CRANFIELD UNIVERSITY

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HYBRID DESIGN BASED ON WIRE AND ARC ADDITIVE MANUFACTURING IN THE AIRCRAFT INDUSTRY

SCHOOL OF APPLIED SCIENCES

MSc by Research Thesis
Academic Year: 2011 - 2012

Supervisors: Dr. Jörn Mehnen and Dr. Helen Lockett
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This thesis is submitted in partial fulfilment of the requirements for the degree of Master of Science

ABSTRACT

Wire and Arc Additive Manufacturing (WAAM) is a developing rapid prototyping and manufacturing technology which allows the production of large custom-made metal parts with high deposition rates, a major concern of the aircraft industry. Despite this, there is little research on the design method and application of WAAM technology in the aircraft industry.

The overall research aim is to develop a step-by-step design method to create and assess hybrid design solutions based on WAAM technology. The main objectives are to: (i) analyse existing design methods and software tools; (ii) collect and analyse technical data about aircraft structure design and WAAM process; (iii) develop a hybrid design method based on WAAM technology; (iv) validate the developed design method through industrial case studies. These four objectives were achieved through the adoption of a four-phase research methodology.

A hybrid design method was developed based on mature design models such as the VDI 2221model, BS 7000 design model and Pahl and Beitz's design model and required prior knowledge of WAAM technology and aircraft structure design. This design method includes a hybrid design model and a WAAM feature based design guideline which enables the designers to create hybrid design solutions step by step and assess the proposed solutions by using the evaluation matrix chart. Hybrid design in this research encompasses design for hybrid manufacturing processes, which means that an object is to be designed partly made from prefabricated or off-the-shelf parts and partly added by WAAM process. Furthermore, Finite Element Analysis is introduced in the design method to check the performance of the preliminary design and the final design.

Three case studies were carried out to verify the developed hybrid design method. The integral panel, a typical structure in aircraft, demonstrates the significant cost advantage of WAAM technology. The pylon frame and forward fitting are the structural parts provided by the Chinese aircraft industry. It shows that the cost of the final design is significantly lower than that of the preliminary design. In addition, topology optimisation is applied to achieve lower weight.

The hybrid design method is validated through academic experts and industrial experts. This research project has contributed to an effective design method based on WAAM technology in the aircraft industry.

Keywords: Wire and Arc Additive Manufacturing (WAAM), Hybrid design method, Aircraft industry, Evaluation

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LIST OF ABBREVIATIONS

AM	Additive Manufacturing
CMT	Cold Metal Transfer
COMAC	Commercial Aircraft Corporation of China, Ltd.
DC	Direct current
DFM	Design for Manufacture
EBM	Electron Beam Melting
e	Elongation in percent, a measure of the ductility of a material based on a tension test
E	Modulus of elasticity in tension
f	Applied ultimate stress
f_{limit}	Applied limit stress
F_{tu}	Tensile ultimate stress
F_{ty}	Tensile yield stress at which permanent strain equals 0.002
F	Allowable stress
GTAW	Gas Tungsten Arc Welding
GMAW	Gas Metal Arc Welding
HF	High frequency
K_C	Critical plane stress fracture toughness, a measure of fracture toughness at point of crack growth instability
LAM	Laser Additive Manufacturing
LF	Low frequency
MIG	Metal Inert Gas
MS	Margin of safety
PMIG	Pulsed Metal Inert Gas
RUAM	Ready-to-Use Additive Manufacturing
SMD	Shaped Metal Deposition
TIG	Tungsten Inert Gas
WAAM	Wire and Arc Additive Manufacturing

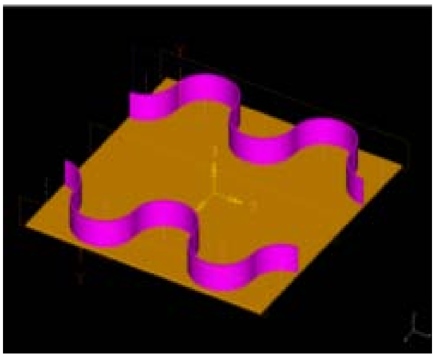
1 Introduction

1.1 Research Background

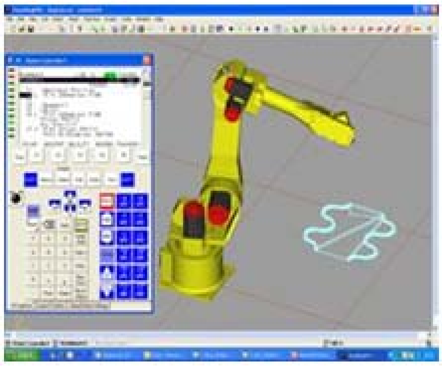
Additive Manufacturing (AM) is an innovative manufacturing process generated as a consequence of developments in diverse technology sectors, especially the advantages in computer technology (Gibson et al., 2010). AM began with stereo lithography in the late 1980s (Levy et al., 2003). At present, AM is widely used in prototypes, tooling components, and manufacturing parts with different materials, etc. According to the study of Wohlers (2010), the demand of AM products and services had increased gradually during the past 22 years with a compound annual growth rate of 26.4%.

The "buy-to-fly" ratio is a frequently-used factor in the aerospace field (the ratio of material bought to material that eventually goes to the aircraft). This ratio is at a range of 10-20:1 in a conventional processes; AM can reduce it by 35%-45% (Smock, 2010). Take the aerospace industry as an example, EADS research team in Filton forecasted that 25 metre-length or approximate component parts of an Airbus airplane could be made by using AM, saving around 3000 tons in weight and a $300bn is saving for airlines (Wilson, 2010). In addition, it is estimated that AM can enable an Airbus aircraft to be 60% cheaper and 30% lighter (Wood, 2009).

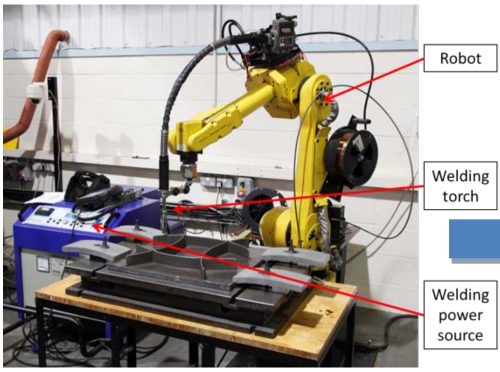
Wire and Arc Additive Manufacturing (WAAM) is a developing AM technology, which uses a welding process to manufacture 3D metal geometries that are ready to use in e.g. the aircraft industry. Figure 1-1 presents the typical WAAM process. The remarkable advantage of WAAM is high deposition rates, large part scale and low cost (Brandl et al., 2010). The deposition of Ti-6Al-4V alloy can exceed 3kg/hr with the effective wall widths ranging from 3.2 to 5.2mm using 1.2mm welding wire (Sequeira Almeida and Williams, 2010). It greatly reduces the manufacturing cost as well as the "buy-to-fly" ratio. Figure 1-2 (a) shows a titanium alloy part used in aerospace. For this part, the WAAM process leads to a material saving of 19.3 kg and a “buy-to-fly” ratio of near to 1. Furthermore, the deposition time for this part is only 1 hour. Figure 1-2 (b) illustrates a 3 metre long aluminium alloy stiffener. It is deposited and machined on the HiVE system (previously an Airbus FSW machine). Figure 1-2 (c) presents a part with numerous crossovers and intersections built by the WAAM process.



(a) CAD model



(b) RUAMRob 2.0



(c) WAAM machine

(d) WAAM workpiece

Figure 1-1 Wire and Arc Additive Manufacturing (WAAM) process

(a)

(b)

(c)

Figure 1-2 WAAM products: (a) Ti alloy part; (b) 3m long Al alloy stiffener; (c) Part with crossovers and intersections

Compared with conventional subtractive processes, the AM process enables a freer and more flexible production design through allowing an extensive choice of materials, manufacturability of complex geometries, low cost and short lead time (Karunakaran et al., 2010; Parthasarathy et al., 2011). WAAM offers designers the opportunity to create objects which were previously considered impossible to manufacture.

At present, numerous progress has been achieved by the study of process parameters, robot programmes, thermal analysis and mechanical properties. However, there is little research about a design method for WAAM technology. As it is commonly known, design is the first and most important step in product manufacturing, and the process method is mainly decided during the design phase (Boothroyd, 1994). Designers would consider using WAAM in their design only if they are familiar with the design method and design parameters. Consequently, the key point that should be considered through immediately is to develop a systematic design method for WAAM technology.

In conclusion, the task of this MSc project is to develop a design method based on the WAAM technology which can be used in the aircraft industry. Real industrial cases will be applied to verify the developed method.

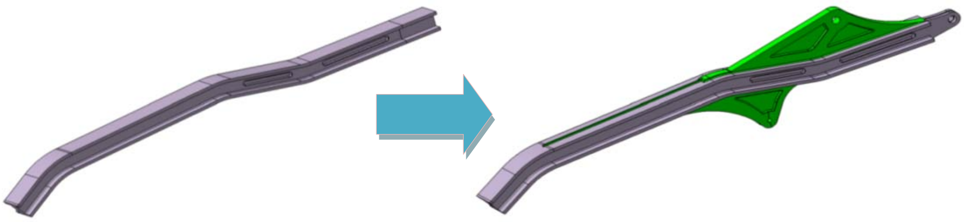
1.2 Problem Statement

Ti alloy is widely used in aerospace, automotive, chemical engineering and medical technology (Hauptmann and Billhofer, 2010). The usage of Titanium has soared in the aircraft industry in recent years. Compared with 15 tons for Boeing 737 in the 1970's, the titanium usage of Boeing 787 in 2009 arrives at 100 tons. However, approximately 90% of the titanium alloy is machined away during conventional subtractive manufacturing. It not only needs a large amount of energy for processing but also results in high production cost (Herranz et al., 2005). Furthermore, Ti alloy is much more expensive and difficult to manufacture than Steel and Al alloy. Therefore, it is necessary to search for a more ideal process for Ti alloy.

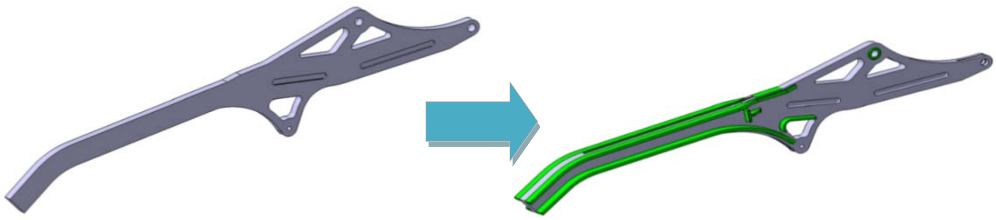
The WAAM process has been proved to be an efficient manufacturing process for Ti alloy components (Lorant, 2010; Sequeira Almeida.and Williams, 2010). With the rapid growth of Ti alloy usage in the aircraft industry, there is large foreseen market of WAAM technology due to its superiority on Ti alloy manufacturing.

