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14th WORLD CONFERENCE IN INVESTMENT CASTING

Sustainable Investment Casting

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Abstract Sustainability is becoming the most important criteria in all aspect of human existence including manufacturing. Investment casting is an old manufacturing method of shaping various alloys. Moulding, melting, alloying, pouring, solidification and finishing are steps in investment casting. Melting and ceramic shell making are the main energy consuming process steps. Findings in this research shows shell making is consuming even more energy than melting and almost 60-75% percent of energy is used to melt gating and sprues. The purpose of this study is to explore “sustainable behaviour” by accurate control of wax room, ceramic shell process, drying, firing time and temperature as well as preheat, melting, pouring, time and temperature and also furnace design with appropriate insulation to save energy and materials. Application of the CRIMSON process in investment casting is also discussed.

Keywords: Sustainability, Firing, Drying, Melting, Time, Energy, CRIMSON

1. Introduction

The world population is continuing to expand, consumption of resources is increasing rapidly, and consequential demands for energy, water and materials are rising. This is leading to the scarcity of energy resources in particular fossil fuels which are threatening everything that depends on it. These trends, combined with the now inevitable impact of climate change, ecosystem degradation, and the exhaustion of a wide range of resources, indicate the need for change in our behaviour towards sustainability [1]. Investment casting is an ancient method of casting metals which has been used from 6000 years ago. According to the literature this method of casting was used by Chinese to make the secret statues [2]. Through the years changes and modification of process enabled us to make complex and accurate near net shape parts such as nickel super-alloy gas turbine blades and implants made of titanium. Using investment casting almost all parts and metals can be cast as long as it is economical. This method is very time and energy consuming and expensive process as compared with other casting processes such as sand and die-casting. Investment casting is normally used for mass production of parts and alloys which will be difficult to manufacture in any other ways. Melted material is poured in to ceramic shell moulds and after solidification by breaking the shell and fettling a near net shape part is produced. No machining or only very limited machining is required. To obtain the required mechanical properties some parts undergo heat treatment process. There has been so much research work done on alloys, ceramic shell, cores and coating materials in particular gas turbine blades and hot section of combustion chamber to produce parts with improved mechanical properties such as fatigue and creep at higher temperatures. Added value parts made by this method are the reason that manufacturers and foundries disregard costly energy and materials waste when casting. It is reported investment casting as the most energy consuming process among casting processes [3]. Investment casting steps include tooling, wax injection, pattern assembly, shell making, de-waxing, firing, preheat, casting, shell removal, fettling, heat treatment and inspection. Melting is the most energy consuming step in foundries [4]. High melting temperature metals are normally cast by investment casting due to high temperature resistance of ceramic shell moulds in particular zirconium oxide (Zircon). Energy consumed in melting depends on the type of alloy and furnace type and condition. There is not much difference in energy consumption of melting per tonne of various alloys. However, difference in energy consumption of casting processes comes from other process steps. It has been reported the main energy consuming step in investment casting is the extra amount of metal melted as sprues and gating to produce good casting as well as very high energy consuming (A-Z) ceramic shell process itself [5]. Here in this work energy consumption challenges and potential savings in some steps of investment casting process is discussed.

2. Energy consumption in foundries

Figure 1, shows energy consumption per tonne of three different foundries, investment, die and sand casting in the UK producing stainless steels, aluminium and cast iron respectively. According to the figure the most energy consuming process is investment casting. Melting operation in all these foundries consume only part of the total consumption. It seems other process steps consuming more energy than melting.

