REPORT

Wire+arc additive manufacturing vs. traditional machining from solid: a cost comparison

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Welding Engineering
and Laser Processing
Centre

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Acronyms

AM Additive Manufacturing.

BTF Buy To Fly.

CNC Computer Numerical Control.

NDT Non-Destructive Testing.

OLM On-line Monitoring.

WAAM Wire+Arc Additive Manufacturing.

WFS Wire Feed Speed.

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Nomenclature

Volumetric costs

C^{M}	Final cost of part machined from billet or forging	£
C^{AM}	Final cost of WAAM deposited part	£
C_i^{M}	Cost of billet for machining	£
C_i^{AM}	Cost of rough part made by additive manufacturing	£
C_m^{M}	Cost of machining of billet or forging	£
C_m^{AM}	Cost of machining of WAAM deposit	£
C_s	Cost of start substrate	£

Specific costs

c_F	Cost of forged titanium	£/kg
c_W	Cost of titanium wire	£/kg
HR^{M}	Hourly rate for machining cell	£/h
HR^{AM}	Hourly rate for additive manufacturing cell	£/h

Volumes

V_f	Volume of final part	m^3
V_i^{M}	Volume of initial forging	m^3
V_i^{AM}	Deposited volume	m^3
V_s	Volume of the start substrate	m^3

Times

t^{AM}	Time to machine the WAAM component	h
t^{D}	Time to deposit the WAAM component	h
t^{M}	Time to machine the component from a billet	h

Other Symbols

ρ	Density	kg/m^3
BTF^{M}	Buy-to-fly ratio of fully machined part	$kg\,kg^{-1}$
BTF^{AM}	Buy-to-fly ratio of deposited part	$kg\,kg^{-1}$
DR	Deposition rate	$kg\,h^{-1}$
MRR	Material removal rate	$kg\,h^{-1}$
SS	Starts and stops, interlayer cooling	

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1 Executive Summary

A cost model that compares the cost of a part produced via the traditional route (machined from solid) to the one of a finished part made via WAAM was produced. The aim is to provide a tool to make informed decision when assessing the convenience of one of the two manufacturing routes for a particular part, as well as to assess the sensitivity of cost to process, material or machine parameters. Provided these are adjusted accordingly, the model can be transferred to other materials beside titanium.

WAAM proved to be a more economic option than machining from solid under most circumstances. It was shown that for a robot-based cell, increasing the deposition rate over 1 kg h^{-1} has a very limited impact, regardless of the Buy To Fly (BTF) ratio of the part made by Additive Manufacturing (AM). For more expensive machine options, increasing the deposition rates has some benefits due to the higher hourly rate. For these setups, maximising the utilisation of the cell is also suggested. It was shown that processes with higher deposition rates are not more convenient than WAAM due to the much higher material cost related to their higher BTF ratios.

Increasing the material removal rate during machining does not reduce the cost substantially, regardless of the BTF ratio.

The specific cost of titanium deposition, which depends mainly on BTF ratio, and feedstock and machine costs, under the current circumstances is roughly £300 kg^{-1}.

It was demonstrated that a powder-based process has a specific cost of deposition which is higher than machining from solid, regardless of the feedstock cost, due to its low deposition rate and high equipment cost.

Finally, the cost model was applied to a variety of aerospace components in titanium, steel and aluminium, and cost savings up to 69% were proven.

2 Introduction

2.1 The traditional approach: machine from solid

In the traditional subtractive approach, a forged billet or an ingot are machined to final shape. According to Allen[1], in the case of a forged billet a minimum section of 25 mm to 30 mm is required in order to complete the forging. If the thickness was lower, the increased cooling rate would result in temperatures that are too low to shape the billet. Furthermore, the extra material also allows for superficial stresses as well as oxide layers to develop; the extra material can be machined off subsequent to the forging process, and normally design tolerances which are around 5 mm to 10 mm account for this.

Consequently, for titanium components encountering Buy To Fly (BTF) ratios as high as 10 or more should not be unexpected. BTF ratio is defined as the ratio of the volume or mass of the initial workpiece to that of the finished product:

$$\mathrm{BTF} = \frac{V_i}{V_f} \tag{2.1.1}$$

The BTF ratio depends on how close the shape of forgings or ingots are to the shape of the finished component. While aero-engines components are machined from forged billets, most aero-structures will be machined from a standard rectangular billet cut from rolled stock, which is also characterised by poor material utilisation. Some typical BTF ratios are shown in Table 1 from Allen[1].

At present, there is a growing requirement for substantial reductions in BTF ratios, which are unsustainable for the following reasons. First, with the increasing usage of carbon-fibre-reinforced polymers, aircraft designers are forced to shift from aluminium to titanium, the former being electrochemically incompatible

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Table 1: Components, weights of billets and finished products, and relative BTF ratios.

Component	**Billet (kg)**	**Finished product (kg)**	**BTF ratio**
Intercase	182	30	6.1
Simple duct flange 1	67	11.1	6
Simple duct flange 2	67	7.7	8.7
Complex duct flange 1	149	7.7	19.4
Complex duct flange 2	207	10.3	20.1
Large blisk	810	97	8.4
Wing rib	657	18	37

with carbon.[2] Second, with the current and forecast aircraft market expansion rate, the demand for titanium parts is increasing accordingly.[3] Third, titanium is an expensive material to source and machine.[4] Fourth, titanium production has a large environmental impact, in terms of energy consumption (361 MJ kg^{-1} to 745 MJ kg^{-1}) and CO_2 emissions (19 kg kg^{-1} to 39 kg kg^{-1}).[5] Even for recycled titanium these values are 258 MJ kg^{-1} and 13.7 kg kg^{-1}, respectively.[5]

2.2 The approach of the future: additive manufacturing

Additive Manufacturing (AM) consists of adding material in a layer-by-layer fashion to produce a (near-)net shape component, thus promising reduction in material waste, lead times, design constraints and ultimately in the total cost of the finished product.[6,7]

The current main AM processes are shown in Figure 1. Wire+Arc Additive Manufacturing (WAAM) relies on an electric arc as the heat source and wire as feedstock. To trace the path associated with each layer, either robots or Computer Numerical Control (CNC) gantries are used. Both setups are shown in Figure 2.

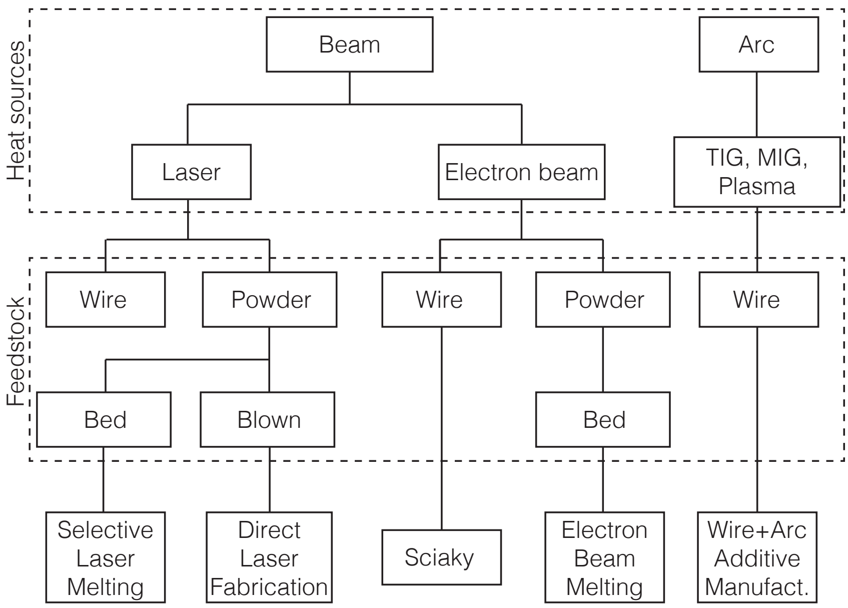

Figure 1: Current main AM processes.