In conventional WAAM design, the whole part is designed for and made by additive manufacturing typically by using a substrate base plate. In the research of Kazanas (2011), the hybrid design concept based on WAAM technology was introduced in product design. Herein, hybrid design based on WAAM encompasses design for hybrid manufacturing processes, which means that an object is to be designed partly made from prefabricated or off-the-shelf parts and partly added by WAAM process. Figure 1-3 shows the hybrid design of the flap track. The green sections of Figure 1-3 (b) and Figure 1-3 (c) were added by WAAM process. The hybrid design concept based on WAAM rationally integrates the advantages of WAAM process and conventional subtractive processes into a single part, which can enhance manufacturability and leads to low cost and less weight. However, it is not easy to create suitable hybrid design solutions and select the best design. Therefore, it is necessary to develop a systematic design method to guide designers towards successfully creating and assessing hybrid design solutions.

(a)



(b)



(c)

Figure 1-3 The hybrid design of the flap track: (a) manufactured by plate machining; (b) manufactured by shaping (in grey) extrusion plus WAAM (in green); (c) manufactured by plate (in grey) machining plus WAAM (in green) (Kazanas, 2011)

1.3 Outline of Thesis

The thesis comprises seven chapters as illustrated in Figure 1-4.

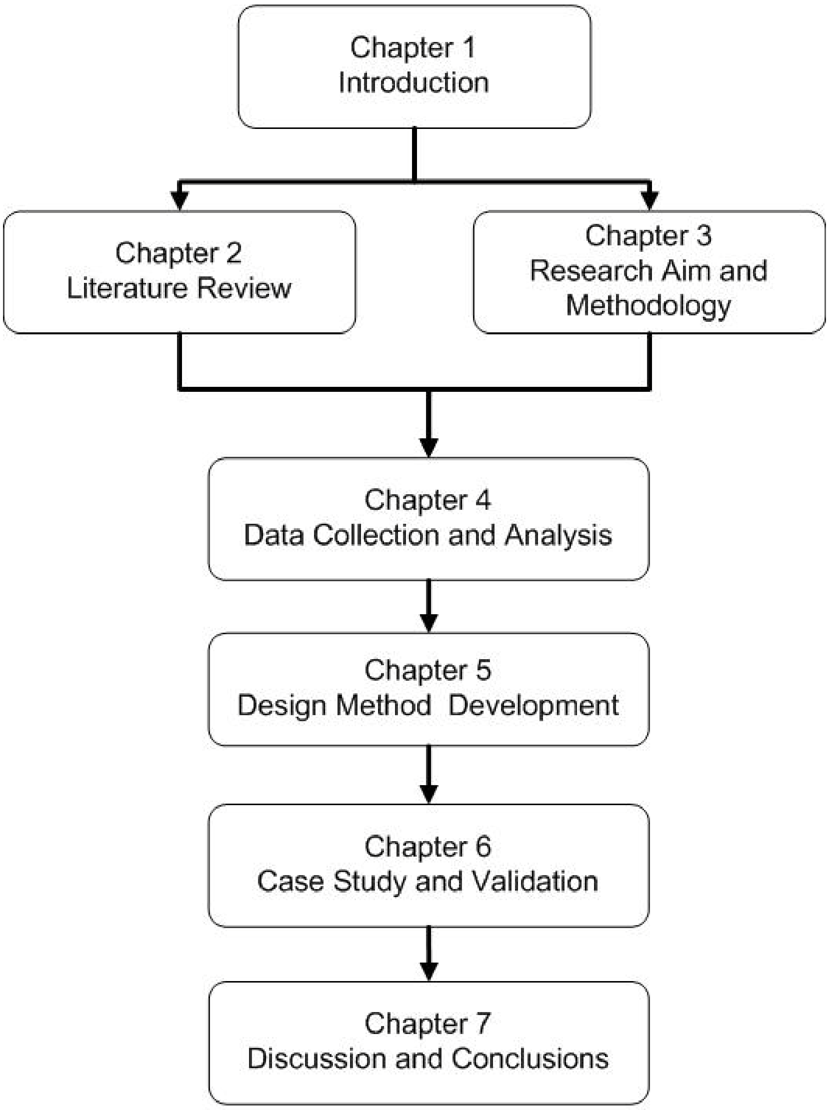


Figure 1-4 Structure of the thesis

Chapter1

This chapter gives an introduction to the research background and problem statement.

Chapter 2

Chapter 2 summarises the state-of-art of the related areas of this research to gain foundational knowledge in design for WAAM.

- Additive manufacturing

- Engineering design methods
- Design For Manufacturing (DFM)
- Design manual

Chapter 3

This chapter outlines the research aim and objectives of this project. The research scope as well as research methodology are also introduced in this chapter.

Chapter 4

Chapter 4 presents the results of data collection and analysis that is the basic for further research.

Chapter 5

The development of design method based on WAAM technology is introduced in this chapter.

Chapter 6

Chapter 6 introduces the case study and validation, so as to verify the developed design method.

Chapter 7

The findings of this research are discussed in this chapter and the conclusions are also summarised.

1.4 Summary

The research background and problem statement of this research has been analysed in this chapter. In addition, the thesis structure and a summary of the chapters have also been provided.

2 Literature Review

2.1 Introduction

This chapter gives a brief introduction of AM technologies with particular focus on WAAM technology and relative design methods. Then, a brief introduction of engineering design methods, Design for Manufacturing (DFM) and design manuals is presented, principally the hybrid design method for AM. The knowledge gained from this literature survey inspires new approaches proposed in this thesis.

2.2 Additive Manufacturing

AM derived from topography and photo sculpture about 150 years ago (Bourella et al., 2010), is also termed additive layer manufacturing, rapid prototyping, 3D printing, etc.

There is no consistent view for the classification of AM technologies. One common method is to classify AM by the initial form of its material, which can be divided into: liquid-based, solid-based, and powder based (Kruth et al., 1998; Chua and Leong, 1998). Another way is to classify AM by material types, such as metal material and polymer material (Levy, 2003).The AM process discussed in this research is focused on metal materials.

2.2.1 Laser Additive Manufacturing (LAM)

Selective Laser Sintering (SLS), Selective Laser Melting (SLM) and 3-D Laser Cladding are the typical laser additive manufacturing systems (Santos et al., 2006). Figure 2-1 describes the current application of laser fabrication.

The latest SLS system is called Vanguard^{TM} which is a powder based process using CO_2 laser (Chua et al., 1998). Figure 2-2 illustrates a schematic of the SLS process.

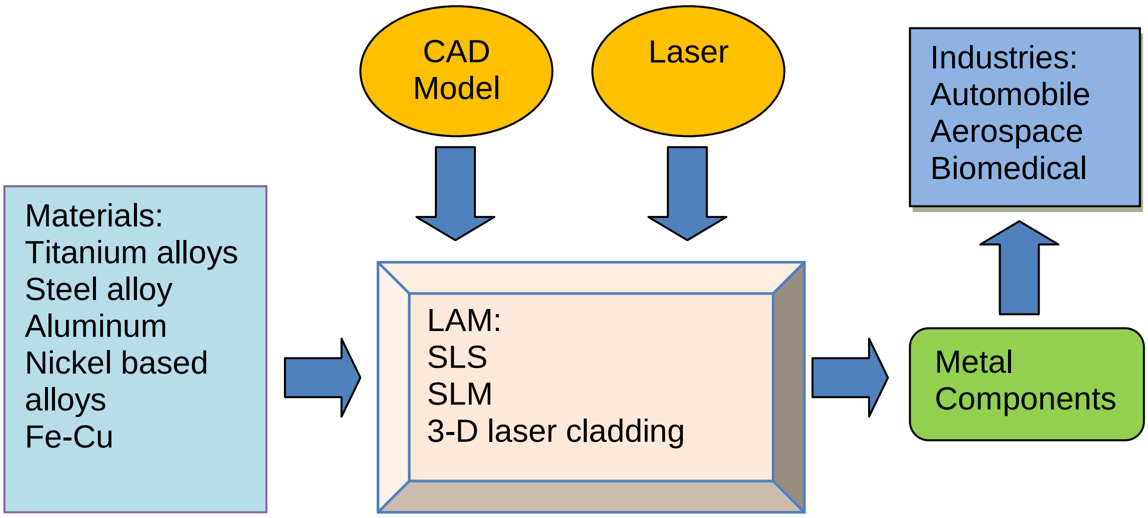
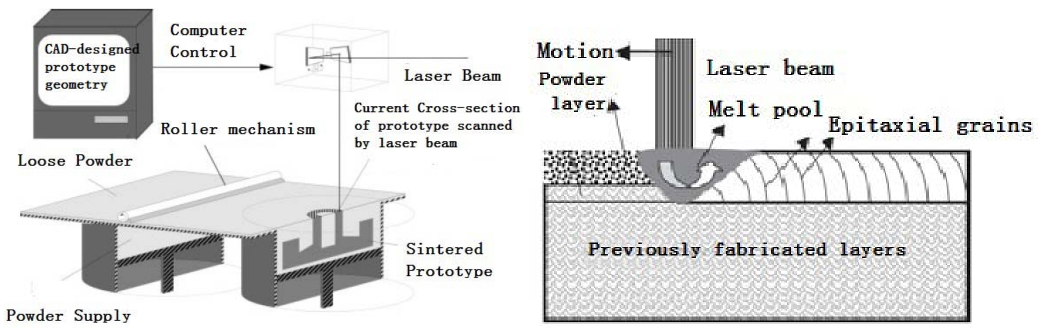


Figure 2-1 Schematic of metal components manufacturing by LAM

(Santos et al., 2006)



(a) (b)

Figure 2-2 Selective laser sintering: (a) SLS process schematic, (b) laser material (Das, 2003)

The advantages of a SLS system are (1) good part stability, (2) wide range of processing materials, (2) no support structures required and (3) little post-processing and no post-curing required. However, the SLS process needs a large sized device that requires high power consumption. In addition, the SLS process has poor surface finish such as porous surfaces, distortion and lower dimension tolerance (Petrovic, et al., 2011). SLS is particularly suitable for producing small functional parts (Kruf, W. et al., 2006). For an instance, the work volume of Vanguard^{TM} si2^{TM} SLS®system is 370mm×320mm×445mm, and the laying time per layer (Min. layer thickness, 76um) is about 10s. (Chua et al.,1998). Figure 2-3 shows an aluminium alloy functional part made by SLS. The scale of part is about 60 x 30mm^2.

