An environmental impact comparison between wire + arc additive manufacture and forging for the production of a titanium component

1. Introduction

Additive manufacturing (AM) is a technique which has gained recent interest for the production of high value components in heavy industries such as defence, maritime, energy and aerospace [1-3]. Primary advantages of AM production include a reduction in lead times [4], low material wastage [5], reduced manufacturing infrastructure and the capability to produce near net shape components [6]. Further advantages for wire based AM processes include lower feedstock costs and high deposition efficiency [7]. Research on the environmental impact of AM techniques is a rapidly progressing field [8, 9], with interest growing in the comparison of AM processes to conventional manufacturing techniques such as machining processes and green sand casting [10, 11].

Wire + arc additive manufacturing (WAAM) is a fusion welding based AM process which uses an electric arc to melt and deposit wire feedstock into a required shape at a higher rate of deposition and lower material waste than other directed energy deposition [12, 13] processes using lasers and metallic powder feedstock [14-16]. The small melt pool and steep thermal gradient of laser powder methods also results in a columnar structure, resulting in potentially detrimental anisotropic properties [7]. Due to the method of deposition, complex geometries which are unavailable to conventional methods can be produced, such as internal passages, unsupported overhangs and computer optimised topologies [17-19]. Further supporting the use of WAAM production, the mechanical properties of titanium components produced using a range of WAAM processes are comparable to wrought, and superior to cast material [14].

An alloy commonly used in the defence and aerospace sectors is grade 5 titanium (Ti6Al4V) [20]. This alloy is often selected for its high strength, low weight [21] and excellent resistance to corrosion [22]. However, titanium alloys are expensive and challenging to extract [23], machine and form [5, 24, 25]. As such, WAAM technology allows for a reduction in waste and simplification of manufacture when compared to production by machining or forging [26, 27].

As the sustainability of industry becomes a greater priority, novel manufacturing techniques, which have the potential to displace conventional methods, must be considered. One method of quantifying the impact of different manufacturing methods is through a life cycle analysis (LCA), which investigates every input and output to the production, life and disposal of components [28]. A wide range of impacts can be considered by an LCA; broadly, these include energy consumption, raw materials utilised and waste produced [29]. Commonly used measures of environmental impact are embodied energy and CO_2 emissions [30]. More detailed LCAs often consider metrics such as acidification and toxification potentials for different environments [21, 31, 32].

To consider only the contribution of manufacturing, a boundary can be set on the analysis from material extraction to the completion of manufacture [32]. This limits the included factors to raw material extraction, feedstock preparation, manufacturing processes and commissioning inputs. Using such a boundary does not include any repair, refurbishment or decommissioning factors, as these will be equivalent between similar components manufactured by different means [31].

A number of case studies exist, detailing the environmental impact of manufacturing of a product, such as the investigation of the manufacture of a bulk carrier including shipyard operations [31], manufacture of propulsion machinery and sea trials: the initial testing of a vessel prior to its acceptance by the operator.

In addition, an in depth study on each operation performed during the production of high speed steel machine tooling was undertaken [33]. Both of these studies conclude that the extraction and primary production of raw materials is a significant contributor to the environmental impact of these manufacturing processes. A limitation of these studies is the lack of comparison to other processes or materials, to quantify an environmental benefit of a design, material or process change.

Studies have also been performed on the energy consumption and carbon emissions of WAAM manufacture of steel and aluminium components [10, 11], comparing them with raw material production and CNC machining. These show a large reduction in energy requirements and carbon emissions. There is also interest in the sustainability of the manufacturing of titanium components [21]; however, this analysis presented by Daniyan et al [21] is limited only to the milling of titanium alloys. To expand the understanding of sustainable manufacturing processes, a comparison has been developed based on data gathered on the production of a titanium component by WAAM and by forging to investigate significant differences in environmental burden. This is a similar study to one recently performed by Landi et al. [34]. The novelty in this work is the comparison of WAAM with forging, both widely used within heavy industry for the manufacture of medium to large components.

2. Methodology and production model

The flow of material and resources from primary production, to component completion and delivery must be considered to compare the environmental impact for WAAM and forging. As such, the provided material flow diagrams depict this for WAAM (Fig. 1) and forging (Fig. 2).

The scope of this model includes all manufacturing techniques and material flows to measure environmental impact. The only item of tooling considered is the forging die as it is a significant investment of material and manufacturing resources for a component produced in low volumes [35]. Items of tooling that have been disregarded include production machinery (due to its long lifespan, spread over many thousands of components) and small consumables (welding torch contact tips, abrasive grinding disks). Meanwhile, where major logistical efforts are required, such as ocean shipping, this has been considered.