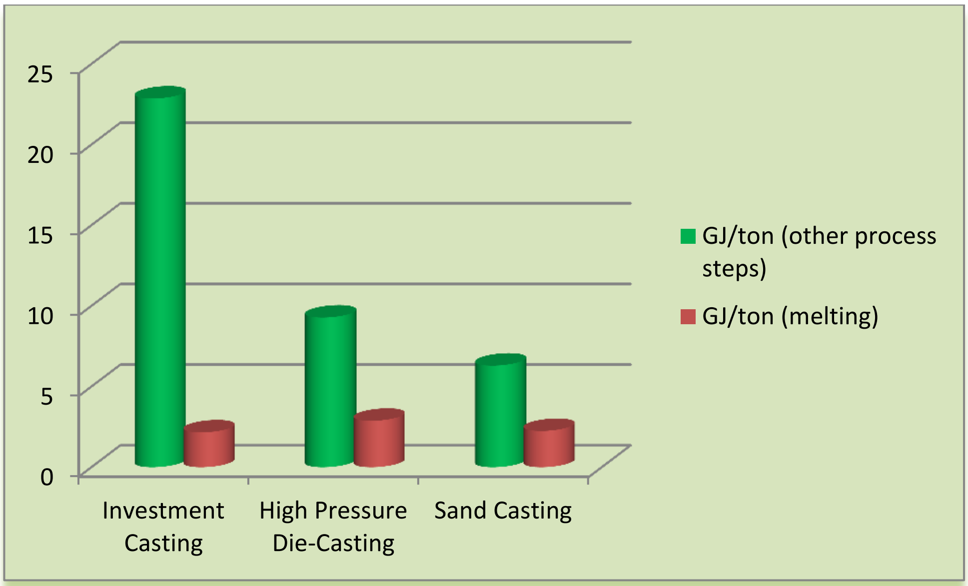

Figure 1: Energy consumption of three different foundries in the UK (GJ/ton)

Data collected from small size investment casting foundry, casting various alloys including stainless steels and some air melt cobalt and nickel alloys shows huge amount of energy is used in other process steps rather than melting. Even though this foundry with a very good layout, clean and organised seemed to be in control of the process, shows huge energy consumption per tonne as compared with other casting operations and foundries. The big difference in energy consumption of investment casting with other casting operations may be found in shell making steps [3]. Ceramic shell process involves energy consuming steps such as melting the wax, injecting the wax into the die, pattern assembly using flame or hot iron continuously, preparing primary and secondary slurries in a rotating tank at a controlled speed over a long period, dipping, stuccoing and drying in a controlled atmosphere with appropriate temperature and humidity for days. Finally de-waxing the dried mould in an autoclave at right temperature and pressure, firing the mould at around 900-1000℃ for 45 minutes to 1 hour makes it a very intensive energy consuming step. In addition shake out, fettling, sometimes ceramic cores and heat treatment makes this process more energy intensive method per tonne of casting. An extra energy consuming parameter is the alloys with higher melting temperatures such as steels; stainless steels, air melt cobalt, and nickel super-alloys which are cast by this method as compared with lower melting point aluminium and cast iron alloys shown in figure 1. Table 1 and figure 2 show energy consumption data of each step of investment casting foundries in 1982 [3].

Table 1: Consumption of energy in different process steps in investment casting foundries, GJ/ton of good casting [3]

Melting	**Ladle Heating**	**Moulding/Core making**	**Fettling**	**Heat treatment**	**Extraction**	**Compressed air**	**Space Heating**	**Lighting**	**Total**	**Mean Energy**
8-15	0-6	100-180	10-15	10-20	7-20	1-2	20-40	2-4	140-280	210

