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Reduced consumption of materials and hazardous chemicals for energy efficient production of metal parts through 3D printing of sand molds

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Metals remain essential structural materials for many demanding engineering applications requiring high strength at elevated temperatures and good performance in environments subjected to high thermal fluctuations such as often encountered in the automotive, rail and aircraft industries. The sand-casting process is one of the most preferred methods of producing complex and intricate shaped components out of metals with good strength at elevated temperatures. Unfortunately, the sand casting process also leads to the direct and indirect production of carbon dioxide. Three-dimensional sand mold printing has been revolutionizing traditional production methods by reducing the unnecessary consumption of metal and chemicals when manufacturing a part through sand casting. This paper explores the opportunities that are emerging in the area of 3D printing of sand molds and the positive impact that these new technologies and practices are having on the environmental impact of current sand-casting processes. The paper demonstrates that 3D printing of sand molds enables new manufacturing strategies reducing the direct CO_2 emissions and reducing the amount of metal required by enabling design optimization of both the component and mold/core assembly. Further benefits will be realized through the development of environmentally friendly binder systems.

1. Introduction

Sand casting is an essential near net shape manufacturing process that has been used for millennia with proven success. A recent survey on the metal casting industry revealed that 37.7% of the American casting facilities favor sand casting over other processes (The American Foundry Society, 2016) due to its long-held benefits and affordable costs when used on a large scale. Globally, the sand casting industry consumes an estimate of 100 million tons of sand each year (Jablonski and Leider, 2012).

Nevertheless, the traditional sand-casting process suffers from several complications. It is considered expensive for custom design/small scale production, and time-consuming. For example, the traditional method of using a wax injection tool to create an axial turbine blade mold requires at least 5 weeks at a very high cost from start to finish (3D Systems, 2017).

Another downside with the present sand-casting process is its energy consumption. Researchers highlighted the need for studies into the energy-efficiency issues associated with casting in response to tighter environmental protection laws (Pagone et al., 2019). Traditionally, patterns and cores are precisely manufactured to be buried in the sand mold forming the mold cavity. This manufacturing process constitutes 7–20% of the total energy consumption of a foundry (U.S. Department of Environment, 1997). For a cast part with an acceptable defect limit, a gating system and risers are connected to the mold cavity whose purpose is to deliver the molten metal into the cavity until the solidification within the cavity is complete. This leads to a casting volume much larger than the part volume. A study (Schifo and Radia, 2004) reported that more than 72% of the energy used for the melting and holding process or post casting is related to unnecessary consumption of metals in the casting industry; this may include the gating system,

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risers and non-optimized part design.

In the last decade, concerns have started to arise about the use of organic chemical binders in sand casting. Emissions of volatile organic compounds and other pollutants like SO_2, CO, NH_3, HCN, H_2S, NO_2, NO_3 adversely affect the air condition (BCS Incorporated, 2002; Tiedje et al., 2010). It has also been suggested that minimizing the contact time between the hot metal and the sand mold can reduce the air pollutant release this means that the casting should be shaken out of the mold as soon as the solidification is complete within the sand mold (Kmita et al., 2016). In addition to these issues, there have been concerns about the amount of waste from sand casting operations being sent to landfills and the associated environmental effects.

Due to the limitations in the properties of recyclable green sand, chemical binders such as phenol-urethane and sodium silicate are often used to cure sand molds. Not only the by-products of using such binders have a direct effect on the greenhouse gas emission, but also the molds themselves are single use (Campbell, 2011). After considering all design allowances and requirements in mold making, it is estimated that one ton of sand is wasted for every 2 tons of sand cast metal in the USA (Dalquist, 2004; Huang et al., 2017; Mitterpach et al., 2017). In other words, this means that 1.45 m^3 of sand is being sent to landfill for every 0.26 m^3 of cast steel or 0.74 m^3 of cast aluminum. These alarming figures show the side effect of the traditional sand-casting process. With the world's increasing concerns about global warming, climate change and greenhouse gas emissions, it is becoming vital for the research community to take serious steps towards cleaner and environmentally friendlier manufacturing approaches.

While replacing sand casting sounds practically impossible, modifications to the process using state of the art technologies such as 3D sand mold printing, can lead to dramatic improvements in many environmental aspects and associated costs of the production process. A good example of this is to compare the cost of traditional processes verses 3D mold printing to make an investment-casting pattern. A 3D printed investment-casting pattern can be produced in a foundry at a cost of under 10% of the traditional production cost and by the next morning, the part would be ready for shipping. With precise mold making processes, the amount of unnecessary alloy material in the final product can be minimized and hence some of the energy requirements can be reduced and this can help reduce CO_2 emissions by at least 30—40%. This is because 3D printing offers an opportunity for casting to rethink old approaches using new manufacturing technologies due to its ability to optimize part design and reduce metal consumption. A unique way to do this is combining 3D sand mold printing with low-pressure sand casting to fully optimize and automate the process.

1.1. *3D printing and sand molds*

3D printing processes have the potential to replace many costly and time-consuming manufacturing processes and reduce their negative environmental impact. The influence of additive manufacturing on energy consumption and environmental sustainability including greenhouse gas emission (Huang et al., 2016; Morrow et al., 2007) and zero waste manufacturing have been highlighted in several studies Mitterpach et al (2017); Ngo et al. (2018); Singh et al. (2017). Extensive research efforts have been directed towards 3D printing in the last decade. Mainly because the process has the potential to replace many costly and time consuming manufacturing processes while potentially preserving the desired mechanical properties of the manufactured part (Ramos et al., 2003). Consequently, 3D printing has been rapidly introduced in to many processes with casting being no exception. Various materials can now be 3D printed through polymer curing, powder sintering/melting, filament extrusion, etc., and shaped into any desired pattern or prototype shape (Campbell et al., 2013). The new trend these days is not only to 3D print patterns but also sand molds. This sand mold printing technology will allow sand casting foundries to compete with investment casters for at least a certain class of complex parts. On the other hand it will also allow investment foundries to provide casting services for printed sand components. (Voigt and Manogharan, 2018).

The 3D sand mold printing process works similarly to traditional 2D inkjet printing (paper printing). Drops of binder (phenol or furan) are spread on a fine layer of acid mixed sand and then the polymerization takes place to bond the sand particles. The binder is only spread in the required locations where the bonding reaction takes place. The platform moves downwards by the set distance and the re-coater spreads another sand layer. The process repeats until all the 2D slices (STL file) of the 3D design are printed. The introduction of 3D printing into sand mold production has many advantages. It provides flexibility to the mold design process and reduces its volume. For example, the shell-truss design of the sand mold which has been recently proposed (Shangguan et al., 2017), helps optimize the consumption of binder/sand during printing and improve the cooling rate during the solidification of molten metals/alloys.

