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The determination of inclusion movement in steel castings by positron emission particle tracking (PEPT)

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Abstract The movement of inclusions in casting has been studied using radioactive labelling of ceramic particles, a process known as positron emission particle tracking (PEPT). Alumina and silica particles of size about 355–710 μm were made radioactive in a cyclotron, by the partial conversion of oxygen to ^{18}F. This isotope has a half-life of 110 min, giving a window of time of around 3 h in which the particles could be detected by this technique. Individual radioactive particles were placed in ceramic moulds at known initial positions, which were then filled with low carbon steel, causing the particle to be entrained into the metal stream during the casting process. After the casting had solidified, the final position of the radioactive particle was determined using a γ-ray positron camera. The initial and final co-ordinates of the deliberately entrained inclusions within the casting could then be obtained, with an accuracy of around 5 mm.

Introduction

Inclusions in castings are detrimental to mechanical properties as they act as sites for fatigue crack initiation leading to failure in service. Inclusions may be either exogenous or indigenous. In steel castings exogenous inclusions are typically ≥80 μm [1] and result from the incorporation of slag and refractories into the liquid metal. Indigenous inclusions are smaller and tend to result from chemical reactions taking place in the melt, such as deoxidation of the steel with Al. Both inclusion types adversely affect fatigue, creep and corrosion properties [1]. In shape castings there are several ways of trying to prevent inclusions from being present in a casting, such as the use of dross traps and ceramic foam filters in the running system, but these methods are applied empirically, and with varying degrees of success. Although computer models aimed at improving the casting production process can often include models of inclusion movement, these have not been experimentally validated in liquid metals, because there is not yet an experimental technique to determine how inclusions move in the liquid metal as a casting is being filled.

This paper introduces an experimental technique that was used to determine the final positions of radioactively labelled inclusions deliberately introduced into steel castings. This involved the use of positron emission particle tracking (PEPT) [2] in which a fluid or particle is radioactively labelled by changing oxygen into the radioactive isotope ^{18}F [3]; the movement of the particles can then be tracked by the detection of the decay products of the radioactive isotope. This procedure has been used extensively to obtain dynamic information about granular flow in the chemical, food and pharmaceutical industries [4–6], but has been applied here for the first time to the problem of tracking inclusions in castings.

Experimental procedure

Alumina and silica particles within the size ranges of 355–710 μm were radioactively labelled by direct irradiation

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with a ^{3}He beam in a 36 MeV cyclotron. This caused the conversion of some of the oxygen atoms of the ceramics into radioactive ^{18}F, which has a half-life of 110 min, via the reactions [3];

^{16}O,(^{3}He, p) → ^{18}F or

^{16}O,(^{3}He, n) → ^{18}Ne → ^{18}F

The initial radioactivity of the particles used was measured to be from 10 to 135 μCi, with the lower figure being about the limit of detection. This meant that, in practice, an irradiated particle could be found by the detector used in the technique typically up to 3 h after the particle was irradiated with, of course, a variation in the detectable time period with the amount of radioactivity possessed by the particle.

To test the applicability of this technique to the casting process, several simple plate castings were made with low carbon steel, with dimensions of 100 × 200 × 15 mm. The first attempt used resin-bonded sand moulds but these were not sufficiently robust, so subsequently ceramic shell moulds were employed, as used in the investment casting process. The design of both these castings is shown in Fig. 1. A stainless steel mesh was fixed at the top of the downsprue opening (shown in Fig. 1), and a single radioactive alumina or silica particle was then glued to the head of a pin and inserted through the mesh, to fix the particle at a known initial position at the centre of the downsprue opening. A charge of 10 kg of a low carbon steel (En3B) was melted in a 45 kW induction furnace, then tapped first into a pre-heated graphite crucible at approximately 1,700 °C, and then poured into the mould. As the steel entered the mould, it vaporised the glue and melted the steel mesh and pin, releasing the radioactive particle into the metal stream. Steel was selected for the casting experiments because it was felt that this would provide the most demanding test of the use of the technique.