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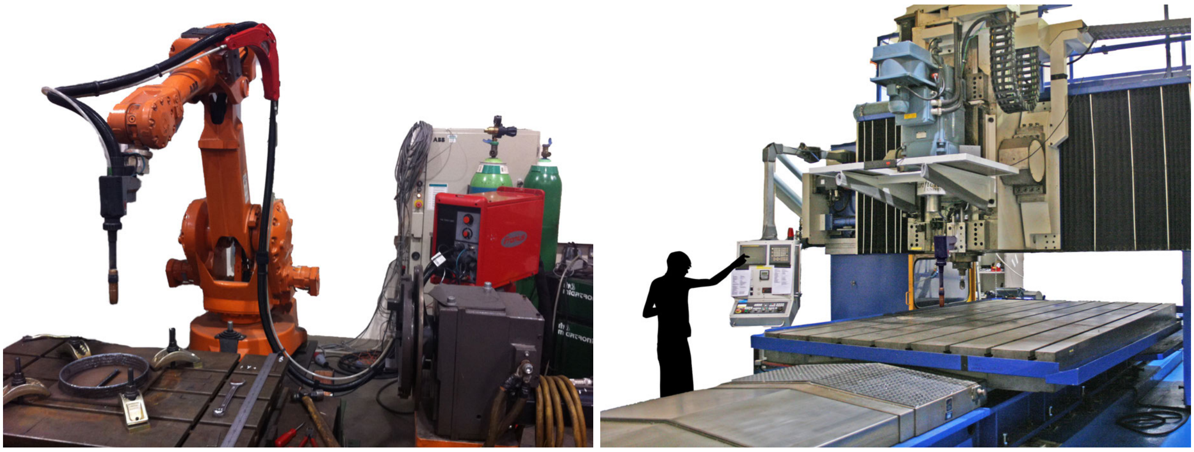

(a) 6-axis welding robotic system

(b) Gantry option, in particular a deposition system retrofitted onto a (former) friction stir welding machine

Figure 2: Typical motion systems options for WAAM.

The specific advantages of this particular class of AM processes are:

- reduction in material waste
- high deposition rate
- much lower manufacturing cost than powder-based processes
- potentially no limitation on part size
- possibility of in-process machining
- possibility of creating functionally graded material.

WAAM is better suited for low to medium complexity components, and due to the size of the deposit bead, the manufacture of small components (below 100 mm in two dimensions) or of those containing intricate features is not normally undertaken. Parts that are several metres in length have been built. The longest part was a 3 m aluminium wall which was deposited and milled *in situ* on the machine shown in Figure 2b. A 2.5 m long aluminium wing spar is shown in Figure 3. The heaviest part built in steel so far was a turbine blade weighing 100 kg. Parts up to 60 kg have been built in titanium. A wing spar part manufactured by WAAM is shown in Figure 4; if machined from solid, it would have a BTF ratio of roughly 20. WAAM is a near-net shape process hence it requires a finish machining pass; while this is definitely necessary for components that are subject to high-cycle fatigue, it might not be needed for components (or particular areas of a component) subject to low-cycle fatigue, or for components loaded statically.

Depending upon the material being deposited, an inert environment might be required. For materials such as aluminium and steel, the shielding provided by the welding torch during deposition is sufficient. For refractory materials and titanium, providing appropriate shielding is critical to success. While efforts to develop a local shielding device are ongoing (an example is shown in Figure 5a), the current best practice is to deposit inside a chamber or tent filled with Argon gas (Figure 5b). From both practical and cost viewpoints, a tent is better than a chamber: firstly, it is cheaper; secondly, it is collapsible consequently the air can be pumped out reducing its volume and Argon gas can be pumped in subsequently. The tent currently in use at Cranfield University requires three pumping cycles to achieve O_2 levels below 200 ppm, and these are completed in a much shorter time and with much less Argon gas compared to a rigid chamber.

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Figure 3: 2.5 m long aluminium rib. For this component, WAAM has enabled material savings of more than 500 kg.

(a) Top view

(b) Side view

Figure 4: 1.2 m Ti-6Al-4V wing spar built by WAAM at Cranfield University. The structure is not a real component however it is representative of an F35 fighter jet wing spar. Please note two components were built back-to-back sharing the same sacrificial substrate. From baesystems.com[8].

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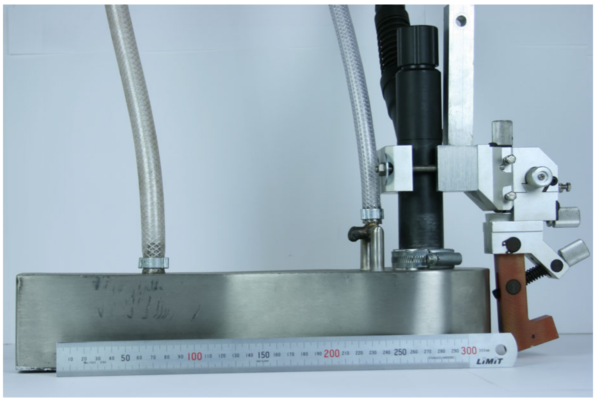

(a) Local shielding device

(b) Collapsible tent enclosing a 6-axis Fanuc welding robot and a 2-axis Fanuc part rotator

Figure 5: Material shielding approaches.

2.3 Scope of the cost model

Numerous factors such as BTF ratios, deposition rate, and material cost affect the final cost figures for a component. This report aims at investigating how sensitive the economical performances of WAAM are to these key parameters, providing a simple and quick tool to compare the cost of any component if manufactured via the additive route, rather than the traditional one. The calculation of a cost figure accurate to the £ lies outside the scope of the present work; indeed the cost model should be seen as a decision support tool, as opposed to a mere calculator. Consequently, besides providing cost estimates, the model answers questions related to the optimal deposition rate and break-even conditions, amongst others.

3 Framework

3.1 Assumptions

The cost model relies on simplifying assumptions which are listed here.

- **General:**
  - *Tooling and set-up:* Because the model calculates the cost of a part manufactured in a series production, the costs for tooling and set-up have been deliberately omitted in both machining from solid and WAAM manufacturing scenarios.
  - *Non-Destructive Testing (NDT) and On-line Monitoring (OLM):* The non-value adding time of NDT and OLM is not included in the calculations.
  - *Operator:* An operator can be busy with one machining cell only.
- **Machining:**
  - *Machining passes:* The machining operation normally consists of two sub-operations, namely roughing and finishing. Different machining parameters and cutters are used for the two, however for simplicity of the cost model here they are considered as as if they were the same. Consequently, only one type of machining operation is taken into account.
  - *Material removal rate:* As explained in the previous paragraph, roughing and finishing have different MRRs. Here an average figure is considered. Please note the calculation of MRR is not limited to the milling parameters (depth of cut and feed rate) but also accounts for tool change

and part manipulation during machining. Consequently MRR should also account for the effect of the geometrical complexity of the part.

- *Hourly rate:* for any WAAM machine cost larger than £250k it is assumed that machining will be performed within the same cell, consequently under these circumstances $HR^M = HR^{AM}$.

- **WAAM:**
  - *Starts and stops:* Due to robot and part rotator manipulation, and possible interlayer cooling, there is an amount of extra time which does not add any value. This is captured by a multiplier defined as "Starts and stops". On the one hand, for a large component built symmetrically on either side of its substrate, or equivalently for two components built back-to-back on either side of a sacrificial substrate, no cooling time is required and the non-value adding time is due exclusively to robot manipulation. On the other hand, for a small component, cooling time can represent a substantial portion of the manufacturing time. Because this model is targeting the evaluation of the cost of large components, we shall not include any cooling time in the calculations. From internal experience, the amount of time required for manipulation is roughly 10% of that of deposition; consequently the SS coefficient is set to 1.1.
  - *High-pressure rolling:* This in-process technique proved to produce increased and isotropic tensile properties in titanium, and pore-free deposits also with increased tensile properties in aluminium.[9,10,11] The addition of rolling increases the total time required for deposition. For any WAAM machine cost larger than £250k it is assumed that rolling will be part of the manufacturing process and the SS coefficient is set to 1.5 instead of 1.1.
  - *Setup prior to machining:* not considered in the present analysis.
  - *Price of substrate:* The market price of titanium plates is the same one of forgings.
  - *Fully finished part:* Although it might not be necessary to finish the whole component, and certain features might be left in the as-deposited condition, here it is assumed that all surfaces will be machined.

3.2 Specific costs

Specific costs are those that are related to units of mass or time. For instance, the cost of 1 kg of titanium wire is a specific cost. The cost of running a milling machine for 1 h can also be considered as a specific cost.

On the one hand, mass or volumetric costs of WAAM are relatively easy to gather - they are often market prices of a commodity. On the other hand, hourly rates account for a mix of *fixed* costs (such as equipment and fully-burdened labour) and *variable* costs (such as those of the consumables required to perform an operation). Fixed costs do not vary, or vary very little, with the levels of the output, for a given available capacity. On the contrary, variable costs are related to the output. Since the relationships between consumables and outputs are known, for a given level of capacity utilisation the hourly requirement of each consumable can be calculated. Consequently both fixed and variable costs can be considered together in one single hourly rate figure, as long as the assumptions on capacity utilisation are made clear.

The fixed costs considered in the present analysis are:

- *WAAM hardware:* robot (£50k), welding power source (£25k), tooling (£10k), torch (£5k), enclosure (£20k - required only for titanium), enclosed safe perimeter (£20k), automatic voltage control (£10k), vision-based process monitoring (£30k), Wire Feed Speed (WFS)-based process monitoring (£1k), electric-based process monitoring (£10k). Total: £181k.
- *WAAM software:* basic slicing package (£10k), auto-programming capabilities (£80k). Total: £90k.

