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The improvement of aluminium casting process control by application of the new CRIMSON process

X Dai[1*], M Jolly[1], B Zeng[1]

[1]School of Mechanical Engineering, University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK

[*]Corresponding author: xiaojundai@yahoo.com

Abstract. All The traditional foundry usually not only uses batch melting where the aluminium alloys are melted and held in a furnace for long time, but also uses the gravity filling method in both Sand Casting Process (SCP) and Investment Casting Process (ICP). In the gravity filling operation, the turbulent behaviour of the liquid metal causes substantial entrainment of the surface oxide films which are subsequently trapped into the liquid and generate micro cracks and casting defects. In this paper a new CRIMSON process is introduced which features instead of gravity filling method, using the single shot up-casting method to realize the rapid melting and rapid filling mould operations which reduce the contact time between the melt and environment thus reducing the possibility of defect generation. Another advantage of the new process is the drastic reduction of energy consumption due to shortened melting and filling time. Two types of casting samples from SCP and ICP were compared with the new process. The commercial software was used to simulate the filling and solidification processes of the casting samples. The results show that the new process has a more improved behaviour during filling a mould and solidification than the two conventional casting processes.

1. Introduction

Foundry practice has been driven by the requirement of improving product quality and minimisation of the production costs. Both casting production process and energy efficiency play critical roles in the foundry to gratify these requirements. Besides the pressure of rising energy cost and the restriction of stern environment protection legislation it is certified that under the right socioeconomic conditions efficiency optimisation of an industrial process can be an important step toward increased industrial sustainability [1]. Selection of the appropriate casting process, facility and minimisation of the energy consumption will be the vital factors for the foundry to become competitive against rivals in a tough market.

In traditional foundries using SCP and ICP, the capacity of melt furnace for aluminium alloy usually ranges from dozens of kilograms to several tonnes. The liquid metal is held at about 700 °C in a holding furnace before it is transferred to a ladle and poured into a casting (shell)mould at a pouring station. It can take long time, or even dozens of hours, for the liquid metal in a batch to be finished and any residual metal is poured off to be re-used or scrapped for re-melting or refining in a secondary processing plant [2].

When the liquid metal reacts with hydrogen, oxygen and water in the surrounding atmosphere quality problems can happen. Once the melted aluminium alloy is exposed to the air an oxide surface layer is created. For the period of filling a sand or shell mould the turbulent filling behaviour of the liquid metal due to gravity is easy to make the oxide films on the surface of the liquid cracked and trapped into the liquid. Also the long exposing time of the liquid surface with the surrounding air during melting, transferring and filling will augment the thickness of the oxide film on the liquid surface and the level of hydrogen absorption. All of these will bring about layers of cracked oxide films, porosity and shrinkage which damage the integration of the micro-structure of the alloy, leading to degraded mechanical properties of the final product [3, 4].

A new CRIMSON (Constrained Rapid Induction Melting Single Shot Up-Casting) process has been co-invented by the researchers and engineers form both University of Birmingham and a local company, N-Tec LTD. The aims in this new process are to improve the casting quality and reduce the energy consumption within light-metal casting industry. The tactic of the new process is to melt just enough amount of alloy in a closed crucible of an induction furnace and to use the counter-gravity filling method to fill a single (shell) mould, thus assure smooth liquid alloy flow behaviour and in the same time avoid unnecessary energy consumption. The new process features rapid melting, quick bottom filling and minimising holding time hence reduces the opportunity of hydrogen absorption and generation of surface oxide film [5].

In this paper, two cases have been investigated: one is the “Tensile bar” where the SCP was applied; another one is the “Filter housing” where the ICP was applied. Using the commercial CFD software to simulate the processes of filling and solidification in sand mould or shell mould, both cases have been compared with the new process. The simulation results for filling the sand (shell) moulds of three different casting processes were compared to see how the new process could avoid the turbulent behaviour of liquid metal flow during filling sand (shell) moulds. The calculation and analysis of energy consumption were completed to see what the difference is between the current melting processes and the new facility. As a result, the quality issue and the potential energy saving for the new process can be found. This comparison is only one of a number being carried out under the support of an EPRSC project where four conventional casting processes will be benchmarked for their scrap rates and energy usage.

