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Investigating the energy consumption of casting process by multiple life cycle method

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Abstract The Constrained Rapid Induction Melting Single Shot Up-Casting (CRIMSON) process is an alternative casting process to conventional casting that can be used for small to medium batch production. The aim of the process is to improve the casting quality and reduce the energy consumption within light-metal casting industry. Multiple life cycle method was used in this paper to investigate the energy consumption of the casting process. From the investigation, it was shown that energy consumption of the casting production is influenced by the Operational Material Efficiency (OME): the higher the OME the lower energy consumption of the casting production. It is concluded that the CRIMSON Process only use 23% of energy compared with conventional method for the same casting production. By adopting the CRIMSON method, 130 GJ/tonne of energy can be saved for aluminium casting production.

1. Background

Casting is the manufacturing process of pouring molten metal into a mould and then allowing it to solidify. It is often used to manufacture complex parts, which are too expensive or too time consuming to produce by other methods.

Because the UK remains at the forefront of light metal casting and investment casting technologies, it has wide experience in the design and manufacture of energy efficient products, which are hugely beneficial for the aerospace and automotive industries. Therefore, even with the high volume of foundry decline, the proportion of aluminium casting has increased from 9% to 20% from 1999 to 2010.

Energy consumption of casting process

As a starting point, the annual casting production, energy consumption and energy price for aluminium foundries needs to be understood. The only data available for aluminium foundries was published in 1996 (DETR, 1997). At that time, in average 55 GJ of energy was required to produce one tonne of aluminium casting (Jolly, 2010). However, the aluminium foundry sector has not reported any useful data since then. Thus these data may be outdated and unrepresentative of the current situation. For this reason, the energy consumption of aluminium casting needs to be reinvestigated. From the UK Industry Energy Consumption data catalogue (Office for National Statistics, 2012), the energy consumption for entire aluminium industry can be found. The data coverage is from 2003 to 2010. However, this data includes energy consumption for all aluminium production, which includes cast, wrought and machined, etc. Therefore, the UK Monthly Digest of Statistics (2000) (2002) (2007) was used to investigate the contribution of the casting products. The coverage of the data is from 1995 to 2007. For the annual production of aluminium castings, either the Monthly Digest or the Census of World Casting Production (WFO, 2003) (WFO, 2004) (WFO, 2005) (WFO, 2006) (WFO) (WFO, 2008) (WFO, 2009) (WFO, 2010) is used, from which the weight of production can be discover. Figure 1 presents the annual UK casting production. As it can be seen the total production declines in the period reported, mainly due to the shrinkage of ferrous foundry sector. The non-ferrous foundries steadily increase their proportion over time. The UK foundry data comes from the 34th and the 38th to 45th Annual Census of World Casting Production.