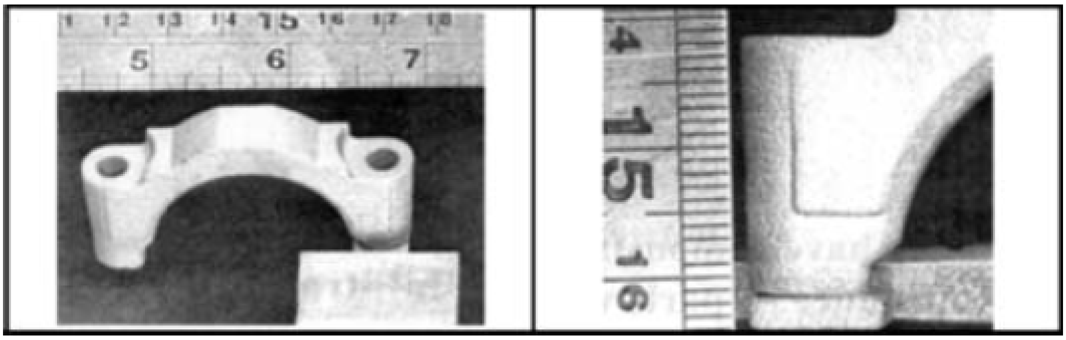


Figure 2-3 Aluminium functional part made by SLS process (Levy, 2003)

SLM is also a popular LAM process. The major difference between SLS and SLM is that SLM uses a higher energy density to fully melt the powers leading to higher density. The typical layer thickness for Ti-6Al-4V produced by SLM is between 30μm to 50μm. Therefore, SLM is suitable for producing thin-walled structures, such as the titanium dental caps and crown, and stainless steel airborne structure (as shown in Figure 2-4).

(a) (b)

Figure 2-4 Parts made by SLM process: (a) titanium dental caps and crown;

(b) stainless steel airborne structure (Santos, 2006)

Compared with SLS and SLM fusing material in a powder bed, powders of 3D Laser Cladding is fed directly from a gas jet through nozzles. The alloys, such as Steel, Aluminium, Titanium and Nickel, are the main powder materials of this process (Santos et al., 2006).

In general, LAM can provide the components with desired geometry, high accuracy due to the extremely focused laser power and accurately controlled powder feeding. However, there are still some drawbacks to powder laser fabrication：

- Relatively low deposition rate, about 50 g/h (Baufeld et al., 2010; Heralic et al., 2010);
- Complex, expensive equipments and strict monitoring (Baufeld et al., 2010);
- Limited build volumes dependent on the size of the bed (Baufeld et al., 2010; Martina,2010);
- Non-perfect surface quality as well as non-fully dense parts (Kruth et al., 1996; Rombouts et al., 2006);
- Non-consistent mechanical properties in all directions (Kruth et al., 2003),;
- Pore formation of tool steel due to higher powder feed rate(Choi and Chang, 2005);
- Contamination (Brandl et al., 2009) and material loss (Heralic et al., 2010).

Recently, wire has been used as a substitute for powder because it reduces contamination, enables much higher deposition rate and offers higher material efficiency (Brandl et al., 2011; Heralic et al., 2010). Furthermore, research illustrates the mechanical properties of wire based AM are similar to casting and wrought (Mok et al., 2008).

2.2.2 Electron Beam Melting (EBM)

Electron Beam Melting (EBM) is also a powder-based AM process, which was developed by Arcam AB, a Swedish technology development company (Chua et al., 2003). The power used in an EBM system is an electron beam in a high vacuum. Compared with a metal sintering process, the products of EBM demonstrate high quality, i.e. they are void-free, fully dense, and high strength properties. For example, a Ti-48Al-2Cr-2Nb alloy part made by an EBM process includes lower impurities (oxygen and nitrogen) and residual microporosity, fine and homogeneous microstructure, and consistent material properties (Biamino et al., 2011). Figure 2-5 shows the working principle of this process.

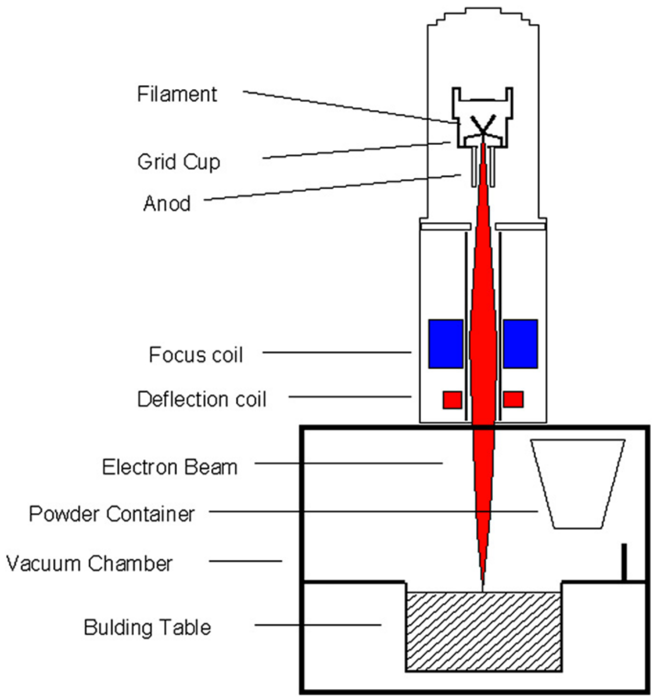


Figure 2-5 Schematic diagram of an EBM system (Biamino et al., 2011)

There are numerous EBM systems. The deposition rate of the EBF3 system developed by NASA can exceed 2500 cm^3/hr with the ability to fabricate a part within 300mm×300mm×150mm (Taminger and Hafle, 2006). Moreover, the Arcam EBN S12 has 0.5-1m/s melting speed with the building volume within 250mm×250mm×200mm.

This process is mainly applied in the medical and aerospace industries to produce Titanium near-net-shape parts, such as cranioplasty plates, mandibular implants and aeroengine components. Ti-6Al-4V part with porosities as high as 50% to 70% by using the EBM process was proven to meet the mechanical strength requirements for craniofacial applications (Parthasarathy et al., 2010). Parts made by the EBF3 system are shown in Figure 2-6. The general sizes of these parts are between 5cm and 10cm. In addition, the height of the Ti-6Al-4V wind tunnel model (see Figure 2-6 (a)) is 40mm and the length of the Ti-6Al-4V guy wire fitting t is 38cm.

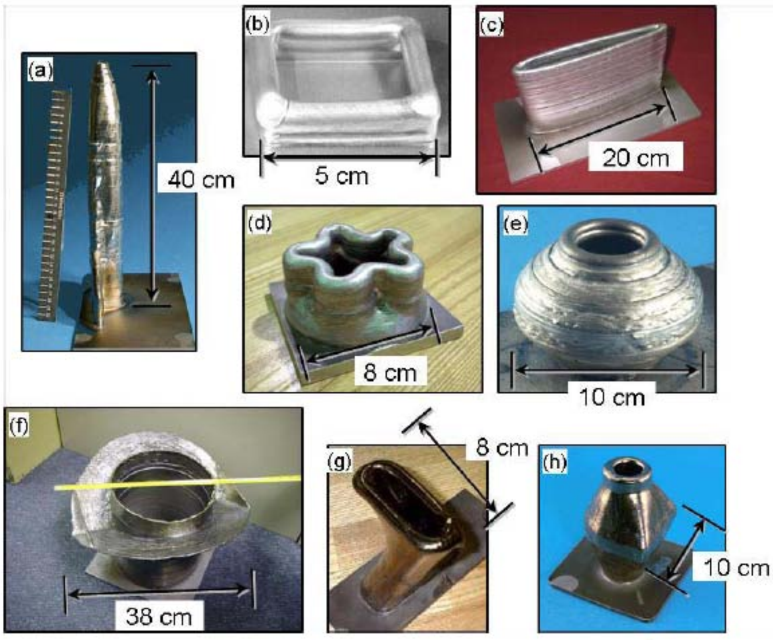


Figure 2-6 Parts made by an EBF3 system: (a) Ti-6Al-4V wind tunnel model; (b) 2219 Al square box; (c) 2219 Al airfoil; (d) 2219 Al mixer nozzle; (e) 2219 Al converging diverging nozzle; (f) Ti-6Al-4V guy wire fitting; (g) Ti-6Al-4V inlet duct; (h) Ti-6Al-4V truss node with flat attachments surface (Taminger and Hafle, 2006)

Similarly to LAM, the EBM system also uses powder based material and the equipment is expensive, complex and large. Moreover, it can only fabricate metal parts and has rather poor surface. However, EBM systems have high deposition rate, good mechanical properties (Baufeld et al., 2010).

2.2.3 Shaped Metal Deposition (SMD)

Shaped metal deposition (SMD) is a layer upon layer rapid prototyping process by welding metal wire. This process was developed at Cranfield University for Rolls Royce for engine castings from 1994 to 1999 (Williams, 2010).

All weldable materials can be used in an SMD process, such as Ni alloys, steel and Ti alloys, though the latter are the most suitable because it is expensive and hard to shape or machine by conventional processes (Baufeld et al. 2010).

SMD is usually applied to near-net fully dense parts. The accuracy and surface finish are worse relative to a laser or electron beam based processes, but its deposition rate is higher, at about 1kg/hr (Baufeld et al. 2010; Skiba et al. 2011). By using SMD, production of a large aerospace engine casting can be decreased from 9 months to a few weeks (AMRC, 2011).

Ti-6Al-4V parts built by SMD process are proven to be dense and pore-free and can meet the minimum strength requirements of AMS 4999. The strength, ductility and cost of the final part are mainly affected by the deposition rate (Baufeld, 2012). Figure 2-7 shows the tubular Ti-6Al-4V parts made by SMD. The width of walls is between 5mm and 20mm in a single run. Studies show that the mechanical properties of SMD features are superior to that of cast processes (Baufeld et al. 2010; Brandl et al., 2011).

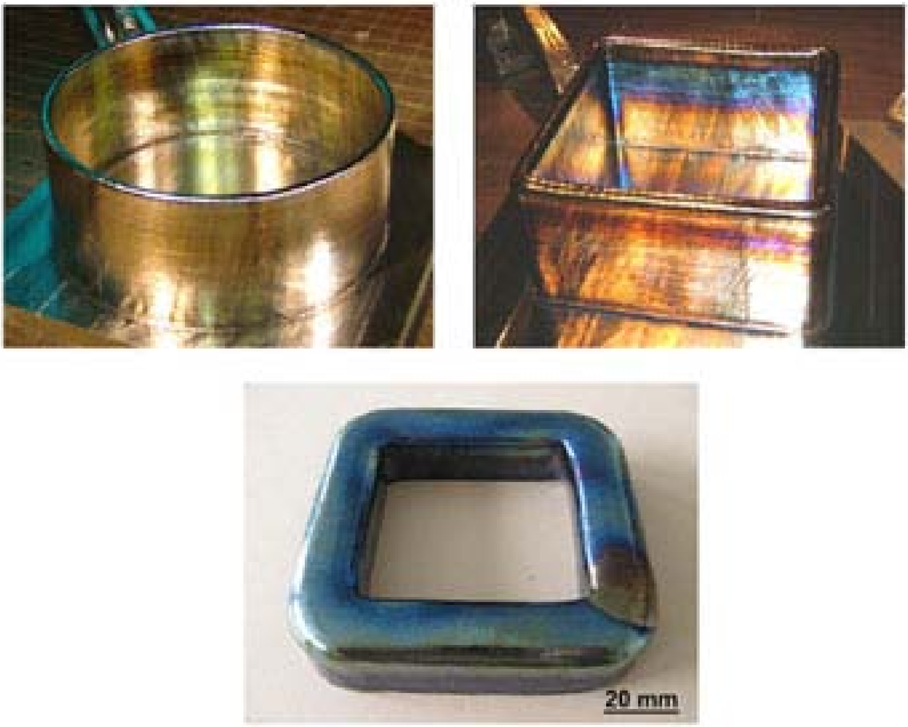


Figure 2-7 Tubular Ti-6Al-4V components made by SMD (Baufeld et al. 2010)

2.2.4 Wire and Arc Additive Manufacturing (WAAM)

Wire and Arc Additive Manufacturing (WAAM) is a SMD technology combining the arc welding techniques with wire feeding. The name was coined at Cranfield University. WAAM process has been successfully applied to aero engine components (Lott, 2009). With the growing demand from the aircraft industry, the application of AM has transferred from engine to airframes. Laser and powder additive manufacturing technology is constrained by its speed and size. However, WAAM is an ideal process which aims to produce large aerospace components.