2. Runner system design and simulation tools

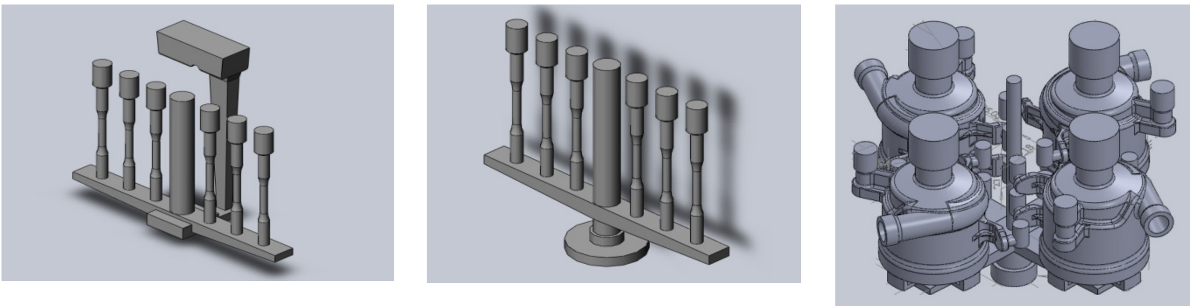
2.1. Comparison of gravity SCP, ICP and CRIMSON process

A runner system using gravity SCP for tensile bar is shown in Figure 1(a) where the system consists of basin, down sprue, runner, ingate, riser, feeder and six tensile bars. A runner system of sand mould for tensile bar using CRIMSON process is presented in Figure 1(b) where the system consists of runner, ingate, riser, feeder and six tensile bars. A runner system of shell mould for filter housing using CRIMSON process is shown in Figure 1(c) where the system consists of runner, ingate, feeder and four filter housing parts. (For the commercial reason, the runner system of current gravity ICP from a local company could not be presented here, However, its filling process, yield and energy consumption can be demonstrated in the “Results and discussion” section of this paper)

2.2. Simulation software and simulation conditions

In order to simulate the liquid metal flow in these three runner systems, the commercial CFD simulation software were used. A ‘velocity magnitude’ method was used to predict the flow behaviour of liquid metal during filling a mould. The simulation was implemented using a Workstation with 16.00GB RAM and eight 2.66GHz CPUs.

For the simulation of the three runner systems, Finite Difference Method (FDM) was used to generate the mesh which includes about 170,000 control volumes (cells) for Figure 1(b) and 17,667,900 control volumes (cells) for Figure 1(c). The filling flow rate of 0.25 $L.s^{-1}$ [6] and a pressure of 9 kPa were used for these two runner systems. For the runner system of gravity sand casting Figure 1(a), the mesh has about 240,000 control volumes (cells). Same main conditions for the simulation of these three runner systems are: pouring temperature is 700 °C and the around atmosphere pressure is 1 atm (1.013×10^5 kPa). Pouring height for the gravity filling method is 50 cm.



(a) Gravity sand casting (b) CRIMSON process for tensile bar (c) CRIMSON process for filter housing

Figure 1. Different runner systems.

3. Test equipment for measuring the energy consumption

In this paper, the experiment and analysis of energy consumption are based on the following assumptions:

- The system assessed is at continuous steady state which includes fuel flow, air flow rate, melting rate, flue gas parameters and thermal conduction through furnace wall;
- The fuel and combustion products behave as ideal gas mixtures;
- The environment temperature and pressure are taken as standard 25°C and 1 atm respectively;
- The electric energy consumption is only applied to the part of electricity resistance heating or induction heating in furnaces, not applied to the motors and control devices which are neglected for the convenient calculation and simplicity;
- The natural gas composition is considered as pure propane due to the small amount of N_2, CO_2, H_2S and H_2O included;
- The lost metal during drossing is neglected for the calculation simplicity.

