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Simulation based energy and resource efficient casting process chain selection: A case study

Konstantinos Salonitis*, Mark Jolly, Binxu Zeng

Manufacturing Department, Cranfield University, Cranfield, MK430AL, UK

Abstract

Casting processes are among the most energy intensive manufacturing processes. A typical modern casting process contains different stages, classified as melting-alloying, moulding, pouring, solidification, fettling, machining and finishing respectively. At each stage, large amounts of energy are consumed. Since a number of different casting processes exist, it is not always straightforward which process chain to select among the available ones. Up to now the selection is based on cost criteria. This paper focuses on the different criteria that needs to be considered and how they can be simulated focusing especially on the energy and resource efficiency of casting stages. A disruptive technology that uses a rapid induction furnace to melt just enough metal for a single mould rather than bulk melting used in traditional processing is proposed and validated.

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Keywords: Casting; Simulation; Energy efficiency

1. Introduction

Energy consumption of industrial processes has been investigated thoroughly in the last years. Manufacturing accounts for 32 % of the total energy consumption [1]. Within the CIRP community a number of papers have been presented focusing on the energy efficiency of manufacturing processes developing methods for improving it [2]. However, these methods are focused on material removal processes and have not been generalized to include primary forming processes such as casting.

* Corresponding author. Tel.: +44(0) 1234 75 8347.
E-mail address: k.salonitis@cranfield.ac.uk

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Casting relies in pouring molten metal into a mould and wait until it solidifies. Although it is one of the oldest manufacturing processes, it is also one of the most challenging. A typical modern casting process contains a number of different stages, including melting, alloying, moulding, pouring, solidification and finishing. Casting is also one of the most energy intensive manufacturing processes with the metal melting consuming over half of the total energy.

Aluminium melting in metal casting industry is an energy intensive process, it has been estimated that the energy consumption is of the order of 6 – 17 GJ.tonne^{-1} in using crucible furnaces and natural gas. The energy efficiency of a casting facility depends largely on the efficiency of its melting and heat treating performance. It has been estimated that these two processes consume over 60 % of the total process energy implying that there are huge opportunities for the metal casting industry to adopt the best energy practices which will provide the great energy saving potential.

Resource efficiency is also an issue in casting processes, with the yield in conventional casting processes being as low as 27 % [3]. Aluminium is a highly reactive material. In particular, when it is molten, it can react with air, moisture, the furnace lining and other metals. Metal loss during the melting process is also due mainly to this characteristic.

However, although energy and resource efficiency are key challenges for the casting processes, foundries do not consider them as key priorities. Cost is still the key decision making attribute for foundries. In this respect, the scope of this paper is to take a more holistic view on how to select between alternative casting process chains, considering energy and resource efficiency as criteria. Simulation can be used for the improvement of both the energy and the resource efficiency of the casting processes as will be shown. Various simulation tools and the potential savings from their use are presented and discussed for the case of conventional sand casting and a disruptive casting technology named CRIMSON.

2. CRIMSON process and case study

In a recent study, the possibilities for saving energy in the foundry sector were discussed [3], assessing the possibility of using lean tools. As an alternative casting process that considers these tools, the CRIMSON process was presented. The Constrained Rapid Induction Melting Single Shot Up-Casting (CRIMSON) process was developed for decreasing the energy consumption and to ameliorate the casting quality within light-metal casting industry [4]. The method is based on using an induction furnace, melting, in a closed crucible, only the quantity of metal required to fill a single mould rather than large batches that use unnecessary energy and increase rejects. The closed crucible is transferred to a station and the molten metal is pushed up using a computer controlled counter-gravity filling method to fill the mould. Due to the rapid melting, transfer and filling; the holding time of molten metal is minimised, a huge amount of energy saving is achieved and simultaneously the possibility of hydrogen absorption and formation of surface oxide film are decreased largely.

