Journal of Cleaner Production 137 (2016) 1532–1542

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Improvements in energy consumption and environmental impact by novel single shot melting process for casting

Konstantinos Salonitis*, Mark R. Jolly, Binxu Zeng, Hamid Mehrabi

Manufacturing Department, Cranfield University, MK43 0AL Cranfield, UK

ARTICLE INFO

Article history:
Received 4 August 2015
Received in revised form
7 April 2016
Accepted 27 June 2016
Available online 29 June 2016

Keywords:
Casting
Foundry sector
CRIMSON
Sand casting
LCA
Yield

ABSTRACT

The CRIMSON (Constrained Rapid Induction Melting Single Shot Up-Casting) method uses a rapid induction furnace to melt just enough metal for a single mould rather than bulk melting used in traditional casting process. The molten metal is then transferred to a computer – controlled platform to complete the counter-gravity up filling. The highly controlled metal flow is pushed into the mould to finish the pouring and solidification. In the present paper the energy saving capability of CRIMSON approach is compared with conventional sand casting process. The paper focuses on the energy and resource efficiency optimization of casting stages through simulation and life cycle assessment analysis simulation for proposing alternative means for the better performance of such processes. It is proven that the CRIMSON process can produce high quality castings with higher energy efficiency and lower environmental impact.

1. Introduction

Casting processes have a reputation of being highly energy demanding. Foundries, who are responsible for the production of castings, are in most cases small and medium enterprises, and as such face great challenges when trying to implement energy efficiency initiatives (Trianni et al., 2013) (Trianni and Cagno, 2012). In the UK only there are more than 450 foundries (Cast Metal Federation, 2016). Recent reports for other countries, indicate that in China there are more than 2600 foundries, in the USA more than 2000 and approximately 900 in Germany.

In all countries, legislation has become more and more strict over the years with regards the energy consumption and emissions of the manufacturing sector related activities. Such legislation attempts to regulate all individual sectors and impose goals for the future. Indicatively, within UK, the Climate Change Agreement requires that the foundries sector in the UK should attain an energy burden target of 25.7 GJ/tonne (Department of Energy (2011)). However, currently the average energy burden for the UK foundry sector is 55 GJ/tonne. Saving energy in foundries by increasing efficiency in production line can help to save millions of pounds for manufacturing sector and reduce emissions. It should be noted as well however, that reducing the energy consumption and keeping the emissions as low as possible is not solely a technical issue, and it is also important to consider the 'human factor' as highlighted by Fatta et al. (2004).

Within the academic community a number of papers have been presented focusing on the energy efficiency of manufacturing processes developing methods for improving it (Duflou et al., 2012). However, these methods are focused on material removal processes and have not been generalized to include primary forming processes such as casting. Casting is a family of processes by which metal is transformed from ingot and/or scrap to a shape that has added value and is close to the final shape of the object required by a designer. 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. However, there are not a lot of available published data to prove this claim. Due to confidentiality, data on energy, material and emissions are not available publicly. Unfortunately, this is true for the casting foundry sector and there are no specific statistical data regarding energy consumption or annual production available for the non-ferrous foundry sector since 1996 (DETR, 1997).

* Corresponding author.
E-mail address: k.salonitis@cranfield.ac.uk (K. Salonitis).

http://dx.doi.org/10.1016/j.jclepro.2016.06.165

Nomenclature

CFD	Computational Fluid Dynamics
CRIMSON	Constrained Rapid Induction Melting Single Shot Up-Casting
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
OME	Operational Material Efficiency
VSM	Value Stream Mapping

In addition to the difficulty of data collection from different industrial sectors, collecting data from within the casting foundry sector faces a number of challenges. Different foundries have different approaches to casting aluminium products. Thus, it is feasible that the energy consumption between foundries is different, even when producing similar products. Dalquist and Gutowski (2004) performed a life cycle inventory (LCI) analysis for sand casting and die casting. Using mould making as an example, the results indicated that energy consumption can vary from 6% to 20% of the total energy. The Department of the Environment, Transport and the Regions published a report in 1997 (DETR, 1997), which suggest that the average energy burden of the casting process is about 40 GJ per tonne. However, it also indicated that there was a significant difference between different casting sectors. For example, the energy burden of die casting foundries was in the range of 26–52 GJ per tonne. By contrast, the energy burden of sand casting foundries was in the range of 30–130 GJ/tonne (DETR, 1997). Such widely scattered data are not helpful for reaching confident conclusions.

However, it is impossible to use a detailed analysis method to investigate the energy burden of metal preparation. As mentioned previously, different foundries have different approaches to making sand casting products. Unlike the process of making the sand mould, the process of metal preparation is not as standardised. To avoid difficulties in the collection of energy data, a concept called embedded energy will be adopted to collect energy input data. Embedded energy is defined as the sum of the all the energy required to produce products or services. In this case, the embedded energy of casting refers to the energy used to produce the casting, which includes the energy input of making the sand mould and preparing the metal (melting, holding, ventilation, fettling, etc.).

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 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% (Salonitis et al., 2016). Aluminium is a highly reactive material. In particular, when it is melted, 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.

The scope of this paper is to investigate and assess the improvements in casting that can be achieved by using a disruptive single-shot metal melting and casting method that is called "Constrained Rapid Induction Melting Single Shot Up-Casting". The analysis of the potential savings that can be achieved in a foundry are discussed, and energy audits are used for supporting these findings. Advanced modelling methods are used for the validation of the improvements and life cycle assessment is finally used for quantifying the environmental impact of adopting this process compared to conventional sand casting.

2. Energy and material audit of the casting process and possibilities for improvement

The energy efficiency analysis can take place on different levels depending on the scope of the analysis. As indicated by Duflou et al. (2012) five different levels can be identified, namely:

- device/process level,
- line/cell/multi-machine system,
- facility,
- multi-factory system and
- enterprise/global supply chain.

Each one of these analysis levels relies on different assumptions, different input and provides different results. All the levels can be affected by the casting processes and makes sense to analyse such processes from their perspective. With regards conventional manufacturing processes, a number of recent studies have been published dealing with the energy efficiency, however, as highlighted by Salonitis and Ball (2013) most of these studies rely either solely on the monitoring of the energy consumption of machine tools or on the monitoring of specific machine tools components, such as the spindle.

The energy efficiency is linked to the energy consumed by the manufacturing process (so in the case of casting the furnace used for melting, the holding furnace, the auxiliary devices, the material handling etc.). Before deciding a strategy for the energy efficiency optimization of the process, a thorough energy consumption audit is required. For the case of conventional manufacturing processes (such as machining or grinding), the analysis relies on the energy audit of the machine tools during the processing. During the last years, a number of studies have been presented dealing with the energy efficiency at this level. The energy consumed by machine tools during machining is significantly greater than the theoretical energy required in chip formation. As an example, the specific cutting energy accounts for less than 15% of the total energy consumed by a modern automatic machine tool during machining. For the determination of the energy consumption of the peripherals of the machine tools, the monitoring procedure has to be designed thoroughly in advance. Salonitis (2015) developed a framework for determining the energy consumption of a machine tool that can be adapted for the needs of the casting processes as well.

