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Reduction of Energy Consumption and GHGs Emission in Conventional Sand Casting Process by Application of a New CRIMSON Process

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Abstracts

In conventional foundry, engineers generally consider the quality of casting part as the most essential issue and regard the energy consumption and Green House Gas (GHGs) emission as the auxiliary ones. This usually causes large amount of energy consumption as a result of the inefficient casting processes used and increases the production costs and environmental pollution. This paper presents the new CRIMSON process where its facility and melting process were compared with conventional melt furnaces and aluminium alloy melting process. An actual case was investigated to reveal quantitatively how the conventional foundry wastes energy and increases GHGs emission, and what the improvement of energy efficiency and the GHGs emission reduction can be achieved using the new CRIMSON process. The results of this investigation will help the foundry engineer recognize the importance of energy saving and environmental protection and show how to utilise this new process to reduce production costs and carbon footprint without decreasing the quality of the cast part.

Key words: Energy consumption; GHGs emission; Furnace; Aluminium; Sanding casting; Melting; CRIMSON

INTRODUCTION

In metal casting industry, aluminium melting is an energy intensive process where it is estimated that the energy consumption is in the order of 1,700-4,700 kWh per tonne in using crucible and natural gas[1]. In UK, most of the foundry use electricity, gas and oil as energy resource in the aluminium melting processes[2]. Because of the pressure of rising energy cost and the restriction of stern environment protection legislation it is substantiated that under the right socioeconomic conditions efficiency optimisation of industrial process can be an important step toward increased industrial sustainability[3]. In metal casting industry the energy consumption of a casting facility depends mainly on the efficiency of its melting and heat treating performance. In connection with the two performances, over 60 % of the total process energy consumptions are represented in a typical casting facility[4] where there are massive chances for metal casting industry to choose the best energy practices which will make the huge energy saving and GHGs emission reduction available.

To reduce GHGs emission and to protect the environment are further vital issues that the casting industry is facing. It was described that when consuming each MWh of natural gas in producing aluminium castings the GHGs emission produce 182.80 kg of CO_2, 0.22 kg NO_x, 0.0047 kg of particulate (when producing one tonne of aluminium castings, combustion-related air GHGs emission are 304.51 kg of CO_2, 0.21 kg of CO, 0.96 kg of SO_x, 0.63 kg of NO_x, 0.85 kg of organics and 0.27 kg of particulate)[5]. For that reason, implementation of new process to reduce the energy consumption and

GHGs emission, increase energy efficiency and improve the quality of castings can drastically help the casting industry to promote the competitiveness and reduce the environment pollution. For example, by implementing some novel technologies such as the CRIMSON process in sand casting process will provide such an opportunity.

A patent CRIMSON (Constrained Rapid Induction Melting Single Shot Up-Casting) process was co-invented by the researchers and engineers of the University of Birmingham and the N-Tec company. The aims to develop this process are to reduce the energy consumption and to improve the casting quality within light-metal casting industry. After being successfully implemented in the light-metal casting area, this process will be further applied in the other type of alloys. The methodology of the new process is that foundries, using an induction furnace, need only to melt the quantity of metal required to fill a single mould in a closed crucible instead of large batches that use unnecessary energy and create more rejects. As shown in Fig. 1, the closed crucible, then, is transferred to a station and the melted metal is pushed up using a computer controlled counter-gravity filling method to fill the mould. Because of the features of quick melting, rapid shift and filling in the new process, the holding time of liquid metal is minimised, a huge amount of energy saving is achieved and in the mean time the opportunity of hydrogen absorption and formation of surface oxide film are reduced greatly[6].