In the present paper different simulation methods are used for comparing CRIMSON with counter gravity sand casting. An ASTM standard tensile test bar was the case study product in a previous study [5], in the present paper a more complex product is used for validation. Computational fluid dynamics (CFD) are used for investigating the filling patterns. The energy savings are analytically estimated and fed into life cycle assessment (LCA) model for assessing the environmental impact. The productivity of the process is assessed using discrete event simulation and a cost model is proposed for the comparison with the sand casting. In such a way a holistic comparison is achieved revealing the possible benefits from the adoption of such process.

3. Numerical simulation of the filling process

CFD analysis has been used extensively in the optimization of the various casting processes. Salonitis et al. [5] used CFD for analysing and comparing the filling process of the mould during the casting of a tensile test bar, proving that for such simple parts the counter gravity filling process can result in better filling patterns compared to the traditional sand casting process. Counter gravity casting is used for the CRIMSON process that was introduced in the previous section, and it was shown that the possibility of oxide film generation on the surface of the liquid metal is considerably reduced and the available time for hydrogen absorption from the atmosphere by reducing time for the reduction of atmospheric moisture [5]. Additionally, they proved that the material lost during fettling is reduced, mostly due to the different design of the mould (lack of down-sprue for example). In the present study, a more complex product is used, namely a "Filter Housing" as shown in figure 1. For the simulation of runner system of filter housing (shell mould) using CRIMSON process, the filling time estimated is 8.96 seconds. The simulation took about 6 hours to be solved using the FLOW3D CFD software. The velocity magnitude of the liquid metal during filling a mould is described in Figure 1 where the velocity of liquid flow can be judged using the velocity scale. For the casting of tensile bar [5], the maximum velocity was estimated to be 0.4 $m.s^{-1}$, in the present study the maximum velocity is calculated to be 0.45 $m.s^{-1}$, proving again that the use of counter gravity filling will result in castings free of trapped oxide films, porosity and other casting defects.

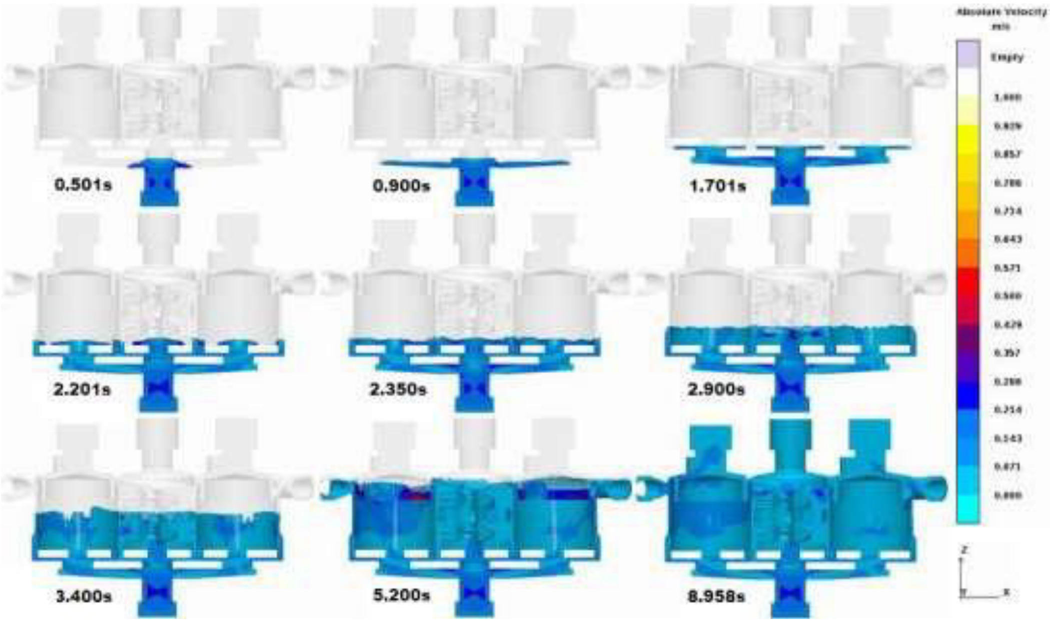

Fig. 1. Numerical simulation of runner system of the filter housing casting using counter gravity filling.