3.1. CRIMSON facility

The layout and main components of the new facility are described in Figure 2 where its main functions and features are:

- High power Induction furnace (275 KW): it is used to quickly heat and melt the metal to the required pouring temperature. Usually each time, a billet of the required size and calculated amount of metal is put in, also the composition of the billet should be consistent with the casting component that will be poured and produced;
- Up-caster: when the crucible with the melted metal inside is ready, it is moved and clamped in the right position in Up-caster and a mould is located on the top of pouring position, a piston in the Up-caster will raise and push the melted metal in the crucible into the mould;
- Computer-controlled operation table of the Up-caster: the movement of the piston in Up-caster is automatically controlled by the pre-programmed computer program;
- Mould transfer stop: after pouring, cooling down and solidification, the mould can be moved to the transfer stop, waiting for lifting and cleaning;

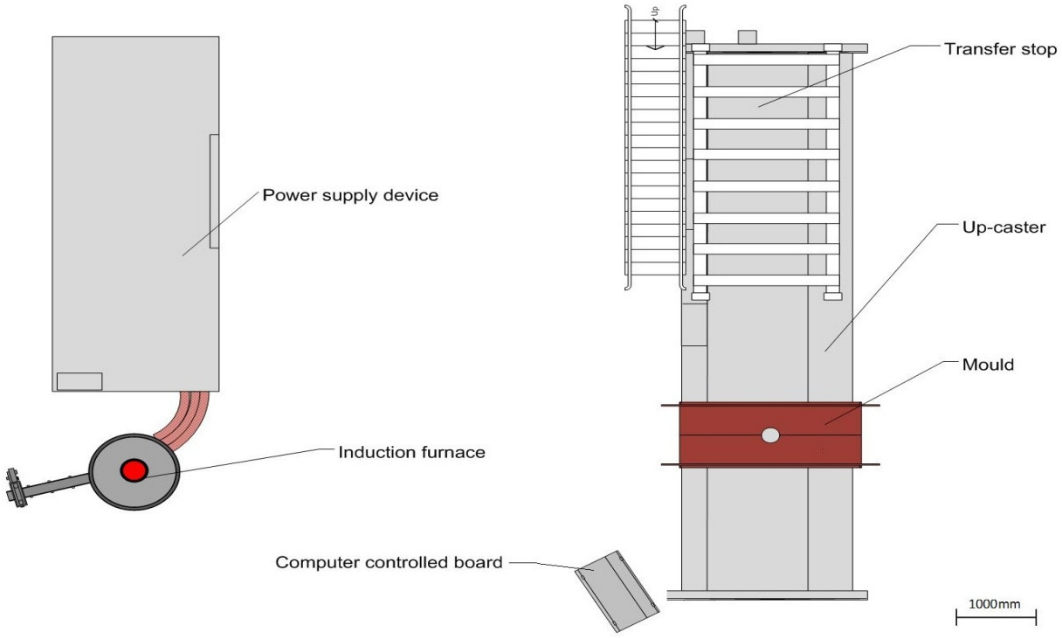


Figure 2. Schematic plan of the CRIMSON facility

3.2. Cosworth facility

Grainger & Worrall (G&W) LTD is using a melting furnace with a capacity of 4 tonne (Figure 3) where the gas is used to preheat and melt aluminium ingot and the electricity is used to adjust the melted liquid alloy to a required overheating temperature. The holding time for the furnace is up to 4-5 days. For aluminium alloy the overheating temperature is 760 °C and the pouring temperature is 700 °C. This furnace is used for gravity SCP.