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Considering a five-year depreciation period, 2000 h of available capacity per year, and 80% capacity utilisation, this leads to a figure of £33.9 h^{-1} for the equipment.

The variable costs considered in the present analysis are:

- Electricity for robot, cooling and power source. Total: £1.2 h^{-1}.
- Shielding gas. Total: £2 h^{-1}.
- Welding consumables: contact tips, liners, rollers, shroud, gas lenses, regulators, torches, electrodes; each of them considered individually in terms of life and replacement intervals. Total: £2.6 h^{-1}.

If fully-burdened labour cost is also considered (£45 h^{-1}, under the assumption that one operator is busy with one machine), the total hourly rate for a WAAM cell is £82 h^{-1}. Please note this is the worst case scenario as it includes the highest cost of automation as well as the enclosure required for titanium deposition (Figure 5b). However, the best case scenario would lead to a hourly rate of £78 h^{-1}. For our conservative approach and given the focus of this paper on titanium, we shall use the highest hourly rate figure.

With regards to machining, experts from established companies were contacted. There was a substantial variability in the figures provided; usually smaller companies quoted lower hourly rates. A sensible value for HR^M of £60 h^{-1} was chosen. Considering the cost of an advanced milling machine, and the extreme wear of tools especially with regards to titanium machining, this is most likely on the very low end of the scale and, if anything, should work against WAAM.

Specific costs and machine performances are summarised in Table 2.

Table 2: Specific cost figures and machine performances.

Parameter	**Abbrev.**	**Value**	**Units**
Cost of forged titanium	c_F	60	£/kg
Cost of titanium wire	c_W	130	£/kg
Hourly rate for machining cell	HR^M	60	£/h
Hourly rate for WAAM cell	HR^{AM}	82	£/h
Starts and stops	SS	1.1	
Material removal rate	MRR	8	kg h^{-1}
		(30)	cm^3/min

4 Cost equations

The equations defined to calculate the costs for a component produced by the traditional route and by WAAM are presented here.

4.1 Machine from solid

The machine from solid approach requires an initial billet or forging. These are machined to the shape of the finished product. The cost of the initial forged workpiece is:

$$C_i^M = V_i^M \rho \, c_F \tag{4.1.1}$$

If BTF ratio is taken into account:

$$C_i^M = V_f \, BTF^M \rho \, c_F \tag{4.1.2}$$

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The cost of machining this part is:

$$C_m^M = t^M\, HR^M = \frac{\left(V_i^M - V_f\right)\ \rho}{MRR}\, HR^M \tag{4.1.3}$$

Therefore the total cost of a part machined from a billet or ingot is:

$$C^M = C_i^M + C_m^M = \tag{4.1.4}$$

$$= V_f\, BTF^M\, \rho\, c_F + \frac{\left(V_i^M - V_f\right)\ \rho}{MRR}\, HR^M = \tag{4.1.5}$$

$$= \rho \left[V_f\, BTF^M\, c_F + \frac{\left(V_i^M - V_f\right)}{MRR}\, HR^M \right] \tag{4.1.6}$$

4.2 Additive manufacturing

WAAM requires an existing plate (or component) to be used as start surface for the deposition. For this investigation the substrate (or at least part of it) is included in the finished product. The cost of the substrate is:

$$C_s = V_s\, \rho\, c_F \tag{4.2.1}$$

The cost of deposition by WAAM is:

$$C_i^{AM} = V_i^{AM} \rho\, c_W + t^D\, HR^{AM} \tag{4.2.2}$$

The $V_i^{AM}\, \rho\, c_W$ term accounts for the cost related to material addition, while the $t^D\, HR^{AM}$ term for the utilisation of WAAM facilities. If the BTF ratio of the near net shape part made by WAAM is taken into account:

$$V_f = \frac{V_i^{AM} + V_s}{BTF^{AM}} \ \Rightarrow\ V_i^{AM} = V_f\, BTF^{AM} - V_s \tag{4.2.3}$$

it follows:

$$C_i^{AM} = \left(V_f\, BTF^{AM} - V_s\right) \rho\, c_W + t^D\, HR^{AM} \tag{4.2.4}$$

considering that:

$$t^D = \frac{V_i^{AM} \rho}{DR}\, SS = \frac{\left(V_f\, BTF^{AM} - V_s\right) \rho}{DR}\, SS \tag{4.2.5}$$

it follows:

$$C_i^{AM} = \rho \left(V_f\, BTF^{AM} - V_s\right) \left(c_W + \frac{SS\, HR^{AM}}{DR} \right) \tag{4.2.6}$$

The cost of machining this component is:

$$C_m^{AM} = t^{AM}\, HR^M = \frac{\left(V_i^{AM} + V_s - V_f\right) \rho}{MRR}\, HR^M \tag{4.2.7}$$

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Substituting from equation 4.2.3:

$$C_m^{AM} = \frac{\left(V_f\, BTF^{AM} - V_s + V_s - V_f\right) \rho}{MRR}\, HR^M = \frac{V_f \left(BTF^{AM} - 1\right) \rho}{MRR}\, HR^M \tag{4.2.8}$$

Finally, the total cost of a part made by WAAM is:

$$C^{AM} = C_s + C_i^{AM} + C_m^{AM} = \tag{4.2.9}$$

$$= V_s\, \rho\, c_F + \rho \left(V_f\, BTF^{AM} - V_s\right) \left(c_W + \frac{SS\ HR^{AM}}{DR}\right) + \frac{V_f \left(BTF^{AM} - 1\right) \rho}{MRR}\, HR^M = \tag{4.2.10}$$

$$= \rho \left[V_s\, c_F + \left(V_f\, BTF^{AM} - V_s\right) \left(c_W + \frac{SS\ HR^{AM}}{DR}\right) + \frac{V_f \left(BTF^{AM} - 1\right)}{MRR}\, HR^M\right] \tag{4.2.11}$$

4.3 Cost comparison

Finally, the total cost of a part made by WAAM is expressed as percentage of the total cost of a part machined from solid:

$$C_{\%} = \frac{C^{AM}}{C^M}\, 100 = \frac{V_s\, c_F + \left(V_f\, BTF^{AM} - V_s\right) \left(c_W + \frac{SS\ HR^{AM}}{DR}\right) + \frac{V_f \left(BTF^{AM} - 1\right)}{MRR}\, HR^M}{V_f\, BTF^M\, c_F + \frac{\left(V_i^M - V_f\right)}{MRR}\, HR^M} 100 \tag{4.3.1}$$

4.4 Validation and verification

In model verification, we must check whether the model implements the assumptions correctly. The model was verified by calculating baseline costs, such as $BTF^M = 1$, or zero deposited volume for WAAM. The model returned meaningful results. Structured walk-through and one-step analysis were also used; process experts were involved in this step.

In model validation, we make sure the assumptions which have been made are reasonable. Process experts were involved also for this step. Furthermore, the results of the cost model were compared to already available measurements.

4.5 Transferability to other materials

While developed for titanium, the model can be adapted to potentially any other material, provided that the following specific costs and machine performances are adjusted accordingly:

- cost of raw materials;
- deposition rate;
- material removal rate.

5 Results and discussion

5.1 Cost curves and sensitivity analysis

Figure 6 shows the cost of three different parts (10 kg, 20 kg and 30 kg each) made by WAAM and machined from solid as a function of their BTF ratio. As an example, if a 30 kg component with $BTF^M = 15$ is

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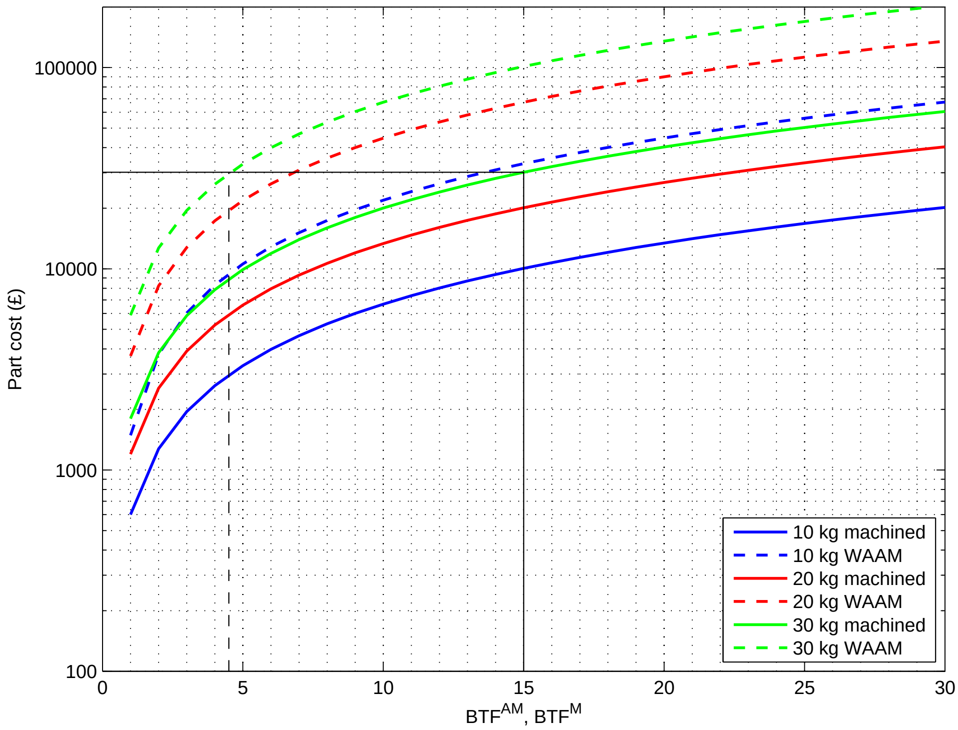