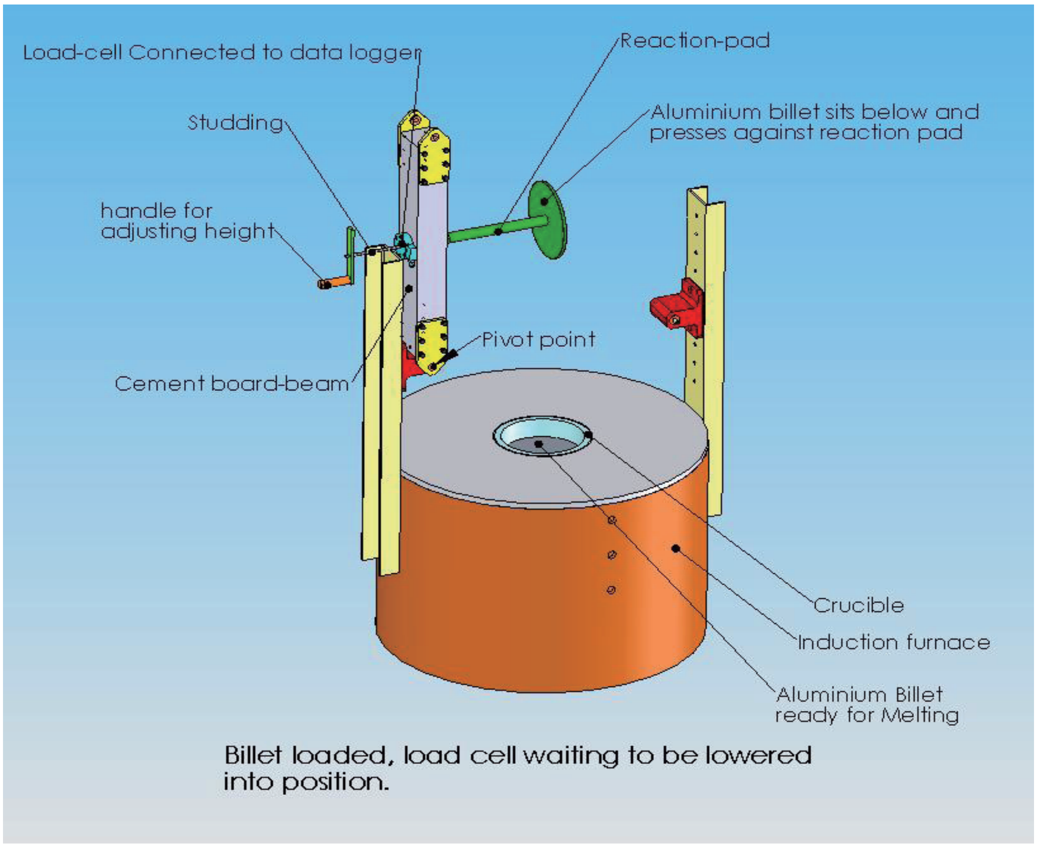

Figure 1
Induction Furnace of the CRIMSON Process

The traditional melting process from a local company was investigated and it was compared with the new process in this paper. We primarily concentrated on the energy consumption and GHGs emission of melting processes, other issues will be investigated later in our research project. The calculation and analysis of energy consumption and GHGs emission were completed to see what the difference between the existing melting processes and the new process. Accordingly, the potential energy saving and reduction of GHGs emission for the new process can be found. This comparison is only one of a number being carried out under the support of an EPSRC project whereby four conventional casting processes will be benchmarked for their energy usage and scrap rates.

1. INVESTIGATION ON THE ENERGY CONSUMPTION AND GHGS EMISSION

1.1 Conventional Melting Process in Grainger &

Worrall ltd

The workshop for producing high end casting parts in Grainger & Worrall (G&W) Ltd. is at present using one type of melting furnace (Fig. 2) with combining melting process where the primary melting area functioning like a stack melter and gas is used to preheat and melt aluminium ingot, after that the melted aluminium alloy flowing along an inclined channel to a refining area where an electric resistance furnace is used. The refined liquid aluminium alloy is held in the electric resistance furnace. "Pouring" is accomplished using an electromagnetic pump to pump the liquid metal to the mould where the process is called "Cosworth Process". In this workshop, there are two furnaces using this type of combining melting processes for producing two kinds of aluminium alloys-A354 and A357. The capacity of both furnaces is 4 tonne. The holding time for each furnace is up to 4-5 days. The overheating temperature of A354 aluminium alloy is 760 °C. The pouring temperature of the melted aluminium alloy is 700 °C.