Measuring the energy consumption of manufacturing equipment pose a number of challenges with the main one being that when measuring the consumption of machine, a number of subsystems and peripherals may be working simultaneously that cannot be isolated and measured individually. The framework presented by Salonitis (2015) for addressing this problem is composed of three major phases: the preparation phase, the measurement phase and the analysis phase. Within the preparation phase, the energy audit approach is structured and designed based on the characteristic of the manufacturing process to be analysed. Within the second phase all the measurements are taking place. The final phase deals with the analysis of the results. The framework is adapted for casting process and schematically presented in Fig. 1. After measuring the energy consumption during the process, the energy consumed from each phase can be estimated. Using the

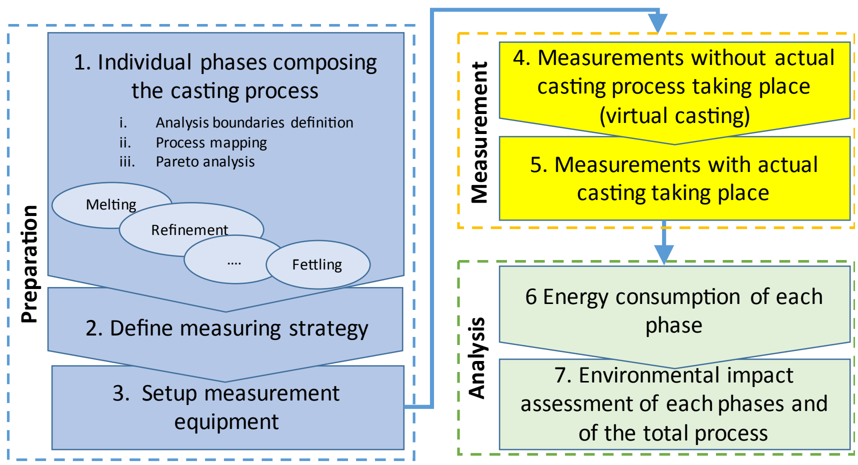


Fig. 1. Energy consumption measurement framework.

Pareto analysis, the various subsystems are ranked with regard to the energy consumption, establishing in this way which subsystems are best to focus improvement efforts.

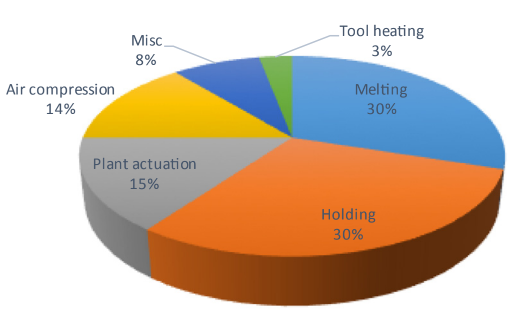
Such a framework can be used in tandem with other process mapping and auditing methods such as Value Stream Mapping (VSM). Girish et al. (2012) used the VSM method in a foundry for investigating the entire production flow of the casting process concluding that with minimum interventions, the foundry could reduce waste by 23%. Kukla (2011) proved that the implementation of total productive maintenance in a casting industry can allow for efficient management of machinery and increase its effectiveness, resulting in improved production flow and lower production costs.

DETR (1997) measured the energy of the key energy consumer equipment and phases in the casting process. Fig. 2(a) presents their findings. Using the Pareto analysis, the various energy consumers are ranked with regard to the energy consumption, establishing in this way which subsystems are best to focus improvement efforts. It is thus straightforward that melting and holding stages are the ones to focus with regards the extend of their energy demand. This finding is in agreement with recent energy audits performed in Italy in five cast iron foundries (Lazzarin and Noro, 2015).

As shown, a rough energy audit analysis can reveal the key areas that the energy efficiency improvement initiatives should focus first. However, the Pareto analysis shown in Fig. 2 does not reveal the whole story. If for example we consider the energy cost and not the total energy consumption the picture to be drawn is different, and this can be attributed to the different sources of energy and the associated cost of this type of energy. Indicatively, a typical foundry consumes 14% of its energy on air compression, which costs even more money than melting or holding since the energy source is electricity. Fig. 3 presents this “weighted” Pareto analysis. Compressed air in a foundry is first of all necessary for combustion in cupola furnaces. Efficient burning of fuels can provide a hotter flame temperature, which gives a higher heat transfer rate and reduces the time required for melting (BCS, 2005). Furthermore, it reduces the heat loss during combustion as well as the environmental impact. However, there are side effects, since although the fuel consumption is reduced during combustion; it consumes significant quantities of electricity. Ensuring that there is no excess air in the burner will help greatly in reducing the need for compressed air. Using the correct size of compressor and routine maintenance can also save energy. Ultimately, using an induction furnace will eliminate the requirement for compressed air and lean tool such as total productive maintenance can be extremely helpful for this purpose.

The material audit can be assessed through the operational material efficiency (OME). OME is the ratio between the good castings shipped to customer and the total metal melted. Improving the true yield is probably the simplest way in which foundries can save energy, as no energy is consumed for castings that are later on rejected and have to be re-melt. The focus in that case is in the improvement of the production process itself, seeking opportunities to save material. However, in order to be able to understand the true yield of the casting process, the entire casting operation needs to be analysed. Using a traditional sand casting as an example, the casting process is analysed briefly in the following paragraphs for the case of aluminium casting.

Aluminium is a highly reactive material at high temperature, it reacts with air, moisture, the furnace lining and other metals. The metal loss during the melting process is due mainly to this characteristic. For simplicity, the casting process is divided into sub-



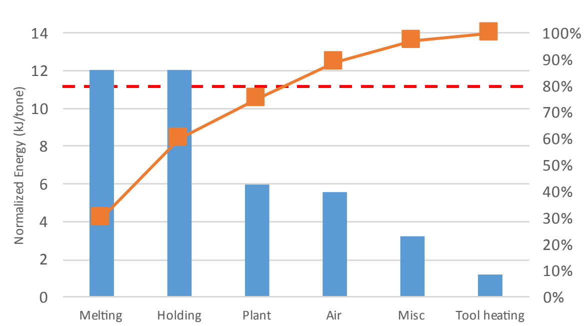


Fig. 2. (a) Typical energy use (based on figures presented by DETR, 1997) and (b) Pareto analysis.