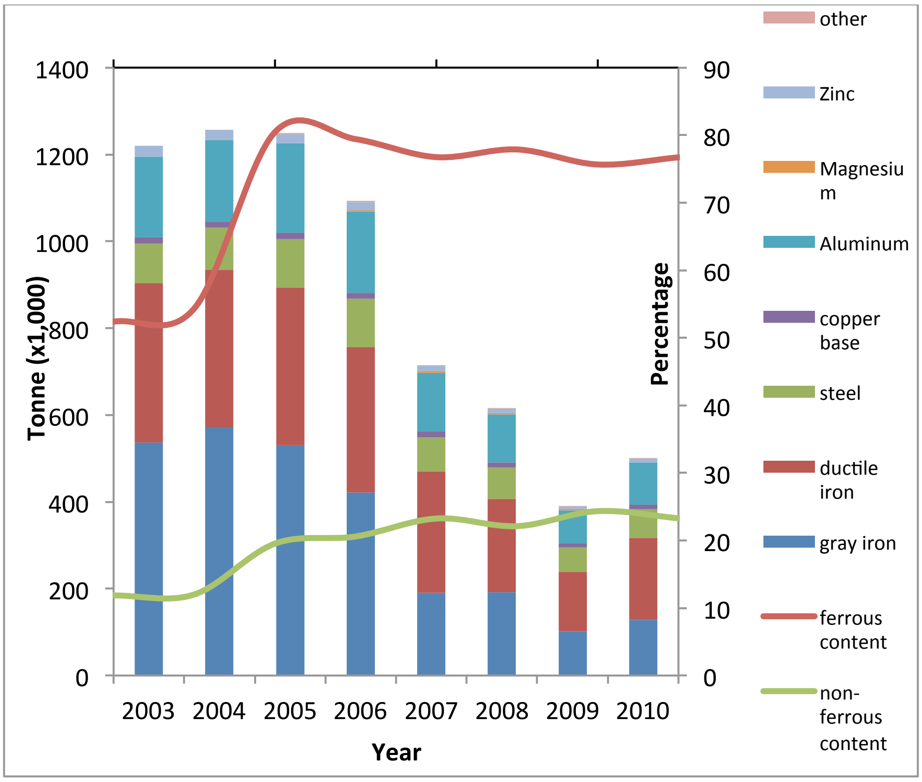

Figure 1 UK annual casting production. The secondary axis is for the metal content

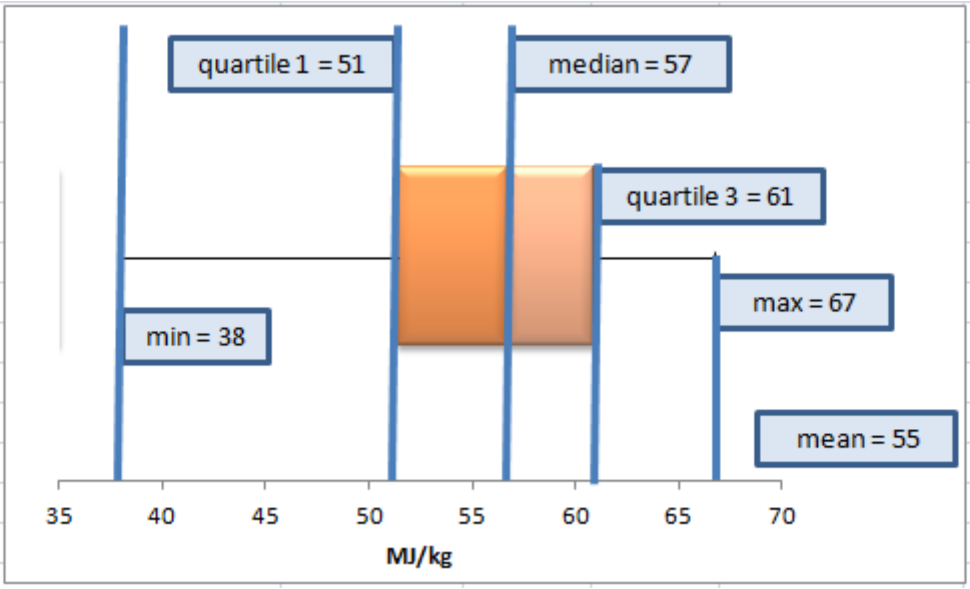

Figure 2 Box plot showing the distribution of energy burden from 1993 to 2010

Figure 2 presents the results of the investigation of the energy burden of the aluminium casting foundry sector. The variation of the energy burden is between 38 and 67 MJ/kg, and the average energy burden is 55 MJ/kg. Compared with 1996 results, it can be safely assumed that UK aluminium foundry sector is more focused on products energy efficiency rather than process efficiency.

2. Literature review

Previous research

The energy request of a process to operate affect the energy cost in the total variable costs and thus to the value of the product (Subrahmanya, 2006). The more energy consuming a process is, the greater the cost of the process. Within manufacturing environments, energy efficiency importance has grown, and it is now considered among other decision-making factors such as productivity, cost and flexibility (Salonitis and Ball, 2013). For this reason, a number of research studies have been reported that aims to identify opportunities for energy saving. Generally, energy saving can be achieved through several techniques and methods, a few of which are outlined hereafter:

Klugman and Karlsson performed an energy audit at a chemical wood pulp mill in Sweden (Klugman, et al., 2006). They used the surveyed data from the pulp mill to identify the saving potential. Their work revealed that the company should update their equipment to reduce their energy consumption by 50%. Furthermore, they found that compressed air has a significant energy consumption and that it would be better to reduce the usage of compressed air. Kabir and Abubakar performed a similar audit in a cement production plant (Kabir, et al., 2010). They discovered that the thermal energy efficiency was quite low; significant thermal energy escaped through the exhaust gas and kiln shell. They suggested that a new waste heat recovery steam generator should be introduced into plant to increase the thermal efficiency.