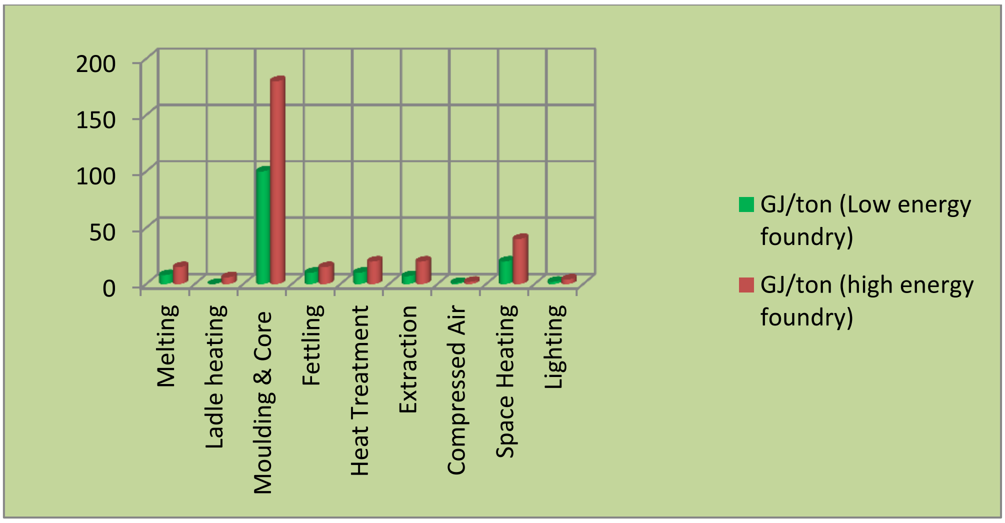

Figure 2: Consumption of energy in different process steps in investment casting foundries [3]

However, the difference in energy consumption of recently visited small investment casting foundry in the UK as compared with data collected from literature [3] shows huge energy savings per ton of casting, figure 3. Obviously the data from literature goes back to 1982 and many foundries have adapted to new technologies and improved their productivity and energy consumption patterns. But there are still few foundries that are operating with their old techniques and equipment that may be losing great amount of energy and materials.

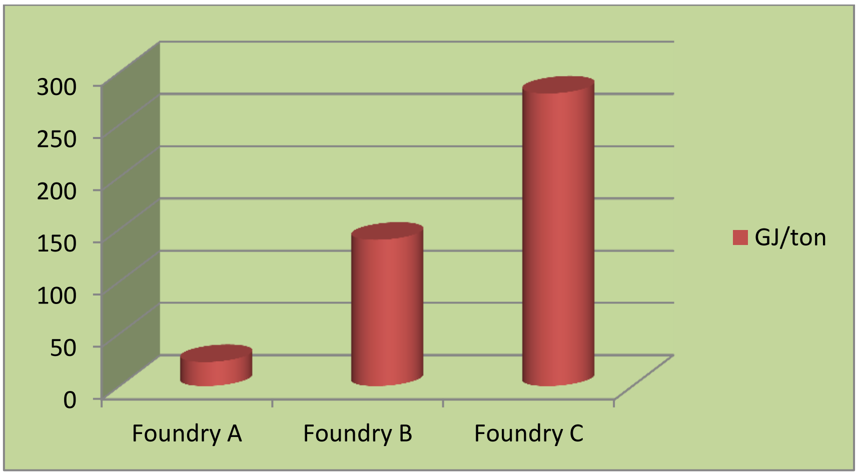

Figure 3: Energy consumption of recently visited investment casting foundry A, compared with data from literature (GJ/ton)

3. Energy consumption calculations for ceramic shell mold process steps

3.1 Wax melting and injection

Pattern materials are starting point in the investment casting process. Mishandling of these materials can result in more material and energy waste and increase the costs. Pattern waxes are blends of petroleum and natural waxes, natural and synthetic resins and organic fillers. Paraffin and microcrystalline waxes are the main constituents of pattern waxes. They are by products of crude oil distillation and are available in various melting temperatures. Proper preparation of the wax prior to injection eliminates defects caused by patterns. Wax work best if it is held within a narrow temperature range. Injecting at 5 ° C higher than recommended temperature can cause defects such as: dimensional changes, excessive cavitation or sink, excessive flash on wax pattern, air entrapment due to turbulence in the die, increased dwell time. Waxes have a melting point as well as solidification point. Solidification point can be as low as 30 ° C lower than melting point with the injection temperature in between.

Injecting the wax at lower specified temperature can cause other types of defects such as: incomplete filling of the die, dimensional changes, knit lines and surface defects [6]. Table 2 shows energy required to melt and inject right amount of wax material for each ton of metal to be cast. Metals and alloys with lower density produce more parts per ton of casting and therefore more wax pattern is needed and additional energy is consumed, figure 4.