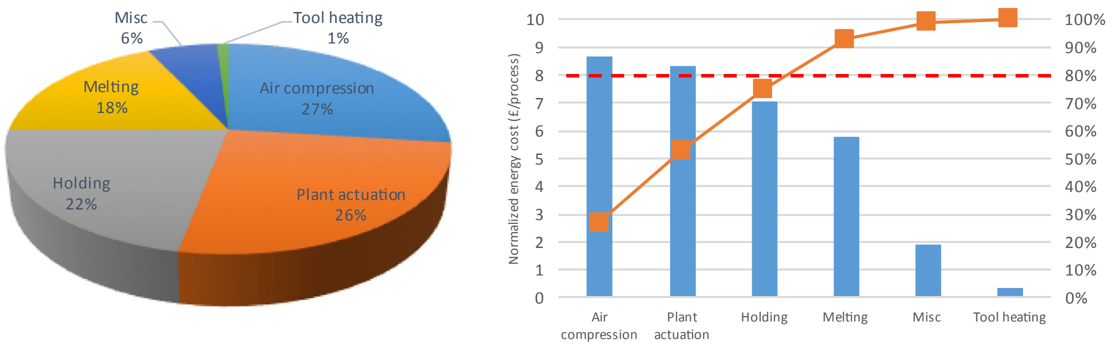


Fig. 3. (a) Energy cost (based on figures presented by DETR, 1997) and (b) Pareto analysis.

processes: melting, holding, refining, pouring (casting), fettling, machining and inspection. Apart from pouring (casting), six out of seven sub-processes result in metal loss. Fig. 4 presents the metal flow during conventional sand casting process using a Sankey diagram. By assuming 1 kg of total metal melted (coming both from raw material and recycling streams), then after the different stages of the operation, the final casting dispatched to customer only weighs about 0.27 kg. Therefore, the operational material efficiency of this casting process is about 27%. For conventional casting, 1 Kg of good casting requires 3.7 Kg of raw and recycled material.

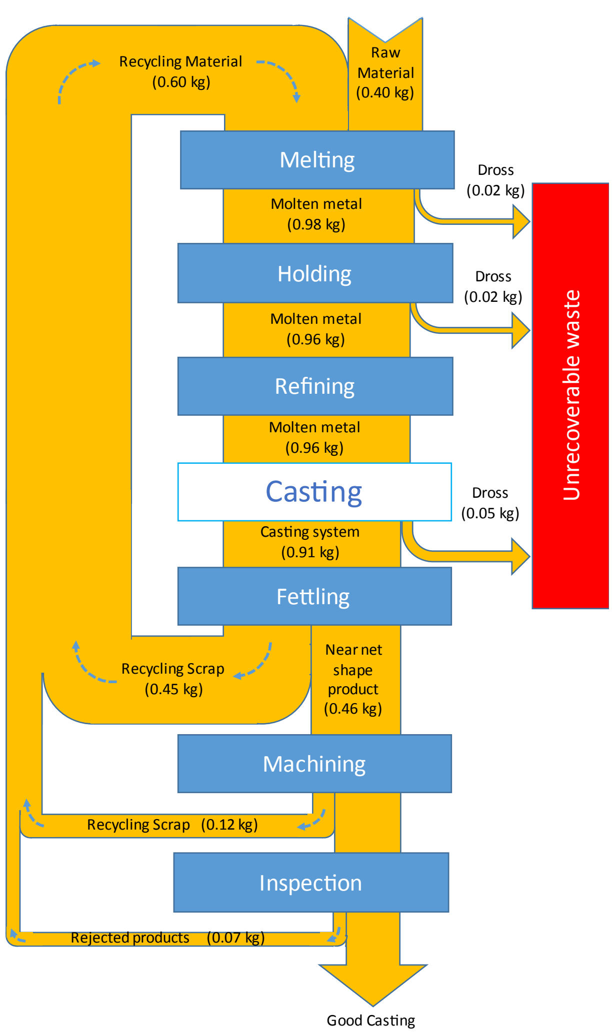


Fig. 4. Metal flow in the foundry.

Therefore, if the true yield of the casting improved, less metal will be required to produce the casting and the energy consumption for the melting reduced.

Salonitis et al. (2016) discussed the opportunities to improve the true yield by improving the metal loss during each operation. The loss during the melting process and the holding is due to the oxidation of the aluminium at the surface of the melt. This can be potentially controlled by making sure that the molten aluminium is kept away from contact with air (for example keeping the lid of the furnace shut, reducing the metal charge time, minimizing the holding time are all good practices). The loss during the refining process can be attributed to oxidation, hydrogen degassing and impurities. A good practice to reduce such losses is by selecting good quality raw material as the rate of loss depends on the material's quality. The losses in these first three steps are permanent losses, which cannot be easily recovered or reused, thus the focus can be only on reducing their occurrence.

As indicated in Fig. 4, the key material waste is produced at the fettling operation. Fettling is used to separate the casting from its running system. The casting itself is only about 50% by weight of the entire casting system, although this depends on a number of aspects such as the number of castings per shot, the feeding and running system etc. and can be up to 90% for applications such as in the aerospace. Thus, reducing the weight of the running system can reduce the metal loss in fettling as can be seen in section 4 of the present paper. Machining (including grinding, drilling, milling etc.) contributes to metal losses as well. Obviously the closer the casting is produced to net shape, the need for machining operations is reduced. The yield is finally affected by the rejections during the inspection process. Defects such as poor tolerance, poor surface finish, inclusions and porosity lead to rejection during the inspection. The last three types of losses are internal scrap. These losses can contribute up to 90% of the metal loss in the casting process, therefore energy savings can be achieved by reducing such losses during the casting process. Table 1 summarizes the energy loss and methods for saving for each process phase.

3. The CRIMSON process

As indicated in the previous section energy savings can be achieved in a foundry environment, if less fuel and less material are used for producing a certain quantity of sound products. As shown by Salonitis et al. (2016), energy savings can be achieved in two ways: direct savings through lower fuel consumption and indirect savings through lower material consumption. Auditing both the material and the energy flow of a conventional sand casting process (Fig. 5) proves these possibilities. Direct energy savings can be achieved in the process phases of melting, refining and holding since they consume more than 50% of the total energy involved in

Table 1
Summary of energy loss and opportunities for energy saving during each operation (Salonitis et al., 2016).

	Energy loss reason	Saving method
Melting	1 Inefficient melting 2 Permanent metal loss	1 Correct size of furnace 2 Rapid melting 3 Keep melt away from air
Refining	Permanent metal loss	1 Using high quality charging metal 2 Cleaning melting
Holding	1 Long-term holding 2 Permanent metal loss	Reducing the holding time
Fettling	Low casting yield	Increase the casting yield
Machining	Rough shape of casting	Making net shape casting
Inspection	Defects such as inclusion, poor surface finish, porosity	1 High-quality melting 2 Good running system

Table 2
Comparison of conventional and CRIMSON melting processes.