After the castings had solidified they were placed in the detector, as shown in Fig. 2, which shows the setup of a casting between the two faces of a γ-ray camera. The ^{18}F atoms created by irradiation of the oxide particles undergo radioactive decay by positron emission. These positrons travelled in the metal until collision with an electron caused their mutual annihilation, causing two "back-to-back" γ-rays to be produced travelling at 180° to each other, which were detected by the camera. The detector used was an ADAC Forte γ-ray positron camera [7]. The position of the entrained radioactive particle with respect to the camera datum was obtained by determining the intersection of many pairs of these "back-to-back" γ-rays. The algorithm used by the detection technique identified and discarded those pairs in which one or both of the γ-rays appeared to have been scattered prior to detection [2].

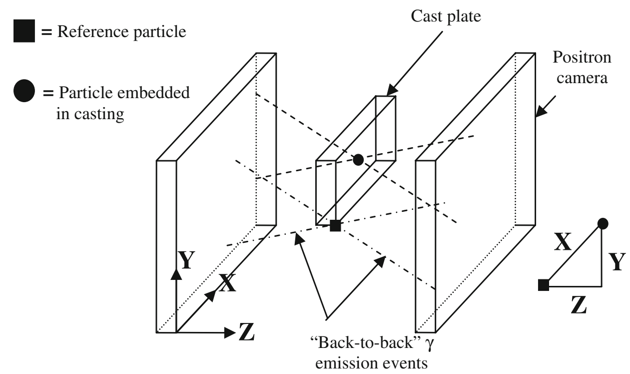

Fig. 2 The arrangement of the cast steel plate between the camera faces. The γ-rays from the positron annihilation events from both the reference and embedded particles form straight lines and the camera located the particles at their intersection

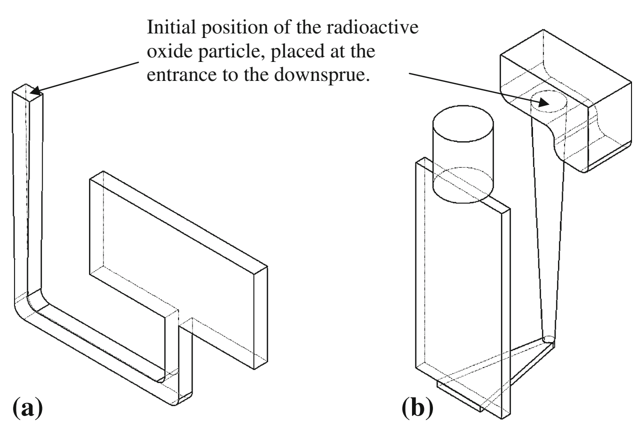

Fig. 1 The design of the steel plate castings **a** made in a resin-bonded sand and **b** made in ceramic shell moulds

To determine the position of the entrained particle, another (reference) particle was placed at known locations around the casting, such as its corners (as shown in Fig. 2), and the positions of both particles determined simultaneously with respect to the camera datum. The position of the particle within the casting was then determined by comparison of the positions of the entrained and reference particles. This allowed the co-ordinates of the entrained particle to be determined with an accuracy of approximately ±2–3 mm.

This technique was used to study the effect of various parameters on the final location of an entrained radioactive ceramic particle, such as the effect of changing initial particle position, changing particle size and density, and the entrainment of multiple particles. However, only selected results have been shown here.

Results

Each point in the results shown in Figs. 3–6 shows an estimated position of the entrained particle in the castings.