Table 2: Energy consumption for melting and injecting required amount of wax for each alloy per ton of casting

Material	Aluminum	Steel	Stainless	Nickel	Titanium	Paraffin Wax
GJ/ton of casting	0.1	0.036	0.035	0.034	0.06	0.28

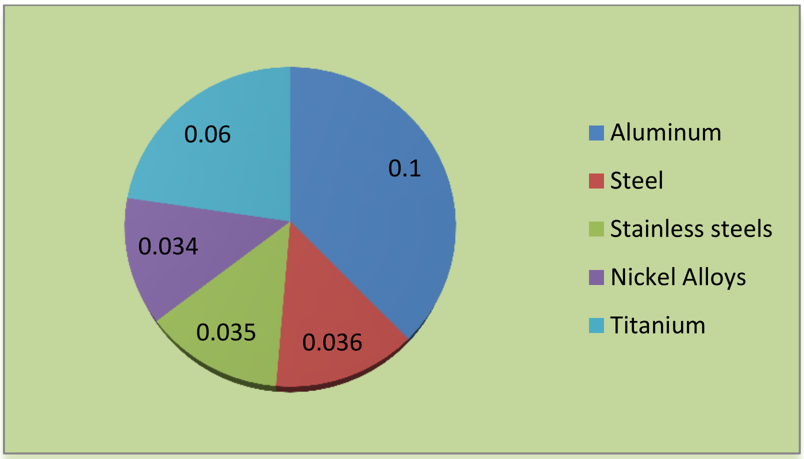

Figure 4: Energy required melting enough pattern wax per ton of metal alloy (GJ/ton)

3.2 Pattern assembly

Pattern assembly is currently performed manually, typically by workers using flat knives heated over inefficient open flames until red-hot. These flames or hot plates consume high amount of energy daily. Excessive smoke and heat must be removed via the building's HVAC system, consuming additional energy. Inconsistent or defective wax welds frequently result in lost patterns or scrapped parts requiring re-processing of the metal (i.e., re-melting) and creating excessive waste wax and mold material that must be landfilled. Automation of wax tree assembly process; reduces energy consumption by improving product quality, reducing scrap rates, and reducing labour costs. An added benefit is that it enables precision alignment of patterns, which potentially facilitates the automation of other downstream processes [7]. For prototypes and short production runs, creating wax patterns from 3D printed molds offers substantial time and cost savings over traditional methods. 3D printing can produce molds with grater complexity without increase in costs [8].

3.3 Slurry preparation and stuccoing

Primary slurry composition and preparation is a sensitive step in shell making. Powder/Binder ratio and the amount of additives and mixing time and speed must be controlled. Alcohol based slurries are not in use in most foundries due to environmental hazards even though mixing and drying time is fast. Water base slurries are most popular but mixing, preparation, and drying time is much longer. Slurry stability and maintenance is another issue to consider. Most foundries keep on adjusting slurry composition by regularly adding water, binder and powder to maintain it, while slurry being stirred continuously fig 5.

Figure 5: Primary slurry coating [9]

Previous works [10, 11] show that powder / binder ratio and the amount of additives directly effects slurry PH, viscosity, thickness of coated layer and its drying condition. Strength of ceramic shell mold and surface quality of the casting also depends on primary slurry behavior and condition. Ready to use ceramic slurry eliminates costs associated with continuous mixing and simplifies the initial mixing process. The pre-mixed, chemically suspended ceramic shell slurry eliminates the need to weigh and mix binder and refractory components. The risk of operator error in adding the proper amounts of flour to a binder is eliminated. Expenses, equipment maintenance and labor costs associated with weighing and mixing flour and binder components is reduced and time wasted waiting for a slurry to wet-out is eliminated [9].