Melting process	Energy consumption (GJ $tonne^{-1}$)	Energy efficiency (%)	Nominal energy efficiency (%)	GHGs emission (kg/tonne casting)
Conventional 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

casting. The indirect savings can be achieved on the other hand in the fettling, machining, and scrap as at least 70% of metal by weight of the total melting is removed in these phases (Zeng et al., 2014).

As an alternative casting process that considers these findings, 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. The method is based on using an induction furnace for melting the metal in a closed crucible. Using such approach, only the quantity of metal required to fill a single mould is molten 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 (see Table 2) and simultaneously the possibility of hydrogen absorption and formation of surface oxide film are decreased largely. Furthermore, the highly controlled metal flow that is pushed into the mould to finish the pouring and solidification reduces the defect generation.

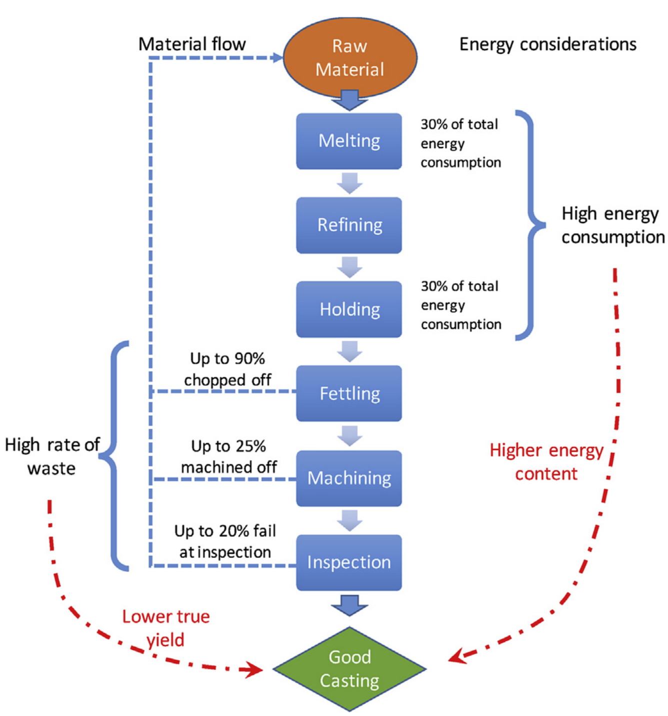


Fig. 5. Material and energy flow chart of a conventional sand casting process.

As highlighted, the furnace melts the correct amount of metal for a single-shot casting. During the melting, the proximity of the lid helps achieve fast melting and precision. Thus, the molten metal has less chance to react with the atmosphere to form an oxide film or to absorb hydrogen; and degassing and drossing (refining stage) become unnecessary processes in this casting process. The quality of the raw material is of paramount importance as has been already highlighted for reducing the generation of defects that could lead afterwards to rejections. CRIMSON process uses pre-alloyed high-quality metal for the casting process. The holding duration is minimum as the raw material is melted in a “just-in-time” fashion. As indicated, reducing the time of the holding can reduce energy consumption and metal loss. Considering that the holding process can consume up to 30% of the casting energy, eliminating this stage can plug a significant drain of energy consumption.

Tredje et al. (2009) claim that by optimizing the casting system, the yield in foundries can be improved by a minimum of 5%, with the associated savings in power consumption. CRIMSON is using a counter-gravity filling method, the liquid metal is pushed into the casting system through a bottom gate. Thus, quiescent and turbulence-free filling can be achieved, which reduces the generation of defects during this stage and ultimately, reduces the quantity of scrap (Campbell, 1997). This up-casting method redefines the casting running system and the pouring basin and down-sprue are no longer required. The importance of this feature is analysed in the following section using numerical analysis. Savings achieved during the fettling, machining and inspection stages of the process are all indirect savings. All of these processes achieve savings by increasing the casting yield. Based on these concepts, the CRIMSON casting process combines direct and indirect saving methods; thus, achieving energy savings in a more efficient way. The energy and material flow diagram of the CRIMSON process is shown in Fig. 6 as a comparison to the sand casting process.

In the following sections, the gain due to the better filling method that CRIMSON system uses is analysed using numerical simulation. Furthermore, the direct energy savings due the use of induction furnace are analytically estimated. Finally, the environmental impact is going to be assessed using life cycle assessment.

4. Validation of the indirect energy savings through numerical simulation

As indicated in the previous sections, redesign of the running system can result in great material and energy savings. The CRIMSON process for this reason is using counter-gravity filling system as indicated in the previous system. The potential savings can be assessed using simulation.

Computational fluid dynamics models (CFD) have been widely used in the past for the design optimization of both the final product and the moulds in casting. Starting from the product design, the behaviour of the fluid inside the casting running system and the performance of the feeder during solidification can be predicted. This allows foundry engineers to develop sound products without doing physical experiments using trial and error.

For the simulation of the runner system of a test case, the FLOW3D CFD software was used. The test case selected was a typical "tensile bar" and the running system was designed for both typical sand casting gravity filling and the counter gravity CRIMSON filing method (Fig. 7).

The velocity of the liquid metal is always a big concern in the design of a running system. Maintaining the velocity of the aluminium below 0.5 m/s is always good practice for maintaining casting quality (Campbell, 1997). The velocity of the liquid metal during filling is shown in Fig. 8. For the CRIMSON process the maximum velocity is estimated to be 0.4 m/s. This flow of liquid metal in the runner system is ideal for avoiding the generation of trapped oxide films, porosity and other casting defects. In addition, the counter-gravity filling method in CRIMSON process decreases the exposure time to air thus reducing the opportunity to generate damaging oxide film inclusions.

The filling process of the gravity filled investment casting process was also simulated, and the maximum velocity of liquid metal flow in down-sprue and in runner exceeded 1.0 m/s. Such violent and turbulent flow will easily entrain the oxide films on the liquid surface and trap them into the metal. Although a filter in the runner system can sieve out the coarse particulate inclusions from the liquid metal; the finer oxide films will still pass through the filter. After solidification, the remaining fine oxide films have shown to generate defects such as porosity and shrinkage. The turbulent flow behaviour will result in air entrapment into the liquid increasing porosity or forming bubbles which will affect the mechanical properties of the casting. Additionally, the long transfer time from furnace to ladle and the use of traditional gravity filling methods exposes the liquid metal to air for a longer time, which increases the possibility of forming oxide films on the surface of the liquid metal.

Thus the CRIMSON counter-casting filling process considerably reduces the possibility of oxide film generation on the surface of the liquid metal and the available time for hydrogen absorption from the atmosphere by reducing time for the reduction of atmospheric moisture. Furthermore, due to the different design of the mould (lack of down-sprue for example), the material lost during fettling is reduced. In the case described here, for an estimated 1 kg of raw aluminium, the material loss due to fettling and machining is reduced from 0.76 kg down to 0.60 kg, which is a 21% reduction.

