different tests have been developed to demonstrate the susceptibility of cast metals to hot tearing. Some of these are described in the following sections.

<u>The I Beam</u>

There are many variants to this method but they all involve casting a bar with resistance to contraction at both ends. This resistance increases the stress and strain in the material promoting hot tearing. The most common I-beam test involves casting fingers of differing lengths, from one runner. The amount of strain available in each finger is proportional to the length of the beam implying that the longest finger should fail first by hot tearing. The more fingers that fail, the more susceptible the material is to hot tearing.

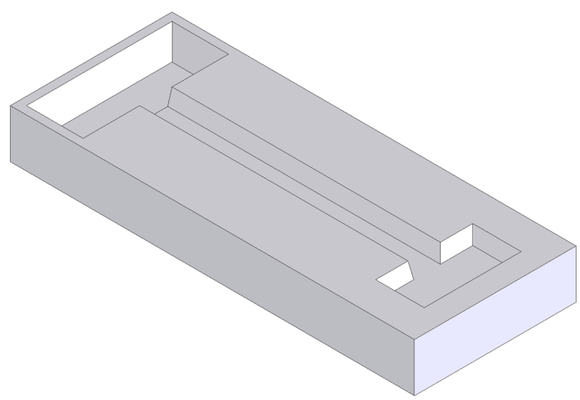


Figure 1: Simple I Beam mould for identifying hot tear susceptibility

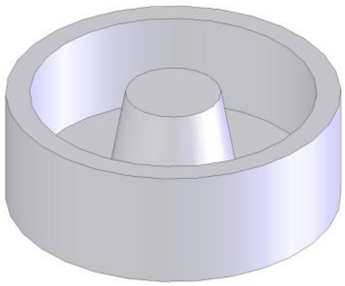


Figure 2: The mould for a ring test used for identifying hot tear susceptibility

The Ring Test

The ring test involves pouring liquid material into the area between the inner and outer regions of a steel ring shaped die, (Figure 2), producing a 'ring' shaped casting.

The cast material cools where it contracts onto the inner section of the die whilst the inner core of the die expands slightly at the same time. This produces the constraining forces, which will initiate transverse hot tears in a susceptible material. It is an unusual test as there is no specific area of strain concentration or a hot spot, yet it still produces notable consistency.

The cold finger test

The cold finger test, developed by Warrington and McCartney, consists of a steel crucible [8] contained within an open furnace, holding the molten metal being tested (Figure 3).

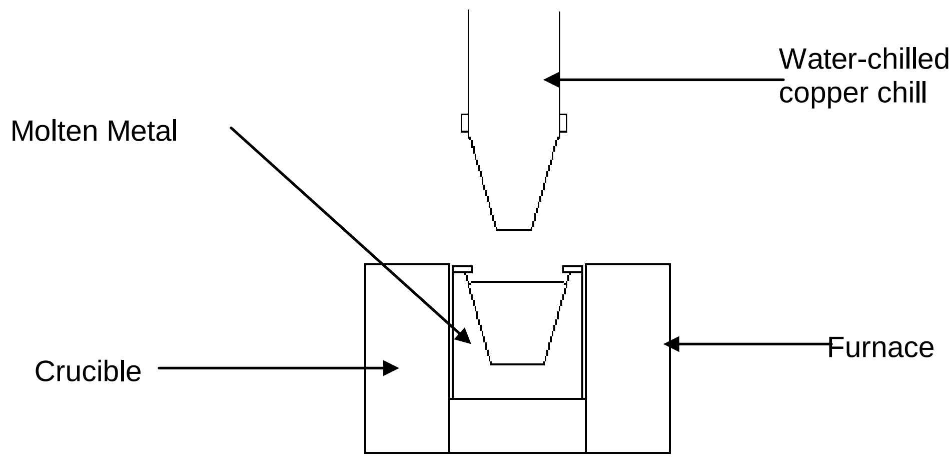


Figure 3: The cold finger test [9]

Above the crucible is a copper chill which is also water cooled. Both the steel crucible and the copper chill have angled sides of 17.5 degrees, which allow an exact match when the chill is lowered into the melt. It is lowered a set distance to produce a casting with a predetermined 10mm thick wall. The melt cools and solidifies with a tear being initiated in the surface where the restraint stress is at its highest.

Hot spots occur at section increases and at intersections in the casting so the die should be designed to have uniform section thickness to equalise cooling[10]. Where this is not possible, chills should be used to alter the cooling rate. Any potential stress raisers should have a gradual change in cross section.