2.1. *Material production and pre-manufacturing*

To produce the final component, each manufacturing process requires different steps to generate the feedstocks needed. For example, with the WAAM process, a hot rolled plate and drawn wire are both required to produce the substrate and filler wire [11]. In the forging process, a cast billet is required to produce the forging blank, while hot rolling is used to produce the tool steel used in the forging [36].

All of these processes result in material loss, as well as incurring an environmental impact in primary energy and carbon dioxide emissions. The fraction of material lost and these environmental impacts are determined based on existing scientific literature [30, 37].

2.2. *WAAM process model*

The primary energy required by the WAAM process is determined by breaking down the electrical energy of each aspect of the process, including standby energy of the deposition equipment, component heater, arc energy of the cold metal transfer (CMT) deposition equipment, in addition to the primary energy of the shielding gases required. The welding parameters, dwell time between welding passes and the required dwell temperature provided by the heater all have an effect on this primary energy. This heater is required in the production of titanium components to maintain a constant component temperature during deposition, reducing the risk of thermal stress cracking [38]. The energy consumption and carbon emissions of the WAAM process are quantified from equations 1-4 and are adapted from a general assessment of the energy required for WAAM [30]. Carbon emissions for processes which use electrical energy are determined using the carbon emission signature (CES) [37], which will be calculated for the global average supply of energy. Western nations typically have a larger proportion of renewable or carbon neutral energy sources, reducing the carbon emissions from the same process.

$$E^{WAAM} = 3.6/\eta \cdot (P_{stb} \cdot t_{stb} + P_{arc} \cdot t_{arc} + dc \cdot P_{heater} \cdot t_{heater}) + t_{gas} \sum_{i=1}^{i} E_{gas}^{i} \cdot q_{gas}^{i} \quad (1)$$

$$SEC = \dot{m}/P_{arc} \quad (2)$$

$$CES = \eta(112 \cdot \%_{coal} + 49 \cdot \%_{natural\ gas} + 66 \cdot \%_{fuel\ oil}) \quad (3)$$

$$C = E_p \cdot CES/1000 \quad (4)$$

E^{WAAM} Primary energy of the WAAM process (MJ)

η Energy grid efficiency (0.34 is assumed [37])

P_{stb} Standby power of the WAAM process cell (robot arm and weld power source) (kW)

t_{stb} Standby and shutdown time for the WAAM process per component (hr)

SEC Specific energy consumption of the deposition process (kWh/kg)

m_{wire} mass of wire required to deposit the part (coefficient of 1.02 [30] used over deposition mass due to material loss to spatter and wire feed maintenance) (kg)

dc Heater duty cycle, ratio used to determine how much of the deposition time the component heater is running. Set at 0.5 based on production data

P_{heater} Power required to operate the component heater (kW)

t_{heater} Production time for the component and therefore time the heater is running (hr)

E_{gas} Primary energy of the shielding gas (MJ/l)

t Time the shielding gas is flowing (hr)

q_{gas} Volumetric flow rate of shielding gas (l/hr)

CES carbon emission signature (kgCO_2eq/GJ)

C carbon dioxide emissions (kgCO_2eq)