5. Validation of direct energy saving by CRIMSON casting process

In order to assess the impact of using an induction furnace instead of a conventional gas fired furnace for melting the raw and recycled material, an energy balance analysis was conducted. The energy balance for these two cases is shown schematically in Fig. 9.

The energy requirements of the gas furnace can be

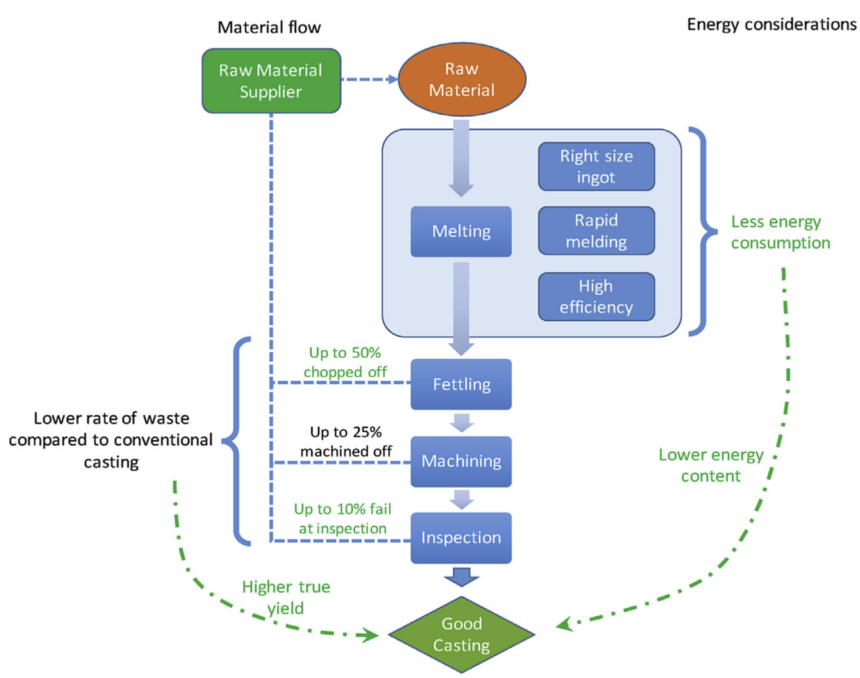


Fig. 6. Material and energy flow chart of a CRIMSON sand casting process.

Fig. 7. Tensile bar casting system used (left) in gravity sand casting and (right) counter-gravity (up casting) CRIMSON sand casting process.

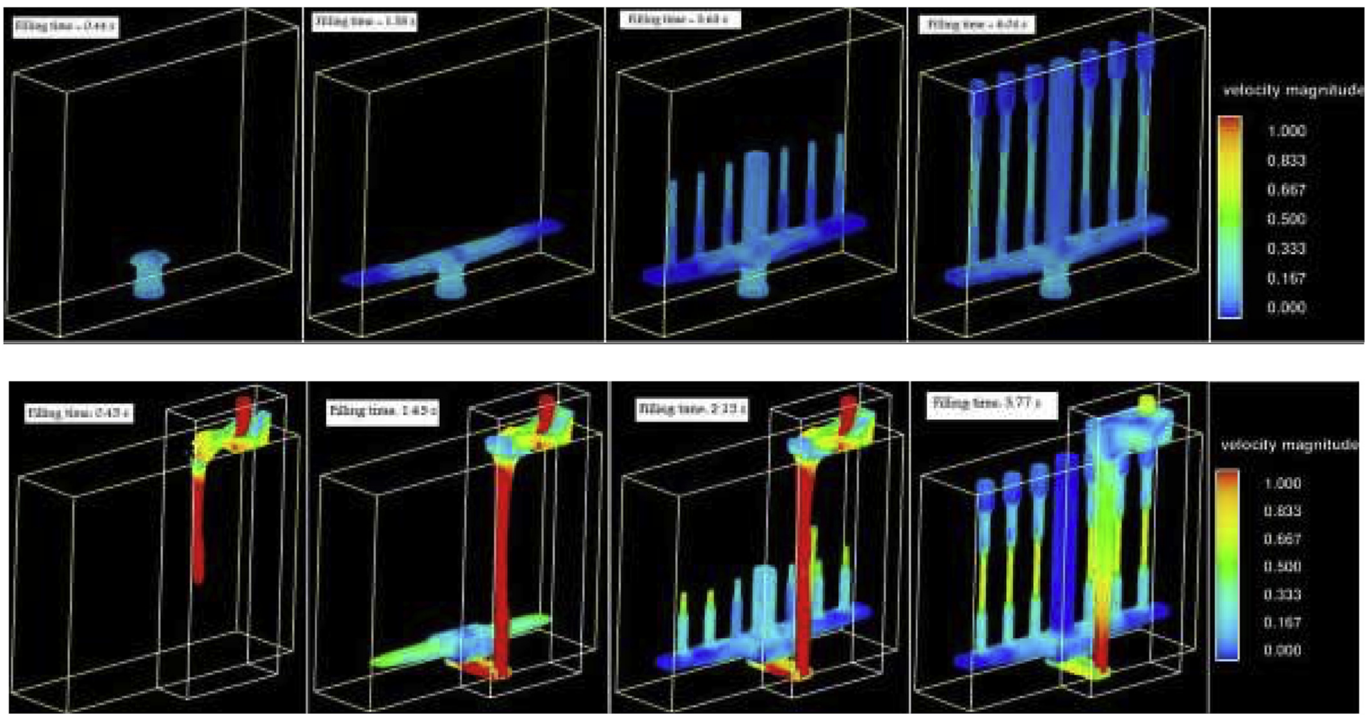


Fig. 8. Numerical simulation of runner system of tensile bar for CRIMSON (up) and conventional sand casting process (down).

mathematically expressed as:

$$E_{in} = E_{fuel} + E_{ingot} + E_{cob\_air} \quad (1)$$

Where E_{fuel}, E_{ingot} and E_{comb_air} are the energy generated from fuel combustion, aluminium ingot, and combustion air respectively. In the present analysis only the energy from the fuel combustion is considered. The energy output of the furnace is then:

$$E_{out} = E_{melt} + Q_{mis} = (E_{ingot} + \Delta E_{Al}) + Q_{mis} \quad (2)$$

Where E_{melt} is the heat transferred to the molten metal; ΔE_{Al} is the energy variation of the metal from ingot to molten metal; and Q_{mis} the energy loss during the melting in the furnace chamber.