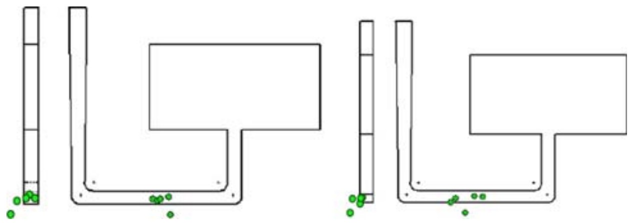

Fig. 3 Two examples of the position of the entrained radioactive alumina particles in the case of steel plates cast in resin-bonded sand moulds

As the reference particle was moved to a new position on the casting, a new estimated location for the radioactive particle inside the casting was obtained, with each location having an associated error. For example, Fig. 3 shows five possible positions for the particle in each of the steel plates cast in the resin-bonded sand moulds (Fig. 1a), with the results from two castings being shown. In each case, the particle was found to be approximately halfway along the lower runner bar, rather than in the cast plate, with the results from the two castings showing good reproducibility. These positions were also verified using a Geiger counter. Some possible particle locations were determined to be slightly outside the casting, partly due to errors in the particle position determined by the PEPT technique, but also due to errors associated with learning how best to apply the technique.

Figure 4 shows the particle positions obtained in two experiments using radioactive silica particles entrained in the ceramic shell moulds (Fig. 1b), with the particles initially placed at the centre of the downsprue opening in both cases. In one case the particle location was found to be in the running system, but in the second experiment it was found in the upper centre of the plate. These results showed that the final location of the particle was not always reproducible.

Figure 5 shows an example of the results obtained when an alumina particle was entrained with a ceramic foam filter placed in the running system (10 ppi, 20 mm thickness). In all the three experiments where a filter was used, the particles were found in the pouring basin above the downsprue, and it seems that the filter, although it did not trap the entrained radioactive ceramic particle, at least prevented it from reaching the casting, perhaps by allowing time for the particle to float back up the downsprue as the liquid steel was slowed in its passage of the filter. The larger scatter of possible positions obtained when the particle was in the pouring basin was a consequence of the larger thicknesses of steel that the γ-rays had to pass through to reach the positron camera.

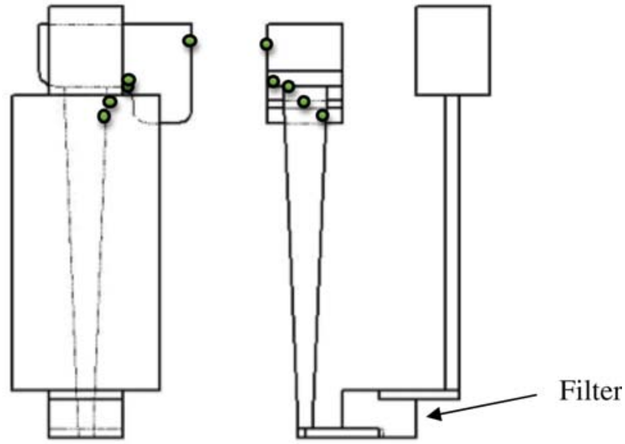

Fig. 5 The particle location (in the pouring basin) after casting in a ceramic shell mould containing a 10 ppi filter

Figure 6 shows the results obtained from an experiment where five radioactive alumina particles were entrained in the same mould. These were also initially placed at the top of the downsprue, on a horizontal plane, in a circular arrangement with a radius of 5 mm. In this case, some of the particles may have agglomerated and come to rest in the lower part of the downsprue, where they were therefore detected by the positron camera as if they were one particle. This was confirmed with a Geiger counter. No source of radiation was detected from elsewhere in the casting,

