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The modelling of oxide film entrainment in casting systems using computational modelling

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ABSTRACT

As Campbell stated in 2006, "*the use of entrainment models to optimise filling systems designs for castings has huge commercial potential that has so far being neglected by modellers*". In this paper a methodology using computational modelling to define entraining events and track the entrained oxide films is presented. Research has shown that these oxide films present within the casting volume are highly detrimental to casting integrity, thus their entrainment during mould filling is especially undesirable.

The method developed for the modelling of oxide entrainment has been validated against previously published data by Green and Campbell (1994) [31]. The validation shows good quantitative correlation with experimental data. However there is scope for further development which has the potential to both improve the accuracy and further validate the technique.

1. Introduction

Minimising development costs and time is now essential to stay competitive in the foundry industry [1]. Therefore computational modelling is now seen as a necessity to give rapid and cost effective product development. This has been further aided by the development of commercially available optimisation software to replace the current qualitative techniques used by the foundry engineer to design casting running systems.

A single quantitative value is required by optimisation software to use as a goal. Kokot and Burnbeck [2] have given an overview of the current state of the optimisation software. The use of optimisation tools has lead to the topic of quantification of oxide entrainment to be of upmost importance for both industry and software companies. Indeed Kokot et al. [3] stated that optimisation can only be "*obtained if the right quantitative criteria to formulate the objective functions are available*". These quantitative criteria for casting integrity still require development. Campbell stated that "*the use of entrainment models to optimise filling systems designs for castings has huge commercial potential that has so far being neglected by modellers*" [4].

Due to the importance of entrainment in the casting process and other applications there have been a number of attempts at developing models to predict and often quantify this entrainment. Historically a variety of different solutions with differing methods, abilities and benefits have been developed to quantify oxide entrainment, as largely summarised by Campbell [4] and critically reviewed by Reilly et al. [5]. The modelling of entrainment can largely be broken into two categories, the modelling of indiscrete and discrete defects. Indiscrete defect modelling is defined as models where the magnitude of the total amount entrained defects may be either quantitatively or qualitatively assesses but the location of each individual

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defect is unknown. This type of model is often computationally more efficient than the modelling of discrete defects. Below, a summary of the significant defect modelling techniques is given.

One of the simplest methods for indiscreetly modelling defects is the assessment of the free surface area as undertaken by Lai et al. [6,7] and Sun et al. [8]. The work by Lai et al. compares the modelled instantaneous free surface area against the minimum free surface area expected if the mould had filled in a perfectly tranquil manner. The greater the difference between these two values, the larger the excess of free surface area, the greater the likely magnitude of free surface entrainment. The major limitation of this methodology is the calculation of the expected free surface area should the mould have filled in a perfectly tranquil manner. For all but the simplest geometry this is extremely challenging to calculate. However, the comparison of the excess free surface area for castings of identical geometry allows direct comparison and thus potential optimisation. Sun et al. report positive results using this technique in an industrial environment.

Methodologies based around dimensionless numbers have been published; these are commonly based around the Froude (ratio of inertial to gravitational pressures) or Weber (ratio of inertial to surface tension pressures) number [9–13]. These models commonly focus upon discrete locations within the model, for example the casting in-gate or runner bar, and thus can only partly describe the entrainment within the casting system.

Cumulative scalar techniques have been developed by multiple software developers [14–16]. These techniques place a scalar value upon the liquid free surface to describe the growth of oxide upon the melt surface. This scalar is allowed to diffuse and advect throughout the liquid. The rate of scalar accumulation is described as a constant growth rate. The scalar represents the likely hood of defects being present. This technique is probably the most widely use entrainment defect prediction tool in the casting industry.

As stated by the Barkhudarov and Hirt [15], the cumulative scalar technique does have some drawbacks in the casting scenario, namely:

- The adhesion of oxide film to mould walls is not accounted for.
- No oxide film strength is modelled.
- No buoyancy of oxide film is modelled.
- Without any experimental results the significance of the absolute values of the scalar are meaningless. However the defect location patterns are still valid.

Many of the other techniques described here also suffer from one or more of the above drawbacks, they are not limited to the cumulative scalar technique.

Blair et al. developed a discrete defect tracking method based upon the growth of discrete particles when they are upon the liquid free surface. The technique is aimed at modelling re-oxidization inclusions in steel. Particles of negligible size are placed in the liquid, when these particles are upon the free surface they grow at a defined rate, this represents their oxidisation. The particles size, mass and advection are modelled. The agglomeration of particles is allowed. The final location of the particles after solidification has shown good agreement with experimental data obtained in industrial settings [17–18].

Work by Ohnaka et al. used a methodology similar to that presented in this manuscript. This manuscript further develops and also experimentally validates this technique. Ohnaka et al. used Boolean logic criteria to predict entrainment, representing the defect by a particle who's advection is modelled [19]. This technique initially modelled bubble entrainment and porosity before being extended to oxide film entrainment [20–21].

This manuscript presents a methodology for modelling free surface entrainment using computational fluid dynamics. The methodology uses Boolean logic criteria to assess if free surface entrainment has occurred, if entrainment is found particles are used to mark the entrained surface film. The motion of the particles is simulated in order to obtain the final defect location. The work has been validated against experimental data obtained from the casting of aluminium A356 samples. The integrity of these samples has been characterised by the Weibull modulus [22], obtained from tensile test data. This study has been focused on aluminium casting and the modelling of the oxide film present upon the melt surface. However, the same methodology could easily be applied to other casting material with surface films, such as iron or steel, and other fluid flow scenarios where entrainment of the free surface within the bulk liquid is of interest.

2. Methodology

A user customisation to the commercial CFD (computational fluid dynamics) software Flow-3D, Oxide Film Entrainment Model (OFEM), has been developed to allow the assessment of entraining events and the marking and tracking of entrained oxide films. This allows the final defect location(s) to be identified. The OFEM has been developed such that it is capable of interrogating the full 3D free surface.

Flow-3D version 9.3.2 was the CFD (Computational Fluid Dynamics) used in this work. A brief description of this software follows, further information on the techniques described here can be found on the Flow-3D website [23] via the Technical Notes and CFD-101 web pages or in the Flow-3D user manual [24].

The software uses a structured Cartesian mesh, either a single or multiple mesh blocks can be utilised in a model. Any mesh block can be manipulated to allow cells of different aspect ratios to be present within a single mesh block. This allows the user the opportunity to improve the definition of geometry within a specific region of the model without generating and

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