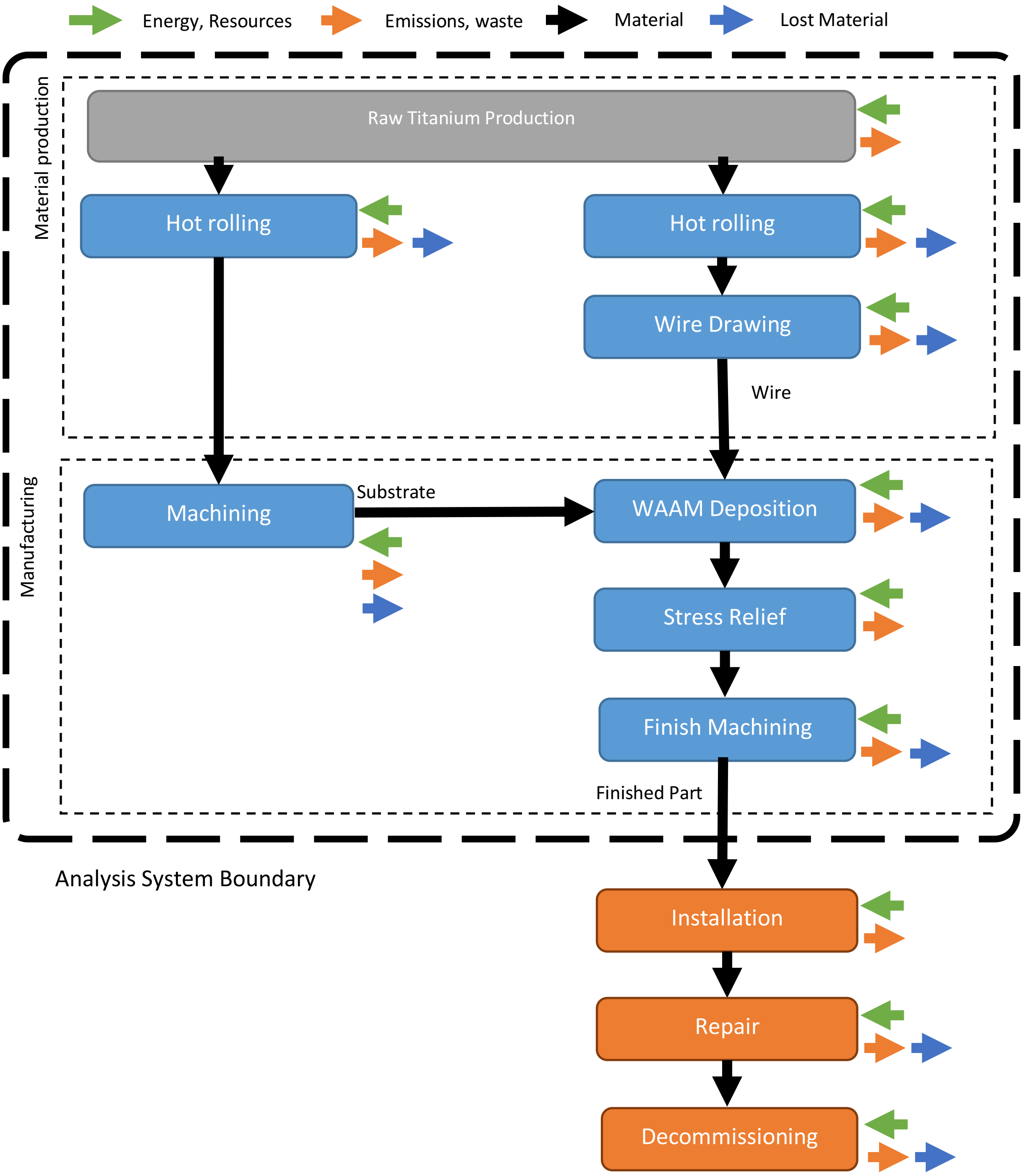

Fig. 1. Resource flow diagram for the WAAM process.

2.3. *Forging Process Model*

Forging produces near net shape components from a billet of material, deforming them plastically [39], generating a directional microstructure following the plastic flow of the deformation process and in titanium, conventional forging results in cumulative deformation of the α and β phases and an improvement in fatigue strength compared cast, which are non-directional, or machined parts which are only directional in the rolling direction [36]. A material flow diagram for the production of a forged component is detailed in Fig. 2. The production of the forging die (tooling) has been included due to its high mass and therefore embodied energy (4370kg), and the low production volume of the component (15 units) leading to the forging die contributing significantly to the environmental impact of production.

The energy consumption of forging is 570.95 kWh/ton [40], converted to a primary energy of 6.05 MJ/kg and carbon emissions of 11.1 $kgCO_2eq/kg$ using CES. The energy cost for the tooling is calculated in the same way as other components, considering the primary energy of the material, processing and machining costs. In this case, the cost is spread between the number of components (batch size), reducing its impact with more components produced.