Figure 6: Cost of 10 kg, 20 kg and 30 kg parts machined from solid and made by WAAM as a function of their BTF ratio. Total cost of hardware = £181k. Substrate mass = 5 kg.

considered, it can be seen that WAAM is more cost effective if $BTF^{AM} < 4.5$. If $BTF^{AM} = 1.5$, the cost of the component is reduced by 69%.

Figure 7 shows the cost of a 30 kg part made by WAAM as a function of its BTF^{AM}. Different curves are plotted for seven deposition rates ranging from 0.5 kg h^{-1} to 5 kg h^{-1}. For different deposition rates, the difference in part cost increases with the BTF ratio. For instance, for $BTF^{AM} = 2$ producing a part with a deposition rate of 5 kg h^{-1} would cost £2k less than one with a deposition rate of 0.5 kg h^{-1}. However, for $BTF^{AM} = 5$ a deposition rate of 5 kg h^{-1} would save £20k over one deposited at 0.5 kg h^{-1}. The conclusion is that for BTF^{AM} ratios such as the one achieved by WAAM (i.e. <2) increasing the deposition rate has a relatively limited economical impact.

Figure 8 shows the specific cost of deposition for WAAM as a function of the deposition rate. Regardless of the BTF^{AM}, curves plateau for deposition rates around 1 kg h^{-1}. Increasing the deposition rate, under the current assumption, brings no economical benefit.

Figure 9 shows the specific cost of deposition for WAAM as a function of the deposition rate; curves are provided for different machine costs. It can be seen that the higher HR^{AM} due to higher machine costs results in higher specific costs of deposition. In these cases, increasing the deposition rates does have economical benefits: the point at which the curve plateaus shifts from 1 kg h^{-1} to 4 kg h^{-1}.

Figure 10 shows the specific cost of deposition for WAAM as a function of the capacity utilisation; curves are provided for different machine costs. Also in this case the higher HR^{AM} due to more expensive equipment justifies the attempt to maximise productivity.

Figure 11 shows the cost of a part made by WAAM and machined from solid, as a function of the MRR; curves are provided for different masses. Because in WAAM the largest part of the cost is due to the material, the MRR has a very limited impact. In the machined from solid case, the MRR has a larger impact due to the much higher material which needs to be removed; the curves seem to contradict the general belief that machining faster results in lower costs; however this is most likely due to the relatively low value

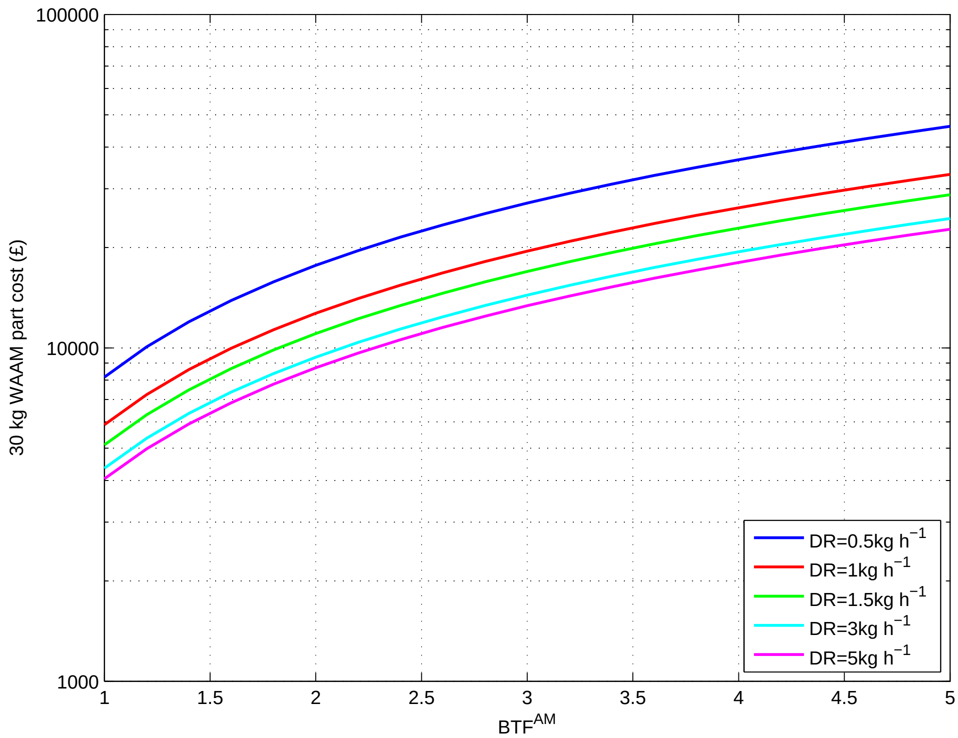

Figure 7: Cost of a 30 kg part made by WAAM as a function of BTF^{AM}. Curves are provided for different deposition rates. Total cost of hardware = £181k.

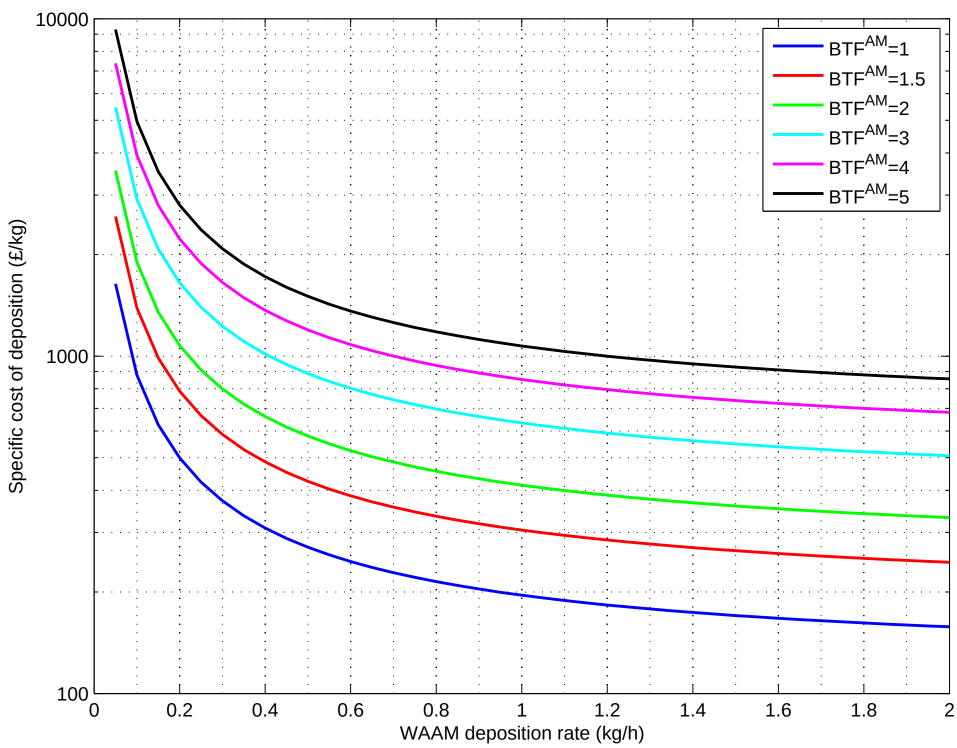

Figure 8: Specific cost of deposition for WAAM as a function of the deposition rate. Curves are provided for different BTF^{AM}. Total cost of hardware = £181k.