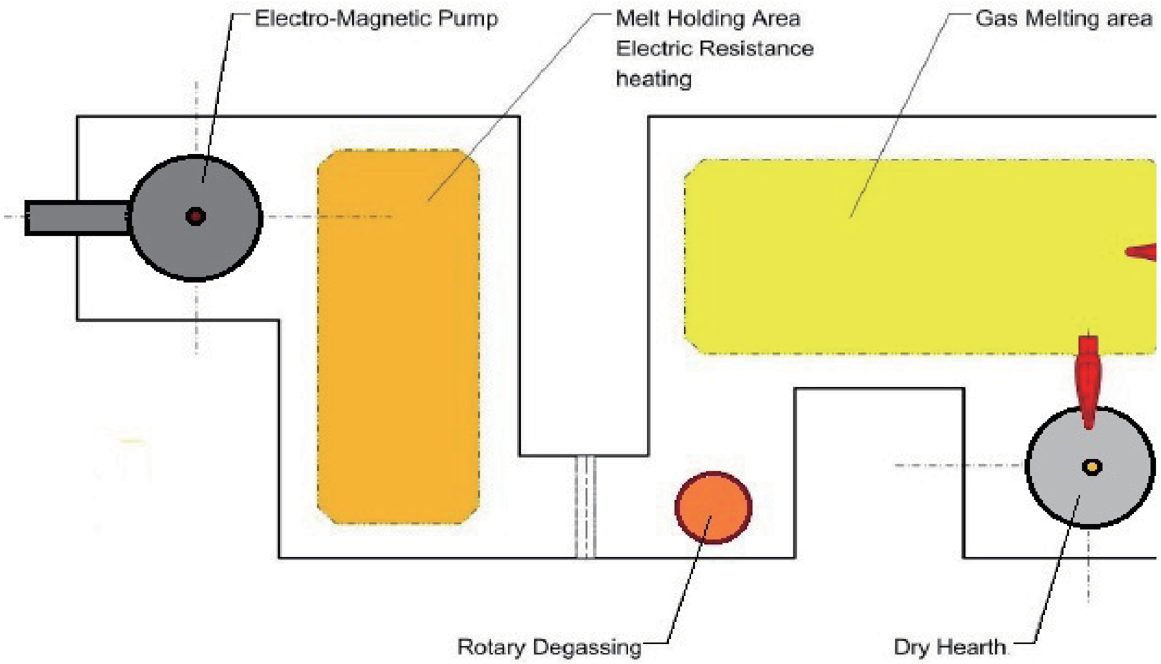

Figure 2
Schematic of the Aluminium Melting Furnace in G&W Ltd.

1.2 The CRIMSON Process

The layout of the novel casting process facility is presented in Fig. 3, where its 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 programme-controlled board: the movement of the piston in Up-caster is automatically controlled by the pre-programmed computer programme;

• Mould transfer stop: after pouring, cooling down and solidification, the mould can be moved to the transfer stop, waiting for lifting and cleaning.

1.3 Casting Sample

A "Test bar" mould has been selected to use new process to examine its energy consumption and GHGs emission. The design of the "Test bar" with a runner system is shown in Fig. 4 which has an outline of 530 mm length × 390 mm width × 100 mm height with a weight of 4 kg[7]. G&W is at present using traditional resin-sand casting processes to produce normal casting components and the Cosworth casting process is particularly selected to produce high quality components.