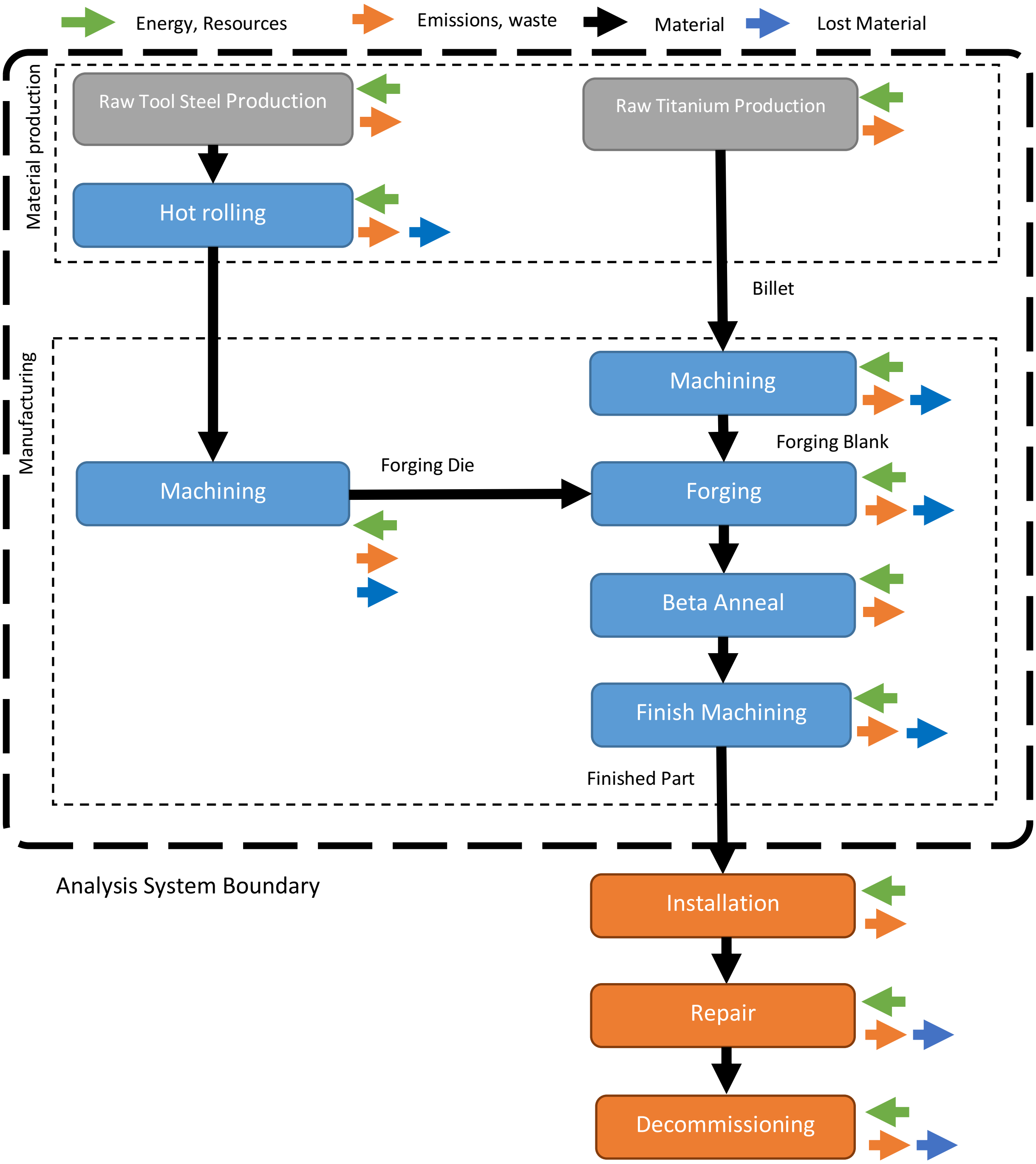

Fig. 2. Resource flow diagram for the forging process.

2.4. *Heat Treatment Model*

In the production by both WAAM and forging, a heat treatment process was used for stress relief and to improve the microstructure, respectively. In the case of the WAAM process, a stress relief heat treatment reduces the residual stresses in WAAM produced Grade 5 titanium [41, 42] and springback during machining, improving the final manufacture tolerances. The beta-anneal used following forging increases the proportion of beta phase in α-β alloys such as Grade 5 titanium (Ti6Al4V). This heat treatment process improves the fracture toughness and crack growth resistance [43]. This is followed by a stabilisation treatment to refine the microstructure and meet the ASTM B381 grade 5 standard [44]. Guidance for the heat treatment processes is given in the ASM guide for heat treating titanium alloys [43].

The energy consumption of a heat treatment is established from the power of the heat treatment furnace, its duty cycle at a range of temperature ramp rates and the time spent at each ramp rate. This is then converted to primary energy and carbon emissions using equations 5-7.

$$E_e = P_f \sum_{i=1}^{i} dc_i \cdot \Delta T_i / \dot{T}_i \quad (5)$$

$$E_p = 3.6 E_e / \eta \quad (6)$$

$$C = E_p \cdot CES / 1000 \quad (7)$$

Where:

E_e electrical energy used to power the furnace during a heat treatment cycle (kWh)

E_p primary energy (MJ)

P_f electrical power of the furnace (kW)

dc_i duty cycle or ratio of time on to time off during each stage of heat treatment

ΔT_i temperature change for each stage of heat treatment (°C)

$\dot{T}_i$ temperature ramp rate for each stage of heat treatment (°C/hr)

CES carbon emission signature (kgCO_2eq/GJ)

C carbon dioxide emissions (kgCO_2eq)

2.5. *Data Gathering*

A titanium-based component produced by an industry contractor has been used as the data source for a comparison between the WAAM and forging processes. For common processes such as primary production, rolling, drawing and machining; data on primary energy consumption and carbon dioxide emissions has been gathered from Ansys Granta Edupack 2021 R2 [45]. Material loss coefficients were also employed for rolling and drawing [10]. The primary energy for argon and helium were calculated from the literature [46, 47].