Hot tear test design for current work

The current work was based around a design from N-Tec, The geometries is expected to create hot tears in a systematic way. The geometry is shown in Figures 4 a&b.

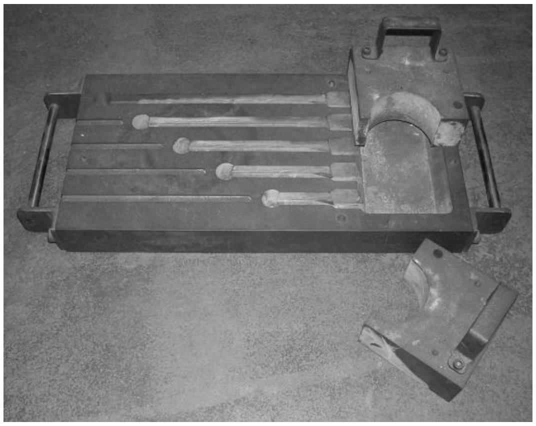


Figure 4a: Photograph of a five fingered die

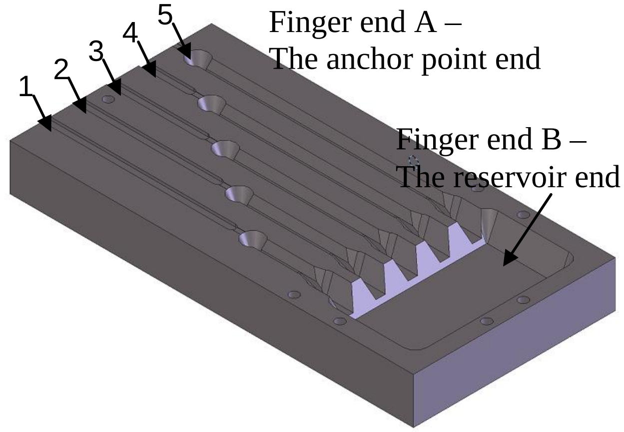


Figure 4b: CAD model of the 5 fingered die

The mould is essentially a multiple finger “I” beam test that produces five cast fingers of increasing length, which are connected to a single reservoir. There are slight differences between the actual mould and the CAD due to manufacturing issues. The fingers are all of the same depth so should all start to fill at the same time. The liquid metal is poured into the reservoir where it subsequently flows down these fingers, filling the mould and solidifies. If the test material is susceptible to hot tearing, the fingers will tear upon solidification. The idea is that the more susceptible to hot tearing the alloy is then the more fingers will show hot tears. Those with lower susceptibility will only show tearing in the longer fingers whereas highly susceptible alloys will show tearing even in the shortest finger.

The fingers and the reservoir have a draft angle on the depth for easy removal from the mould after solidification. The reservoir was originally triangular in shape but after testing and previous modeling at the University of Birmingham, it was found that a rectangular reservoir allowed the fingers to fill quickly and more evenly. The mould contains vents at the end of each finger, ensuring there is no backpressure build-up during filling. One of the most important aspects of this design are the cones located at the end of each finger. These downward pointing cones fill with the liquid material and solidify providing an anchor point allowing stress and strain to build in the fingers.

The mould produced by N-Tec does induce hot tears in the cast material but there is inconsistency with the location of the failure. Figures 5 a&b show castings produced from the mould. It is clear that despite using the same alloy and mould, the hot tears have occurred at different locations on each test.

Experimental Parameters

Table 2 gives the initial experimental parameters used in the initial simulations which were run using Magmasoft casting simulation software running on a Dell PC running an Intel Dual Xeon 3.06 GHz processor and 4 Gb RAM.

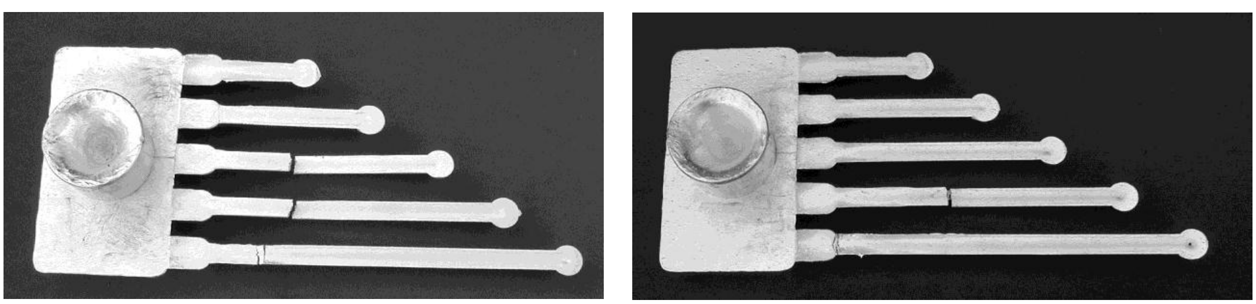


Figure 5 a&b: Test castings showing the random location of cracks in the hot tear test