Environmentally, 3D printing has been claimed to be a “disruptive” technology, being able to reduce scrap, energy use[1], and enhance resource productivity. It can also help meet the demands of a large population and aid pollution problems. The design-based economies are transforming some developing countries into manufacturing hubs through outsourcing many manufacturing entities from the developed countries. This increases lead-time and the release of geographically concentrated pollutants. By moving towards 3D printing, small-scale custom-design production can be restored which may reduce the lead time and cost, especially for complex parts (Philip Hackney, 2017). Additionally, 3D printing allows the integration and optimization of traditionally separated parts within a product (Kang et al., 2017) and this can be another approach to minimizing the cost and materials consumption. This also indirectly reduces the carbon footprint in the transportation sector, as designs rather than products are shared across the world, and the parts are manufactured at locations close to the point of consumption (Campbell et al., 2012).

Based on previous reports, it might appear that 3D printing of sand molds is a much cleaner and more efficient production method but, the literature lacks a comprehensive report on the environmental impacts of the materials used in the 3D printing of sand molds, as these may not be necessarily "green". Previous reports have been limited; suggesting that the toxicity and environmental potency of 3D printing materials have the potential to offset the benefits of material savings (Ford and Despeisse, 2016; Huang et al., 2016; Kellens et al., 2017; Morrow et al., 2007). More recently, a few critical reviews (Le Néel et al., 2018; Upadhyay et al., 2017; Zhao et al., 2018) have focused on the research trends and the benefit of using the 3D sand mold but the topic of environmental aspects has not been comprehensively included. Hence, the current work aims to shed light on the effect of product design and the new manufacturing processes on the energy consumption and CO_2 gas emissions. In addition, a critical analysis on the influence of using 3D sand mold printing over conventional methods to reduce the CO_2 emission is presented. The study also advocates for further work to understand the environmental impact of 3D printing, using a complete lifecycle approach. This paper is devoted to the

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[1] Highly depends on the type of process, but an overall reduction in energy use during the entire production- and life-cycle are optimized.

interaction between 3D sand mold printing and the global carbon emission and energy consumption of the metal casting industry.

2. Energy efficient production: the effect of product design and manufacturing process on energy consumption and CO_2 emission

Every unit of efficient energy input considerably increases the economic development of any country and therefore energy efficiency is an important issue. There have been significant improvements around the world in this sector. Energy efficient passenger transport is a growing and large-scale market (International Energy Agency, 2014). Many energy efficient methods for producing shaped alloy products have been proposed which have also led to a reduction in non-renewable energy consumption (Estrada et al., 2018; Salonitis et al., 2016a). But, the primary challenge in reducing energy consumption is increasing the casting yield and reducing the use of metals (Salonitis et al., 2016b), especially in the form of waste or non-optimized part design due to traditional mold making and casting process requirements, rather than the part service requirements.

The total carbon emission in manufacturing a metal part through the casting process, ignoring the emissions produced when manufacturing and assembling any type of machinery used as part of the casting process, would be the sum of the emission caused by the primary production of consumables such as sand, furan resins and acids, metal, or other packaging materials, and the waste of non-renewable energy during machining or transport. The CES software package[2] is an interactive, material data visualization software package that uses a database of published results such as, properties, price, energy consumption during primary production, and current recycling rate of a material, etc. Using the CES software, researchers have identified suitable materials for a range of applications based on several materials properties (Navarro et al., 2012; Pascal et al., 2009). A detailed explanation of how the software works can be obtained in technical documentation available from the supplier of the software (Thakker et al., 2008). A list of cited references is also provided (Granta, 2018). The software package can give a summary of any information within the database on demand by applying the user's conditions and hence it is a valuable tool for decision making before selecting a material for advanced applications. The software can be used to produce a non-renewable energy data chart and compare various materials but it lacks the ability to calculate the total actual non-renewable energy/CO_2 production as a whole, i.e. the sum of actual non-renewable energy consumed using any type of machinery. However, it is a great tool for selecting a suitable material for optimized use in applications requiring a set of target properties and design constraints, *e.g.* high strength and low density and price or even low non-renewable energy consumption during the primary production of the material. These calculations can be performed on any standard computer with the following specification: A compatible Microsoft® Windows® operating system 7/8/10 with 32-bit or 64-bit configuration, 2 GB of RAM (more is recommended when using large databases), and 3.5 GB of available hard disk space. The actual computer used in this study was an HP model with an i7 processor using a windows 10 operating system. This study also performs a comparison with other data from the literature in order to critically analyze the influence of 3D sand mold printing technology in the casting industry in order to determine whether the introduction of 3D printing technology will reduce global CO_2 emissions.

2.1. Metal parts: global greenhouse gas emissions and optimized part design

Electricity is consumed at every stage of manufacturing processes and its generation causes about 35% of global/29% of US greenhouse gas emissions and similar percentages are contributed by the transportation and industry sectors (Desai and Harvey, 2017). There are two ways to reduce greenhouse gas emissions; reduce the consumption of materials or increase the production of green energy. Iceland is the top 'per capita consumer' (Askja Energy, 2014) of electrical energy in the world due to the abundance of green energy; 100% of renewable energy in Iceland is produced by hydro and geothermal sources. Therefore, countries like Iceland do not need to put much effort into taking account of energy consumption. Using green energy for production ultimately leads to greener products. Additional energy savings can be obtained by reducing material consumption through optimized part design (Fig. 1) and the 3D sand mold printing technology is an example of emerging technologies and practices which are providing substantial new opportunities to optimize designs in order to reduce the use of metallic materials which are energy intensive to produce. Even if parts are produced in countries that rely heavily on non-renewable energy, an optimized design will also reduce in-service energy requirements with both weight reduction and better performance.

2.2. Materials: smelting and casting using renewable energy

There are few countries that primarily use renewable energy sources, for example, hydro and geothermal energy in Iceland or nuclear energy in France and Germany, which may reduce their carbon footprint considerably. The World Nuclear Association has carried out a lifecycle assessment to compare the emission of greenhouse gas by different electricity production methods; the emission by nuclear electricity production is comparable to the renewable energy sources and is much lower than that from "fossil fuel" sources (WNA, 2011). However, this emission is mainly during the mining operation of nuclear fuel, plant construction, uranium mining and milling but not during electricity production (Lenzen, 2008; Sovacool, 2008). Nevertheless, the global interest in affordable electricity production using renewable energy sources is a key priority driving research and development, eventually reducing the carbon footprint. The significant part of CO_2 release during the casting process comes from the primary production of molten metal which makes a much greater contribution that the energy used in the mold making and casting process. If the casting and smelting industry can efficiently use renewable energy, then it would not be a matter of how much energy is used but of how much CO_2 is released. Moreover, with the developments in nuclear waste disposal technologies, the nuclear energy supply becomes an even more important source of renewable energy as the waste produced is extremely small in quantity compared to the waste and greenhouse gas emissions from fossil fuel-based electricity production.