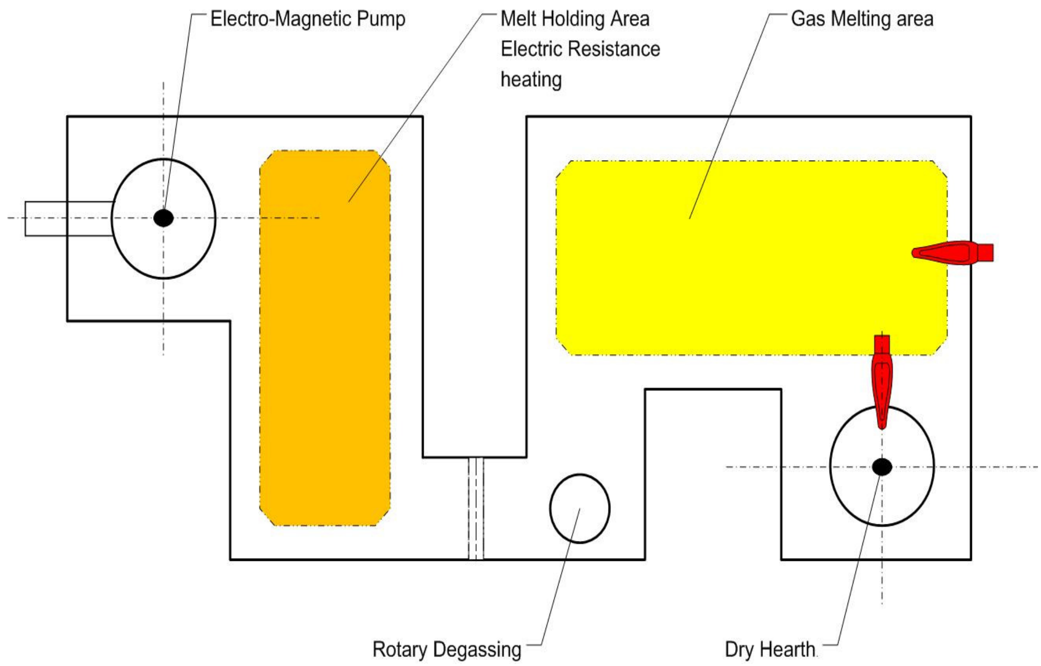


Figure 3. Schematic of the aluminium melting furnace in G&W LTD

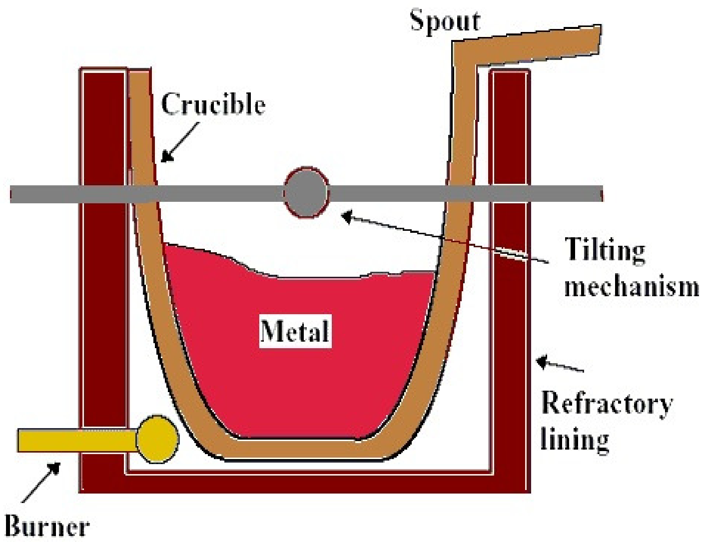


Figure 4. A typical crucible furnace

3.3. Crucible furnace

Aeromet LTD. is currently using the conventional crucible furnaces, each with a capacity of 400 kg. The natural gas is used to heat and melt aluminium alloys. The furnace has an average 2.5 hours' melting period and 1.5 hours' holding period. The overheating temperature of aluminium alloy is 780 °C. The normal pouring temperature is 700 °C. The typical crucible furnace is shown in Figure 4. This furnace is used for gravity ICP.

4. Results and discussion

4.1. Simulation

For the simulation of runner system of tensile bar (sand mould) using CRIMSON process, the filling time is 6.08 seconds. The simulation took about 30 minutes. The velocity magnitude of the liquid metal during filling is depicted in Figure 5 where the filling velocity of liquid metal can be observed using the velocity scale.