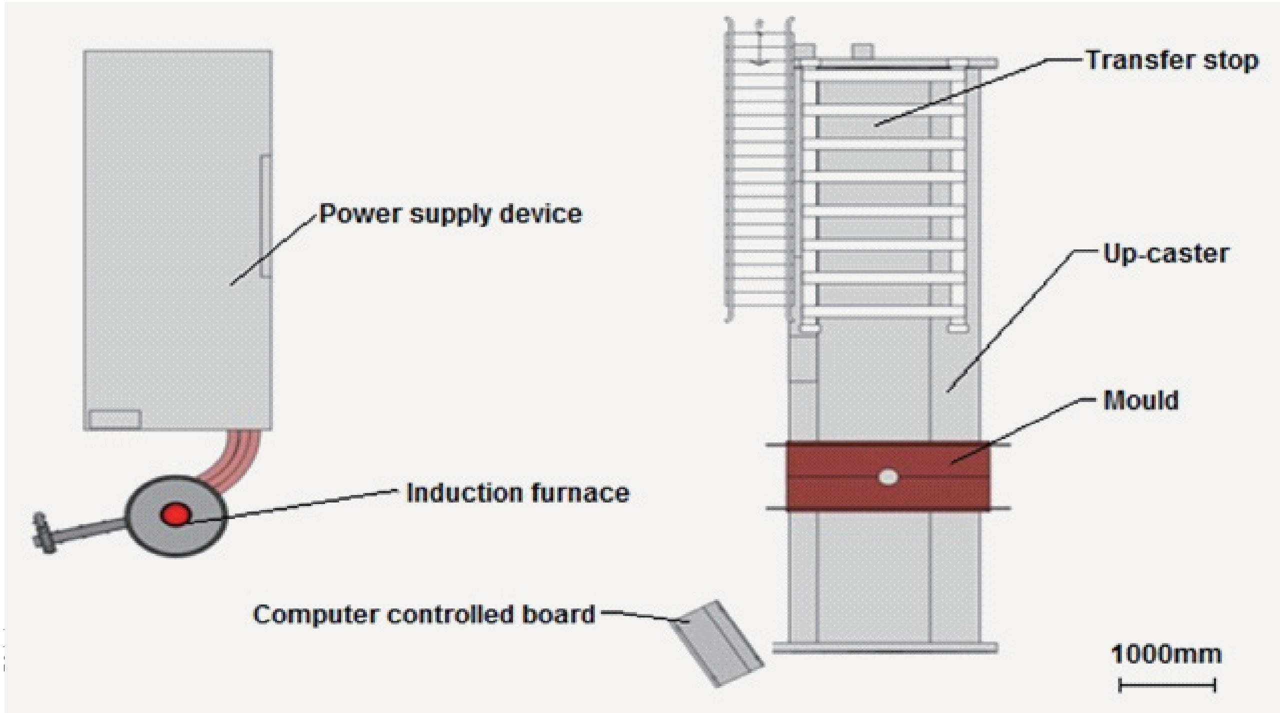

Figure 3
Schematic Plan of the New Casting Process Facility

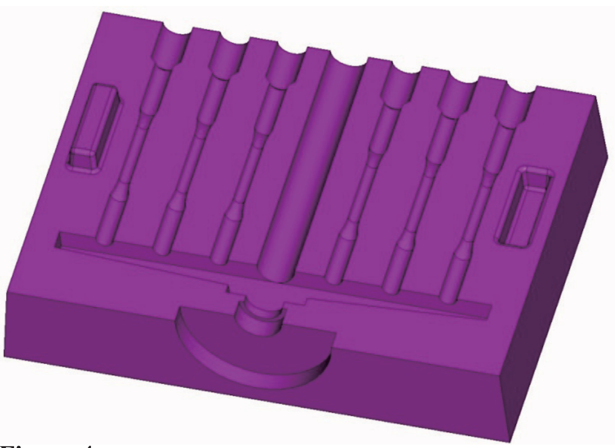

Figure 4
Mould of the "Test Bar" with Runner System

2. THERMODYNAMIC ANALYSIS, ENERGY CONSUMPTION AND GHGS EMISSION

2.1 Thermodynamics Analysis of the Furnace

Aluminium melting processes in both crucible and induction furnace include complex physical-chemical phenomena such as gas combustion, dross generation, phase change and heat transfer (radiation, conduction and convention). Some of the thermodynamic parameters can be measured readily such as temperature and pressure and at the same time some parameters are difficult to measure such as the heat loss in the way of radiation and conventions. However, thermodynamic analysis of the energy consumption during the melting process in a crucible or a furnace depended on the test results is attainable[8]. These test results and the related thermodynamic analysis can be a reference to help casting industry to improve the energy efficiency and decrease the GHGs emission.

In this paper, an aluminium melting/holding furnace from a local company – G&W ltd., and an induction furnace in the CRIMSON process are used to carry out the tests and thermodynamic analysis. The schematics of energy balance in the aluminium melting furnace of G&W ltd. and CRIMSON are shown in Fig. 5 and Fig. 6, correspondingly. The test and analysis of energy efficiency is based on the following assumptions:

- The properties of A354 alloy are different with those of pure aluminium. Based on the calculation simplicity, both aluminium ingots used in crucible furnace and induction furnace are assumed as pure aluminium;
- The system is considered as 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 correspondingly, which are also applied to gas, combustion air and aluminium ingot;
- The electric energy consumption is only applied

to the part of induction heating in induction 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.