3D sand mold printers mainly consume energy in the form of electricity and optimize the use of other materials compared to more traditional labor-intensive sand molding operations (use of wood can be renewable/green as long as forestry is sustainably managed) or polymer pattern making process which are not "green". As previously discussed, the 3D printing process consumes only a small portion of the total energy for a final product, when ignoring the CO_2 release in manufacturing the 3D printers. Therefore, there is no doubt that greener electricity and 3D printing can positively contribute to practices that seek to address the world's climate change issues. Coupled with the use of renewable energy

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[2] Produced by a spin off company of the University of Cambridge.

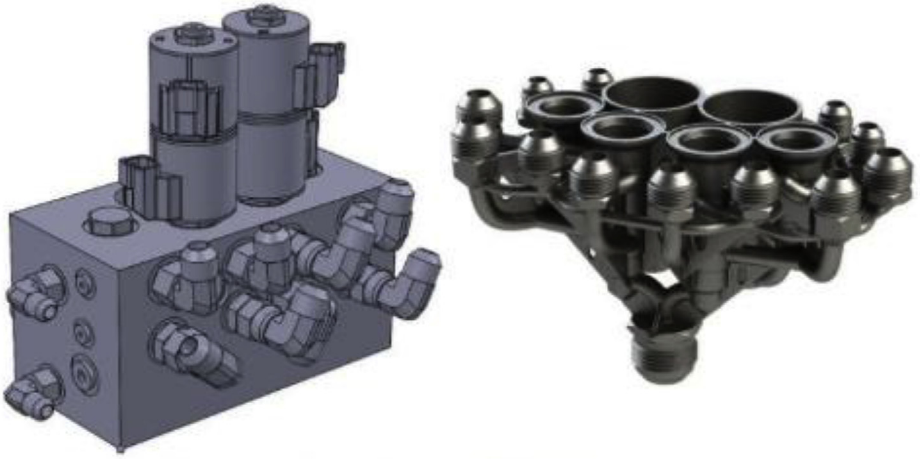


Fig. 1. "*Conventionally machined hydraulic manifold (left) and a new version designed for and produced by metal AM (right) consolidates 13 parts into one and reduces weight by 91%, courtesy of Atlas Copco*"; An example of optimized and combined part design, cited in Ref. (Wohlers Associates, 2018).

for melting metals, significant reductions in the carbon footprint can be realized.

3. Effects of 3D sand molds printing on CO_2 emission

3.1. Reduction in metal consumption

Fig. 2, which is produced using the CES software, justifies (eco-audit) and compares the benefit of the 3D sand mold production in terms of the CO_2 footprint of some materials. The emissions associated with the production of metals, Fig. 2, is greater than that of other materials, *e.g.,* polymers. On the other hand, the use of metals is unavoidable in specific applications due to their superior thermal and mechanical properties. Hence, reduced consumption of these metals using technologies which minimize material usage through optimized design and by scrap recycling would considerably reduce the carbon emissions as the recycling energy is much smaller than that for the primary production of these metals, Fig. 2.

Most of the casting alloys consume more non-renewable energy in order to produce the final product compared to any other production method, as seen in Fig. 3(a)-(d); most of the materials are above the $y = x$ line plotted in each figure. It is also reported that sand casting can consume as much as 15 MJ/kg (Ciceri et al., 2010) or 16.34 MJ/kg even when using one of the advanced energy-saving methods called the "Constrained Rapid Induction Melting Single Shot Up-Casting (CRIMSON) process (Salonitis et al., 2016a; Zeng et al., 2014). For a successful casting yield of 1 kg, between 3.7 and 9 kg of metal needs to be melted and this is where most of the energy is wasted (Salonitis et al., 2016a; Zeng et al., 2014). However, this can be significantly reduced through the application of 3D sand mold printing technologies and practices as these processes offer greater freedom in part design, Fig. 1, as compared to the traditional means of production (Wohlers Associates, 2018). An optimized part design will lead to decreased carbon emissions. Additionally, near-net-shape production and minimal post processing after casting have significant advantages of using the 3D sand mold printing technology. Furfuryl alcohol production, the primary element in the printer resin is near the lowest side of the CO_2 footprint. Additionally, Haapala and co-workers have developed a sand casting model (Haapala et al., 2012) that replaces polyurethane sand binder with furan resin, reducing emissions by 50% and sulfur dioxide emissions by over 90%. In the meantime, 3D printing also reduces the amount of these resins used compared to the counterpart production method due to the fact the furan is only sprayed on demand and only on precise locations. This optimizes both sand and resin use.

The build speed (volumetric) of commercially available 3D sand mold printers improves when the cross-sectional area of the job-box is increased and hence the energy required to print a unit volume of sand mold is reduced; as can be seen for the VX4000 printer which uses 293 MJ/m^3, Table 1 and A1. Therefore, the benefits of this technology can be extended from small to large-scale production. The casting (cavity in the mold) to sand consumption volume ratio lies within the range of 1:2 to 1:6 in the traditional casting processes. Using the 3D printed sand mold this ratio can be optimized to a very low value, where it can be assumed to be 1:1 at maximum efficiency due to the shell structure design of the mold (Shangguan et al., 2017). Reduced consumption of metal can save energy in the range of GJ/m^3 to TJ/m^3 or even higher see Fig. 4. The 3D sand mold printing process can consume electric energy in the range up to MJ/m^3 to produce sand molds as shown in Table 1. There is evidence for volume or weight reduction in the consumption of metals by combining many parts into one when using a 3D printed sand mold (up to 91%), Fig. 1. It is now very clear that the non-renewable energy saving during casting and material usage is just the beginning with 3D sand mold printing. Additional savings result from reduced machining after casting. By suitably choosing engineered sand and process parameters during printing, the surface finish can be controlled by varying the gas permeability of the printed mold (Sivarupan et al., 2018). This coupled with the increased casting yield mainly due to the design freedom can add another dimension to the non-renewable energy saving by 3D sand mold printing.

3.2. CO_2 emission calculations

An approximate value for the total CO_2 emission of furan resin has been calculated to be 4.70 kg per kilogram of resin produced (Tumolva et al., 2009). This data has been included in Fig. 5 in order to compare these values with the data obtained in the analysis using the CES software package for other materials and this suggests that most of the metal or alloys are mostly high-density materials and hence on the right side of the x-axis in Fig. 5 because they show greater CO_2 emissions compared to other materials especially polymers, and the same can be compared with the emissions associated with the furan resin. The furan resin is usually