Composition and preparation of secondary slurry has a tremendous effect on interval drying time after each coat and final thickness and drying time of ceramic shell. Powder/binder ratio and mixing time and speed are essential criteria to consider when preparing slurry. The higher powder content increases the thickness and reduces the drying time of each coated layer and at the same time can reach required thickness with less number of coatings as long as there is no loss of permeability [11].

Stuccoing can be performed by fluidised bed or rain sander. For the first layer use of rain sander has been advised to avoid uneven coating and drying by fluidised bed. Rain sander can be operated mechanically which saves energy as compared with fluidised bed. Thickness, permeability of ceramic shell molds increase with increase in stucco size. Required thickness can be achieved with less number of coating using large stucco size after first coat. This will reduce number of layers and therefore drying time and saves materials and energy [11].

3.4 Drying

Table 3 shows the green strength of ceramic shells after various drying time at constant temperature and humidity. Increase in drying time from 2 to 4 hours is accompanied by an increase in the green strength of the shells. It suggests that green strength of ceramic shells depend on the type and amount of binder used as well as drying time [12]. During the production of ceramic shells, it is necessary to dry the ceramic slurry after each layer is applied. This is usually accomplished by conventional convection air drying at ambient temperature to prevent cracking of the shell. As a result, drying is a time consuming step in the process and can take days to produce a shell. Studies indicate materials, time and energy can be saved by using fresh primary slurry mixture, reducing drying time in a controlled temperature and humid environment. Increase workshop temperature by 1 degree centigrade or decrease humidity by 5-10 can speed up drying with little loss in strength [12].

Table 3: Green strength of ceramic shells at different drying times [12]

Drying Time / Hour	2	3	4
Green Strength (MPa)	4.2	4.3	4.8

3.5 De-waxing

De-waxing normally takes place in autoclave. Size, pressure and temperature of autoclave and type and melting point of wax are crucial factors here. At the same time method of used wax collection as well as burnout furnace to burn off the residual wax should be considered. It has been reported auto-clave dewaxing consumes more energy per ton of casting than flash firing dewaxing [13]. Table 4 shows energy consumption of dewaxing step for these two methods. Accurate control of these processes, results in time and energy saving and reduces shell cracking and waste. However, flash firing is accompanied by wax waste and environmental pollution. Use of microwave is steadily growing in industrial processes and research carried out on the possibility of carrying dewaxing via microwave showed that microwave dewaxing is viable, significantly decreasing the incorporation of dirt and water, which is inevitable in the autoclave dewaxing process [14].

Table 4: Energy consumption of dewaxing operations per ton of casting (GJ/ton) [13]

	Aluminium	Steel	Stainless steel	Nickel alloy	Titanium alloy
Auto-clave	3.23	1.15	1.13	1.1	2
Flash firing	2.6	0.92	0.9	0.88	1.6

3.6 Firing

Table 5 shows energy consumption for firing ceramic shells using two different furnace types [13]. Huge amount of energy is consumed per ton of casting almost as much as melting. The design and operation of the furnace system can have a great impact on overall energy efficiency of the process. Firing temperature of 950 degree centigrade for 1 hour is routine for most foundries. Previous work shows by appropriate design, firing temperature can vary from 800-950 degree centigrade and from 30 to 60 minutes, depending on the type of refractory, size and thickness of ceramic shell mold. Reducing firing time and temperature can save energy for investment casting foundries. On the other hand by appropriate layout and time management and control of preheat and firing process, required microstructure and mechanical properties of some casting may be achieved without a need for further heat treatment, (3 in 1) [12].

Table 5: Energy consumption of ceramic shell firing per ton of casting (GJ/ton)

	Aluminium	Steel	Stainless steel	Nickel alloy	Titanium alloy
Pusher furnace	4.9	1.76	1.72	1.67	3.05
Box furnace	6	2.14	2.1	2.04	3.72

4. Energy consumption of melting

Table 6 shows calculated, furnace manufacturer specified and actual foundry energy consumption of stainless steel melting operation in an investment casting foundry. The melting efficiency is directly as the result of furnace energy efficiency and operation control. Correct amount of charge and low or no holding time, shutting the furnace door during melting help to improve efficiency and lower energy consumption. Appropriate furnace insulation reduces thermal losses to the atmosphere and protects the structure of the furnace. Two main factors that impact the effectiveness of insulation system are the type of refractory and the thickness of insulation [13].