However, audit methods only provide theoretical figures about energy saving and often simply suggest major equipment updates or exchange. This kind of energy efficiency management often requires significant capital investment on new equipment. Comparing energy saving and capital investment, Anderson and Newell (2003) pointed out that plants are 40% more responsive to initial cost rather than annual saving. With regard to new equipment and the adoption of new technology for long-term savings, organisations prefer projects with shorter payback times, lower costs and greater annual saving. Therefore, it is not surprising that Thollander's (2010) research indicated that about one-half of the foundries in Sweden lack a long-term energy strategy and only about 25% may be categorised as having a successful energy management practice (Ottosson, 2010).

Further evidence for this can be found in the Climate Change Agreement published by UK Government (Anon, 2011). According to the agreement, the foundries sector needs to attain an energy burden target of 25.7 GJ/tonne by 2010. However, the average energy burden for the UK foundry sector is 46 GJ/tonne (Statistics, n.d.). A company runs its business for profit. No matter what strategy is employed by the company, the priority is profit and energy saving could be one of the many goals within this strategy. It is more likely that a firm may operate based purely on the benefits of cost saving rather than energy saving. Furthermore, according to Thollander's research (Thollander & Ottosson, 2008) (Thollander & Ottosson, 2010), there are several barriers that prevent a company becoming energy efficient. They identified that the main barriers are technical risks, such as the risk/cost/hassle/inconvenience of production disruptions, inappropriate technology for the operation, lack of time and priorities, lack of access to capital and slim organisation. In particular, for small enterprise foundries, the lack of time, proper personnel and insufficient resources are the largest barriers to energy efficiency (Trianni, 2012). Unfortunately, this is quite true for most UK foundries; many of the UK's foundries are small and medium enterprises.

Salonitis and Ball (2013) summarized the main barriers that companies face when they try to implement energy efficiency initiatives, concluding that although three major categories of barriers exist, i.e. economic, behavioural and organization; the key for succeeding is the broad acceptance of such initiatives must have been achieved in advance from the human resources.

Fundamentals of energy saving

In the casting industry, instead of direct energy saving through huge investments in new equipment, a new technique was introduced to eliminate waste, improve quality and eventually, achieve the goal of energy saving. This technique is called Constrained Rapid Induction Melting Single Shot Up-casting Method (CRIMSON) process. It is specially designed for the light alloy foundry sector.

Energy saving can be achieved in two ways: direct savings through lower fuel consumption and indirect savings through lower material consumption. Therefore, the rule for energy saving in the foundry sector is simple; use less fuel and less material in making a certain quantity of sound products (summarised in table 1). To accomplish this, an understanding of the flows of energy and materials in the casting process is required. Figure 3 presents the material flow for the conventional casting. This can be divided into six sub-processes: melting, refining, holding, fettling, machining and inspection. The melting, refining and holding activities consume most of the energy involved in casting (at least 60%); thus, the direct energy savings should be achieved in this step. Fettling, machining, and scrap contain at least 70% metal by weight of the total melting; thus, the indirect saving should come from these three processes.

The CRIMSON process

Based on these concepts, the novel CRIMSON casting process combines direct and indirect saving methods; thus, achieving energy savings in a more efficient way. Instead of using cheap bulk metal, the CRIMSON process uses pre-alloyed high-quality metal for the casting process. Moreover, the CRIMSON casting process uses a rapid induction furnace to melt just enough metal for a single casting. The time for melting is normally under 10 minutes, which reduces significantly the chance of the oxidation and hydrogen absorption. Therefore, the refining stage of the operation is no longer necessary. Because of the single melting, the melt can be transfer to the pouring operation immediately; thus, the holding operation can be also removed from the casting process. 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.

Owing to the new filling feature of the CRIMSON process, the liquid metal is pushed into the casting system through a bottom gate. This up-casting method redefines the casting running system and the pouring basin and down-sprue are no longer required. Because of the new running system, less metal is fed into the running system and thus, the casting yield increases. With regard to quality, the up-casting process provides a turbulence-free filling, which means that defects, such as air entrapment and DOF[1] formation can be minimised. The quality of the casting can be improved and fewer rejections reduce the energy consumed for re-working.