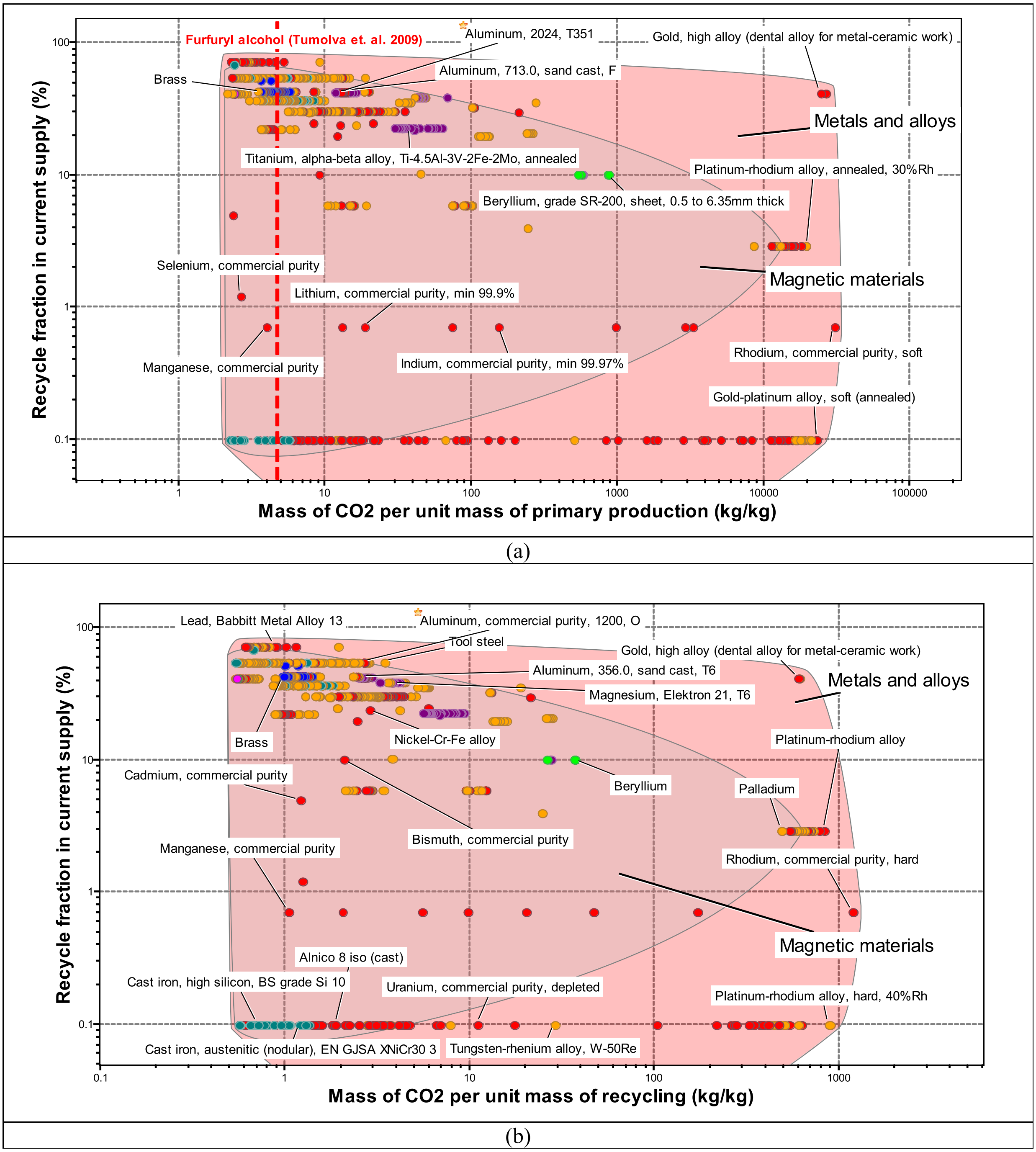
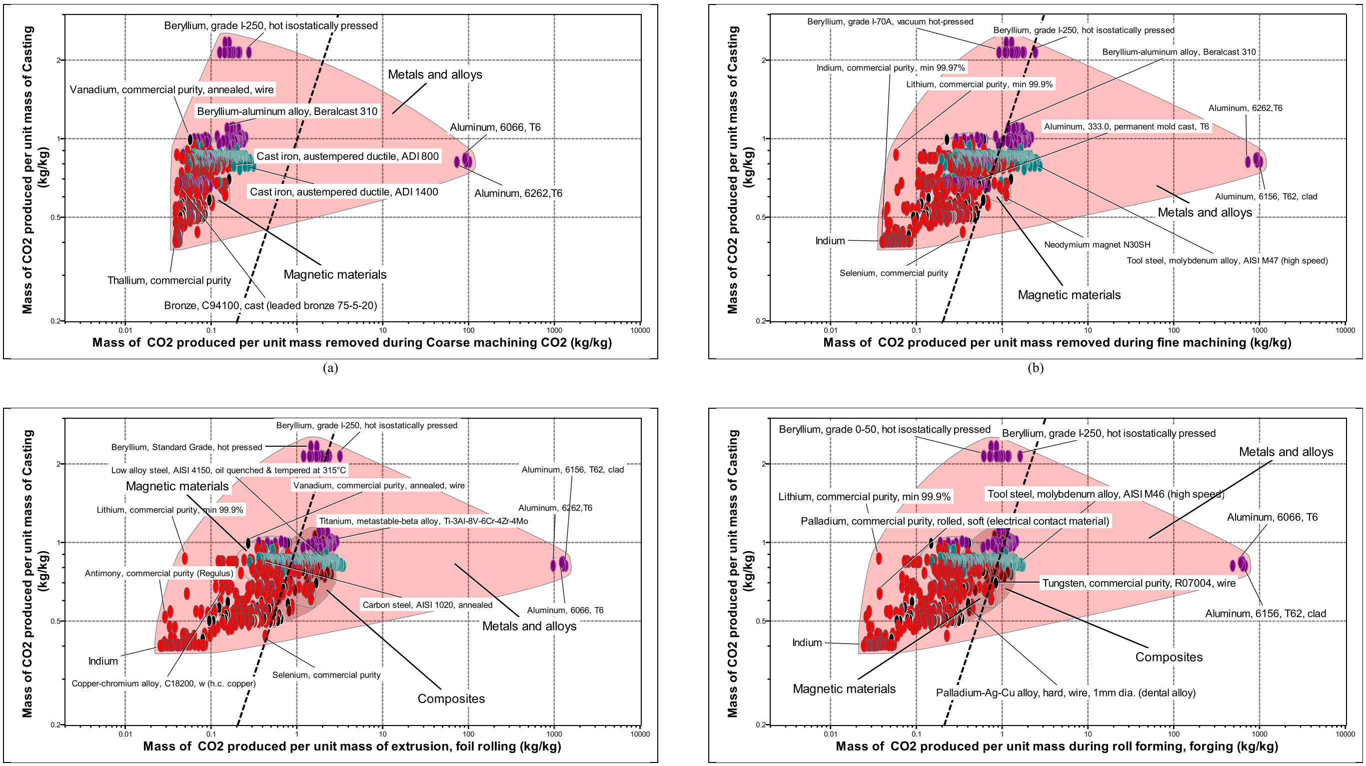