Research presents that WAAM can reduce the cost by 62.5% and the wastage material by 90% for complex Ti-6Al-4V parts compared with the conventional process. It also shows that WAAM combined with conventional manufacturing process can decrease cost and lead time significantly (Shettigar, 2010).

2.2.4.1 WAAM system

A great progress in WAAM technology is the WAAM system which integrates the NC controller, wire feed system and electric arc heating sources (as shown in Figure 2-8). Compared with laser powder systems, the hardware cost of WAAM system is much lower. It can be established by combining the common motion system (e.g. industry robots) and the commercial wire based welding equipment (as shown in Figure 2-9 (a)), but also by refitting existing welding machines (as shown in Figure 2-9 (b)). The scale of the working envelope of the HiVE system at Cranfield University is 5 x 3 x 1m^3 (Mehnen, 2011).

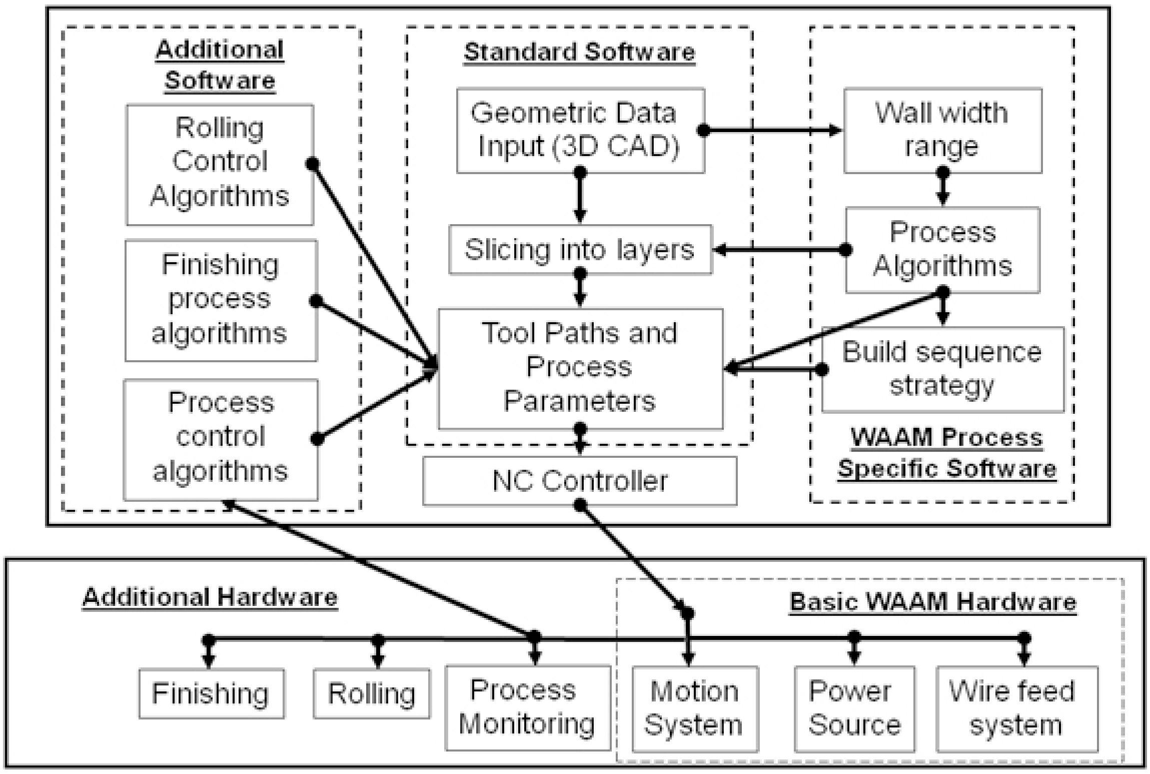


Figure 2-8 Schematic of WAAM system developed in Cranfield University (Williams, 2011)

(a) (b)

Figure 2-9 WAAM systems: (a) robot with welding equipment; (b) HiVE system (Williams, 2011)

2.2.4.2 Materials

Technically, all weld able materials can be used in WAAM, such as mild steel (S355), high strength steel, stainless steel, aluminium alloy (4043,6082), Titanium alloy (Ti-6Al-4V) and copper alloy (Kazanas et al.2012; Sequeira Almeida and Williams, 2010; Deherkar, 2010).

Furthermore, WAAM supports mixed material use, i.e. can produce part by using not just one single material only but also multiple materials (Williams, 2011). Figure 2-10(a) shows the steel/bronze (CuSi3%) part produced by mixed material system. Figure 2-10(b) presents the corresponding tension specimen. The fracture does not occur in boundary between steel and bronze, which indicates that WAAM offers excellent mechanical properties.

(a) (b)

Figure 2-10 Mixed material systems: (a) steel/bronze (CuSi3%) part produced by mixed material systems; (b) corresponding tension specimen (Williams, 2011)

2.2.4.3 Welding process

Gas Tungsten Arc Welding (GTAW) and Gas Metal Arc Welding (GMAW) have been investigated at Cranfield University in the Welding Engineering Research Centre (WELPC). WAAM deposition rate can reach 1kg/h for GTAW based process, while several kilograms per hour can be achieved by GMAW based process. A shortage of GMAW is arc wandering and spattering during Ti and Ti alloys deposition (Sequeira Almeida and Williams, 2010).

The situation has been improved with the utilizing of Cold Metal Transfer (CMT), which is a modified GMAW process. The manufacturing parameters of this process were investigated by Deherkar (2010). Research clearly show that CMT based WAAM has numerous advantages (Sequeira Almeida and Williams, 2010; Pickin and Young, 2006; Mehnen et al.,2010) such as:

- High quality and spatter free deposition;
- Low heat input ;
- excellent reproducibility;
- High deposition rate and thicker material sections;
- Finer microstructure.

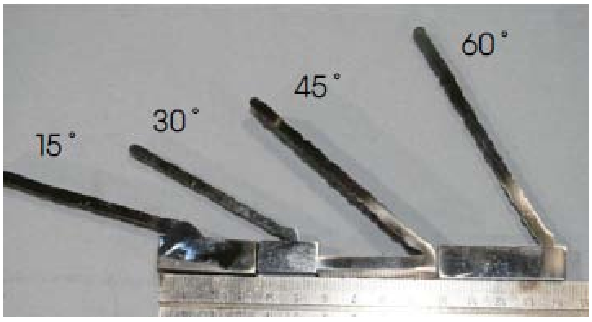
Table 2-1 summarised the characteristics of welding process for WAAM according to the studies at Cranfield University.

Table 2-1 Characteristics of welding process for WAAM (Williams, 2011)

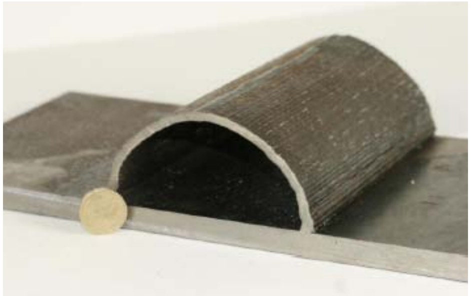
Process	Characteristics
Pulsed Metal Inert Gas (PMIG)	Consumable wire electrode, typical deposition rate 3-4kg/hr, coaxial system, can be prone to spatter, very robust, simple
Tandem MIG	Two consumable wires electrodes feeding the same weld pool allowing easy mixing to control composition, typical deposition 6-8kg/hr
Cold metal transfer (CMT)	Medium quality (zero spatter) low heat input process with reciprocating consumable wire electrode, typical deposition rate 2-3kg/hr, coaxial system
TIG-DC, pulsed (HF+LF)	High quality separate wire feed process with non-consumable electrode, typical deposition rate 1-2kg/hr, wire and torch rotation needed
Plasma-DC pulsed (HF+LF)	High quality separate wire feed process with non-consumable electrode (no contamination), typical deposition rate 2-4kg/hr, wire and torch rotation needed

2.2.4.4 WAAM features

The development of a feature based design handbook for WAAM is under development (Williams, 2011; Kazanas, 2011). Figure 2-11 shows several typical features built by WAAM. The walls (e.g. inclined wall, curved wall, horizontal wall), intersection and closed semi-circle are the main features of WAAM process. There is still significant research to be completed before a comprehensive feature based WAAM handbook is available.



(a) (b)



(c) (d) (e)

Figure 2-11 WAAM Features: (a) inclined walls (steel); (b) curved walls (steel); (c) horizontal walls (Aluminium); (d) intersection (Aluminium); (e) closed semi-circles (steel) (Williams, 2011)

2.2.4.5 Process parameters

Effective wall thickness (EWT) and surface waviness (SW) are the two key objectives to assess the quality of WAAM features (e.g. walls) (as shown in Figure 2-12).