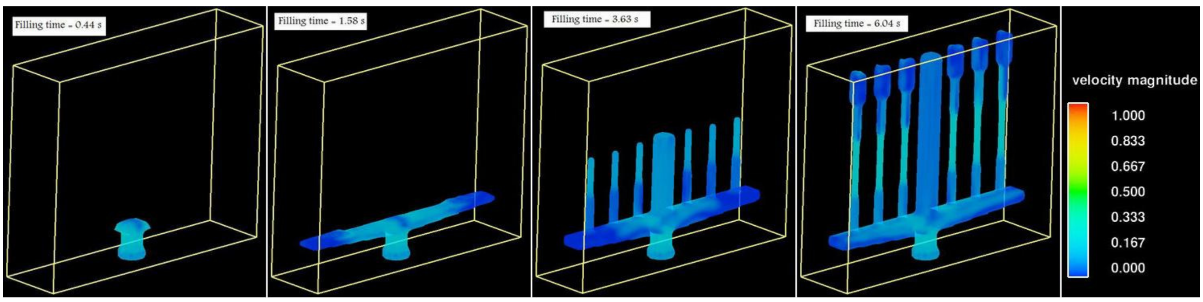


Figure 5. Numerical simulation of runner system of tensile bar using CRIMSON process.

For the simulation of runner system of tensile bar (sand mould) using gravity SCP, the filling time is 3.67 seconds. The simulation took about 20 minutes. The velocity magnitude of the liquid metal during filling a mould is described in Figure 6 where the velocity of liquid flow can be judged using the velocity scale.

For the simulation of runner system of filter housing (shell mould) using CRIMSON process, the filling time is 8.96 seconds. The simulation took about 6hours. The velocity magnitude of the liquid metal during filling a mould is described in Figure 7 where the velocity of liquid flow can be judged using the velocity scale.

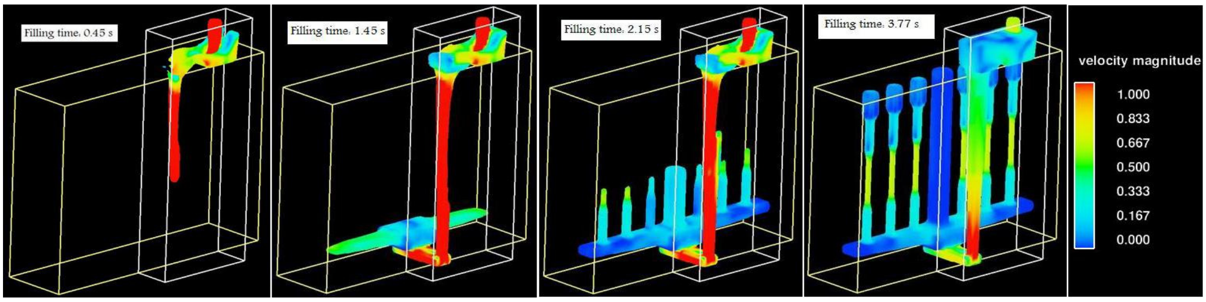


Figure 6. Numerical simulation of runner system of tensile bar using gravity SCP.