The energy balance of the furnace at G&W in Figure 5 can be expressed as[9]:

$$E_{in}=E_{out} \tag{1}$$

$$E_{in}=E_{fuel}+E_{ingot}+E_{comb\ air} \tag{2}$$

$$E_{out}=E_{melt}+Q_{mis}=(E_{ingot}+\Delta E_{al})+Q_{mis} \tag{3}$$

$$Q_{mis}=E_{in}-\Delta E_{al} \tag{4}$$

$$\eta=\Delta \mathrm{E}_{\mathrm{al}} / \mathrm{E}_{\mathrm{fuel}} \tag{5}$$

Where,

• E_{in} is the energy input of the furnace system;

• E_{out} is the energy output of the furnace system;

• E_{fuel} is the energy generated from fuel combustion;

• E_{ingot} is the energy generated from aluminium ingot, here $E_{ingot}=0$;

• $E_{comb\ air}$ is the energy generated from combustion air, here $E_{comb\ air}=0$;

• E_{melt} is the heat transferred to the melted metal;

• ΔE_{al} is the energy variation of the metal from ingot to melted metal;

• Q_{mis} is all the energy loss during the melting process in a furnace chamber;

• η is the energy efficiency of the furnace at G&W

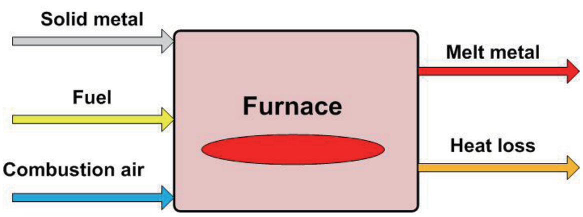

Figure 5
Schematic of Energy Balance in the Aluminium Melting Furnace of G&W Ltd.

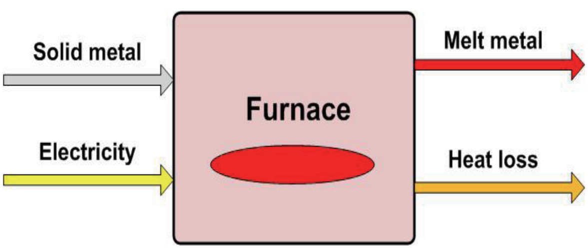

Figure 6
Schematic of Energy Balance in the Induction Furnace of CRIMSON

The energy balance of the induction furnace of the new process in Fig. 6 can be expressed in a bit different type: equations (1) and (4) are the same; (2), (3) and (5) can be revised to as follows:

$$E_{in}=E_{electricity}+E_{billet} \tag{6}$$

$$E_{out}=E_{melt}+Q_{mis}=(E_{billet}+\Delta E_{al})+Q_{mis} \tag{7}$$

$$\eta=\Delta E_{al} / E_{electricity} \tag{8}$$

Where,

• is the energy generated from electricity;

• is the energy generated from aluminium billet, here ;

• is the energy efficiency of the induction furnace;

It should be pointed out here that the conventional foundry usually is provided with the aluminium ingot with trapezoidal cross section came from the primary industry. The quality of this type of ingot is generally poor because of the severe and chaotic flow behaviour of melt during the primary production process. The new process requires the billet with round cross section and in good quality so as to better suit for the crucible of the induction furnace in the new process. At current stage, it is impractical for the suppliers to provide this kind of billet due to the small amount of requirements. However, after contacting several suppliers of the direct chill billet in UK, it is likely for them to supply the round cross section billet with required diameters and sound quality if the ordered amount is appropriate. The compromising way in this project is that the scrape and ingot are remelted and recast into round shape with required chemical compositions. The energy consumption and GHGs emission happened due to remelting and recasting is not audited in this paper.

2.2 Test Results, Assessment and Discussion

The energy consumption at G&W where the Cosworth process was applied was investigated where both gas (propane) and electricity were included and the usages were recorded in Tab. 1. It should be noticed that power measurement may be connected with the day or night rate. During the investigation, only the energy consumption ($kJ \cdot kg^{-1}$ or $MJ \cdot kg^{-1}$) was measured and the cost which linking with the rate was not considered.

Table 1
Actual Consumption of Gas and Electricity in G&W Ltd.

Energy type	Energy consumption	Energy density by mass ($MJ \cdot L^{-1}$)[10]
LPG (propane) (Wikipedia)	($0.7\ m^3 \cdot tonne^{-1}$) ($4939\ kWh \cdot tonne^{-1}$) $17.78\ MJ \cdot kg^{-1}$	25.4
Electricity	($2800\ kWh \cdot tonne^{-1}$) $10.08\ MJ \cdot kg^{-1}$	--------
Accuracy (%)	± 0.02	

From Table 1, the total actual energy consumption ΔE_{al} for melting A354 Al alloys in G&W can be calculated as $\Delta E_{al} = 27.86$ MJ•kg^{-1} (7739 kWh•tonne^{-1}). The thermal efficiency of using the LPG for melting the alloys is η_1=5.65%. The thermal efficiency of using the electricity for holding the melt is η_2=1.70%[11]. In consideration of conversion efficiency of 50% in a natural gas-fired power plant[12] for melting A354 in new process the total energy consumption is 2800 kWh•tonne^{-1}/50% + 4939 kWh•tonne^{-1} = 10543 kWh•tonne^{-1} and the thermal efficiency for holding the melt is η'_2 .= 0.85%.