CES is determined from equation 3, using data from the BP statistical review of world energy [48] shown in Table 1 giving a global average CES of 1829.4 $kg_{CO2}eq/GJ$.

Table 1

Percentage of electrical energy generation by source [48].

Supply %	Coal	Natural Gas	Fuel Oil	Biomass	Hydro	Solar	Wind	Other Fuels	Pumped Storage	Nuclear
World	36.5	22.2	3.1	2.7	15.3	3.7	6.6	0	0	9.9

Quantifying the energy consumption and carbon emissions of logistics can be performed to a high level of precision where required. In some cases, where only an estimate is required, figures from BS EN 16258 [49] place the energy consumption and carbon emissions of ocean freight at 561.8 MJ/km/ton and 40 gCO2/km/ton, respectively. This is then detailed as energy consumption and carbon emission per kg of cargo in Table 2.

In this assessment, the primary feedstock (substrates and filler wire for WAAM, rolled billets for forging) has been assumed to have been transported across the Atlantic, from the Eastern United States to Europe, by a container ship.

Table 2

Energy and Emissions for Ocean Freight.

	Distance (km)	Energy (MJ/kg)	Carbon ($kgCO_2eq/kg$)
US to Europe	5285	2.97	0.21

To assess the environmental impact of a heat treatment, data from the bespoke top-hat furnace was collected using integrated thermocouples calibrated by the manufacturer and by monitoring the duty cycle of the heating element over time. This included the temperature ramp rates and the temperature ranges for each ramp rate. The electrical energy input (kWh) was then converted to primary energy consumption (MJ). The carbon dioxide emissions are then calculated using CES in equation 6.

3. Results and Discussion

When the mass of the component is determined for each stage of production the process data can be used to generate a life cycle of carbon emissions and energy consumption for the manufacture process. The mass breakdown and process parameters are shown in Table 3 and Table 4, respectively.

Table 3

Mass breakdown for component production by WAAM.

Component Mass breakdown (kg)	
Deposition	75.27
Substrate	191.4
Coarse machining	-48.79
Fine machining	-1
Component Total	216.88

Table 4
Process parameters for WAAM.

WAAM process parameter	
Deposition rate (ideal)	1.80kg/hr
Arc power	1.78kW
Standby power	0.1kW
Startup time	1hr
Arc time (operating in pulses)	25.7hr
Gas flow time	133hr
Heater on time	133hr
Building time	133hr
Heater power	2.5kW
Argon flow rate	1440l/hr
Helium flow rate	1800l/hr

Similar to that of WAAM, a mass breakdown for both the forged titanium and machined forging dies is required to determine the energy consumption and carbon emissions; these are shown in Table 5 and

Table ***6***.

Table 5
Mass breakdown for forged component.

Component Mass breakdown (kg)	
Forging Blank	496.10
Coarse machining	-71.55
Fine machining	-1.00
Scrapped	206.55
Component Total	217

Table 6
Mass breakdown for tooling dies.

Tooling Mass breakdown (kg)	
Rolled Billet	4370.6
Coarse machining	-1311.2
Fine machining	-437.1
Component Total	2622.4

3.1. *Environmental Impact*

Using the data gathered on the WAAM and forging processes, the primary energy and carbon dioxide emissions for the production of a component are tabulated in Table 7 and

Table **8**, then compared as presented in Fig. 3 and Fig. 4. These figures show that the principal source of environmental burden is the primary production of titanium through the energy intensive Kroll process [23], with the wire drawing being the next most significant energy demand. WAAM deposition was found to be the next most energy intensive step in the process. The bulk of this energy demand is contributed by the deposition and by operating the component heater, with idle time such as startup and shutdown contributing a negligible amount. Fig. 5 and Fig. 6 exhibit the components of energy consumption and carbon emissions in more detail, by excluding primary production costs. These figures demonstrate that wire drawing is the most energy intensive and has the highest carbon emissions for the WAAM process. For comparison, within the forging process, the highest energy consumption and carbon emissions come from the forging press.

Table 7

Energy and carbon costs for the component produced by WAAM.

Process	Primary Energy (MJ)	Carbon Dioxide ($kgCO_2eq$)
WAAM idle	1.06	1.936
WAAM deposition	806.6	1474
WAAM heater	1763	3223
WAAM shielding gases	733.1	1476
WAAM total	3304	6176
Wire Primary Production	30725	29842
Substrate Primary Production	70550	12996
Wire Drawing	10288	260.3
Substrate Rolling	3464	767.8
Coarse Machining	155.6	11.71
Stress Relief	5349	9779
Fine Machining	27.2	2.04
Shipping	824.6	58.7
Total	124687	59894

Table 8

Energy consumption and carbon emission for forged component.