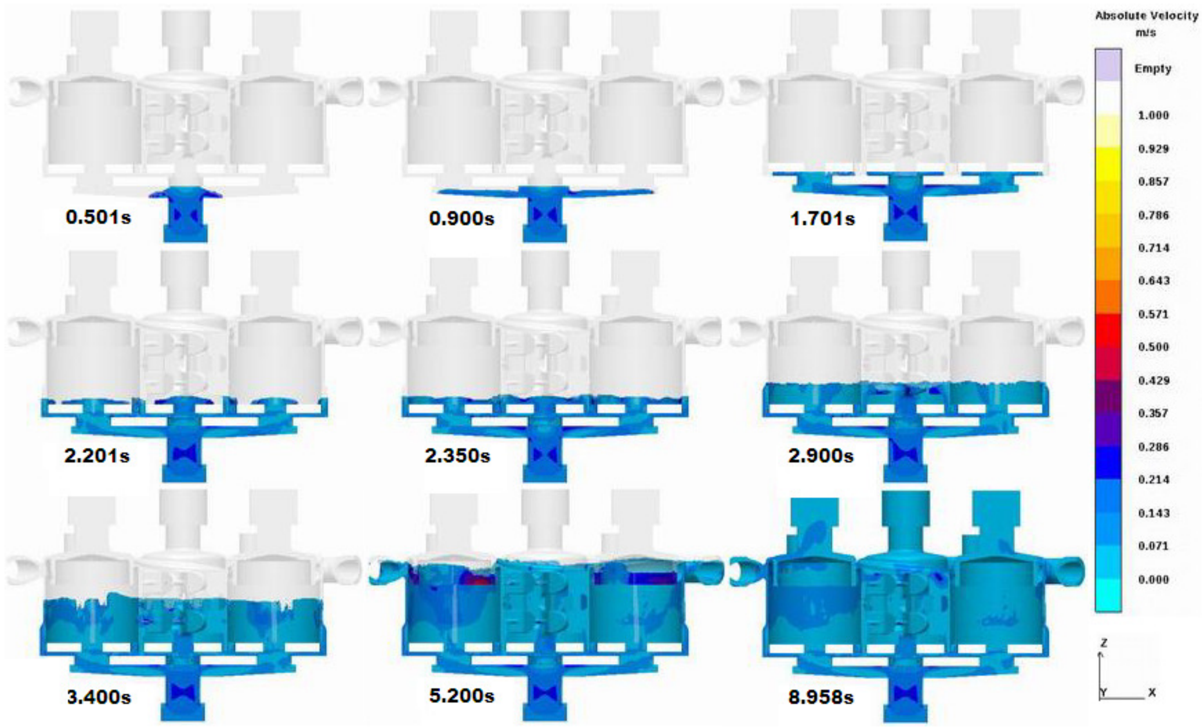


Figure 7. Numerical simulation of runner system of filter housing using CRIMSON process

From Figure 5 and Figure 7, it was found that the maximum velocities of liquid metal flow during filling are 0.4 $m.s^{-1}$ and 0.45 $m.s^{-1}$ respectively. Both the maximum velocities are less than 0.5 $m.s^{-1}$. The quiet flow behaviour of liquid metal in these two runner systems during filling the sand/shell moulds was considered appropriate for avoiding the generation of trapped oxide films, porosity and other casting defects [8]. In addition the counter-gravity filling method in CRIMSON process decreases the exposure time to the air which will reduce the opportunity of generating oxide films.

From Figure 6 and the filling process of the current gravity ICP from a local company, the maximum velocities of liquid metal flow in downsprue and in runner during filling are more than 1.0 $m.s^{-1}$, respectively. This means that the violent and turbulent follow flow behaviour will easily crack the oxide films on the liquid and make them trapped into the liquid. Although the filter existed in the runner system can leach the coarse trapped oxide films from the liquid which depends on the size of the holes and effectiveness of the filter, the fine oxide films will still pass through the filter and remain in the liquid. After solidification, these remaining fine oxide films will generate defects such as porosity, shrinkage etc [3, 4]. In the mean time, the turbulent flow behaviour of liquid metal in the downsprue and runner will readily make the air or hydrogen entrapped into the liquid where the porosity or bubble will be formed which will damage the mechanical properties of the casting [9]. In addition the long transferring time from furnace to ladle and the usage of the traditional gravity filling method make the melted liquid metal exposed to the air for long time, which increases the opportunity of generating oxide films on the surface of the liquid metal.

According to the abovementioned discussion, it is assumed that the counter-casting filling process that the new process used can considerably reduce the opportunity of oxide film generation on the surface of the liquid metal and the potential time for hydrogen absorption. As a result, the quality of the casting can be assured consequently. In comparison with the new process, the filling process of the conventional gravity SCP and ICP have the violent flow behaviour which will easily make the oxide films on the liquid metal and the air entrapped into the liquid which will generate different type of casting defects and damage the mechanical properties of casting. It should be pointed out here that all these results from the computer simulations will be validated by the actual experiments such as filling mould, strength test and SEM observation of next stage.