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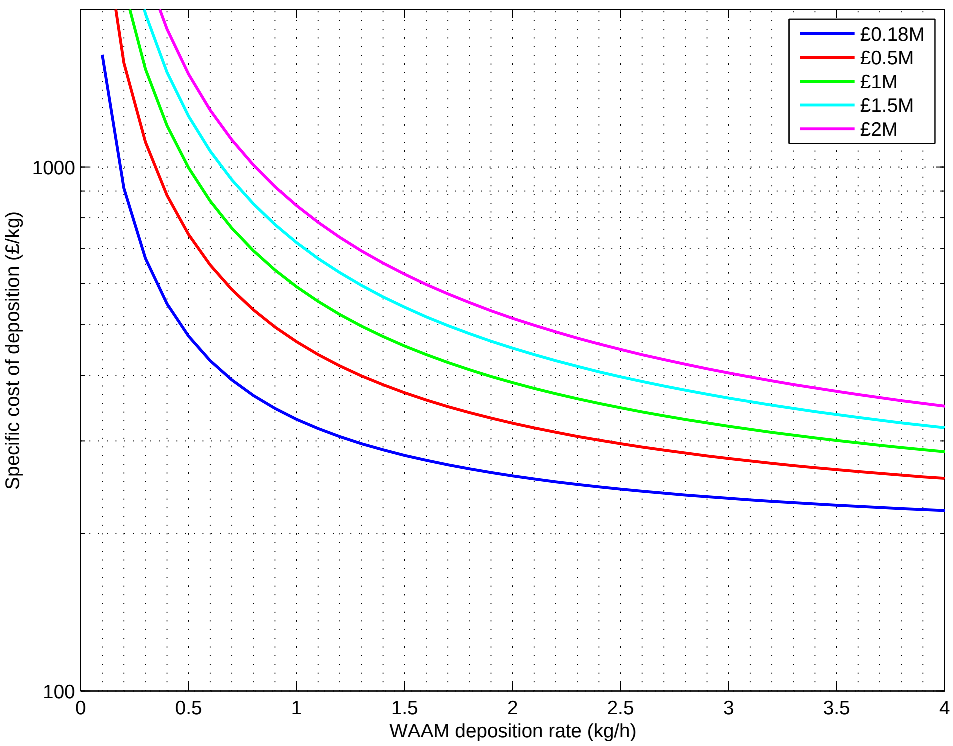

Figure 9: Specific cost of deposition for WAAM as a function of the deposition rates. Curves are provided for different machine costs. Depreciation = 5 years, $BTF^{AM} = 1.5$.

chosen for HR^{M}.

Figure 12 shows the cost of a part made by WAAM as a function of the MRR; curves are provided for different BTF^{AM}. Also in this case the extremely high material costs make the machining speed irrelevant.

Figure 13 shows the specific cost of deposition for WAAM as a function of the wire cost. Curves are provided for different BTF^{AM}. Considering current BTF^{AM} achieved and wire cost (£130 kg^{-1}), WAAM is always a better option than machining from solid for $BTF^{M} > 5$.

Figure 14 shows the specific cost of deposition for WAAM as a function of the wire cost. Curves are provided for different machine costs. There is very little difference in the sensitivity of the specific cost of deposition to the changes in machine cost, for a given change in the cost of raw materials. For instance, if the wire prices increases from £100 kg^{-1} to £200 kg^{-1}, the increase in the specific cost of deposition is roughly £100, whether the machine costs £180k or £2M.

Finally, Figure 15 shows the specific cost of deposition for WAAM as a function of starts and stops. Curves are provided for different machine costs. The specific cost of deposition changes similarly to when the utilisation is reduced, and it is more sensitive when using expensive hardware. In fact, while a change in the starts and stops factor from one to two for a £181k machine would result in an increase of the specific cost of deposition of about 50%, the same change would result in an increase of almost 100% when using a £2M machine.

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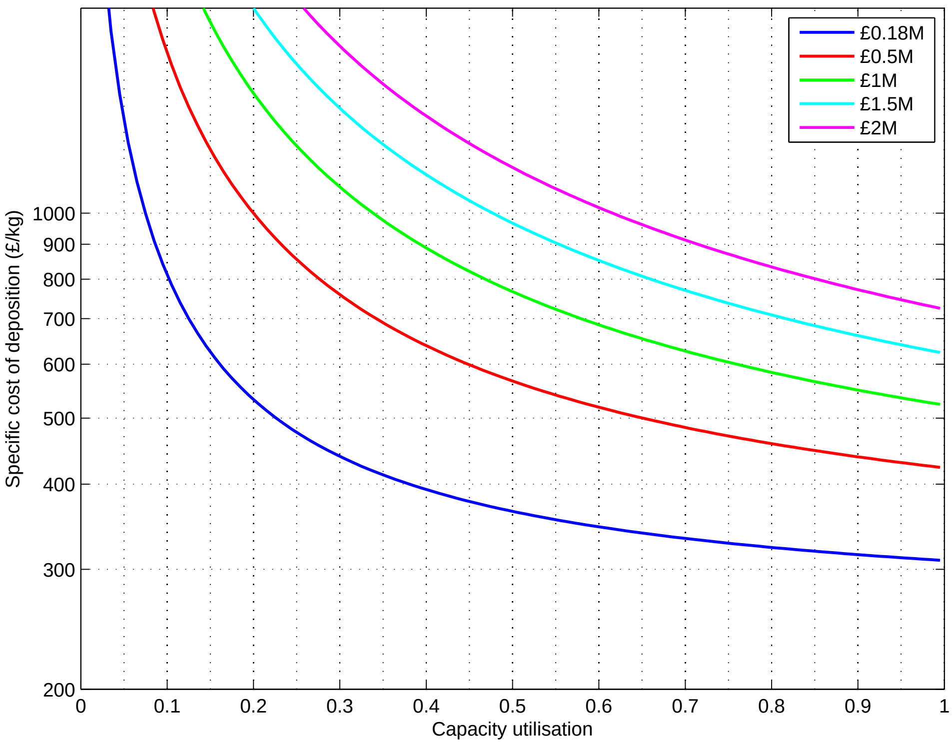

Figure 10: Specific cost of deposition for WAAM as a function of the capacity utilisation. Curves are provided for different machine costs. Depreciation = 5 years, $BTF^{AM} = 1.5$.

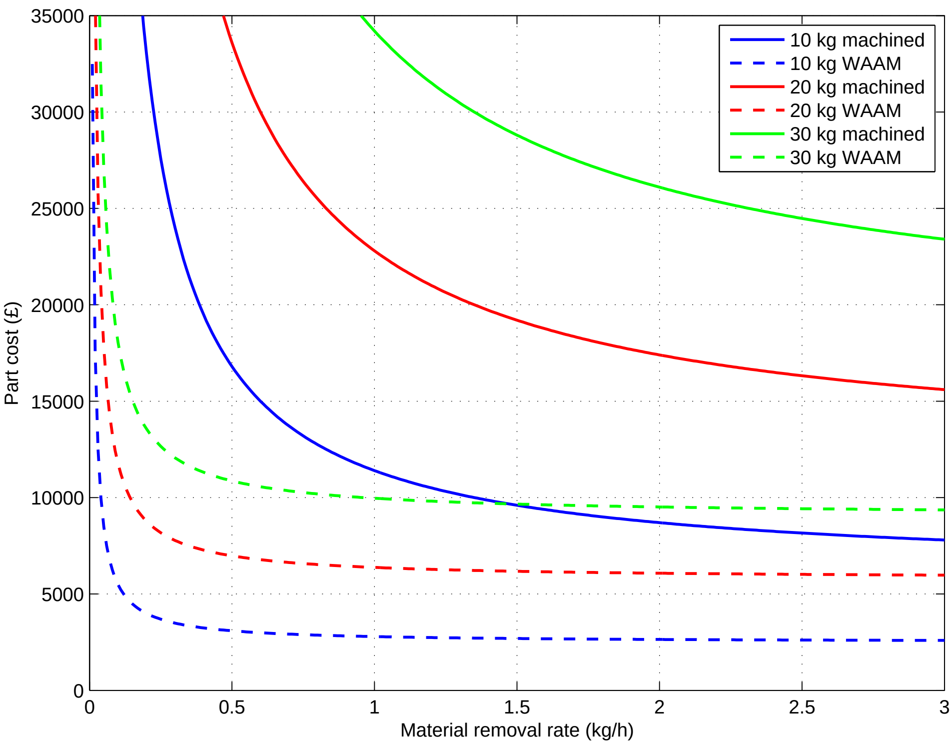

Figure 11: Cost of a part as a function of the MRR. Curves are provided for different deposited masses. Total cost of hardware = £181k. $BTF^{M} = 10$.