Process	Primary Energy (MJ)	Carbon Dioxide ($kgCO_2eq$)
Billet Primary Production	174154	73666
Coarse Machining	228.2	19.2
Fine Machining	27.2	10.2
Forging	11049	20201
Die Tooling Manufacture	8050	717.46
Beta Anneal	13036	23833
Shipping	1472.9	104.9
Total	206248	104182

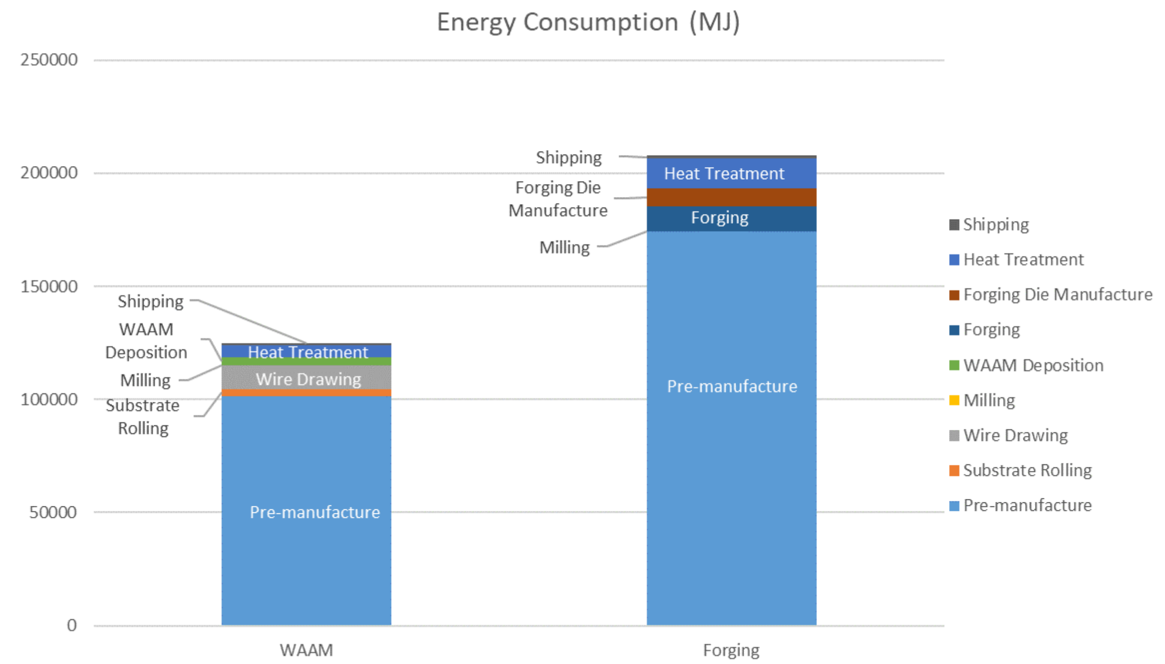

Fig. 3. Energy consumption required to produce the component.