The efficiency of the furnace can be estimated from the following equation.

$$n = \Delta E_{Al}/E_{fuel} \quad (3)$$

For the CRIMSON process, the equations need to be replaced with the following three:

$$E_{in} = E_{electricity} + E_{billet} \quad (4)$$

$$E_{out} = E_{melt} + Q_{mis} = (E_{billet} + \Delta E_{Al}) + Q_{mis} \quad (5)$$

$$n_c = \Delta E_{Al}/E_{electricity} \quad (6)$$

Similarly, the energy generated from aluminium billet is considered negligible. Energy auditing, as structured by Dai et al. (2011) was used for collecting energy data from a local foundry and the CRIMSON experimental facility available at Cranfield University. The analysis results are shown in Table 2. The energy efficiency estimations are validated by comparing with the nominal efficiencies provided by the furnace manufacturers. The green house gas (GHG) emissions were estimated using the Greenhouse Gas Protocol. It is evident that the furnace used for the CRIMSON process is more efficient mainly due to the fact that the energy

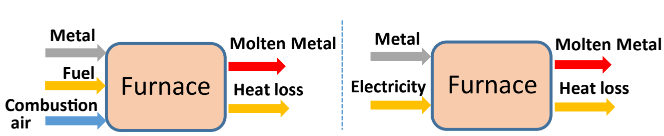


Fig. 9. Energy balance in a conventional melting furnace (left) and in the induction furnace for CRIMSON process (right).

source is electricity and the energy transfer is by induction rather than conduction.

6. Life cycle analysis comparison

The previous section focused on the efficiency of the melting furnaces. However, this cannot be used as a representative metric for assessing the environmental impact of the whole process. Life Cycle Assessment (LCA) method can deliver this. As indicated by Yilmaz et al. (2015), LCA can be used as a decision support tool for improving the energy efficiency practices in foundries. According to the ISO 14040 standard, LCA can be defined as a four-phase process: goal definition and scoping, inventory analysis, impact assessment and interpretation. The primary goal thus was set to be to compare the CRIMSON process with the conventional sand casting for the production of the tensile bars. The life cycle of the production system of the tensile test bar includes raw material production, manufacturing, production use and recycling. Because the same product is produced by both casting processes, the use phase of the tensile test bar (tensile test) is not included in this LCA. One of the key decisions thus that are required early in the implementation of LCA is defining the boundaries of analysis, in order for the two alternatives to be compared meaningfully (Fig. 10). For both casting processes, the material and energy required for each operation were estimated. However, due to complexity of the mould making process, the embedded energy was adopted to represent it.

Life cycle inventory (LCI) analysis is a process by which the input and output of a product, service, or activity are quantified. The input refers to the initial design, energy and raw material. The output refers to atmospheric emissions, waterborne waste, solid waste, co-products and other releases throughout the entire life cycle. This means that all the resource inputs and emission outputs involved from raw material extraction to the final disposal of the product need to be understood. Appendix 1 demonstrates the entire life cycle of the sand casting product. As the colours indicate, the life cycle of a casting product can be divided into six phases: metal extraction (yellow - also known as primary aluminium production), extraction of sand and its additives (green), casting (red - Casting can be treated as secondary aluminium production), mould making (light blue), use (dark blue) and disposal (purple). Meanwhile, the energy and material inputs are shown by black arrows and the emission outputs are shown by red arrows.

Every single step in the life cycle has inputs and outputs. Starting from the metal extraction process, the following factors need to be considered: the energy consumption for bauxite mining, alumina production, electrolysis and ingot casting; the material consumption of caustic soda, limestone, petrol coke, aluminium fluoride and so on. Similarly, each phase in the life cycle needs to go through the same investigation to collect data for the LCA.

Taking into consideration the system boundaries, the required data can be identified and collected. The energy and material consumption for primary ingot production are the hardest to estimate. Therefore, the LCA simulation package inventory database was used as a source, that however are in agreement to previous studies such as the ones presented by Tan and Khoo (2005), and Norgate et al. (2007). For sand mould making process, energy and material audit was performed. The LCA was conducted in Simapro software. Four scenarios were modelled: conventional casting and CRIMSON casting with and without recycling. Different inventory data were used for the raw material depending on whether recycling was used or not.

The loss in melting, holding, and degassing operations are oxidation and impurities loss. They are treated as permanent loss. The recycling in this study refers to the reuse of the high energy content metal removed from fettling, machining, and scrap. They can be recycled to reduce the virgin aluminium requirement. Therefore, the raw aluminium input can be divided into three categories: permanent loss, scrapped, and final product, which refers to non-recyclable, recyclable, and other. Beside the metal input, sand is also required. Assuming a metal and sand ratio of 1:6, the sand required for sand mould is 40 kg for the CRIMSON test bar, and 76 kg for the conventional test bar based on the optimized design from section 3. The material needed for sand mould can be 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.

Two impact assessment analyses were run: the Eco-indicator 99 HA and the Eco-Points 97. Eco-Indicator expresses the emissions and resource extractions in 11 impact categories. The conclusions drawn from this analysis (see Fig. 11) are 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. Comparing CRIMSON with conventional casing though, the CRIMSON process has almost half the impact.

Eco-Points is based on actual pollution and on critical targets that are derived from Swiss policy. The emission results are compared with the target values set by government. Similar to Eco-Indicator, the use of CRIMSON process reduces significantly the environmental impact of the casting. 55% of impact can be reduced when using recycling in the CRIMSON process and 55% of impact can be reduced for conventional process (see Fig. 12).

7. Conclusions

The purpose of this paper was to assess the potential energy and resource savings when using CRIMSON process as an alternative casting process. For this reason, CRIMSON process was compared to conventional sand casting as a case study. The validation was performed through mould design optimization and environmental impact assessment. Using CFD the casting system design can be optimised, and for the case presented this resulted in 21% material

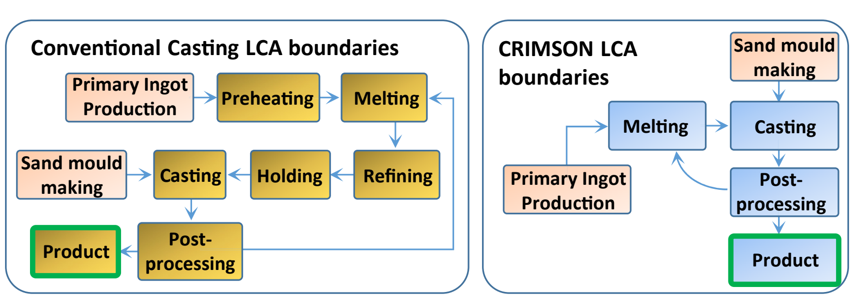


Fig. 10. System boundaries for the LCA of both casting processes.