Fig. 2. Recycling fraction of materials as a function of CO_2 foot print for (a) the primary or (b) secondary production. The red line in fig (a) is the data for the Furfuryl alcohol from the reference (Tumolva et al., 2009). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

added to a maximum of 2 wt% of the sand mixture based on the experimentally obtained loss of ignition value as reported elsewhere (Mitra et al., 2018). The overall maximum density of a 3D printed **silica** sand mold is 1423 kg/m^3 (Sivarupan et al., 2017) and hence the maximum furan resin (and sulfonic acid) in a unit volume of sand mold would be 2% x 1423 which equals to only 28.46 kg/m^3 and the related CO_2 emission would be 133.76 kg (28.46 × 4.7 kg) per unit volume of sand mold printed. This is much smaller compared to the emissions caused by producing an A356 aluminium alloy, calculated by CES as 29500 kg/m^3. The maximum non-renewable energy consumption during the 3D printing process using the industrial Voxeljet VX4000 printer would be 10498 kg/m^3. Therefore, the total emissions associated with printing would be the sum of 10498 and 133.76 which is equal to 10631.76 kg/m^3 for the sand mold. If 1:1 is assumed as the casting to sand mold volume ratio, then the reductions in metal usage achieved using this method would reduce more CO_2 emissions than the emissions caused by the 3D printing process. Therefore, the emission caused by 3D sand mold printing is nearly 1/3 of that for the primary production of aluminum metal. The same calculation for a stainless steel, calculated by CES, would be 51900 kg/m^3, which is much higher than that achieved for the same volume of



(a) (b) (c) (d)

Fig. 3. The carbon footprint of various process of metals and alloys, produced using CES software. CO_2 production during casting compared to (a) coarse machining, (b) fine machining, (c) extrusion or foil rolling and (d) roll rolling or forging. A line of y = x is added as a reference ratio in each figure.

lower density alloys. Overall, reduced consumption of metals can save significant energy and reduce the related CO_2 emissions, compared to the emission caused by the 3D sand mold printing process. In this calculation process, the CO_2 emissions produced by the interactions between the molten metal and the 3D printed sand mold (burning the furan resin by the molten alloy) during the casting process are not factored in. This value is not known and will require measurements and future work as it will need to be accounted for in a more complete calculation of the CO_2 emissions by the casting industry.

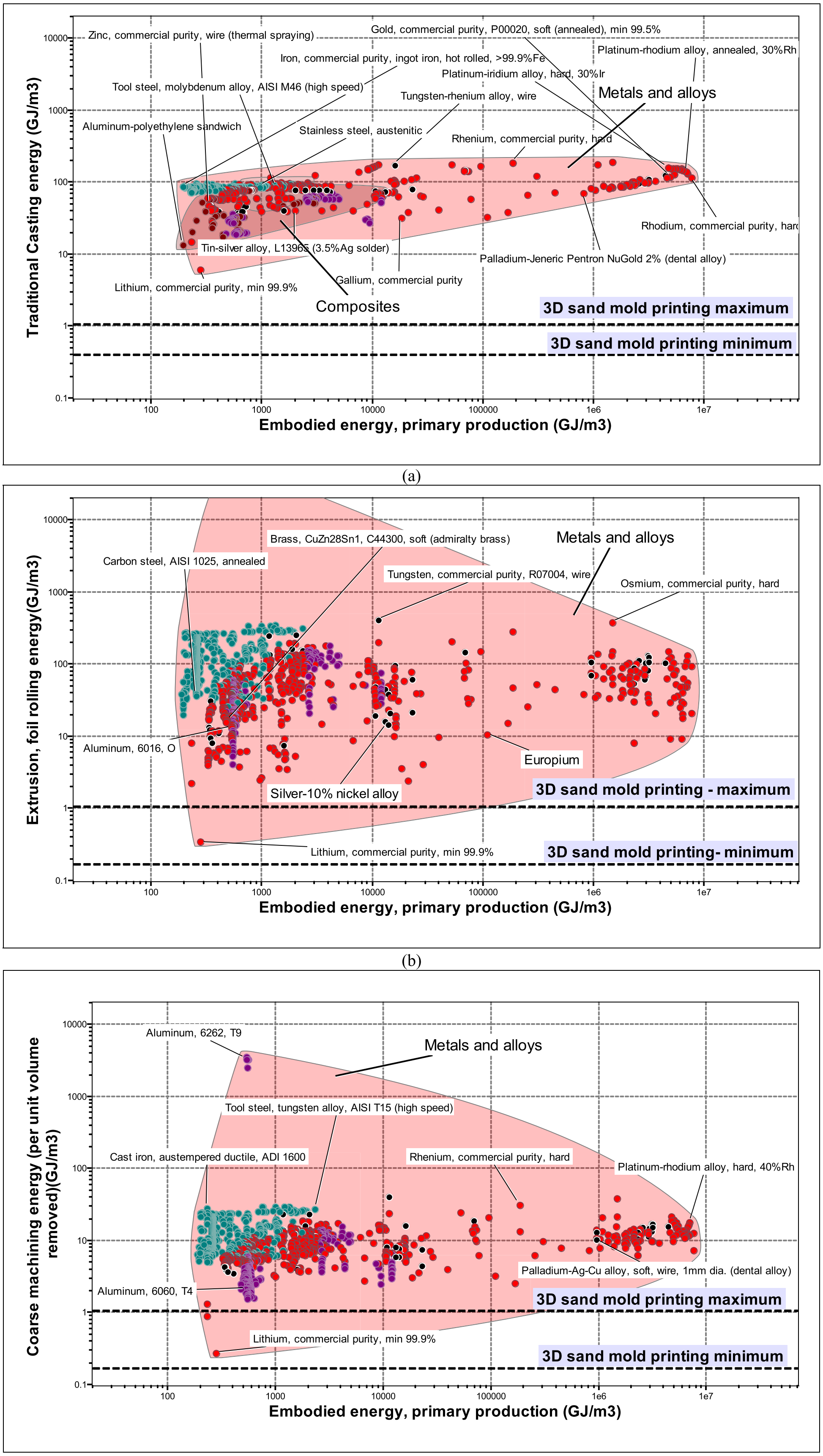
The casting of most alloys releases more CO_2 than other shaping processes such as extrusion, rough rolling, and coarse/fine machining, except for some Al alloys, Fig. 3; and for this reason, the data for most alloys used in structural applications falls above the y = x line drawn in each figure presented. Casting is the most preferred method for any complex shape whereas the 3D printed sand mold is superior in producing highly intricate shapes and additionally allows for reduced mass consumption without sacrificing the expected properties of the part. This is discussed in detail in the next section.

3.3. *Effects of 3D sand mold printing on the casting process*

The rapid casting process can be easily applied to low melting point alloys of interest today such as aluminium and magnesium alloys, etc. These alloys are mainly cast by the die casting technique. Dies are long-term capital and for this reason must be meticulously designed and are constructed from difficult to process high energy intensive materials. Here the repeated prototyping and testing required for the die contributes to a higher carbon footprint. Apart from that, the use of SF_6 as a cover gas during liquid processing of magnesium alloys also adds significantly to the footprint (Butler, 2008) during the production of lightweight magnesium parts. Additionally, in the production of sand for steel and cast-iron casting applications, sea coal, a carbonaceous additive, contributes significantly to CO and CO_2 emissions. Cores in cored green-sand mold can release 0.25–0.35 kg of CO for every ton of metal manufactured and are big contributors towards CO and CO_2 emissions (United States Council, 2008). Some core curing processes also use CO_2 to complete the reaction and harden the mold.