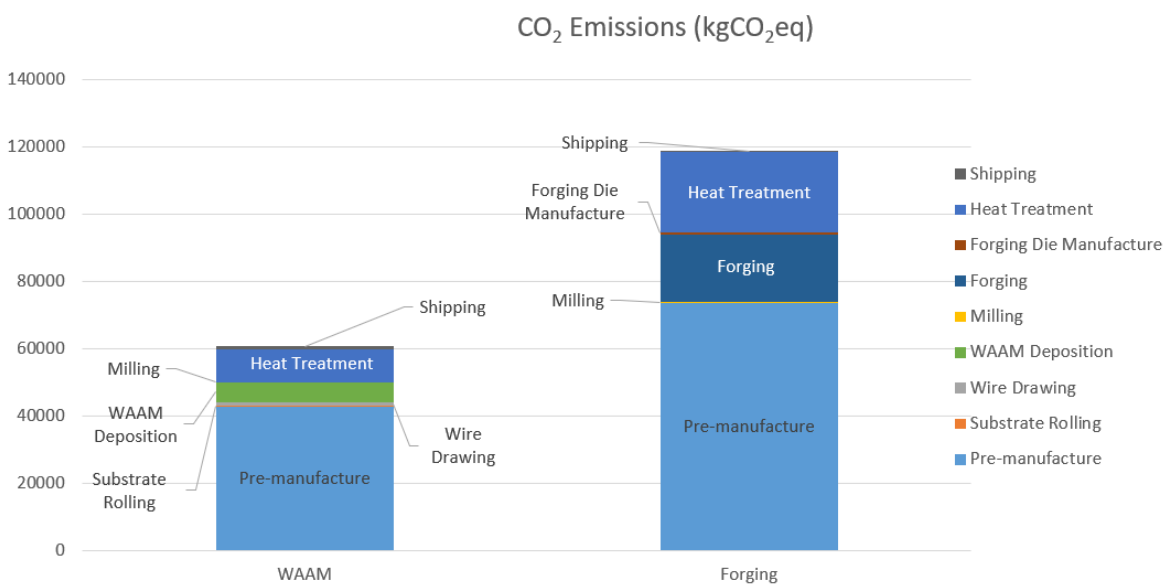

Fig. 4. CO_2 emissions produced during manufacture of the component.

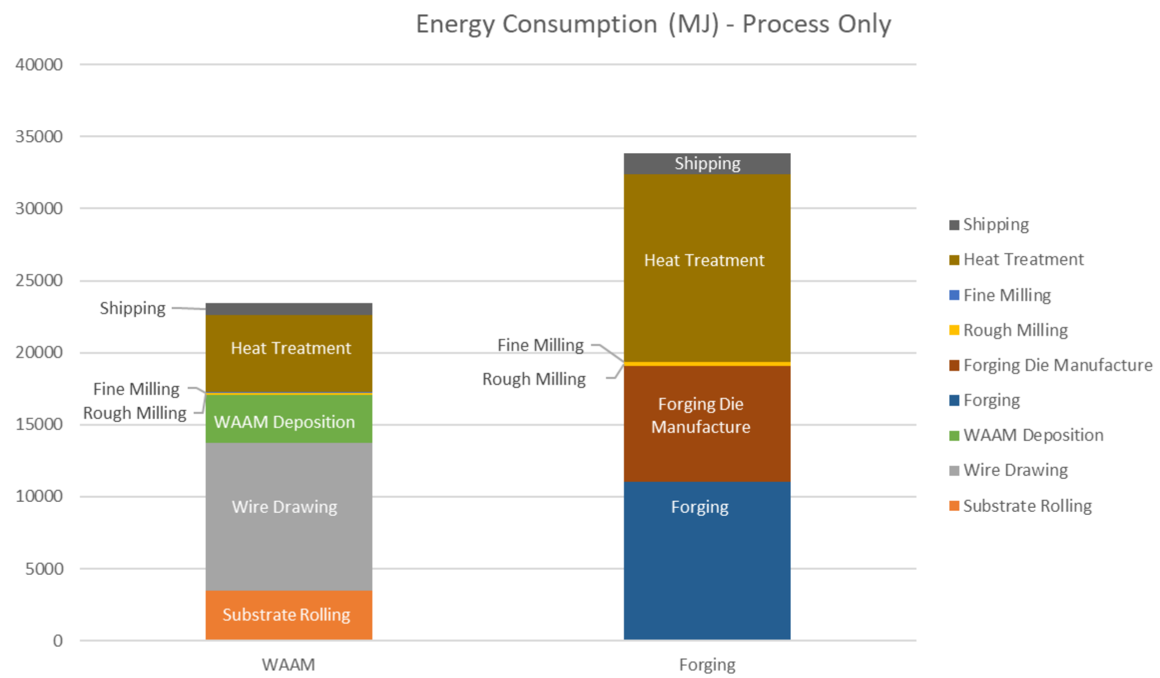

Fig. 5. Energy consumption required to produce the component where primary production is excluded.