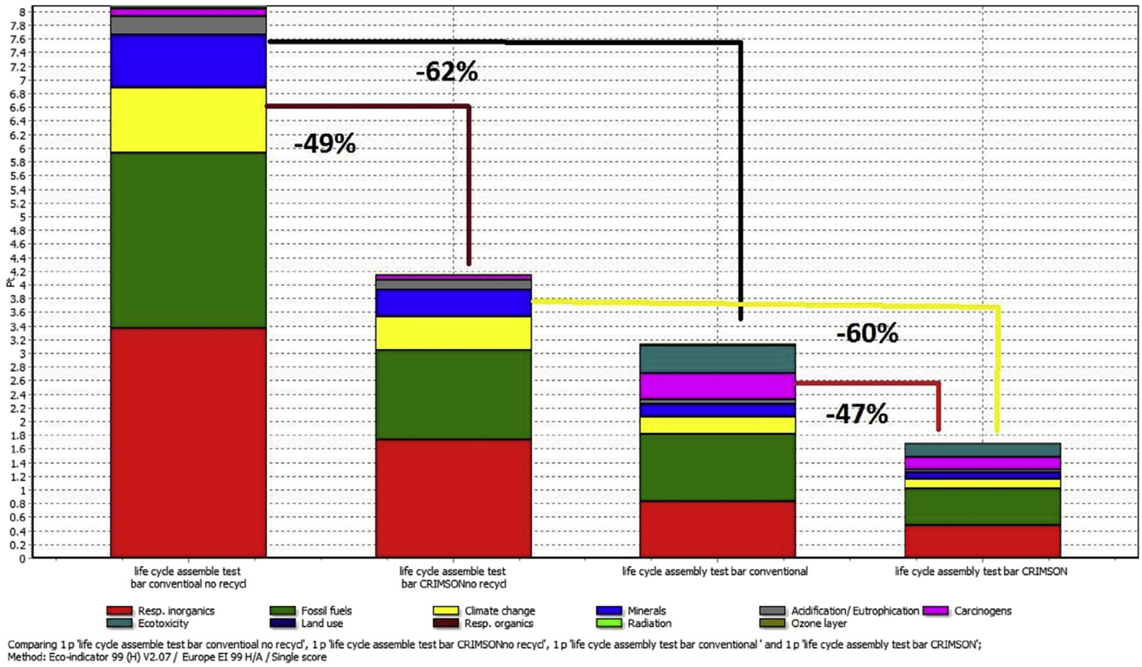


Fig. 11. ECO-indicator single score results for the four casting scenarios.

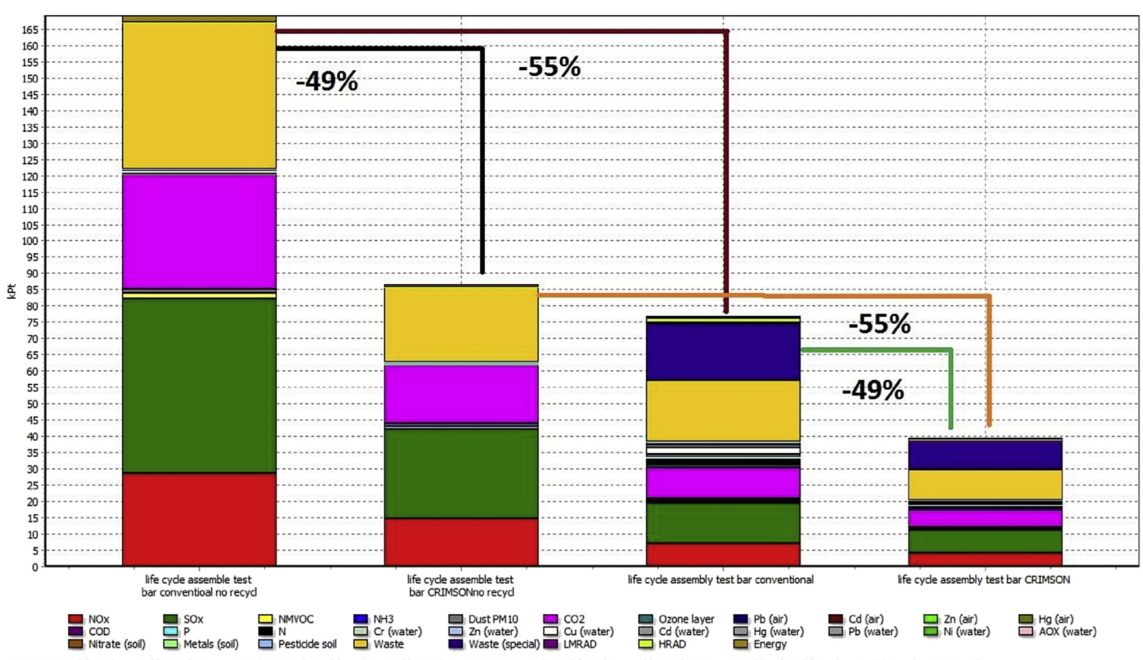


Fig. 12. ECO-point single score results for the four casting scenarios.

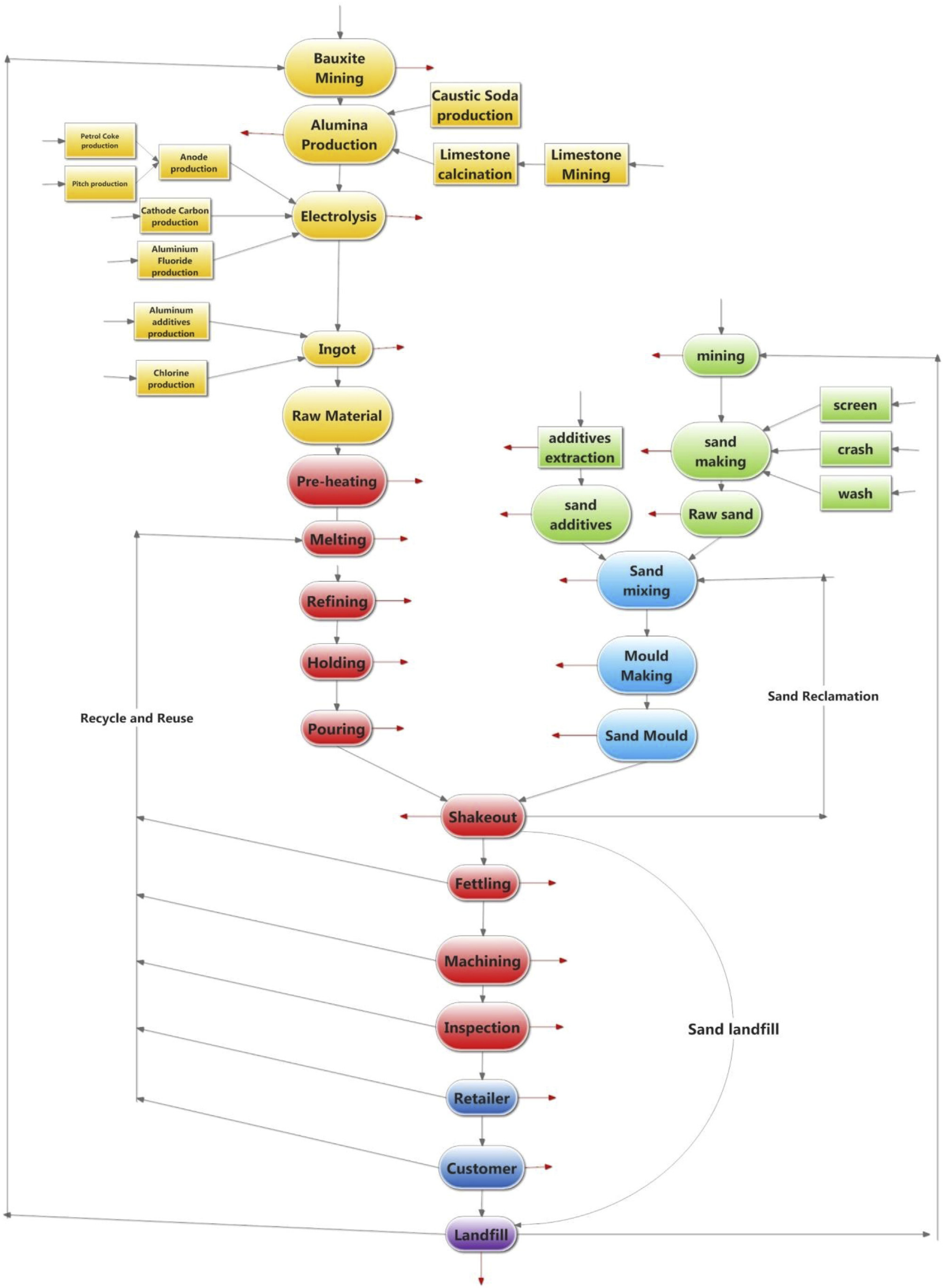
loss reduction. Based on the LCA analysis, using two different assessment methods, it was shown that the environmental impact can be reduced in average by 57% when using CRIMSON instead of conventional sand casting process.