4. Energy savings, efficiency and GHG emissions

Salonitis et al. [5] presented a simplified energy balance analysis for estimating the energy consumption during the melting of the aluminium. They compared the use of a conventional to an induction furnace. They proved that a conventional gas furnace requires more than double the energy compared to the induction furnace for melting the raw material. Additionally, the green-house gas (GHG) emissions were estimated using the Greenhouse Gas Protocol, showing that again the induction furnace produces almost half the emmissions compared to the conventional gas furnace.

Although melting is usually accounted for more than 50% of the total energy consumption in a foundry, the rest of the processes have to be considered as well [3]. Die casting consists of six main steps and each of them has very specific variables that need to be controlled along the process. The firsts two steps are melting and holding process that consists of heating the metal to transform it to liquid and hold it until pouring. These two combined are accountable for 72% of the energy consumption [6]. This operation is complex, involving a series of steps that incur in material and energy losses. The extend of the losses depends on the furnace design, the fuel used and the method of imparting heat to the metal [7]. According to a number of studies (as highlighted already by the authors in [3] and supported by Melorose, Rerroy and Careas [8]) induction furnace is the best option when melting aluminium in terms of thermal efficiency and metal loss. The holding step add inefficiencies to the process, energy is utilized in holding the metal in the molten state. An ideal operation would melt and then pour directly into the mould, as is the case for the CRIMSON process. Despite inefficiency, holding is a normal practice in aluminium die casting foundries [7].

Heat treatment process is also an intensive energy consumer in a foundry. It is usualy used for a number of reasons: to increase hardness and mechanical properties, to stabilize the mechanical and physical properties, to ensure dimensional stability where the castings are used to temperature and to relieve residual stress. A full heat treatment cycle involves a solution treatment, quenching and then precipitation heat treatment or aging [9]. Given the importance, some studies have been reported attempting to reduce the energy consumption keeping the resulting mechanical properties by optimising the Temperature-Time curve [10].

Fettling process is important with regards the material yield as almost 40% by weight of the part is chopped off as part of its running system. Reducing the weight of the running system can reduce the metal loss in fettling [3].

For the conventional manufacturing of the housing filter, investment casting using conventional crucible furnaces, each with a capacity of 400 kg is used. 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 consumption of gas was measured to be 236.25 $m^3.tonne^{-1}$. The energy consumption thus was 8.65 $MJ.kg^{-1}$ (2401.88 $kWh.tonne^{-1}$). The energy density by mass thus 45.57 $MJ.kg^{-1}$. Based on the model proposed by Salonitis et al. [5], the energy consumption, thermal efficiency and GHGs emission between the investment casting process and CRIMSON melting processes can be found in Table 1.

Table 1. Comparison of conventional and CRIMSON melting processes.

Melting Process	Energy consumption ($GJ.tonne^{-1}$)	Energy efficiency (%)	Nominal energy efficiency (%)	GHGs emission (kg/tonne casting)
Gas furnace	8.65	13.86	7 – 19	CO_2: 430.086 NOx: 0.528 Part.: 0.011
CRIMSON induction furnace	3.96	57.82	59-76	CO_2: 201.08 NOx: 0.242 Part.: 0.0052

5. Life cycle analysis comparison

As indicated by Salonitis et al. [5], the efficiency of the melting furnaces cannot be used as a representative metric for assessing the whole process. Life Cycle Assessment (LCA) has been shown in a number of studies that can be used for this reason, allowing the assessment of the environmental impact of the whole life cycle of the product. With the proper selection of the boundaries of the analysis, the environmental impact assessement of the manufacturing processes is possible. Salonitis et al. [5] compared in that sense the manufacturing of the conventional gravity sand casting process with the CRIMSON process for the case of the ASTM standard tensile test bar. They used energy audits for collecting data for both cases. The conclusions drawn from this analysis were that recycling sand and metal can reduce the environmental impact for casting process. 62% of impact can be reduced when using recycling in the CRIMSON process and 60% of impact can be reduced for conventional process.