Experimental parameters for casting the "Test bar" mould in the new casting facility are given in Tab. 2:

Table 2
Experimental Parameters for the "Test Bar" in the New Casting Process Facility

Experiment parameter	Value	Accuracy (%)
Weight of metal charge	4 kg	± 0.5
Melt temperature	729°C	± 2.9
Melting time	2 minutes	± 0.001
Injection time of Up-caster	10 Seconds	± 0.001
Holding time	20 Seconds	± 0.001
Solidification time	28 Seconds	± 0.001
Measured energy consumption for melting the charge	7.92 MJ	
(2.2 KWh)	± 0.02	

The theoretical energy consumption $\Delta E'_{Al}$ for heating the A354 alloy to 729 °C is $\Delta E'_{Al}$=318 kWh•tonne^{-1}. The energy consumption measured during the melting is 1.98 GJ•tonne^{-1} (550 kWh•tonne^{-1}) (Table 2). The thermal efficiency of the induction furnace can be calculated from these two figures and is η_c = 57.8% [11]. In consideration of conversion efficiency of 50% in a natural gas-fired power plant[12, 13] for melting A354 in new process the total energy consumption is 550 kWh•tonne^{-1}/50% = 1100 kWh•tonne^{-1} and the total thermal efficiency can be calculated as η'_c = 57.8% × 50% = 28.9%.

The thermal efficiency of the melt furnace at G&W for gas is η_1=5.65% and for electricity is η'_2 = 0.85%. The former η_1 is near the normal thermal efficiency of crucible furnace using gas (7~19%). The later η'_2 is far more less than the normal thermal efficiency (59~76%) of an induction furnace using electricity. This 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 single shot melting method, the thermal efficiency in using electricity will be increased up to 28%. When melting the same weight of the Al alloys, G&W used about 10 times more energy than the new casting facility. It is estimated that 34.00 GJ•tonne^{-1} (9.44 MWh•tonne^{-1}) can be saved and the reduction of the GHGs emission such as 1725.63 kg•tonne^{-1} of CO_2, 2.08 kg•tonne^{-1} of NO_x and 0.0444 kg•tonne^{-1} of particulate could be achieved for producing every tonne of A354 casting alloys when using the new process. Therefore, to use the new process, the melting cost and harmful GHGs emission will be radically reduced.

Other reasons for recommending the new process in place of using crucible furnace at G&W are: even if a crucible furnace is economical method for melting Al alloys which is popular in foundry because of its easy for tapping and charging different alloys, the thermal efficiency of the crucible furnace is far lower (normally 7~19 %) than the new process (28.9 %) and the temperature of the melted alloy is hard to control. It has been proved in this test that the thermal efficiency of furnace at G&W is only 5.65%. Moreover, the new process employs a quick filling method once the alloy is heated to the required temperature, avoiding using holding furnace for holding long time and therefore reducing the potential energy wastage. At the same time, because of the rapid melting and filling processes, the chance of generating the oxide film on the surface of the melted alloy and the possible time for hydrogen absorption are significantly reduced. The quality of the casting can be secured as a result.

CONCLUSIONS

The investigation on melting efficiency of both conventional and new melting processes has revealed that the new process is an innovative method for saving energy in the casting industry. If the conventional foundries could use the novel melting method instead of their traditional melting method, the estimated energy savings could be of the order of 34 GJ•tonne^{-1} (9.44 MWh•tonne^{-1}) for A354 alloy. This would drastically reduce the production cost by about £718 pounds•tonne^{-1} (7.6 p•kWh^{-1}). This could be crucial in the rigorously competitive market of casting industry. The GHGs emission i.e. 1725.63 kg•tonne^{-1} of CO_2, 2.08 kg•tonne^{-1} of NO_x and 0.0444 kg•tonne^{-1} of particulate could be reduced.

According to the investigation, the new process is proved to be an effective method in increasing the energy efficiency, reducing the production costs and the GHGs emission.

The energy consumption and energy efficiency for other stages of the sand casting process will be further investigated in this research project.

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