Table 2: Experimental parameters for hot tearing

Variable Experimental Parameters	Value
Cast Alloy Type	AlSi7Mg [~LM25]
Pouring Temperature	715 °C
Permanent Die Material	Grey Cast Iron - Grade 250
Permanent Die Initial Temperature	300 °C
Pouring Sleeve	Foseco Kalpur insulating sleeve
Filter	10 ppi

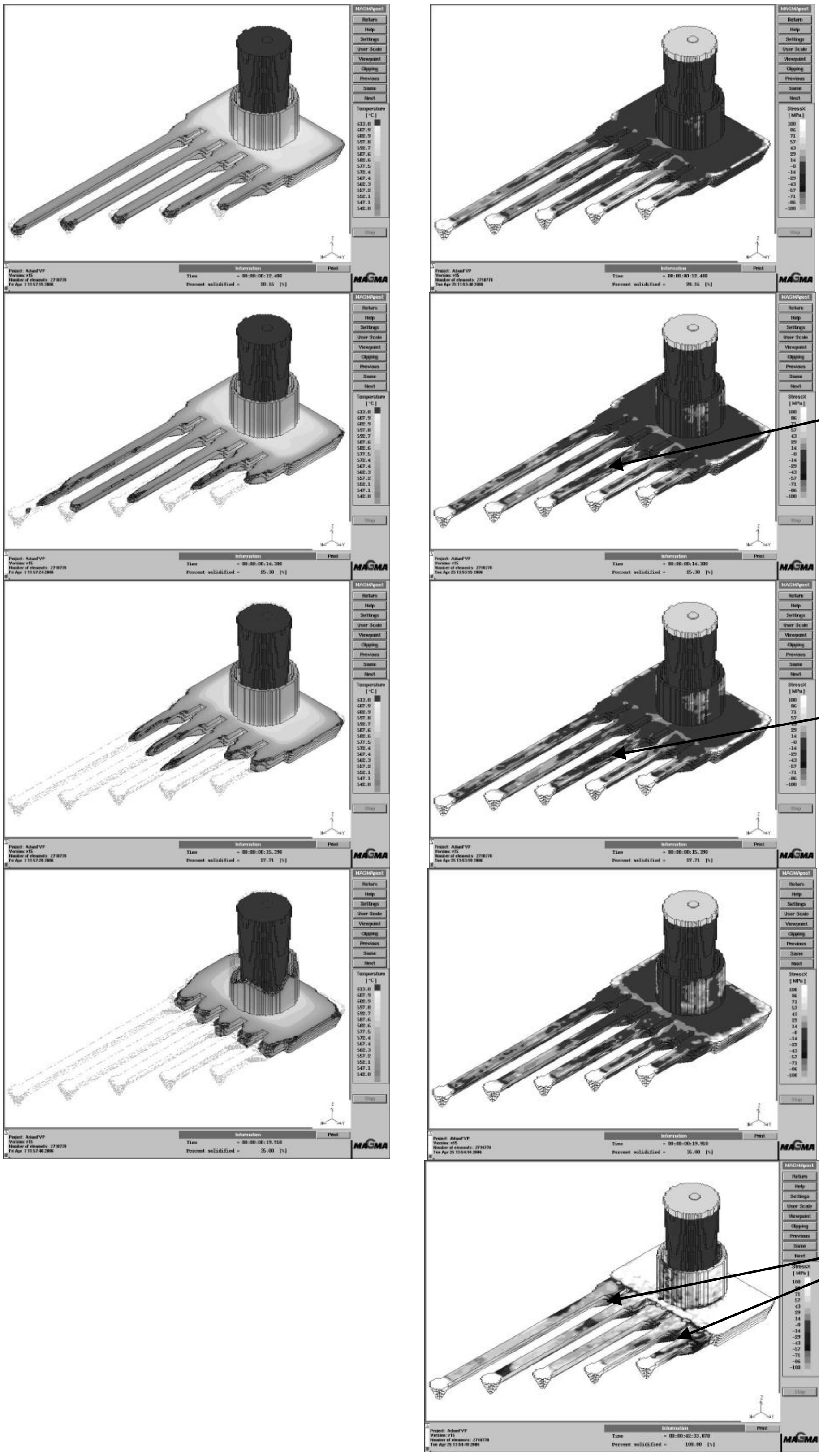
Simulation results

The simulation results for the unmodified die are shown in Figure 6. The figure shows the order of solidification on the left hand pictures and indicates there is a progressive solidification front which moves back towards the reservoir. This would be an ideal scenario if we wanted to avoid hot spots and the associated hot tearing. However the premise for this test is that materials that are susceptible to hot tears will tear within the test section. The right hand pictures show the development of stresses in the direction along the fingers. Hot tearing is indicated by a region where the maximum difference of stress occurs. During the solidification the only region where this appears to be of significance is in the centre of the middle finger. However the differences of stress levels are not high. It would appear that the location of any tears in the other fingers will be totally reliant on the existence of a defect to initiate the tear. Thus this backs up the results obtained from the experimental work where hot tears appeared in a random fashion. The highest level of stress predicted from the modeling was at the junction between the shoulder and the reservoir (Fig 6e).

Mould redesigns based on initial simulation results

One obvious conclusion from these results is that a focused hot spot would be a method of concentrating where the hot tears should occur. It was decided that providing a section of insulation on the mould which would retard the solidification in that area. Figures 7 a&b show two of the iterations. Figure 7a depicts a mould with a ceramic section replacing the top part of the mould. Another feature which was incorporated into all the moulds was a