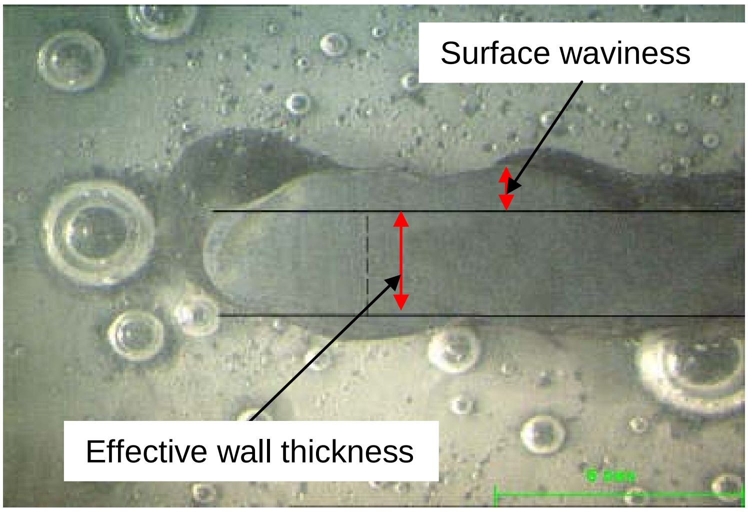
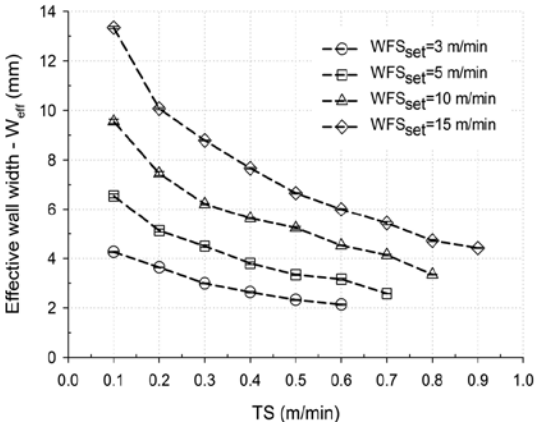
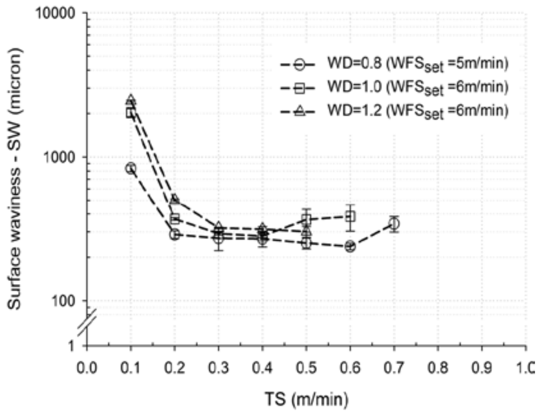


Figure 2-12 Example of measuring surface waviness (SW) and effective wall thickness (EWT) (Deherkar, 2010)

Research (Kazanas, 2012) shows that the process parameters (e.g. travel speed (TS), wire feed speed (WFS) and wire diameter (WD)) have significant effect on EWT and SW. Figure 2-13 shows the empirical curves for mild steel walls. Figure 2-13 (a) illustrates that the EWT of mild steel decreases as the TS increases. The faster the WFS, the great the EWT is. Figure 2-13 (b) presents that the SW reduces sharply until 0.2m/min, and then level off. In addition, the WD has slightly effect on the SW.



(a)



(b)

Figure 2-13 Effect of process parameters on EWT and SW: (a) EWT versus TS; (b) SW versus TS (Kazanas, 2012)

Figure 2-14 shows the effect of TS, WFS on surface waviness (SW) for aluminium alloy walls. As can be seen, the TS within 0.2-0.3m/min can obtain lower SW for the WFS/TS ratio at 15 and 30, while 0.1-0.2m/min is better for the WFS/TS ratio at 45.

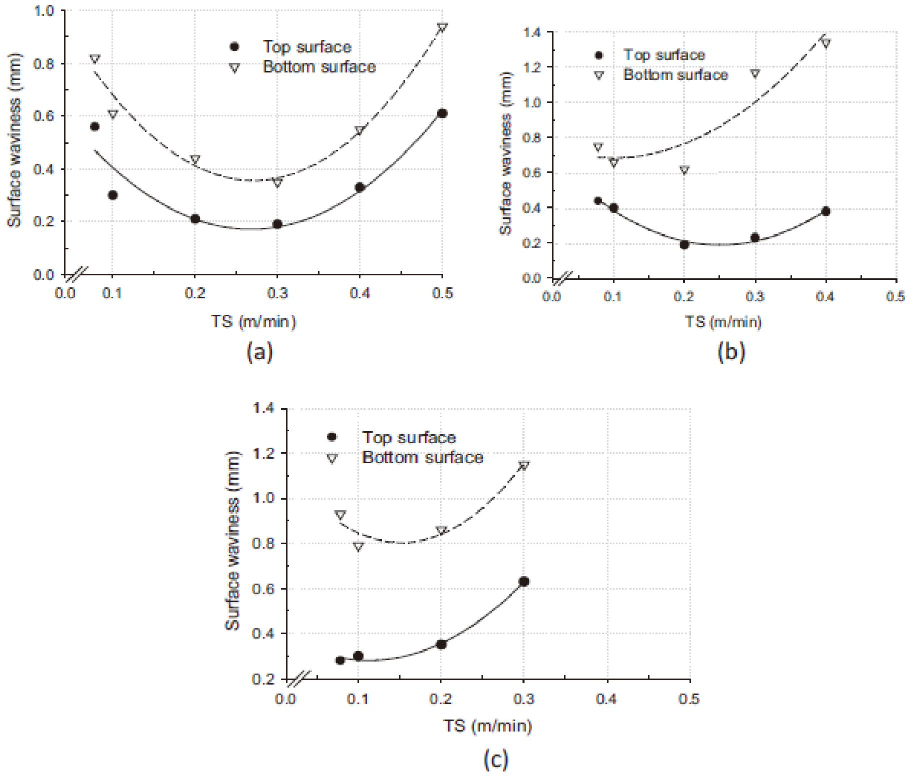
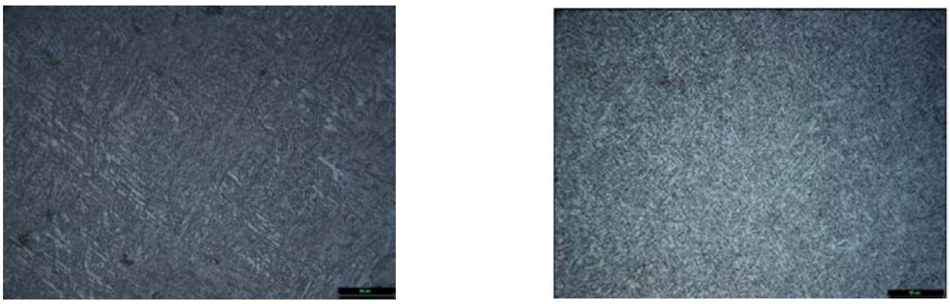


Figure 2-14 SW versus TS for different constant WFS/TS ratio:
(a) 15; (b) 30; (c) 45 (Kazanas, 2012)

2.2.4.6 Microstructure and mechanical properties

2.2.4.6.1 Microstructure

The studies of Lorant (2010) illustrates that the microstructure of Ti-6Al-4V wall feature presents a coexistence of alpha laths colonies, beta grains and large prior beta grains (see Figure 2-15). It is a typical Widmanstätten microstructure of Ti-6Al-4V obtained by cooling from above the beta transus temperature, which has lower ductility and higher creep resistance compared with the equiaxed structure.



(a) (b)

Figure 2-15 Microstructure of the Ti-6Al-4V wall: (a) longitudinal direction; (b) transverse direction (Lorant, 2010)

2.2.4.6.2 Mechanical properties

Research also shows that tensile and fracture toughness properties of Ti-6Al-4V wall built by WAAM process and the wrought Ti-6Al-4V are similar. Nevertheless, compared with wrought Ti-6Al-4V, the fatigue crack growth rate of the WAAM-built wall is lower (Lorant, 2010). Table 2-2 summarizes the mechanical properties of Ti-6Al-4V wall features of WAAM (Lorant, 2010).

Table 2-2 Mechanical properties of Ti-6Al-4V wall features of WAAM

Specimens direction	T-L	L-T
Tensile Properties		
F_{tu} (MPa)	906	923
F_{ty} (MPa)	810	840
e (%)	11.6	8.5
E (GPa)	126.5	123.5
Fatigue Crack Growth Rate		
	Initial stress intensity factor: $7\mathrm{MPa}\cdot\mathrm{m}^{1/2}$	
Paris Law	$\frac{da}{dN} = 2.51 \cdot 10^{-11} \cdot (\Delta K)^{29}$	$\frac{da}{dN} = 10^{-10} \cdot (\Delta K)^{25}$
Number of cycles for a 50mm length crack	2969000	1434500
	Initial stress intensity factor: $6\mathrm{MPa}\cdot\mathrm{m}^{1/2}$	
Paris Law	$\frac{da}{dN} = 2.51 \cdot 10^{-11} \cdot (\Delta K)^{30}$	$\frac{da}{dN} = 2.58 \cdot 10^{-11} \cdot (\Delta K)^{33}$
Number of cycles for a 50mm length crack	5691700	3511040
Fracture Toughness		
K_C $(\mathrm{MPa}\cdot\mathrm{m}^{1/2})$	73.9	81.9

2.2.5 Summary

Additive manufacturing technologies, LAM, EBM, SMD and WAAM, are introduced in this chapter. Compared with LAM and EBM processes, the necessary equipment needed for a WAAM process is much cheaper and easier to build. Furthermore, the productivity of WAAM is typically higher than that of LAM and EBM. These advantages make the WAAM process especially suitable for fabricating large scale components. However, due to the process constrains of arc welding, the complexity of WAAM components is comparatively low.

2.3 Engineering Design Methods

Design is defined as a procedure for determining product functions and design requirements based on the clarification of tasks, which are subsequently converted into solution variants. A lot of research has focussed on design philosophies; and design models are developed based on the philosophies to show how design can be done (Evbuomwan, 1996; Van Aken, J. E., 2005). Below are several typical engineering design models.

2.3.1 Pahl and Beitz’s design model

Pahl and Beitz’s design model (1984) is a reasonably comprehensive model (as shown in Figure 2-16). It includes the following design phases:

- Clarification of the task: collect information and constrains of the object.
- Conceptual design: analyse functions and seek for feasible solutions.
- Embodiment design: determine the layout starting from conceptual design.
- Detail design: finally check and finish the detail drawings and production documents.