When energy and emissions of the manufacturing process are considered, the impact of avoidance is not often highlighted. With the 3D printing of sand molds, the step of coring can almost entirely be removed. It is known that the molds with cores produce more emissions because core preparation usually requires additional binders such as phenolic binders (National Center for Manufacturing Sciences, 1999). Using 3D printing means, all internal features of the part can be modelled and printed. While floating sections still cannot be produced without the aid of chaplets, this does not undermine the efficacy of the process. Additionally, the thickness of the mold can be varied to achieve the right thermal properties for efficient heat transfer while reducing the overall area over which the resin is deposited. The unbound sand can be treated to remove the accumulated moisture and recycled, further reducing emissions. The chemically bound sand can also be recycled, but the reuse rate is low due to the degradation of the sand particles between runs (Dalquist, 2004).

Apart from the metal and sand use optimization benefits, 3D printing of sand molds can reduce the number of steps required in the process of making a functional mold. One of the significant steps is the production of patterns. Produced in a wide variety of materials, from wood to polymers, patterns play an important role in traditional molding. However, these are subject to abrasion and subsequent degradation by contact with sand particles. They lose



(a)

(b)

(c)

Fig. 4. Energy consumed in 3D printing compared with energy consumption in (a) Traditional casting (b) Extrusion, foil rolling and (c) Coarse machining.

Table 1
The comparison of maximum non-renewable energy consumption during printing of sand molds by commercially available printing machines from the two major producers, and the corresponding energy consumption for each unit volume of manufactured metal component; ExOne (2018) and Voxeljet (Foerder, 2018; Voxeljet, 2018). Note: Further data on how and what is used to calculate in this table are given in the[12] Appendix, Eq. (A1), A2, and Table A1.

3D printer; company name	Machine power (max) (W)	Heater power (max) (W)	Build speed (max) ($\times 10^{-6} m^3.s^{-1}$)	Energy/volume (sand) ($MJ.m^{-3}$)	[3]Energy required to print a mold for a casting of material with density 1738 [4] kg/m^3 (MJ/kg)
S-Print; ExOne	6200	6300	10	1250	0.719
S-Max; ExOne	6200	19200	24	1076	0.609
S-Max plus; ExOne	6200	10500	24	707	0.400
VX500; Voxeljet	5000	–	3	1875	0.959
VX800; Voxeljet	5000	–	8	625	0.360
VX1000; Voxeljet	5500	–	4	1375	0.791
VX2000; Voxeljet	10300	–	11	976	0.539
VX4000; Voxeljet	9200	–	31	293	0.170

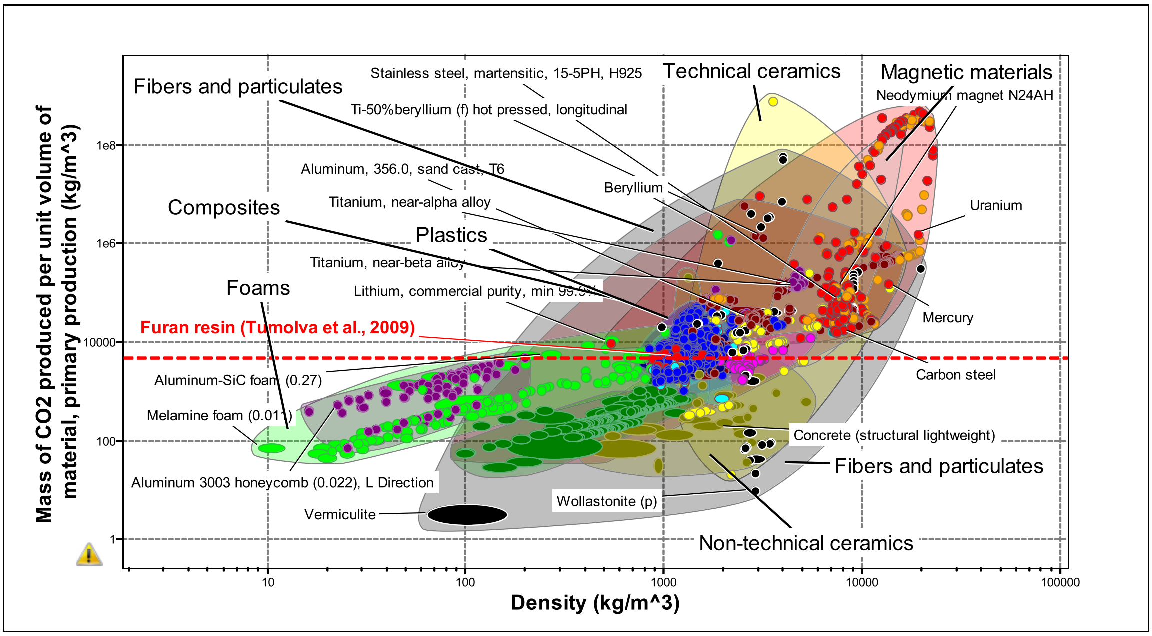


Fig. 5. CO_2 footprint for unit volume of materials produced as a function of density, compared with data (Tumolva et al., 2009) for furan resin.

their dimensional accuracy over time, leading to higher than necessary tolerances and hence over-consumption of metals or increased scrap rate. With 3D printing, it is possible to achieve dimensionally near perfect molds with each print, thus eliminating the design and production of such dies or molds (traditional sand mold or permanent dies and cores), reducing the overall energy consumption and carbon emission of the process.

It should also be noted that the actual non-renewable energy consumption in producing a final finished part does not only depend on the energy consumed during production but also it includes the amount of energy consumed in setting up a factory with all its machinery and facilities. A reasonable portion of this energy must be assigned to any finished part by the factory. In this regard, the energy consumption in producing a 3D sand mold printer and in-service consumption should be taken into consideration in a more accurate calculation of energy consumption compared to the traditional casting process. Future research should also focus on the development of alternative and environmentally friendly binder systems suitable for use in 3D sand mold printing machines.

4. Conclusions

1. 3D printing of sand molds enables new manufacturing strategies which significantly reduce the CO_2 emissions associated with metallic component production via casting. The application of this technology for the production of sand molds for shape casting optimizes the consumption of materials through design optimization of both part and mold/core, and hence this reduces the energy consumption and the use of metal. This metal saving results in at least 2/3 of the CO_2 emission compared to the traditional casting process.
2. 3D printing of sand molds also reduces the metal to sand ratio (maximum 1:1) compared to traditional sand-casting practices. This significantly reduces the use of toxic consumables in the sand mold production process compared to the traditional sand-casting process.
3. Future research should focus on the development of environmentally friendlier binders for use in 3D sand mold production systems.
4. The non-renewable energy consumption during the production of 3D printed sand molds is mainly in the form of electricity and therefore when green energy is used, as there is an increasing global trend in consumption of cleaner energy, then the CO_2 emissions will be negligible during the production of structural alloy components.
5. A 3D sand mold printer with a large cross-sectional area job-box may extend the benefits of this technology from small to large scale production scenarios.