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

Table 1 Summary of energy loss and opportunities for energy saving during each operation

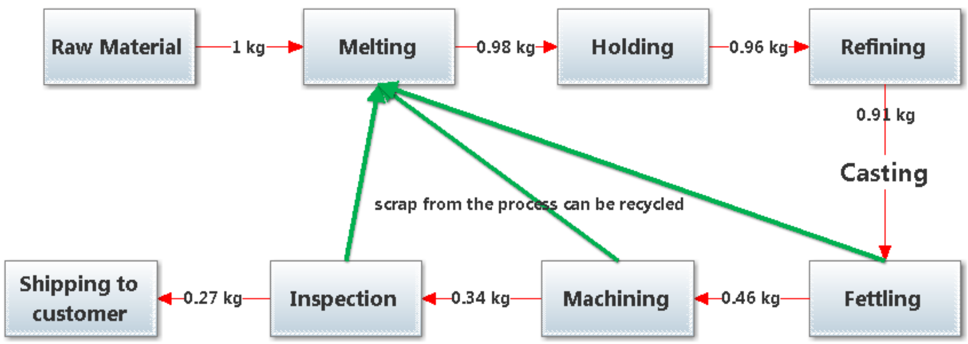

Figure 3 general example of Metal flow in a conventional aluminium foundry

3. Methodology

[1] Double oxide film (DOF) is a defect during casting production.

The multiple life cycle method is adopted to investigate the performance of the CRIMSON process. This method is used to calculate the environmental cost of a material that undergoes recycling and reuse (Brimacombe, et al., 2005). It focuses on the impact of the product production phase and not on the use of the product. It is a useful tool for investigating the material flow and energy burden over a series of life cycle stages (Brimacombe, et al., 2005).

Since the CRIMSON process is relatively new technique, there is no data available to benchmark its performance. However, due to high quality of CRIMSON casting products, its performance is assessed through a comparison with the aerospace investment casting process.

In order to collect energy consumption data using the multiple life cycle method, it is important to measure or estimate the following factors:

Process yield (Y): This is used to describe the true mass loss from a unit, normally less than 1 (Jolly, 2010). The true mass loss in an aluminium foundry can be defined as the oxides loss during the melting, holding and degassing. The fettling, machining and scrap are not taken into consideration because they can be recycled.

Recovery Ratio (RR): This is the parameter which considers the recycle from the process as a percentage of the material put in (Jolly, 2010). It includes the fettling loss, the machining loss and the scraps. As research has shown, the worst case RR for a general/automotive foundry can be estimated at 64%. For quality reasons, the RR can be as high as 86% in an aerospace foundry (Jolly, 2010).

Recycling Efficiency (r): This factor represents how efficient the process is over one production cycle. It is the product of the process yield and the recovery ratio (Jolly, 2010).

$$\boldsymbol{r = Y \times RR} \qquad \textbf{Equation 1}$$

To calculate the energy burden for different foundry sectors by using the multiple life cycle approach, the following equations are required.

The total mass (M) passing through the chosen number of production cycles[2] (n), (Jolly, 2010)

$$\boldsymbol{M = 1 + r + r^2 + \cdots + r^{n-1}} \qquad \textbf{Equation 2}$$

[2] This production cycle includes melting, holding, refining, casting, shakeout, fettling, machining, and inspection.

The total energy consumption for the chosen number of cycles can be calculated as follows (Jolly, 2010):

$$Total\ Energy\ consumption = X_{pr} + rX_{re} + r^2X_{re} + \cdots + r^{n-1}X_{re}$$ **Equation 3**

where X_{pr} is the energy from the primary process and X_{re} is the energy for the recycling process. Normally, the primary process energy is 55 MJ/Kg and the secondary energy is only about 5% that of the primary energy (2.754 MJ/Kg) (Jolly, 2010).