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. It saves energy through holding free casting production and high OME. With regard to quality, the up-casting process provides a turbulence-free filling, which means that defects, such as air entrapment and DOF formation can be minimised.

Acknowledgements

The authors would like to acknowledge the UK EPSRC Small is Beautiful (EP/M013863/1) project for the support of this work. All data are provided in full in this paper.

Appendix 1. Schematic of the entire life cycle of the sand casting product.



References

BCS Incorporated, 2005. Advanced Melting Technologies: Energy Saving Concepts and Opportunities for the Metal. Casting Industry U.S. Department of Energy can be retrieved from: http://www1.eere.energy.gov/manufacturing/resources/metalcasting/pdfs/advancedmeltingtechnologies.pdf (accessed 02.04.16.).

Cast Metal Federation 2016. Website: http://www.castmetalsfederation.com/ (accessed 31.03.16.).

Campbell, J., 1997. Ten rules for good casting. Mod. Cast. 97 (4), 36–39.

Dai, X., Jolly, M.R., Zeng, B., 2011. The capability enhancement of aluminium casting process by application of the novel CRIMSON method. In: Shape Casting. John Wiley & Sons, Inc., pp. 265–272

Dalquist, S., Gutowski, T., 2004. Life Cycle Analysis of Conventional Manufacturing Techniques: Sand Casting. ASME International Mechanical Engineering Congress and RD&D Exposition, Anaheim, California, USA url: http://web.mit.edu/skd/www/casting/casting-v2.pdf (accessed 02.04.16.).

Department of Energy & Climate Change, UK, (2011). Website: https://www.gov.uk/government/organisations/department-of-energy-climate-change (accessed 02.04.16.).

DETR, 1997. Energy Consumption Guide 38 Non-ferrous Foundries, second ed.

Duflou, J.R., Sutherland, J.W., Dornfield, S., Herrmann, C., Jeswiet, J., Kara, S., Hauschild, M., Kellens, K., 2012. Towards energy and resource efficient manufacturing: a processes and systems approach. CIRP Ann. – Manuf. Technol. 61, 587–609.

Fatta, D., Marneri, M., Papadopoulos, A., Savvides, Ch, Mentzis, A., Nikolaides, L., Loizidou, M., 2004. Industrial pollution and control measures for a foundry in Cyprus. J. Clean. Prod. 12, 29–36.

Girish, C.P., Naik, G.R., Naik, P.G., 2012. Application of process activity mapping for waste reduction, a case study in foundry industry. Int. J. Mod. Eng. Res. 2 (5), 3482–3496.

Kukla, S., 2011. Maintenance system improvement in cast iron foundry engineering. Arch. Foundry Eng. 11 (3), 185–188.

Lazzarin, R.M., Noro, M., 2015. Energy efficiency opportunities in the production process of cast iron foundries: an experience in Italy. Appl. Therm. Eng. 90, 509–520.

Norgate, T.E., Jahanshahi, S., Rankin, W.J., 2007. Assessing the environmental impact of metal production processes. J. Clean. Prod. 15, 838–848.

Salonitis, K., Ball, P., 2013. Energy efficient manufacturing from machine tools to manufacturing systems. Proced. CIRP 7, 634–639.

Salonitis, K., 2015. Energy efficiency assessment of grinding strategy. Int. J. Energy Sect. Manag. 9 (1), 20–37.

Salonitis, K., Zeng, B., Mehrabi, H.A., Jolly, M.R., 2016. The challenges for energy efficiency casting processes. Proced. CIRP 40, 24–29.

Tan, R.B.H., Khoo, H.H., 2005. An LCA study of a primary aluminum supply chain. J. Clean. Prod. 13, 607–618.

Tredje, N.S., Drivsholm, C., Crepaz, R., 2009. Resource savings by optimising process conditions in foundries. Foundry Trade J. 156–158. June 2009.

Trianni, A., Cagno, E., 2012. Dealing with barriers to energy efficiency and SMEs: some empirical evidences. Energy 37 (1), 494–504.

Trianni, A., Cagno, E., Thollander, P., Backlund, S., 2013. Barriers to industrial energy efficiency in foundries: a European comparison. J. Clean. Prod. me 40, 161–176.

Yilmaz, O., Anctil, A., Karanfil, T., 2015. LCA as a decision support tool for evaluation of best available techniques (BATs) for cleaner production of iron casting. J. Clean. Prod. 105, 337–347.

Zeng, B., Jolly, M.R., Salonitis, K., 2014. Manufacturing cost modelling of castings produced with CRIMSON process. TMS Annu. Meet. 201–208.

Improvements in energy consumption and environmental impact by novel single shot melting process for casting

Salonitis, Konstantinos

2016-06-29

Konstantinos Salonitis, Mark R. Jolly, Binxu Zeng, Hamid Mehrabi, Improvements in energy consumption and environmental impact by novel single shot melting process for casting, Journal of Cleaner Production, Volume 137, 20 November 2016, pp1532-1542

http://dx.doi.org/10.1016/j.jclepro.2016.06.165