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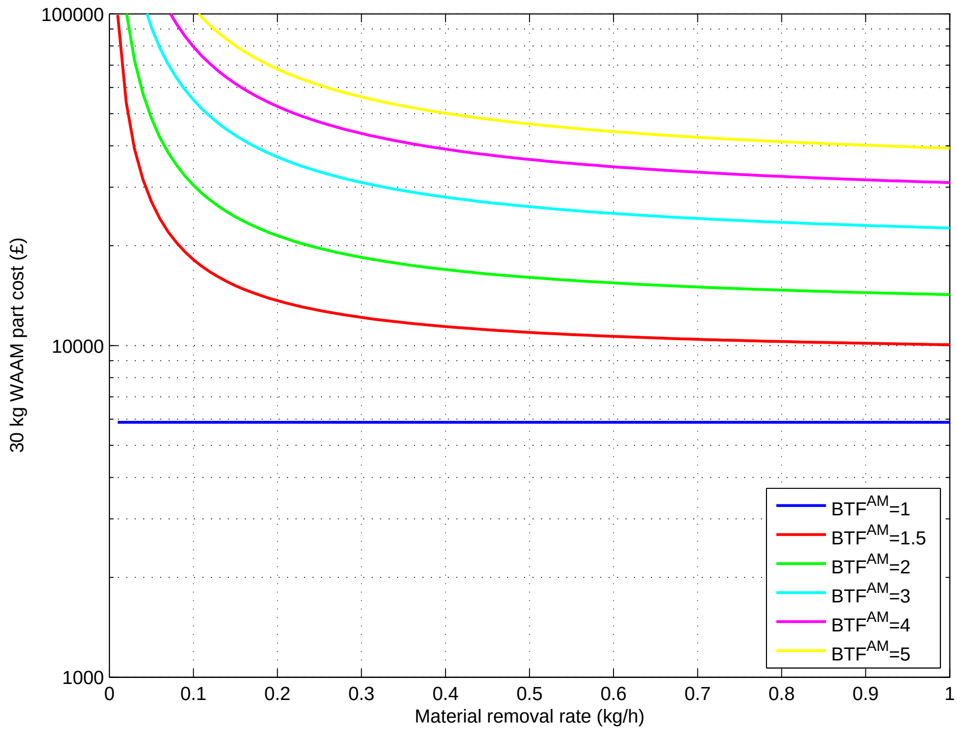

Figure 12: Cost of a 30 kg part made by WAAM as a function of the MRR. Curves are provided for different BTF^{AM}. Total cost of hardware = £181k.

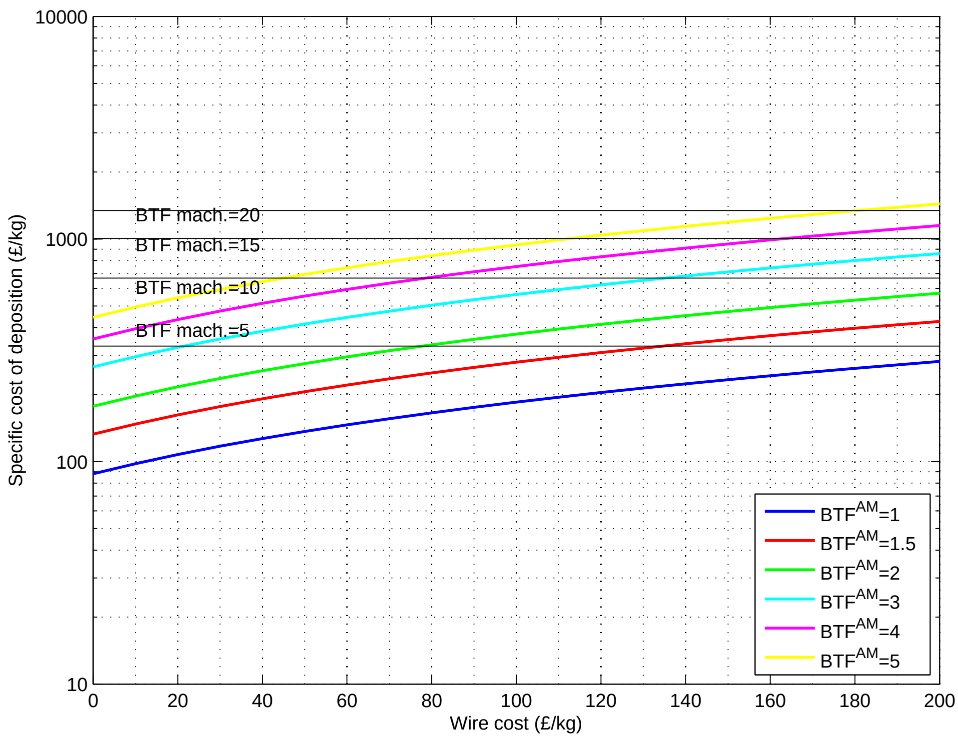

Figure 13: Specific cost of deposition for WAAM as a function of the wire cost. Curves are provided for different BTF^{AM}. Total cost of hardware = £181k.

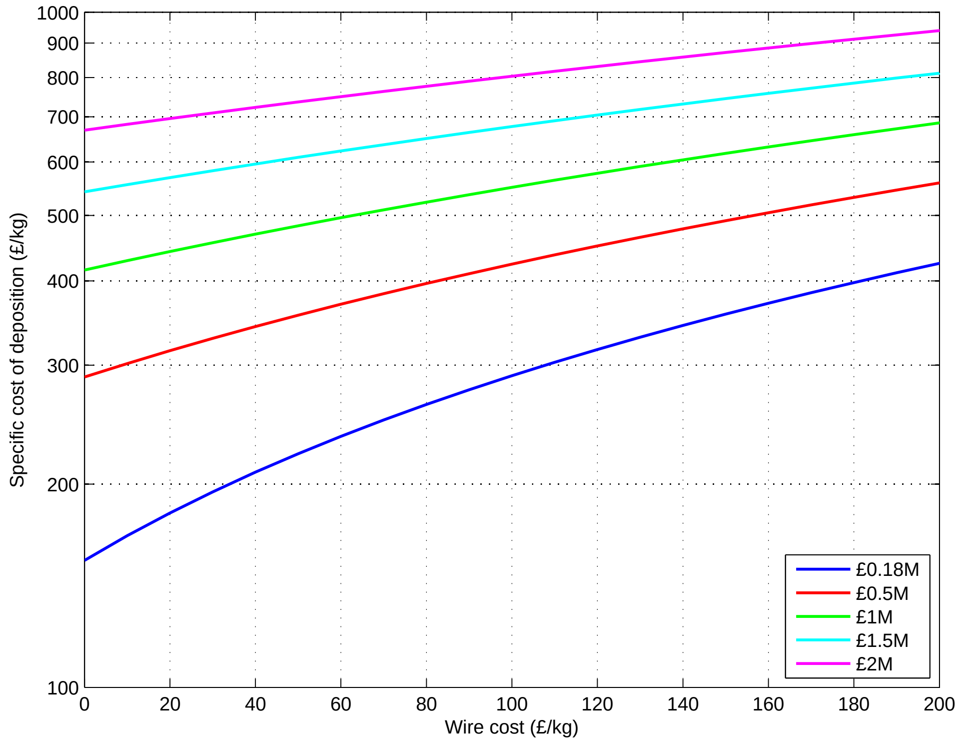

Figure 14: Specific cost of deposition for WAAM as a function of the wire cost. Curves are provided for different machine costs. $BTF^{AM} = 1.5$.

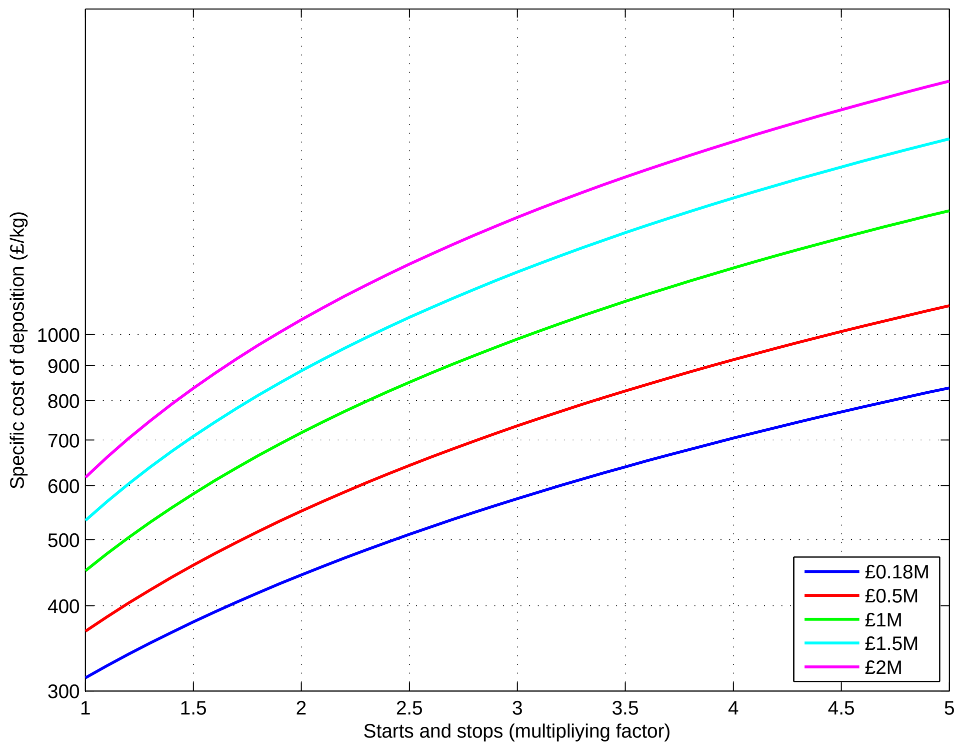

Figure 15: Specific cost of deposition for WAAM as a function of starts and stops. Curves are provided for different machine costs. $BTF^{AM} = 1.5$.