For the case of the housing filter the data were collected or estimated when energy or material audit were not an option. Furthermore, the LCA simulation package (Simapro) inventory database was used as a source, mainly for a sound check of the collected or estimated data. Similar assumptions to the ones suggested by Salonitis et al. [5] were considered, i.e. the loss in melting, holding, and degassing operations are oxidation and impurities loss and are treated as permanent loss. The recycling refers to the reuse of the high energy content metal removed from fettling, machining, and scrap. The sand required is also considered, with a metal and sand ratio of 1:6. The material needed for sand mould is classified into sand that can be recycled and sand to be disposed. According to industrial practice, 90 % of the sand can be recycled and 10 % can be disposed to landfill.

For the present case only Eco-Indicator 99 HA impact assessment was run, as in previous studies it has been shown that it is a good representation of the manufacturing impact on environment [5], [11], [12]. Eco-Indicator expresses the emissions and resource extractions in 11 impact categories. The conclusions drawn from this analysis are that recycling sand and metal can reduce the environmental impact for casting process. 58% of impact can be reduced when using recycling in the CRIMSON process and 56% of impact can be reduced for conventional process. Comparing CRIMSON with conventional casing though, the CRIMSON process has almost half the impact, as was the case for ASTM tensile parts in [5].

6. Discrete event simulation

Thus far, the quality and environmental impact of both casting processes have been investigated and the advantages of the CRIMSON process identified. In order to measure the labour productivity of the CRIMSON process, a complete casting model was developed. A survey was undertaken to investigate parameters such as cycle time, casting yield, operational material efficiency (OME) and recovery ratio. The CRIMSON furnace can melt up to 30 kg of aluminium (although as a result of metal loss, the actual casting weight is less), it is therefore sensible to investigate the influence of casting weight at the limit of production performance. The OME for the CRIMSON and conventional casting processes is 34 % and 27 % respectively [4]. Thus the CRIMSON process can produce at maximum 10 kg of good casting. WITNESS discrete event simulation software was used for the modelling of both casting methods.

Beginning with the conventional casting sand process, the model's first phase is the entry of raw metal into the foundry. Following the material flow, the metal passes though preheating, melting, refining, until holding with respective cycle times. After the holding operation, the molten metal is poured into 135 sets of casting moulds (assuming 1 kg of good casting required). Moreover, the holding is used to supply liquid metal continuously for casting. It works as a buffer to supply the downstream operations. In order to apply these two characteristics into the simulation, the holding operation is set as a production process in WITNESS, which can produce 135 sets of casting moulds. However, as a buffer it is not assigned a cycle time. Following the material flow, the parts then go through the casting process and the mould is transferred to the safety area for solidification. In the model, a buffer is used to represent the safety area and a 30-minute delay is applied to represent the solidification time. Afterwards, the material is moved into the shakeout process, in which a work-in- process buffer was added to collect parts after the shakeout process. The purpose of this buffer is to supply parts continuously to the downstream operation. After the buffer, there is a container to collect a certain amount of parts and to await transfer to the next process (to simulate the batch production process). In the current situation, the container only collects one part to act as the one-piece flow. Similarly, for fettling and machining, a work-in-process buffer and container are located at the end of each process before delivery to the next process.

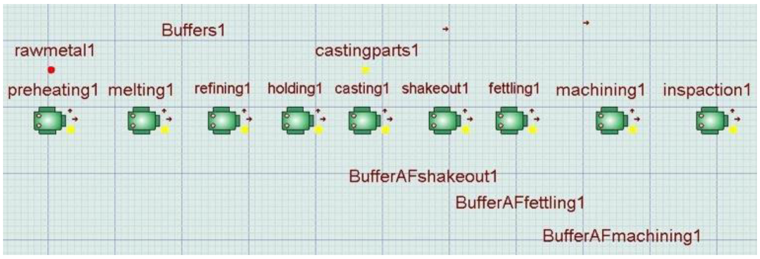

Fig. 3. Layout of the conventional sand casting process in WITNESS.