cooling fin which replaced the conical anchor of the original mould and an additional cooling fin just after the shoulder form the reservoir. The fins perform two functions; they promote a rapid solidification from each end of the gauge length by having lower thermal modulus than the conical sections they replaced trapping liquid metal in the centre of the gauge and they function as the anchor point to ensure stress build up within the gauge length of the test pieces. Fig 7b is a section through the cut-away mould. In this case the thinnest section was 10 mm. Figure 8 shows the location of the hot spots predicted from these design iterations. Although both of these designs worked reasonably effectively there some issues with each one. It was felt that the large ceramic insert would be difficult to use without damage and the large differences in thermal expansion coefficients might give problems during the use of the mould. Although not complex in shape it was also felt that this would be an expensive mould to manufacture. The cut-away mould didn’t give as precise a hot spot as the ceramic insulated mould. An extreme cut-away mould was modeled with thinnest section being only 1 mm and although this gave a more controlled result it was felt that the mould would be prone to distortion over time.

The final design was adapted from the large ceramic insert and consisted of 5 ceramic fiber inserts 15x 25x30 mm with the cutout of the finger cross section in them (Figure 9a), positioned close to the reservoir end fins (Figure 9b). The mould was developed to be practical, cheap and effective in producing localized hotspots in each test finger.



a) 20% solid
Stress pattern fairly even

b) 25% solid
Start of larger stress differences in middle finger (arrowed)

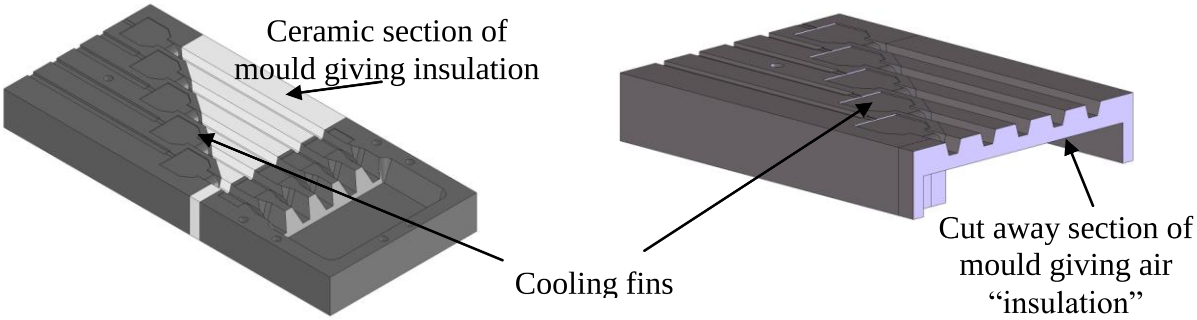
c) 28% solid
Well developed area dark grey showing large difference in stress (arrowed)

d) 35% solid
Similar to c)

e) 100% solid
Final stress distribution showing maximum differences in stress at join between fingers and reservoir.