5.2 WAAM vs. a high deposition rate process

Let us look at a competing AM process with much higher DR than WAAM, for instance Sciaky's. According to Sciaky[12], their system is capable of depositing up to 10 kg h^{-1}, but their BTF^{AM} ratio of more than 10[a] makes their process less attractive from an economical point of view. In fact, for such high BTF^{AM} ratios, an AM approach would be more convenient than machining from solid only if BTF^{M} $>$ 28 (see plot of "High deposition rate AM process 1" in Figure 16) which represents a rather restrictive condition. Please note that identical assumptions were used to plot the cost curves for the two AM processes, apart from different values for equipment costs (which result in different HR^{AM}) and deposition rates. For completeness another cost curve was plotted; this referred to a system cheaper to run (HR^{AM} $=$ £170 h^{-1}) to assess whether a lower hourly rate (while retaining the high DR) resulted in better economics. Unfortunately BTF^{AM} is what drives the largest part of the cost, and no substantial difference exists.

From the curves it appears that WAAM is always more expensive than both high DR AM processes. However it can be seen that WAAM only needs to achieve a BTF^{AM} $<$ 8 to be more cost effective. For a typical BTF^{AM} $=$ 2, WAAM would be 78% cheaper than the high DR AM process. This highlights the significance of achieving a low BTF^{AM}.

In conclusion, high deposition rates do not result in any economical benefit unless they are accompanied by low BTF^{AM} ratios.

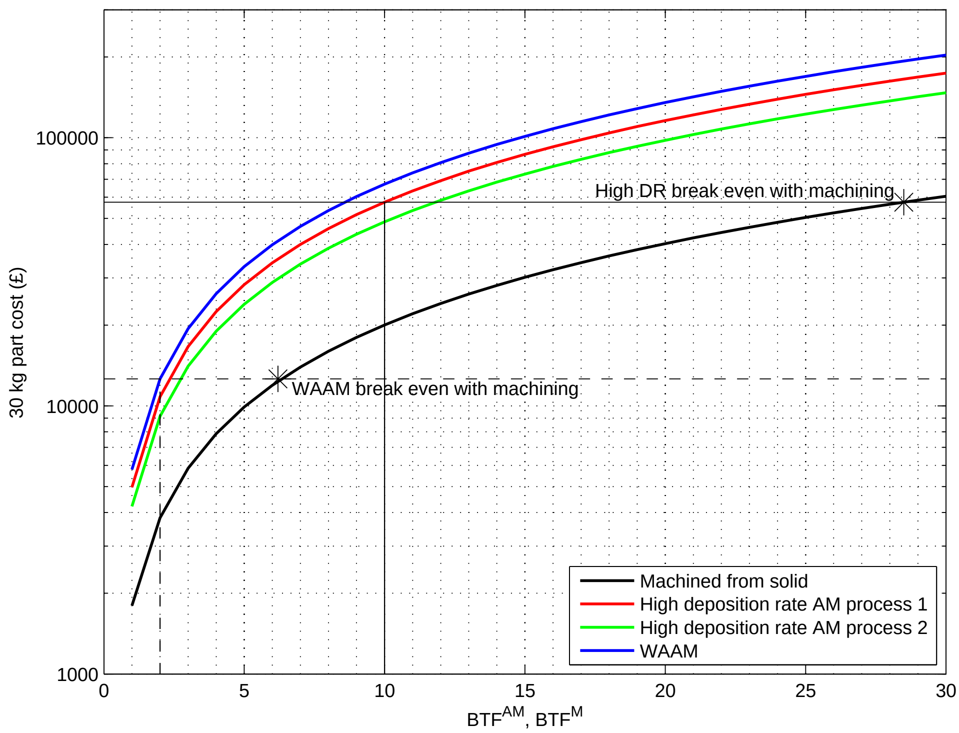

Figure 16: Cost of a 30 kg part machined from solid, made by WAAM and by a high deposition rate wire-based AM process, as a function of their BTF ratio. For WAAM: total cost of hardware = £181k, HR^{AM} $=$ £82 h^{-1}, DR $=$ 1 kg h^{-1}. For high DR AM process 1: total cost of hardware = £2M, HR^{AM} $=$ £363 h^{-1}, DR $=$ 7 kg h^{-1}. For high DR AM process 2: HR^{AM} $=$ £170 h^{-1}, DR $=$ 7 kg h^{-1}.

[a] This value was calculated from an example part discussed in Sciaky[12]. Considering the declared initial mass of 22.7 kg, and the final mass after machining of 2 kg, the BTF^{AM} is 11.4

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5.3 The problem of powder-bed processes

Powder-bed processes are affected by high capital and material costs. The low deposition rates result in extremely long deposition times; considering the high hourly rates due to the high capital cost, regardless of the feedstock price a powder-bed process would be always more expensive than machining from solid, as shown in Figure 17. In other words, while WAAM can build its business case upon material savings, and lead times and cost reduction, powder-bed processes must rely on their freedom of design, until faster and cheaper machines become available.

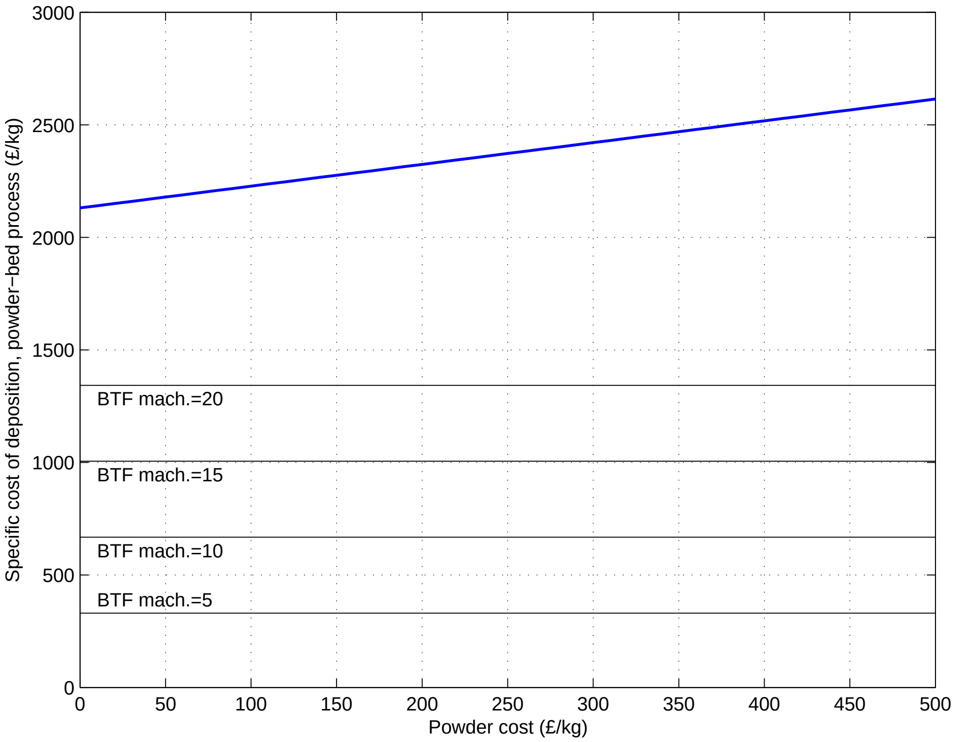

Figure 17: Specific cost of deposition for a powder-based process as a function of the powder cost. Total cost of machine including software = £500k. $BTF^{AM} = 1$. DR =0.1 kg h^{-1}. 100% powder utilisation was assumed. No post processing (although required so far) is considered. 50% beam-on time is considered (SS = 2).

5.4 Case studies

Wing spar The cost model was applied to the wing spar shown in Figure 4. For the calculation, a single-sided build was considered using a 1200 mm×200 mm×100 mm substrate. The results are summarised in Table 3.

External landing gear assembly The cost model was applied to an external landing gear assembly, shown in Figure 18. This component was built symmetrically on either side of a plane which coincided with the substrate; its size was 800 mm×700 mm×14 mm. The results for the part in titanium and steel are summarised in Table 4a and Table 4b, respectively. Interestingly the cost savings are very similar regardless of the material.