Table 6: Energy consumption of induction melting stainless steels

Material	Calculated Energy Required to melt GJ/ton	Induction Furnace Manufacturer GJ/ton	Foundry Record for Induction Furnace GJ/ton	Melting Temperature ˚C
Stainless (316)	1.1	2.1	2.2	1450-1640
Stainless (304)	1.13	2.1	2.2	1450-1640

5. CRIMSON application in Investment Casting

CRIMSON employs a high-powered furnace to melt just enough metal to fill a single mould in a closed crucible. The crucible is transferred to a station with computer controlled counter gravity filling of the mould/shell for optimum filling and solidification. Minimum holding time drastically reduces the energy losses; rapid melting time, up casting, no turbulence during filling, few hydrogen absorption, few oxide films formation improve the quality of the aluminium casting. To use the novel CRIMSON method instead of the current gas fired crucible furnace in conventional ICP foundry, the estimated energy savings could be of the order of 4.69 GJ per ton for A356 alloy [5].

6. Simulation

Simulation plays an important part in design when casting a component by investment casting. Various sizes and alloy types requires a vigorous design of parts to avoid material and waste of energy. Simulation has been in use for some time in foundries. Mould filling, solidification, gating, detecting defects and single crystal integrity during the directional solidification of the turbine blades fig 7 are the main purpose of using simulation. Little simulation has been carried out on energy consumption of investment casting process due to high added value of the parts produced. But foundries attitude is changing and very tight competition with recent climate changes, global issues and new standards guide them to act sustainable. Simulation techniques of different kinds have been used frequently in the foundry industry [15]. Simulation results from case studies have shown that it is possible to use existing simulation technologies to analyse and also improve the energy efficiency without too much extra effort. These studies have shown potential for reducing energy and material use through reduced melting temperature, designing appropriate gating system for each specific alloy [16].

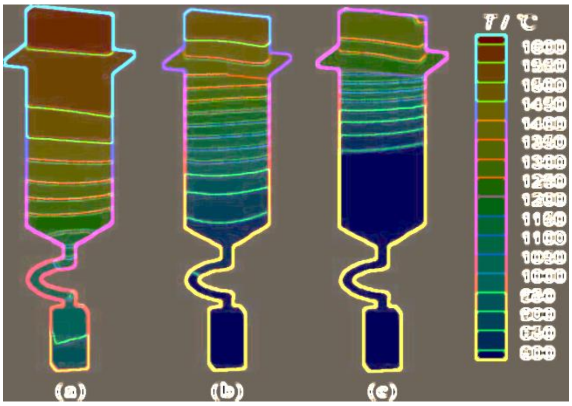

Figure 7**:** Temperature distribution of single crystal casting at different time [16]

7. Conclusion

From the present research, it was found investment casting operation consumes more energy per ton of casting as compared with die and sand casting processes. Huge amount of energy used in investment casting is related not only to melting (~2.2 GJ/ton) but also energy is used to melt, inject and assemble the wax pattern about 1GJ/ton of casting, between 0.7-3 GJ/ton for dewaxing, 1.4-4.5 GJ/ton for firing ceramic shell depending on the alloy type. However these figures exclude energy consumption of continuous slurry mixing, fluidised bed stuccoing, heating and ventilating the workshop and offices, compressed air, fettling and heat treatment. By measuring final casting dimensions prior to fettling, it was found gating and sprues form 60-75% of the assembly. Another word 60-75% of energy was consumed for melting gating and sprues which will be cut off and may be recycled. Increase in yield is an important issue in investment casting foundries. Simulation can help investment casting foundries to design appropriate gating and sprues as well as choosing the correct superheat temperature for good fill ability and repeatability for each specific product.

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