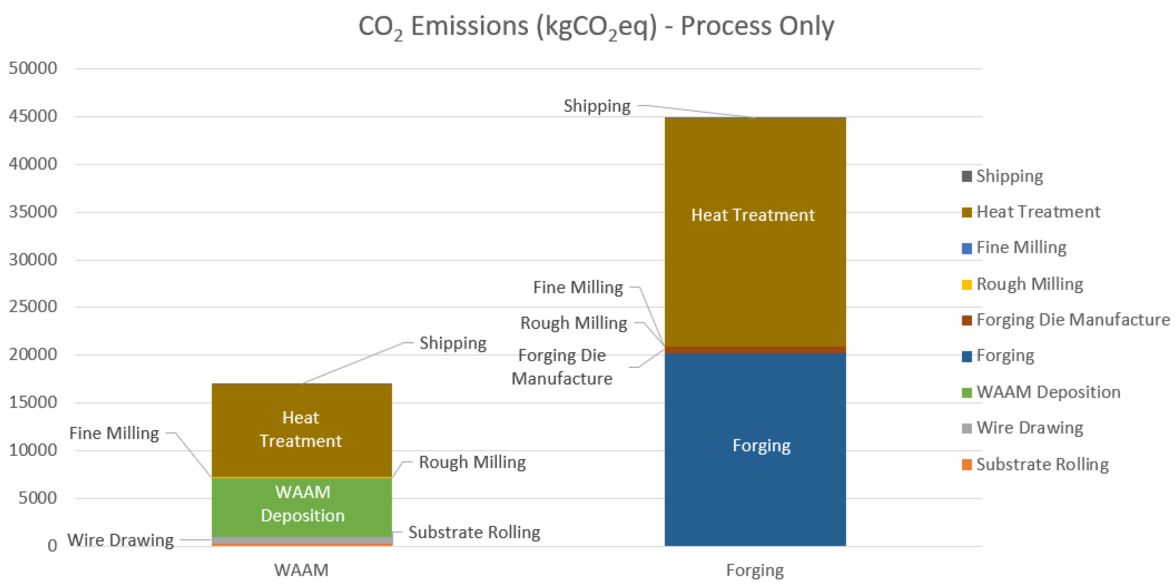

Fig. 6. CO_2 emissions produced during manufacture of the component where primary production is excluded.

From the results presented herein, direct comparisons can be made on 3 environmental impact metrics: material waste, carbon footprint and energy consumption. These were selected due to their accessibility and ease of comparison by future studies. Other metrics such as acidification potential and abiotic depletion require access to a detailed environmental database.

A comparison of forging against WAAM is introduced in . The carbon footprint and energy consumption can also be converted to a specific value by dividing by component mass, to yield specific carbon emissions (kgCO_2eq/kg) and specific energy consumption (MJ/kg). The results of this are shown in Table 9.

Table 9

Environmental impact metrics and specific impact by process.

	WAAM	Forging
Material Waste (%)	24.8	56.3
Carbon Emissions (kgCO_2eq)	59894	118541
Specific Carbon Emissions (kgCO_2eq/kg)	276.2	546.3
Energy Consumption (MJ)	124687	208017
Specific Energy Consumption (MJ/kg)	574.9	958.6

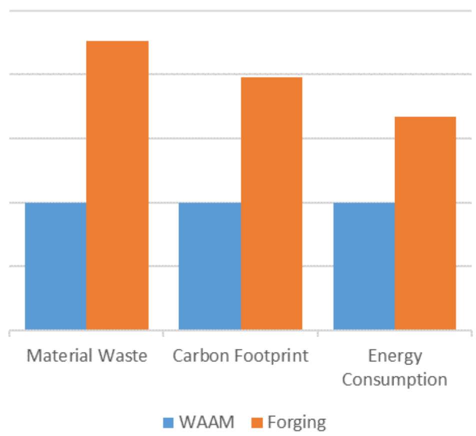

Fig. 7. Comparison of environmental metrics.

4. Conclusions

In this study, a method has been proposed to assess and compare the environmental impact of two industrially relevant manufacturing techniques. WAAM and forging are common methods of producing titanium components. The comparison between these manufacture processes has shown that while forging overall has a larger environmental impact, the proportionally largest environmental burden is caused by the primary production of titanium in both processes.

The results also reveal that the forging process produces 2.3 times more material waste compared to WAAM. This additional material, combined with the energy intensive processes of forging, die production and heat treatment, lead to CO_2 emissions 2 times that of WAAM. When the primary production of material is excluded, this difference increases to 2.6 times. Therefore, the usage of a low material waste process such as WAAM will considerably reduce the environmental burden of the production of this component compared to production by forging. This study was limited to data on a single component design, produced by two different manufacturing methods, and does not account for any improvements in the design of the component to design for the AM process. This would likely reduce the environmental impact further.

The greatest contributors to environmental impact of the WAAM process when pre-manufacture impact is ignored (which is the case when material waste is reduced to a minimum) are: heat treatment, wire drawing and deposition energy. As such, to reduce energy consumption in future components, designing for the WAAM process to maximise usage of the rolled substrate is important. This minimises the quantity of drawn wire feedstock required, and reduces the deposition time, thus deposition energy. To reduce heat treatment energy, either a more efficient furnace could be sourced for the facility with superior insulation or a volume more closely matching the component, or a less energy intensive heat treatment regime could be investigated, while still achieving a reduction in residual stresses.

The introduction of specific energy consumption and specific carbon emissions, as a metric for the sustainability of different manufacture processes or production lines, allows for these to be directly compared, regardless of component size. In the production of a titanium component by WAAM, the SEC was found to be 574.9MJ/kg compared to 958MJ/kg by forging.

5. Conflict of interest

The authors declare no conflict of interest.

6. References

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