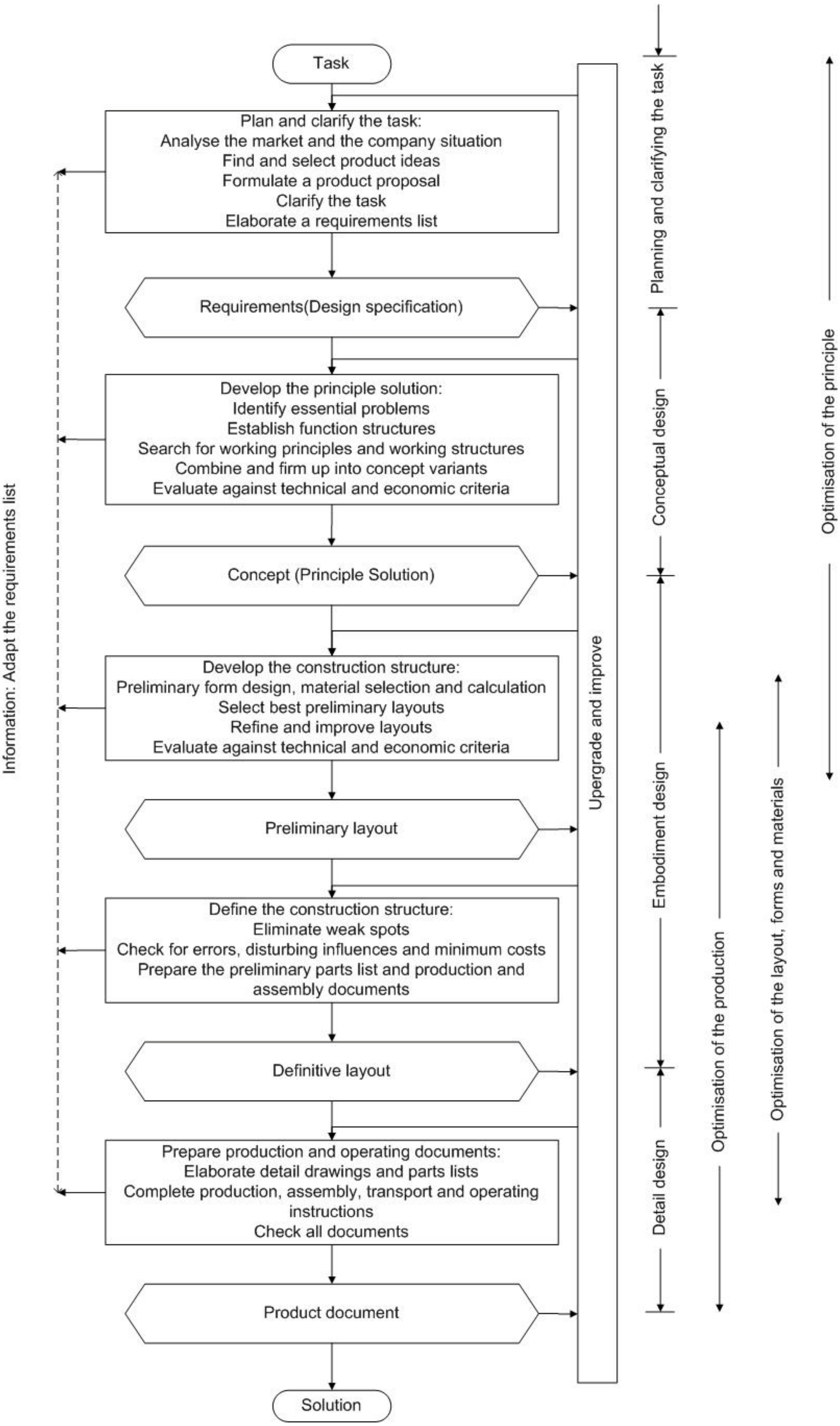


Figure 2-16 Pahl and Beitz's model of the design process (Pahl and Beitz, 1999)

2.3.2 VDI 2221 Model

The VDI 2221 model is a systematic design approach of various systems and products, which is more recent than Pahl and Beitz's model. This model aims to offer a general design approach for various design tasks. Figure 2-17 shows the VDI 2221 model divided into seven stages.

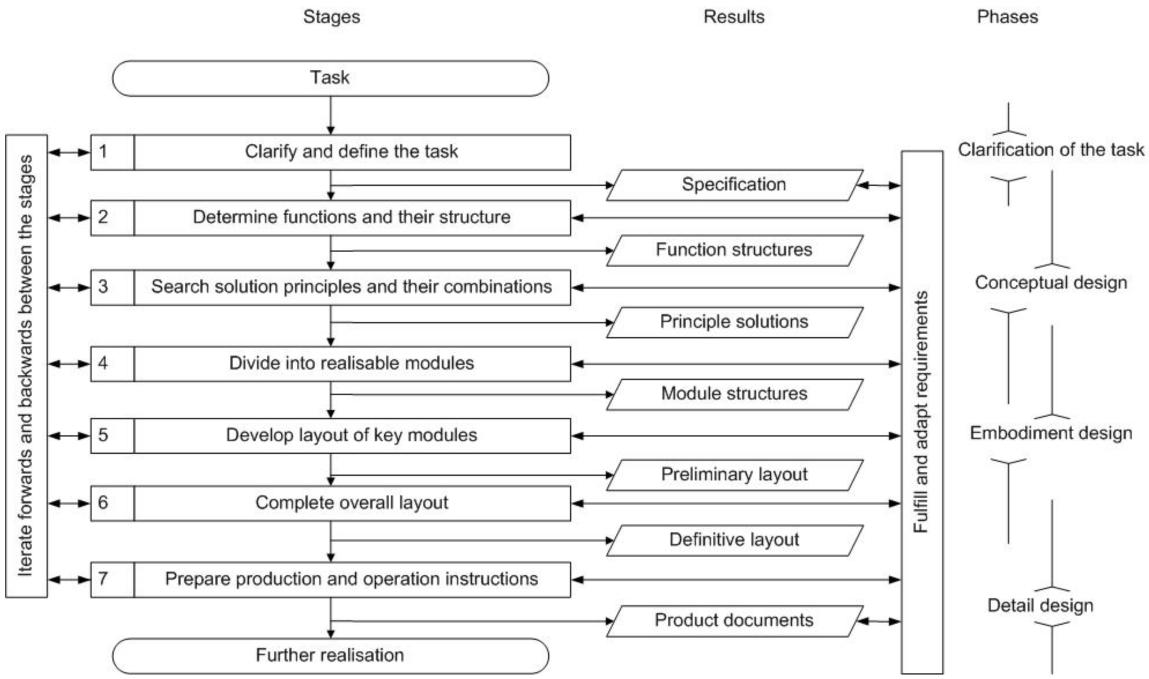


Figure 2-17 The VDI 2221 model of the design process (Cross, 2000)

- Stage 1-design specification, which is then constantly reviewed, kept up to-date and used as a reference in all the subsequent stages.
- Stage 2-determine the required functions of the design.
- Stage 3-search solution principles for all sub-functions and then combined them into a principal solution for overall function.
- Stage 4-divided into realisable modules and establish a module structure representation the breakdown of the solution into fundamental assemblies.
- Stage 5-develop key modules as a set of preliminary layouts.
- Stage 6-refine and develop into a definitive layout.
- Stage 7- produce final product documents.

In the model, analysis and evaluation is emphasised throughout every step. Furthermore, the steps are flexible so that they can be re-organized based on the necessity of design. Every step in this model is not independent but interactive so as to achieve a step-by-step optimization.

2.3.3 BS 7000 design model

The BS 7000 design model derives from Pahl and Beitz's design model (Erbuomwan, 1996), but it is simplified and has added the design for manufacture stage (as shown in Figure 2-18).

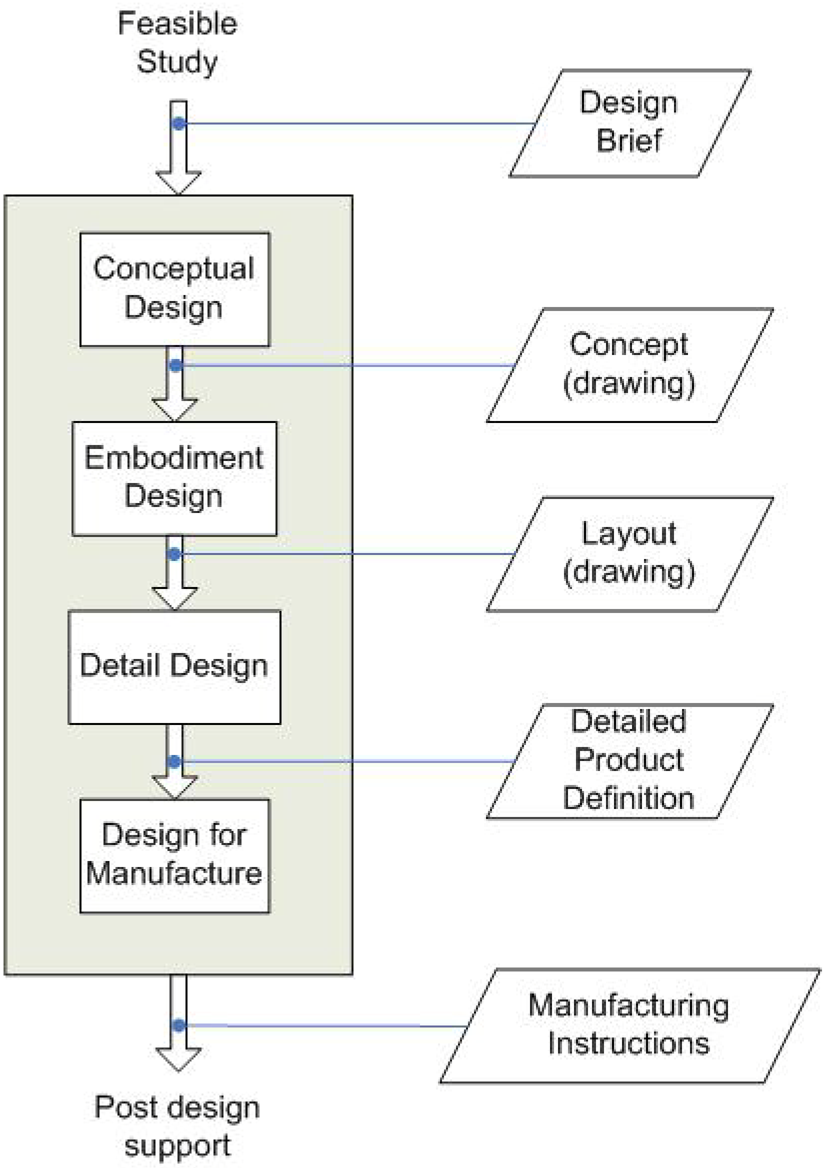


Figure 2-18 The BS 7000 design model (Erbuomwan, 1996)

2.3.4 Nigel Cross's design model

Nigel cross's design model also has seven stages (as shown in Figure 2-19). It is a typical problem-solution model. This design model combines the design procedure with design problems. The design procedure is represented by the sequence of methods while the design problems are presented by the arrows showing the alternative relationship between problems and solutions.

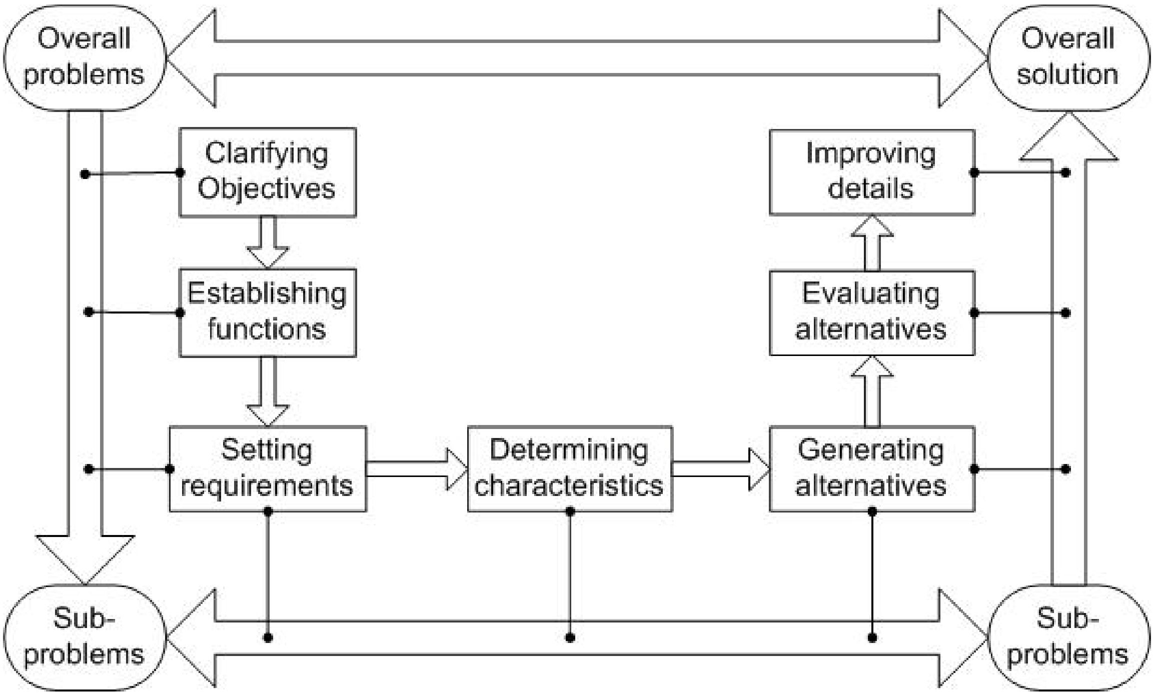


Figure 2-19 Nigel Cross's design model (Cross, 2000)

2.3.5 Summary

Selected design models were evaluated in this section-Pahl and Beitz's design model and the VDI 2221 model are general engineering design model, and the latter overly focussed on conceptual design rather than embodiment design and detailed design. Nigel cross's design model is too general to guide engineering design, such as aircraft structure design, which needs to be detailed in specific activity. However, the BS 7000 design model offered significant inspiration for developing a new design process as it introduced the Design for Manufacture (DFM) concept in design flow.