Pylon mount The cost model was applied to a titanium pylon mount with two different designs (Figure 19). The first option was the original design, to be machined from solid (Figure 19a); the second option

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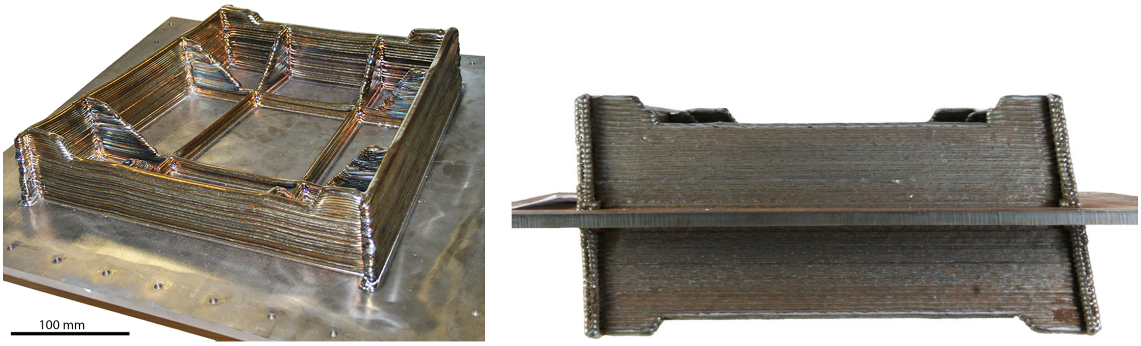
Table 3: Costs of different manufacturing routes for the 17 kg wing spar shown in Figure 4.

Manufacturing option	**BTF**	**Cost (£k)**	**Cost reduction**
Machined from solid	6.5	7.2	-
Made by WAAM	2.15	5.1	29%



(a) Isometric view, titanium part

(b) Side view, steel part

Figure 18: Part of an external landing gear assembly.

Table 4: Costs of different manufacturing routes for the external landing gear assembly shown in Figure 18.

(a) Titanium (20 kg)

Manufacturing option	**BTF**	**Cost (£k)**	**Cost reduction**
Machined from solid	12	16.2	-
Made by WAAM	2.3	5	69%

(b) Steel (36 kg). DR = 4 kg h^{-1}; c_F = £1 kg^{-1}; c_W = £2 kg^{-1}; MRR= 20 kg h^{-1}

Manufacturing option	**BTF**	**Cost (£k)**	**Cost reduction**
Machined from solid	12	1.6	-
Made by WAAM	2.3	0.7	55%

was a topologically optimised version which included WAAM's manufacturing constraints (Figure 19b). The costs are summarised in Table 5. Please note the costs were calculated using the parameters described in Table 2. The cost reduction of 7% appears modest due to the relatively low BTF^M of 5 for the original design. A larger cost savings of 29% is achieved for the topologically optimised shape due to its larger BTF^M.

Aluminium wing rib Finally, the model was used to assess the cost of the aluminium rib shown in Figure 3. The component features a stiffening web which could be either deposited (WAAM option 1, see Figure 20a), or machined from a thicker substrate (WAAM option 2, see Figure 20b). The former is of great interest due to the possibility of using different materials for the main plate, the stiffening web and the rib feet. The latter offers a poorer BTF^{AM} but potentially a quicker turnaround. Given the BTF^M of 45, both WAAM options were worth investigating. The results are shown in Table 6a and Table 6b for conventional and high-speed machining, respectively.

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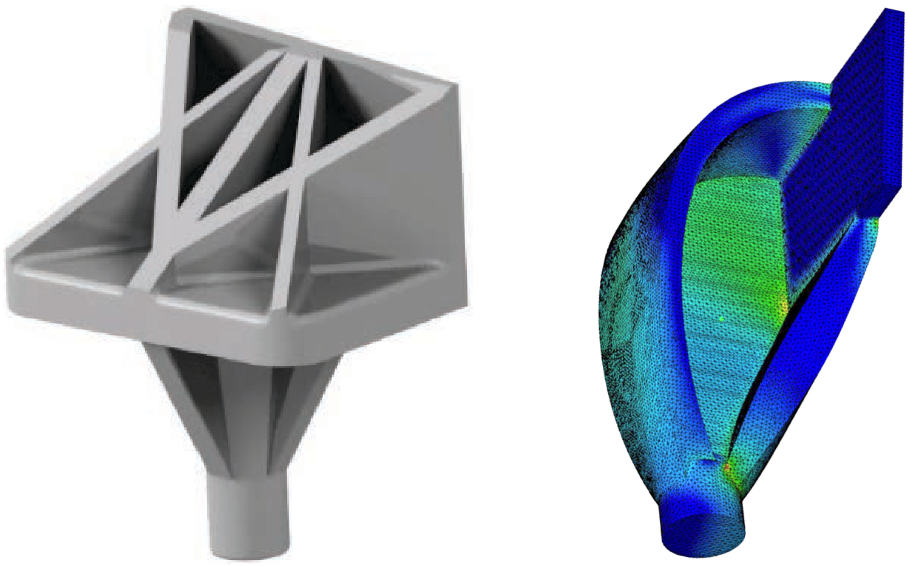

(a) Original design (b) Topologically optimised design

Figure 19: Different designs of a titanium pylon mount.

Table 5: Costs of different designs and manufacturing routes of the pylon mount shown in Figure 19.

Design and manufacturing option	**Mass (kg)**	**BTF**	**Cost (£k)**	**Cost reduction**
Original design, machined from solid	7.6	5.1	2.5	-
Original design, made by WAAM	7.6	1.5	2.4	7%
Topologically optimised, machined from solid	3.9	6	1.5	-
Topologically optimised, made by WAAM	3.9	1.5	1.1	29%

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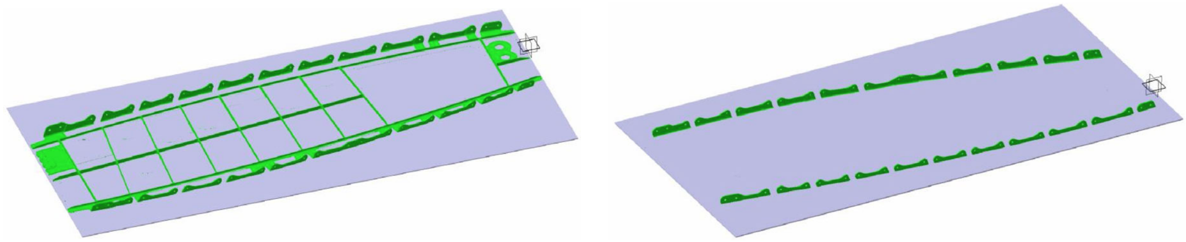

(a) WAAM option 1: 4 mm substrate and deposited web (b) WAAM option 2: 22 mm substrate and machined web

Figure 20: Different manufacturing options for a large aluminium wing rib.

Table 6: Costs of different manufacturing routes and options for the 15 kg aluminium wing rib shown in Figure 20. DR = 1 kg h^{-1}; c_F = £6.1 kg^{-1}; c_W = £53 kg^{-1}.

(a) Conventional machining, MRR = 65 kg h^{-1}

Option	BTF	Cost (£k)	Cost reduction
Machined from solid	45	4.9	-
WAAM (option 1)	2.9	1.7	65%
WAAM (option 2)	12.3	2	58%

(b) High-speed machining, MRR = 323 kg h^{-1}

Option	BTF	Cost (£k)	Cost reduction
Machined from solid	45	4.4	-
WAAM (option 1)	2.9	1.7	61%
WAAM (option 2)	12.3	1.9	56%

6 Conclusions

A model to compare the cost of a titanium part produced by WAAM or via the traditional route of machining from solid was defined. The model was capable of providing reliable component cost estimations on the basis of cost drivers including capital and material costs, machine and process performance, and size of a part.

All example parts analysed were cheaper to produce by WAAM, and cost savings ranged from 7 % to 69 %.

Sensitivity analyses were carried out, and it was demonstrated that:

- for a robot-based WAAM cell, increasing the deposition rate above 1 kg h^{-1} has no significant economical benefit, regardless of the BTF^{AM};
- if the equipment cost increases, a higher DR results in a lower specific cost of deposition, due to higher hourly rates; the same applies to the capacity utilisation; however if the BTF^{AM} is increased as a result of the higher DR this does not result in any saving;
- the cost of a WAAM part is insensitive to the material removal rate for speeds above 0.4 kg h^{-1}, regardless of the BTF^{AM};

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- considering the current feedstock cost, BTF^{AM} delivered by WAAM and some typical BTF^{M}, WAAM is always a cheapest option than machining from solid;
- due to high capital and material costs, and low deposition rates, powder-bed processes are always more expensive than machining from solid, and must build their business case upon other drivers rather than cost saving.

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