By dividing the total mass passing through the cycles by the total energy consumption, the energy burden per mass (X) can be defined as below (Jolly, 2010):

$$X = \frac{X_{pr}+rX_{re}+r^2X_{re}+\cdots+r^{n-1}X_{re}}{1+r+r^2+\cdots+r^{n-1}}$$ **Equation 4**

Let n approach to infinity[3], Eq. 4 can be derived as below (Jolly, 2010):

$$X = \left(X_{pr} - X_{re}\right)\left[\frac{(1-r)}{(1-r^n)}\right] + X_{re}$$ **Equation 5**

4. Data collection

The values of RR and r need to be determined in order to find the Process Yield (Y). Assuming that there is 1 Kg of virgin aluminium before melting, after different stage of the casting operation, the weight of the saleable casting, process yield, recovery ratio and recycling efficiency are shown in table 2 (Jolly, 2010). Applying these factors into Equation 5, the LCI for different foundry sectors can be estimated and presented in Figure 4:

Traditional running system			CRIMSON running system		
Virgin aluminium	**(kg)**	1	Virgin aluminium	(kg)	1
2% Melting loss	**(kg)**	0.02	0.5% Melting loss	(kg)	0.01
2% Holding loss	**(kg)**	0.02	0% Holding loss	(kg)	0.00
5% Degassing loss	**(kg)**	0.048	0% Degassing loss	(kg)	0.000
90% Fettling loss	**(kg)**	0.821	59% Fettling loss	(kg)	0.587
25% Machining loss	**(kg)**	0.023	25% Machining loss	(kg)	0.102
20% Scrap loss	**(kg)**	0.013	10% Scrap loss	(kg)	0.030
Good casting	**(kg)**	0.054	Good casting	(kg)	0.275
Process yield	**(%)**	91	Process yield	(%)	99.5
Recovery Ratio	**(%)**	86	Recovery Ratio	(%)	74.4
Recycling Efficiency		0.783	Recycling Efficiency		0.74

Table 2 saleable casting per unity melting aluminium, process yield, recovery ratio and recycling efficiency for two different casting routes

[3] This means foundry is continuously producing castings

5. Results

Casting production energy

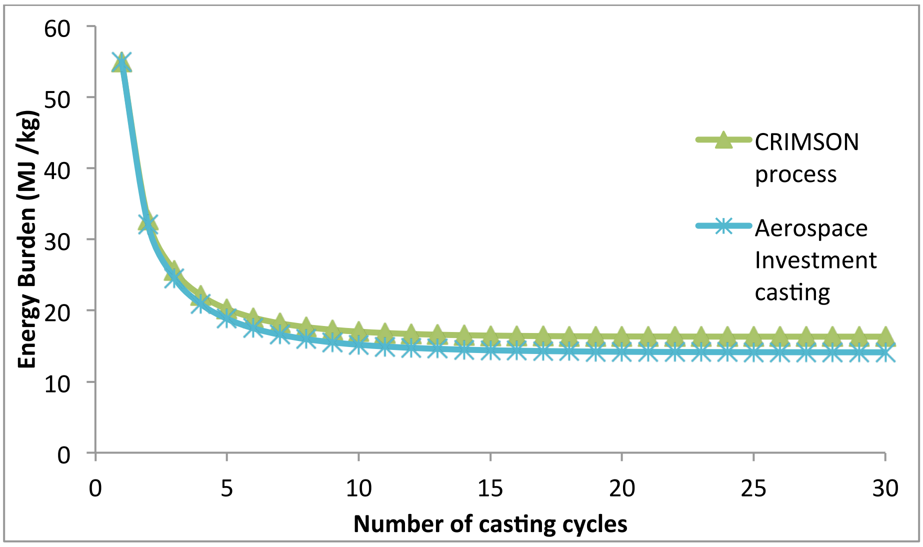

Figure 4 Melting energy burden of casting method

Figure 4 compares the melting energy burden for Aerospace route and the CRIMSON process. By using the recycled aluminium from the fettling, machining and scrap, the energy consumption of producing and using raw material can be reduced. From this graph, after 10 operation cycles of the continued recycle and reuse aluminium, the energy burden of melting is reduced to 14.14 MJ/Kg for traditional route, and 16.34 MJ/Kg for the CRIMSON process. From equation 4, it can be seen that the recycling efficiency is the only factor influencing the melting energy burden. The more material is recycled in the process, the less melting energy required.