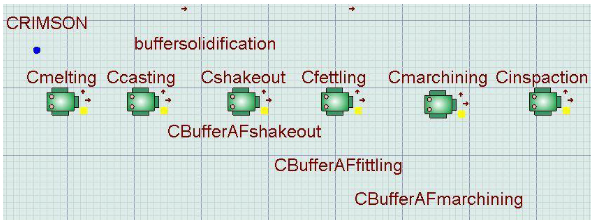

Fig. 4. Layout of the CRIMSON process in WITNESS.

A similar model was developed for the CRIMSON process. However, the furnace used in CRIMSON melts only enough metal for a single shot and has no holding in the process. Figures 3 and 4 represent the actual layout used in simulation for both casting process.

The productivity of both casting processes for different casting weights has been investigated for a period of one year. Figure 5 presents the product outputs for different casting weights under different power outputs. Several conclusions can be drawn from this graph. First, the conventional process is more productive for small-sized casting products, especially those castings below 2 kg in weight. Secondly, the product outputs increase as the power increases, especially for large-sized casting products. Finally, as the casting size increases, the product output decreases. This can be justified by considering the way the utilisation of the major casting operations changes for different casting weights. The simulation results thus suggest that the CRIMSON process should be used for casting sizes between 2 and 10 kg, using the correct power output.

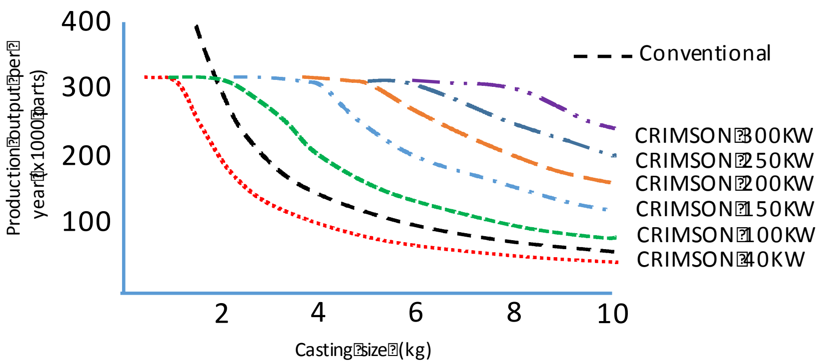

Fig. 5. CRIMSON product output under different power outputs.

7. Manufacturing cost modelling

It has been shown that CRIMSON process can result in better quality castings with higher energy efficiency compared to the conventional casting process. Despite these advantages, manufacturing sector cannot consider the process without realistic and accurate cost estimations. Analytical cost estimation technique was used for assessing the process cost. Using this method, only the production time and hourly rate for the man, machine and resources need to be accurately calculated. The associated manufacturing costs can be calculated by multiplying times and rates together. The main challenge with such an approach is that the accurate and precise collection of production information is time consuming and costly. However, through the discrete event simulation presented in the previous section, the production time can be estimated.

The variable costs modelled include raw material cost, energy cost for melting and labour cost. For the estimation of the raw material cost, the key element is the unit cost of the aluminium. For the CRIMSON process, pre-alloyed high-quality aluminium was used. For the conventional sand casting process, a normal ingot was used as the input metal for the purposes of cost reduction. As this is a continuous production process, it is possible to use recycled material for the casting production. Therefore, the price of recycled metal and sand will be used. Regarding the melting, the conventional sand casting process uses a gas furnace to melt the aluminium to its melting point (660 °C), after which it is transferred to a holding furnace to be superheated to 700–750 °C. The energy efficiency for a gas furnace is about 50 %. For the holding operation, the literature indicates that it uses the same amount of energy as the melting process but costs more because it uses electricity. As the literature shows, the holding operation costs 1.2 times more than the melting process. By contrast, the CRIMSON process only uses electricity to melt metal up to 750 °C with 50 % energy efficiency. Labour cost is a function of the equipment, the labour and the time required to produce a certain amount of products. CRIMSON process can be assumed to have six operators and the conventional process seven. Because the melting process has the longest cycle time, the labour hours will be determined by the melting time for the CRIMSON process. By contrast, the conventional process uses a different approach because of the fixed furnace. For the conventional process, a 500 kg furnace with a two-hour melting time was used. Depending on the casting size, the number of moulds that can be poured is different. Figure 6 shows the relation between the variable cost and the variables. Most of the variables are related to more than one variable cost. Any change of a parameter might cause a different cost estimation result. Moreover, not only the total cost of the production might change but time distribution and cost contribution might change as well.