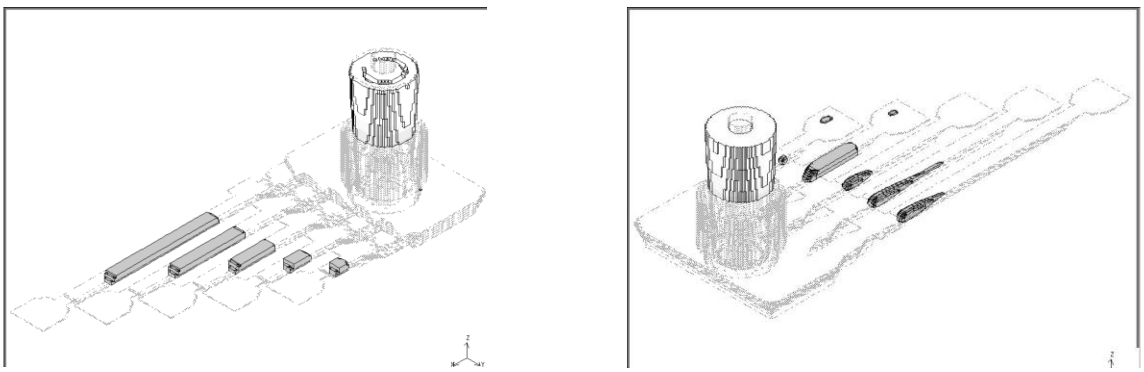
Solidification pattern Stress

Figure 6: Predicted solidification sequence for the original 5 fingered die and stresses developed within the fingers at different times during the solidification



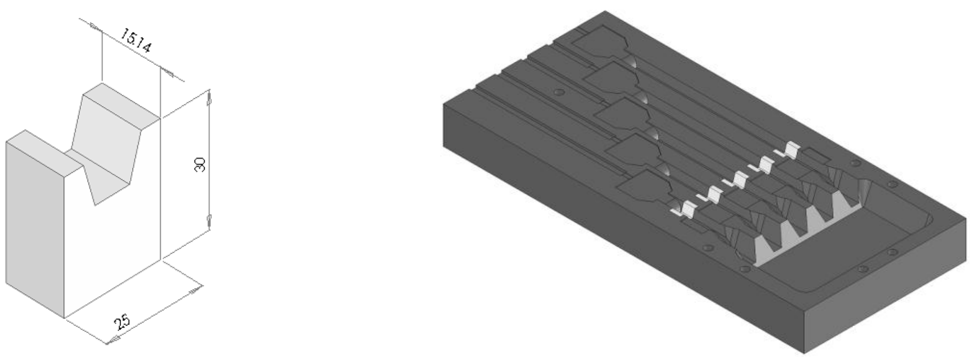
a) large ceramic section insulated mould b) cut-away section insulated mould

Figure 7: Two of the design iterations considered in the research work.



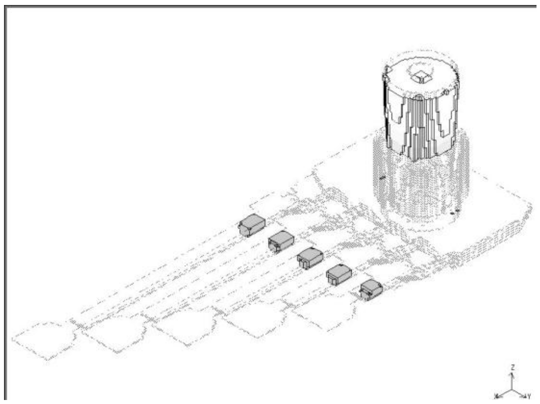
a) large ceramic section mould b) cut-away section mould

Figure 8:Hot spot prediction from two of the design iterations.

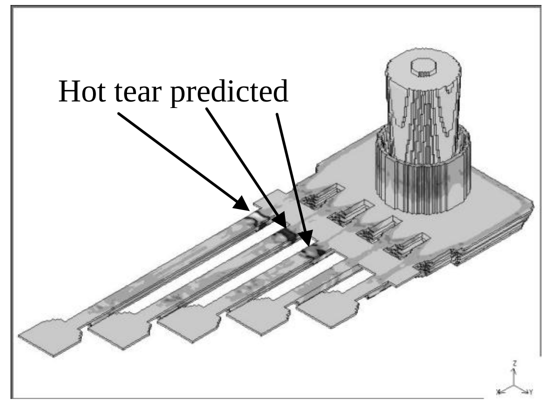


a) ceramic fiber insert design b) location of ceramic inserts

Figure 9: Final design of mould to promote highly localized hot spots



a) Hot spot prediction showing the extremely localized hot spot produced.



b) MAGMA prediction using a bespoke hot tear criterion indicating hot tearing in the middle and two longest fingers.

Figure 10: Simulation results for the final design using small ceramic fiber inserts near the chills at the reservoir end of the mould.

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Redesign of an industry test for hot tearing of high performance aluminium casting alloys using casting simulation software

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