4.2. Energy efficiency

The energy consumption of the three types of melting processes was measured [7, 10]. The results and the calculated energy efficiency [7, 10] were demonstrated in Table 1.

Table 1. Energy consumption and energy efficiency of the three different melting facilities.

	Measured Energy consumption	Energy efficiency	Normal energy efficiency of furnace	Melting and holding time (hours)
Aeromet (Gas)	8.65 $MJ.kg^{-1}$ [10] (2401.88 $kWh.tonne^{-1}$)	13.86% [10]	Gas: 7~19%[10]	Melting 2.5 [10] Holding 1.5
G&W (Gas+Ele)	27.86 $MJ.kg^{-1}$ (Gas: 17.78 $MJ.kg^{-1}$ Ele: 10.08 $MJ.kg^{-1}$)[7]	Gas: 5.65% Ele: 1.70% (*0.85%)[7]	Gas: 7~19% Ele:59~76% (*29.5~38%)[10]	Melting + holding 96~124 [7]
CRIMSON Induction furnace	1.98 $MJ.kg^{-1}$[7,10]	57.82%[7,10] (*28.91%)[10]	Ele:59~76%[7,10] (*29.5~38%)[10]	2 minutes for melting 4kg A354 3 minutes for melting 6kg A356

(*the value is in consideration of conversion efficiency of 50% in a natural gas-fired power plant)

As shown in Table 1, in consideration of conversion efficiency of 50% in a natural gas-fired power plant, the thermal efficiency of the melt furnace at G&W for electricity is 0.85 % [7]which is far lower than the energy efficiency of the new process (28.91%[10]). It means that there is lot of energy loss for the current melting process at G&W due to the long holding time. Therefore, it is suggested that if the current long melting and holding process at G&W could be replaced by the new process (induction heating) the thermal efficiency in using electricity will be increased up to 28%. It is estimated that

34.00 GJ.tonne^{-1} (9.44 MWh.tonne^{-1}) [7] could be saved for producing every tonne of aluminium casting alloys when using the new process.

Similar to the Aeromet company, the thermal efficiency of the crucible furnace using natural gas is 13.86% [10] which is lower than the thermal efficiency of the new process (28.91%) [10]. If the current melting and holding process at Aeromet could be replaced by the new process, the thermal efficiency will increase up to 15.05 %. When melting the same amount of aluminium alloy, it is estimated that 4.69 GJ.tonne^{-1} (1.30 MWh.tonne^{-1}) [10] could be saved.

5. Conclusions and future works

From the computer simulation results, the maximum flow velocity of the new CRIMSON process during filling a mould is less than 0.5 m.s^{-1}. The total flow behaviour is quiet and stable which potentially reduce the opportunity of generation of oxide films and other casting defects. In comparison with the new process, the conventional gravity SCP and ICP have turbulent flow behaviour during filling a sand/shell mould where the maximum velocities of liquid flow in the downsprue and runner are more than 1.0 m.s^{-1}. The violent flow behaviour will not only easily make the oxide films on the liquid metal cracked and entrapped into the liquid but also make the air trapped into the liquid. These entrapped oxide films and air will probably generate different types of casting defects such as porosity, shrinkage and bubble etc which will damage the mechanical properties of the final casting. To validate the computer simulation results, the experiments on comparing the mechanical properties of the tensile bar using different filling processes and related SEM observation on micro structure will be implemented in next stage.

The investigation on energy consumption and energy efficiency of three processes has showed that the new process is a novel method for reducing energy consumption. If the traditional melting process at G&W and Aeromet could be replaced by the new process, the estimated energy savings for the former could be of the order of 34 GJ.tonne^{-1} (9.44 MWh.tonne^{-1}) and for the later could be the order of 4.7 GJ.tonne^{-1} (1.30 MWh.tonne^{-1}).

The other issues of the energy efficiency for the foundry will be considered too where not only the melting process is included, other relevant processes should be considered.

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