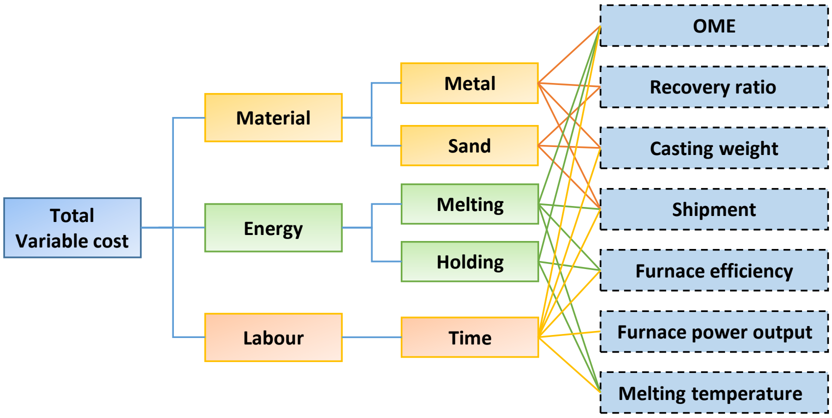

Fig. 6. Schematic of the relation between variable cost and variables.

Solving the model for the case study can result in interesting results (figure 7). For both CRIMSON and conventional casting process, raw metal is the major cost contributor in the variable cost. Its contribution can vary from 30 % to 80 % of the total variable cost. The sand cost is the second cost contributor in variable cost, which can contribute 10 % to 70 %. However, the energy cost only contributes 1 % of the variable cost. Because the CRIMSON has higher material utilization compared to the conventional casting process, it uses less material to produce casting products. This is the main reason why the CRIMSON process has less manufacturing cost compared with conventional casting process under most circumstances. These results indicate that cost reduction should focus on the utilization of raw material. It is also a clear reminder that the primary goal of energy saving is not necessary cost reduction, but it is also related to environmental impact reduction and sustainability, to indicate few. The natural ability of CRIMSON, as a counter-gravity filling process, also enjoys the massive benefit of the superb quality of the product, and the hugely important benefit of the reduction of scrap, with clear advantage of avoiding the necessity to re-make the product more than once to achieve a saleable quality.

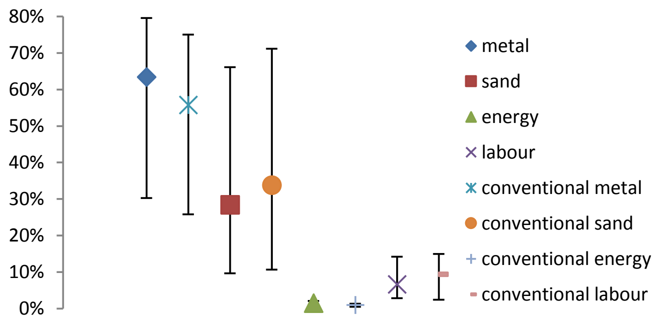

Fig. 8. Average cost contribution and distribution of each variable cost.

8. Conclusions

The purpose of this paper was to validate various simulation methods for improving the energy and resource efficiency of casting process chains. For this reason, CRIMSON process was compared to conventional sand casting as a case study. The validation was performed through mould design optimization, productivity analysis, environmental impact assessment, and cost estimation of the production. As the findings indicate, the CRIMSON process has many advantages compared to the conventional sand casting process. It can result in better casting quality due to better filling rate control; with higher energy efficiency and better material yield. Furthermore, with discrete event simulation it has been shown that it can have higher productivity at a lower cost. The use of multiple simulation methods can help assess a process in a more holistic way.

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