2.4 Design For Manufacturing (DFM)

The concept of Design For Manufacturing (DFM) can track its history back to 1788. LeBlanc put forward the concept of interchangeable parts in muskets manufacturing, whereas the term DFM was very well known until the late 20th century (Bralla, 1999).

DFM is defined as designing objects considering the materials, manufacturing process, based on the combination of varieties of capabilities and restrictions. Its goal is to simplify production, reduce manufacturing cost and lead time, and improve production quality (Kuo et al., 2001).

Generally, design costs occupies about 10% of the total project budget, but 80% of manufacturing costs are decided by the design (Cakira and Cilsalb, 2008). Traditional design method, such as sequential design approach, can hardly affect the overall project costs. DFM is a useful design concept to achieve this aim by integrating certain factors into the design stage (as shown in Figure 2-20).

It is difficult for designers to obtain the required information and knowledge from DFM because of the lack of formalized procedures. Ferrer (2010) presented a methodology for identifying and formalizing the relative manufacturing information by developing a systematic procedure based on the Axiomatic Design theory (Suh, 2001) and DFM techniques.

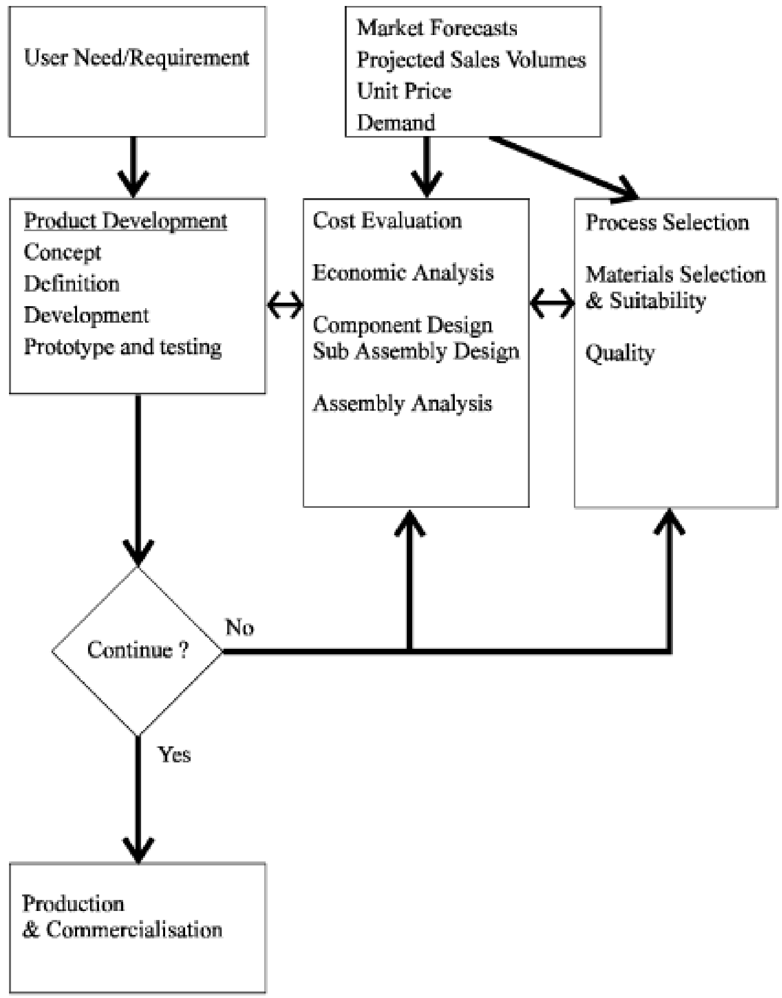


Figure 2-20 Typical DFM flowchart (O'Driscol, 2002)

2.4.1 Design for Additive Manufacturing (DFAM)

With the significant development of Additive Manufacturing (AM), it is necessary to re-think DFM to take advantage of the superiorities of this technology. This is the main reason why Design For Additive Manufacture (DFAM) was brought forward. DFAM is defined as follow: Integrate factors of structure and material to achieve desired product by using unique capabilities of additive manufacturing process such as shape complexity, material complexity and hierarchical complexity (Rosen, 2007; Chu et al., 2008).

Rosen (2007) analysed the necessary capabilities and new technologies for mesostructures; and then developed a formal framework for DFAM (as shown in Figure 2-21). The process, structure, and property models are divided into geometric and material models. The goal of this DFAM framework is to decrease the size scale of mesostructure for Cellular Structures, which is based on laser additive manufacturing. It has been applied to aerospace structures design and analysis, such as aerofoil shape, cover plate, and beam (Rosen, 2007; Chu et al., 2008).

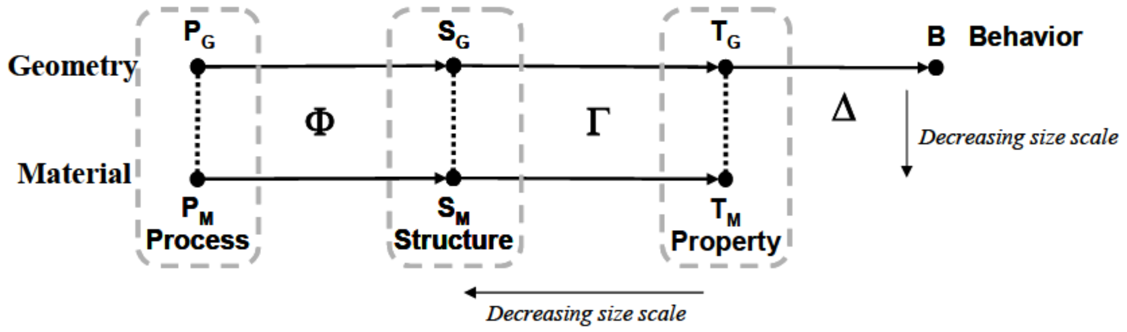


Figure 2-21 DFAM framework with geometry and material layers
(Rosen, 2007; Chu et al., 2008)

In Kerbrat et al.'s research (2011), a new DFM method was provided—a hybrid modular concept, combining Additive Manufacturing and Subtractive Manufacturing. It includes a manufacturability evaluation method. A quantitative measure of manufacturability is carried out using CAD software (SolidWorks by Dassault Systems). The analysis result is presented as the manufacturability indexes that are classified as global and local type. Figure 2-22 shows the example of the modular method. This single part is re-designed as a simple assembly which reduces the amount of machining significantly.

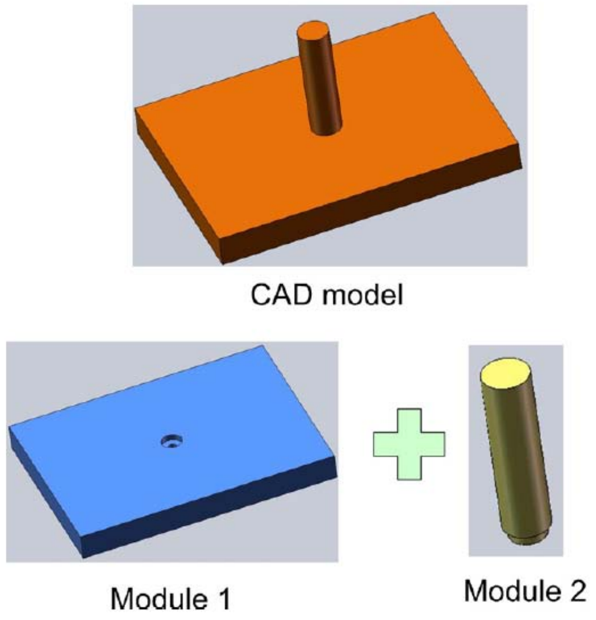


Figure 2-22 Example of the modular method (Kerbrat et al., 2011)

Figure 2-23 presents an example of hybrid approach. In the hybrid design, four sharp corners were realized by additive fabrication, which are difficult for conventional machining.

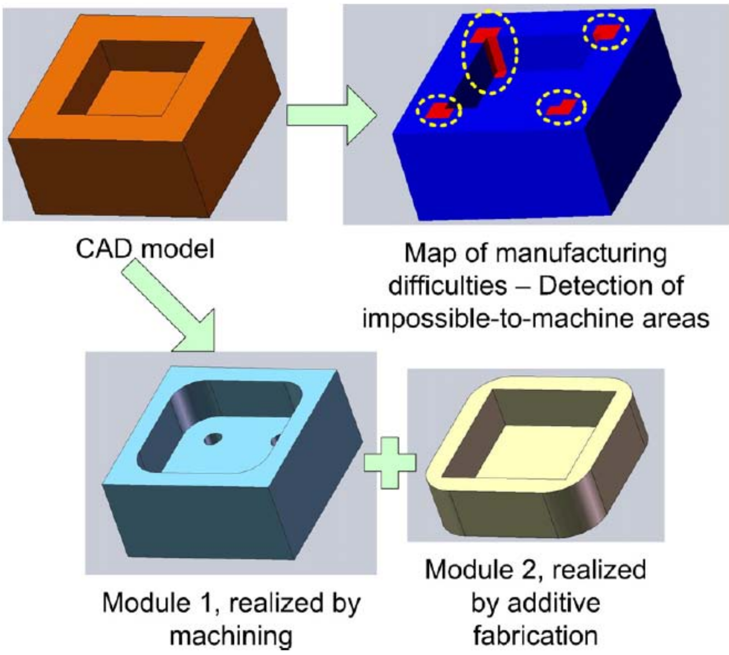


Figure 2-23 Example of the hybrid approach (Kerbrat et al., 2011)

This DFM method depends greatly on the manufacturing difficulties analysis. However, it is hard for a designer to calculate the manufacturing indexes without a complete process parameter data base. Hence it is a huge challenge to establish agreed criteria for the manufacturability evaluation. Furthermore, the biggest weakness of this method is that the materials, functions and design requirements of object are not considered.