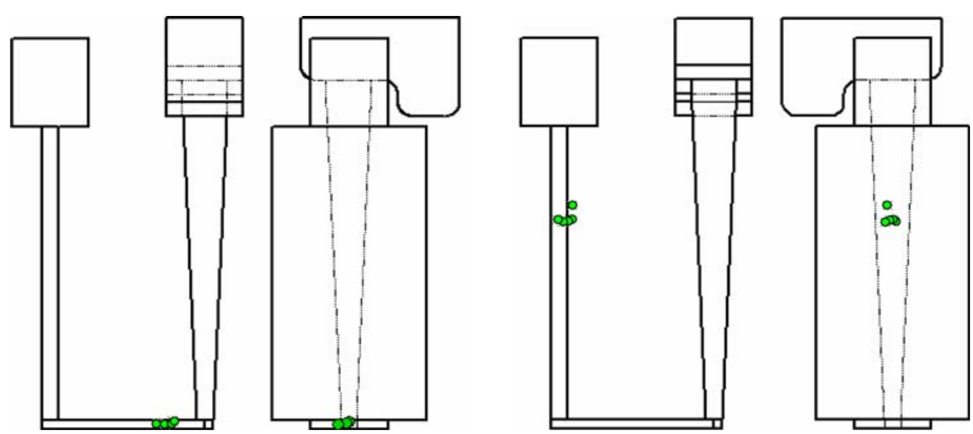

Fig. 4 Two examples of the final positions determined for entrained particles of silica, initially placed at the centre of the sprue opening (Cast in a ceramic shell mould)

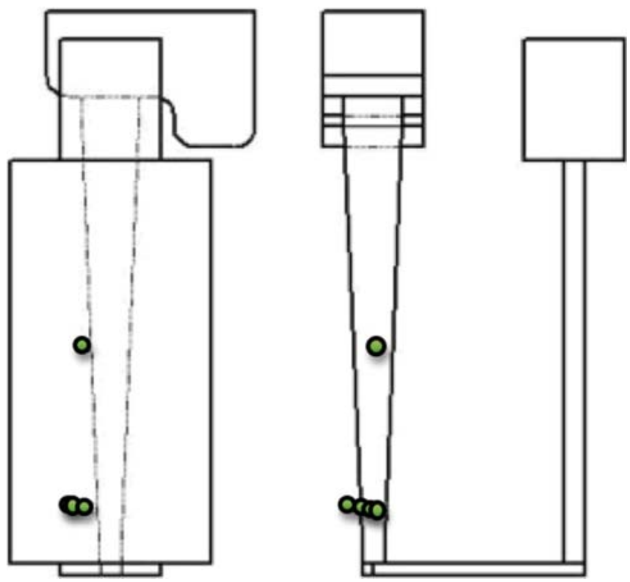

Fig. 6 Particle locations detected when five alumina particles were entrained

which suggested that the point recorded from higher up in the downsprue was a rogue result.

In one experiment, it was not possible to detect the inclusions in the castings at all. The particles employed in this experiment were alumina (of size 355–425 μm), and had a greater radioactivity (up to 400 μCi) than was normally obtained. SEM examination of unirradiated and irradiated particles suggested that the more intense radioactivity obtained had been accompanied by some damage to the alumina particles and this may have caused the particles to shatter due to thermal shock during casting, creating a dispersed cloud of fragments from the original particle, which individually possessed too little radioactivity to be detected.

Discussion

These experiments have therefore demonstrated the feasibility of entraining a radioactive particle in a mould as it is cast, and determining its final location in the casting after solidification, using the PEPT technique. The technique can be developed further so that the actual particle movement can be followed, which could be accomplished by carrying out the casting process between the faces of the camera.

A reproducible location of the entrained radioactive inclusion was occasionally observed, for example as shown in Fig. 3, but did not always occur (as was shown by Fig. 4). This was attributed to the variability inherent in the actual process of casting, where changes in the nature of the flow of the liquid steel, although being poured into the same mould, could result in the inclusion being displaced to different positions in the casting and its running system. Nonetheless, this technique offers a way of investigating the effect of various parameters on inclusion movement in castings, such as running system design, the use of filters of different type and the effect of their placement, and the effect of inclusion size and density.

The technique also offers a method of validation of mathematical models of inclusion movement in castings. However, to use PEPT in this way, the casting process itself must be strictly controlled so that it is reproducible. It should also be borne in mind that most current casting simulations do not include models that incorporate post-filling fluid flow, although in a real casting this would affect the final inclusion location to some extent.

Conclusion

The PEPT technique has been shown to be capable of determining particle positions in steel castings that were reproducible, provided the casting procedure was carried out well. The technique could be used to test the value of inclusion removal strategies to improve the quality of castings, and to validate casting modelling software and its ability to predict the movement of inclusions in castings.

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