Saleable casting[4] production energy

So far the energy burden for melting aluminium is calculated. The investment casting foundry has the lower energy burden to melt aluminium. However this result only considers the production of the casting, the energy burden of the saleable casting is not included. In order to investigate this energy, the Operational Material Efficiency (OME) is introduced to calculate the energy burden for saleable casting. It represents how much material pass through the process and is shipped to customers (Jolly, 2010).

[4] The good casting passes all operations and can be sold to customer

The operational material efficiency is defined as

$$\boldsymbol{OME} = \frac{AlMt - AlWs - AlWr}{AlMt} \times \mathbf{100}\% \quad \textbf{Equation 5}$$

Where AlMt stands for aluminium melted, AlWs stands for aluminium waste sold, and AlWr stands for aluminium waste recycled in-house.

By using the OME, the efficiency of the good casting per unit mass can be calculated. Based on the information provided in table 2, the OME for both routes can be calculated. A casting is about 1 Kg. As a result, the conventional aerospace investment casting requires 18.18 Kg of aluminium to produce saleable filter housing. The CRIMSON route only requires 3.65 Kg of aluminium. Multiplying the quantity of the metal and energy burden of melting together, the energy requirement to produce 1 kg of casting is 257.09 MJ and 59.64 MJ respectively for the conventional and the CRIMSON route.

	Conventional investment casting	**The CRIMSON process**
Virgin Aluminium (kg)	1.00	1.00
Good Casting (kg)	0.05	0.27
Recycling Efficiency	0.78	0.58
OME (%)	5.5%	27.4%
The Weight of good casting (kg)	1.00	1.00
Metal required to produce a filter housing (kg)	18.18	3.65
Energy burden of melting for recycle aluminium (MJ/kg)	14.14	16.34
Energy for good casting (MJ)	257.09	59.64

Table 3 OME for both route and the energy consumption for them to produce one filter housing

6. Discussion

By using the recycled aluminium from the fettling, machining and scrap, the energy consumption of producing and using raw material can be reduced. The energy burden of melting is reduced to 14.14 MJ/Kg for conventional investment casting process, 16.34 MJ/Kg for the CRIMSON process. Comparing with primary melting energy (55 MJ /kg), the recycling and reusing route bring down the energy requirement of casting production. The reason why the conventional investment casting has lower melting energy burden is because of the recycling efficiency. According to equation 5, the energy burden is totally relying on the recycling efficiency: the higher value of the recycling efficiency, the lower energy burden of the melting. It is very easy to find out that the biggest metal loss is by fettling loss from table 2. As a typical aerospace casting product, chunky and heavy casting running system is used to ensure the casting quality. Assuming 1kg of good casting is produced, 9 kg of molten metal need to be yielded into the casting running system. On the other hand, the CRIMSON process only yields 1.4 kg of metal into the running system (casting yield 48%). Because the investment casting process recycles more high energy content metal, it is make sense that such process has lower production energy burden.

However, even the investment casting process has the lower production energy burden. It still produces 0.055 Kg of good casting per unit mass of the metal melted. As a result, it only gives 5.5% of OME and requires 18.18 Kg of metal to make 1 kg of good casting cost 257 MJ energy. By contrast, the CRIMSON process uses much less energy. Because the casting yield is increased, the utilization of the metal is much higher than the Investment casting method. Compared with the conventional casting method, the OME is increased from 5.5% to 27.4%. The energy required to produce 1 kg of good casting reduced from 257 MJ to 59.64MJ. It is only about 23% of the energy consumed by the investment casting route.

7. Conclusion

From the above investigation and analysis using multiple life cycle method and energy efficiency calculation, following conclusions can be drawn:

1. By using the CRIMSON method, the running system yield can be increased from 10% to 42%.
2. The energy burden of a foundry is heavily influenced by its recycling efficiency. More material recycled the less energy burden.
3. After the recycling and reusing, the energy burden reduced to 14.14 MJ/Kg and 16.34 MJ/Kg respectively for conventional investment casting process and the CRIMSON process. Only about 25% to29% of using primary energy.
4. Since the casting yield increased, the OME of the casting process increased as well. It turns out that the CRIMSON Process only use 23% of energy compared with conventional method. By adopting the CRIMSON method, all most 200 GJ/tonne of energy can be saved for good casting.

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