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Appendix

Total power consumption of a printing machine- P (in J/s).

Volumetric build speed of a sand mold printer- V (in m^3/s).

Energy required to print sand mold per unit volume - E (in J/m^3)

$$E = \frac{P}{V} \tag{A1}$$

For Voxeljet printers:

Vertical build speed[**]- V_z (in mm/hour), and this can be written in layers/hour as well.

Length of the job-box of the printer- L_x (in mm).

Length of the job-box of the printer- W_y (in mm).

Volumetric build speed of a sand mold printer, V, can be written as,

$$V = V_z \times L_x \times W_y \tag{A2}$$

Table A1

The energy usage by the various Voxeljet 3D sand mold printer and their dimensions and printing speed (Foerder, 2018).

Printer	V_z(mm/hr.) Foerder, (2018)	L_x(mm)	W_y(mm)	Job box cross sectional area $L_x \times W_y$(m^2)	V × 10^{-6}(m^3/s)
VX500; Voxeljet	48	500	400	0.2	3
VX800; Voxeljet	48	1000	600	0.6	8
VX1000; Voxeljet	24	1000	600	0.6	4
VX2000; Voxeljet	19	2000	1000	2	11
VX4000; Voxeljet	14.12	4000	2000	8	31

References

3D Systems, 2017. Investment Casting Solutions. http://www.ferret.com.au/ODIN/PDF/WebsiteCustomers/86.pdf.

Askja Energy, 2014. Iceland is the world largest energy consumer (per capita) [WWW Document]. Icelandic Energy Portal. URL. https://askjaenergy.com/2014/11/17/iceland-is-the-world-largest-energy-consumer-per-capita/.

Butler, W.A., 2008. The " Carbon Footprint " of Aluminum and Magnesium Die Casting Compared to Injection Molded Components, pp. 1–36.

Campbell, J., 2011. Complete Casting Handbook: Metal Casting Processes, Metallurgy, Techniques and Design . John Campbell.

Campbell, Thomas Williams, Ivanova, Christopher, Olga Garrett, B., 2012. Strategic Foresight Report, pp. 3–7.

Campbell, I., Bourell, D.D., Gibson, I., 2013. Additive manufacturing: rapid prototyping comes of age. https://doi.Org/10.1108/13552541211231563 18, 255–258. https://doi.org/10.1108/13552541211231563.

Ciceri, N.D., Gutowski, T.G., Garetti, M., 2010. A tool to estimate materials and manufacturing energy for a product. In: Proc. 2010 IEEE Int. Symp. Sustain. Syst. Technol. ISSST 2010. https://doi.org/10.1109/ISSST.2010.5507677.

Dalquist, S., 2004. Life cycle analysis of conventional manufacturing techniques: sand casting. In: ASME International Mechanical Engineering Congress and Exposition, pp. 1–11.

Desai, M., Harvey, R.P., 2017. Inventory of U.S. Greenhouse gas emissions and sinks: 1990-2015. Fed. Regist. 82, 10767. https://doi.org/EPA 430-R-13-001.

Energy Efficiency Market Report 2014, 2014. IEA. https://doi.org/10.1787/9789264218260-en.

Estrada, O., López, I.D., Hernández, A., Ortíz, J.C., 2018. Energy gap method (EGM) to increase energy efficiency in industrial processes: successful cases in polymer processing. J. Clean. Prod. 176, 7–25. https://doi.org/10.1016/j.jclepro.2017.12.009.

ExOne, 2018. Production Printers [WWW Document]. Prod. Printers (accessed 2.9.2017). http://www.exone.com/Systems/Production-Printers.

Foerder, A., 2018. Email Comunication; Power Consumption of Voxeljet Printers.

Ford, S., Despeisse, M., 2016. Additive manufacturing and sustainability: an exploratory study of the advantages and challenges. J. Clean. Prod. 137, 1573–1587. https://doi.org/10.1016/j.jclepro.2016.04.150.

Granta, 2018. A selection of publications referencing CES Selector [WWW Document]. http://www.grantadesign.com/userarea/papers/.

Haapala, K.R., Catalina, A.V., Johnson, M.L., Sutherland, J.W., 2012. Development and application of models for steelmaking and casting environmental performance. J. Manuf. Sci. Eng. 134, 051013. https://doi.org/10.1115/1.4007463.

Huang, R., Riddle, M., Graziano, D., Warren, J., Das, S., Nimbalkar, S., Cresko, J., Masanet, E., 2016. Energy and emissions saving potential of additive manufacturing: the case of lightweight aircraft components. J. Clean. Prod. 135, 1559–1570. https://doi.org/10.1016/j.jclepro.2015.04.109.

Huang, R., Riddle, M.E., Graziano, D., Das, S., Nimbalkar, S., Cresko, J., Masanet, E., 2017. Environmental and economic implications of distributed additive manufacturing. J. Ind. Ecol. 21, 130. https://doi.org/10.1111/jiec.12641.

BCS Incorporated, 2002. Energy and environmental profile of the. U.S. Mining Industry 11.

Jablonski, David, Badger mining corp., berlin, Wisconsin, and N.L., 2012. 48th census of world casting production, steady growth in global output. Mod. Cast. Am. Foundry Soc.

Kang, J., wu, Ma, xian, Q., 2017. The role and impact of 3D printing technologies in casting. China Foundry 14, 157–168. https://doi.org/10.1007/s41230-017-6109-z.

Kellens, K., Mertens, R., Paraskevas, D., Dewulf, W., Duflou, J.R., 2017. Environmental impact of additive manufacturing processes: does AM contribute to a more sustainable way of Part Manufacturing?. In: Procedia CIRP, pp. 582–587. In: https://doi.org/10.1016/j.procir.2016.11.153.

Kmita, A., Fischer, C., Hodor, K., Holtzer, M., Roczniak, A., 2016. Thermal decomposition of foundry resins: a determination of organic products by thermogravimetry-gas chromatography-mass spectrometry (TG-GC-MS). Arab. J. Chem. https://doi.org/10.1016/j.arabjc.2016.11.003.

Le Néel, T.A., Mognol, P., Hascoët, J.-Y., 2018. A review on additive manufacturing of sand molds by binder jetting and selective laser sintering. Rapid Prototyp. J. 24, 1325–1336. https://doi.org/10.1108/RPJ-10-2016-0161.

Lenzen, M., 2008. Life cycle energy and greenhouse gas emissions of nuclear energy: a review. Energy Convers. Manag. 49, 2178–2199. https://doi.org/10.1016/j.enconman.2008.01.033.

Mitra, S., Rodríguez de Castro, A., El Mansori, M., 2018. The effect of ageing process on three-point bending strength and permeability of 3D printed sand molds. Int. J. Adv. Manuf. Technol. 1–11. https://doi.org/10.1007/s00170-018-2024-8.

Mitterpach, J., Hroncová, E., Ladomerský, J., Balco, K., 2017. Environmental analysis of waste foundry sand via life cycle assessment. Environ. Sci. Pollut. Res. 24, 3153–3162. https://doi.org/10.1007/s11356-016-8085-z.

Morrow, W.R., Qi, H., Kim, I., Mazumder, J., Skerlos, S.J., 2007. Environmental aspects of laser-based and conventional tool and die manufacturing. J. Clean. Prod. 15, 932–943. https://doi.org/10.1016/j.jclepro.2005.11.030.

National Center for Manufacturing Sciences, 1999. Ferrous Foundry Air Emissions Study. Performed by the University of Alabama at Birmingham.

Navarro, M.E.E., Martínez, M., Gil, A., Fernández, A.I.I., Cabeza, L.F.F., Olives, R., Py, X., 2012. Selection and characterization of recycled materials for sensible thermal energy storage. Sol. Energy Mater. Sol. Cells 107, 131–135. https://doi.org/10.1016/j.solmat.2012.07.032.

Ngo, T.D., Kashani, A., Imbalzano, G., Nguyen, K.T.Q., Hui, D., 2018. Additive manufacturing (3D printing): a review of materials, methods, applications and challenges. Compos. B Eng. 143, 172–196. https://doi.org/10.1016/J.COMPOSITESB.2018.02.012.

Pagone, E., Salonitis, K., Jolly, M., 2019. Energy-Efficient Casting Processes. Springer, Cham, pp. 77–98. https://doi.org/10.1007/978-3-030-03276-0_4.

Pascal, C., Chaix, J.M., Doré, F., Allibert, C.H., 2009. Design of multimaterial processed by powder metallurgy: processing of a (steel/cemented carbides) bilayer material. J. Mater. Process. Technol. 209, 1254–1261. https://doi.org/10.1016/j.jmatprotec.2008.03.058.

Philip Hackney, R.W., 2017. Optimisation of Additive Manufactured Sand Printed Mould Material for Aluminium Castings.

Ramos, F., Cristino, A., Carrola, P., Eloy, T., Silva, J.M., Castilho, M.D.C., Noronha Da Silveira, M.I., 2003. Clenbuterol food poisoning diagnosis by gas chromatography-mass spectrometric serum analysis. Anal. Chim. Acta 483, 207–213. https://doi.org/10.1016/S0003-2670(02)01020-6.

Salonitis, K., Jolly, M.R., Zeng, B., Mehrabi, H., 2016a. Improvements in energy consumption and environmental impact by novel single shot melting process for casting. J. Clean. Prod. 137, 1532–1542. https://doi.org/10.1016/j.jclepro.2016.

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[3] If sand to casting (cavity) ratio of 1:1 is applied when casting the alloy.

[4] To represent pure Mg.

[5] Depends on the layer thickness set during printing but this speed is for the layer thickness of 300 μm.

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Salonitis, K., Zeng, B., Mehrabi, H.A., Jolly, M., 2016b. The challenges for energy efficient casting processes. Procedia CIRP. In: https://doi.org/10.1016/j.procir.2016.01.043.

Schifo, J., Radia, J., 2004. Theoretical/best practice energy use in metalcasting operations. US dep. Energy, energy effic. Renew. Energy 116.

Shangguan, H., Kang, J., Deng, C., Hu, Y., Huang, T., 2017. 3D-printed shell-truss sand mold for aluminum castings. J. Mater. Process. Technol. 250, 247–253. https://doi.org/10.1016/j.jmatprotec.2017.05.010.

Singh, S., Ramakrishna, S., Gupta, M.K., 2017. Towards zero waste manufacturing: a multidisciplinary review. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2017.09.108.

Sivarupan, T., Mansori, M.E.L., Coniglio, N., 2017. 3D printing process parameters and properties of additively manufactured sand mold for rapid Casting : strength and permeability. Addit. Manuf.

Sivarupan, T., El Mansori, M., Daly, K., Mavrogordato, M.N., Pierron, F., 2018. Characterisation of 3D printed sand moulds using micro-focus X-ray computed tomography. Rapid Prototyp. J. https://doi.org/10.1108/RPJ-04-2018-0091.

Sovacool, B.K., 2008. Valuing the greenhouse gas emissions from nuclear power: a critical survey. Energy Policy 36, 2940–2953. https://doi.org/10.1016/j.enpol.2008.04.017.

Thakker, A., Jarvis, J., Buggy, M., Sahed, A., 2008. A novel approach to materials selection strategy case study: wave energy extraction impulse turbine blade. Mater. Des. 29, 1973–1980. https://doi.org/10.1016/j.matdes.2008.04.022.

The American Foundry Society, 2016. MCDP breaks down the U.S. metalcasting industry by material, process, coremaking and value-added capabilities. Met. Cast. Des. Purch.

Tiedje, N., Crepaz, R., Eggert, T., Bey, N., 2010. Emission of organic compounds from mould and core binders used for casting iron, aluminium and bronze in sand moulds. J. Environ. Sci. Health. A. Tox. Hazard. Subst. Environ. Eng. 45, 1866–1876. https://doi.org/10.1080/10934529.2010.520595.

Tumolva, T., Kubouchi, M., Aoki, S., Sakai, T., 2009. Evaluating the carbon potential of furan resin-based green composites. In: 18Th Int. Conf. Compos. Mater, pp. 1–6.

United States Council, 2008. Carbon Monoxide and Carbon Dioxide Emissions in Metalcasting Pouring, Cooling and Shakeout Operations.

Upadhyay, M., Sivarupan, T., El Mansori, M., 2017. 3D printing for rapid sand casting—a review. J. Manuf. Process. https://doi.org/10.1016/j.jmapro.2017.07.017.

U.S. Department of Environment, 1997. Energy and Environmental Profile of the. U . S . Aluminum Industry. Office.

Voigt, R., Manogharan, G., 2018. 3D Printed Sand Molds-An Opportunity for Investment Casters.

Voxeljet, 2018. Productivity in 3D: printing systems from VOXELJET [WWW document]. Product. 3D print. Syst. from VOXELJET. https://www.voxeljet.com/3d-printing-systems/(accessed 1.24.2019).

WNA, 2011. Comparison of Lifecycle Greenhouse Gas Emissions of Various Electricity Generation Sources 10. https://doi.org/10.1002/esp.

Wohlers Associates, I., 2018. Wohlers Associates to host design for additive manufacturing course in the mountains of Colorado [WWW document]. http://wohlersassociates.com/press76.html.

Zeng, B., Jolly, M., Salonitis, K., 2014. Investigating the energy consumption of casting process by multiple life cycle method. In: Proceeding 1st Int. Conf. Sustain. Des. Manuf, pp. 28–30.

Zhao, D., Guo, W., Zhang, B., Gao, F., Bonnefoy, H., 2018. 3D sand mould printing: a review and a new approach. Rapid Prototyp. J. https://doi.org/10.1108/RPJ-05-2016-0088.