2.4.2 Design optimisation based on AM technology

Emmelmann et al. (2011) has made significant progress with the DFAM concept by introducing Finite Element Analysis (FEA) based structural optimisation, which can perfectly utilize the unique advantages of AM. In his research, bionics was taken into consideration in the design process. Figure 2-24 shows the application of DFAM based on bionics.

The FEA method was also studied in design for EBM, which was applied to biomedical parts such as bones (Parthasarathy et al. 2011). Compared with the original design, the final design is much lighter.

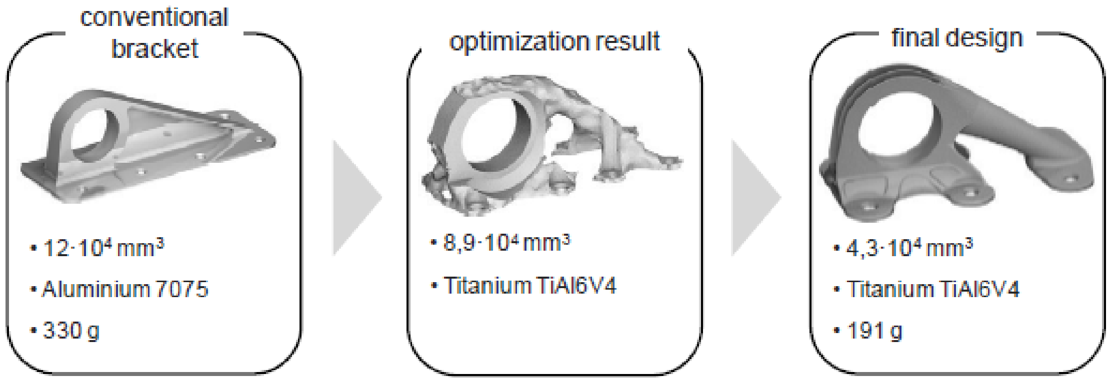


Figure 2-24 Application of DFAM based on bionics (Emmelmann et al., 2011)

2.4.3 Design for WAAM

As a new manufacturing process, WAAM lacked sufficient information and knowledge to guide design for WAAM. In the RUAM project, the design for stiffened panels and crossing features was researched (Mehnen, 2010). In addition, Kazanas (2011) re-designed a flap track of the A-9 Dragonfly based on WAAM technique in his research (as shown in Figure 1-3). The A-9 Dragonfly is a 270 seat civil transport aircraft designed by Cranfield University Aerospace Vehicle Design MSc students in October, 2009. After re-design, the flap track can be 30% lighter and 66% material can be saved by using WAAM process when compared to traditional machining approach.

2.4.4 Summary

In conclusion, the theory of DFM is quite mature in contrast to additive manufacturing technologies, especially WAAM technology, which are still relatively novel. Hybrid design concept is proven to be an effective design method for WAAM technology. It is a new and potential design concept that can fully exploit the advantages of WAAM as well as conventional processes. Therefore, it is necessary to establish a systematic hybrid design method to spread the use of this concept.

2.5 Design Manual

Design handbooks are the important tools which can guide designers to make their designs more efficient and have better manufacturability. Usually, a handbook comes from a great quantity of accumulated of knowledge and experience from industry experts and needs continuous improvement and update.

2.5.1 Design manual in the aircraft industry

Figure 2-25 presents a castings design manual in the aircraft industry. It mainly consists of material, process, design considerations, classification, etc. This manual is quite useful and effective to guide aircraft casting design.

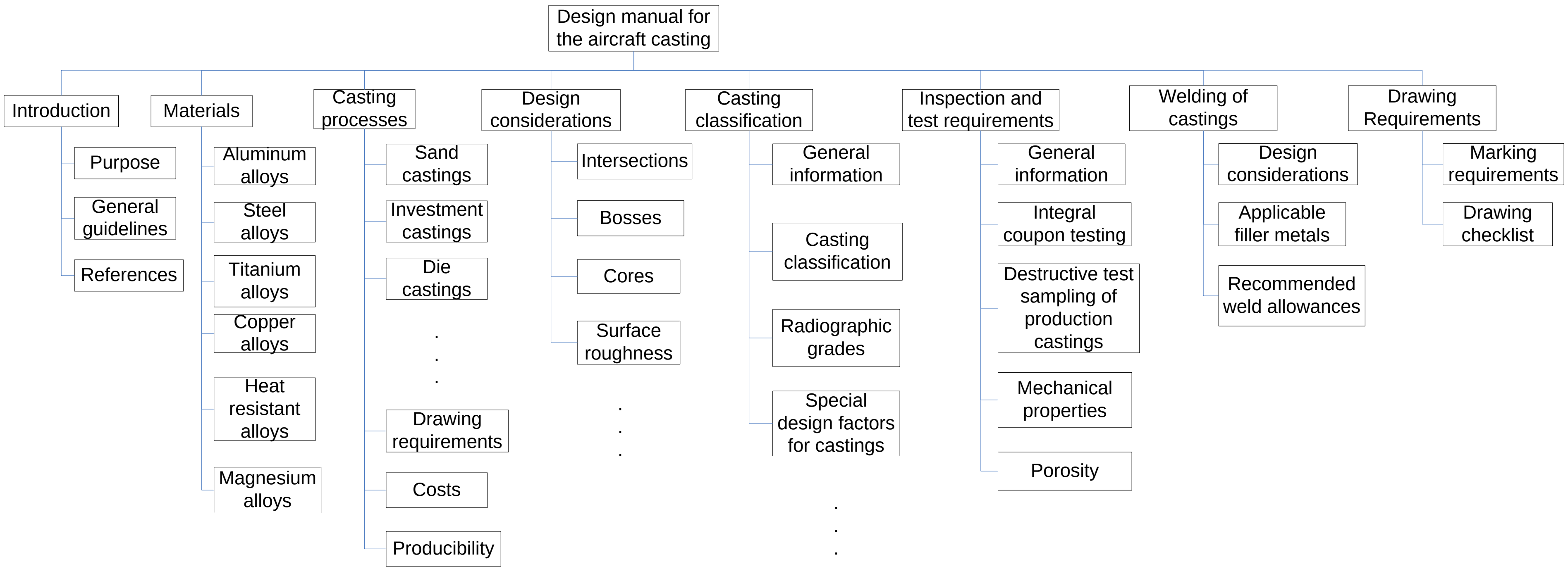


Figure 2-25 Casting design manual in the aircraft industry (Chief Edition Committee of the Aircraft Design Handbook, 2000)

2.5.2 WAAM feature based design manual

The framework of WAAM feature based manual is shown in Figure 2-26. This handbook contains WAAM features, material and process. A part of this manual has been finished, but a lot of work is still required to complete the overall content.

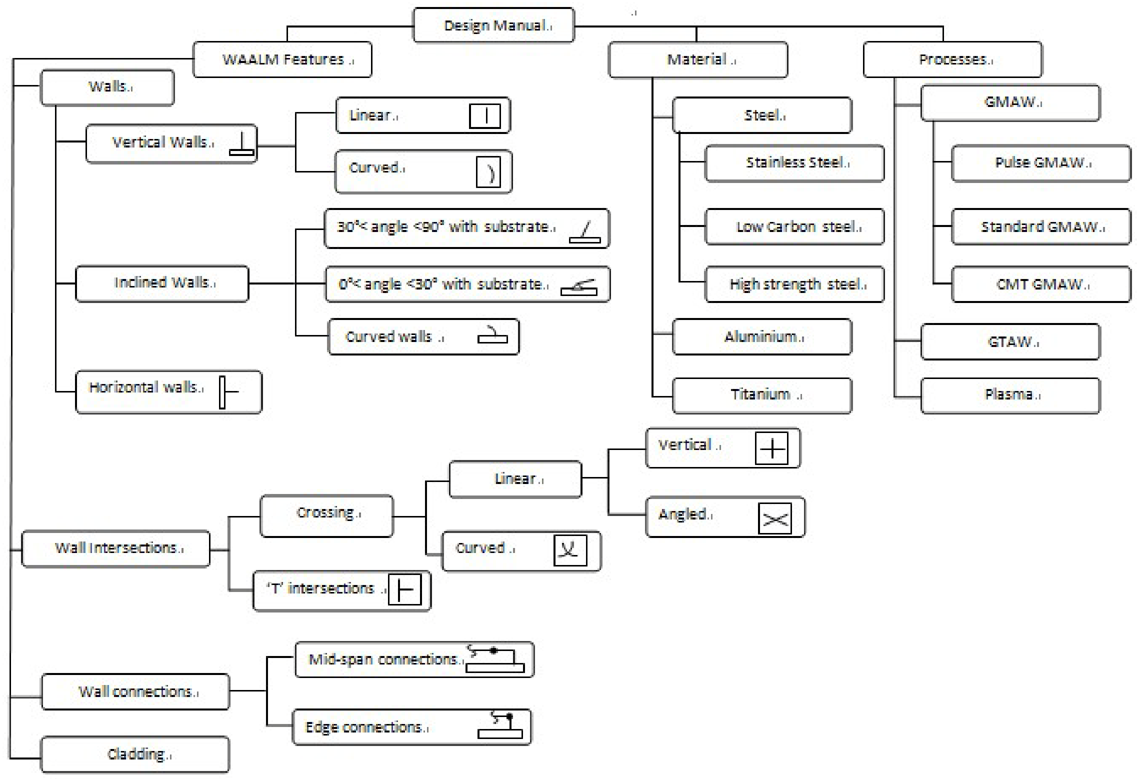


Figure 2-26 Framework of the WAAM feature based manual (Williams, 2011)

2.5.3 Summary

It is necessary to establish a design manual which can satisfy the demand of target industry. Therefore, it can be developed by collecting and analysing the suggestions and demand from designers. Also, it can refer to existing design manuals.

2.6 Research Gap Analysis

At present, low carbon and environmental protection is the mainstream trend in the manufacturing industry. The main aircraft manufacturers, such as Boeing and Airbus, are devoted to make their airplanes more economic with higher performance and lower fuel consumption. WAAM technology is considered a novel manufacturing process, which is expected to bring great changes in the aircraft industry. However, more research of WAAM technology is needed regarding its commercialization in the aircraft industry. The following research gaps have been identified through the literature review.

- There is little publication about the application of WAAM technology in the aircraft industry.
- There is little publication about design method or design manual of WAAM technology.

2.7 Summary

The literature review has examined the following areas related to this research:

- Additive manufacturing.
- Engineering design methods.
- Design for manufacturing.
- Design manual

The findings of the literature review contribute to shaping the focus of this research. The research aim and objectives of this thesis are formalised in Chapter 3 according to the research gap summarised in this chapter.

3 Research Aim and Methodology

3.1 Introduction

In Chapter 2 the research gap was summarised based on an extensive literature survey. This chapter clarifies the aim and objectives of this thesis to meet the research gap. The scope of this thesis is outlined according to the objectives. The methodology followed in this research to achieve the objectives is introduced and the main deliverables during the completion of the research are listed.

3.2 Research Aim

The overall aim of this research project is to develop a step-by-step design method, to create and assess hybrid design solutions based on Wire and Arc Additive Manufacturing (WAAM) technology.

3.3 Research Objectives

This research has the following objectives:

- Analyse existing design methods and software tools.
- Collect and analyse technical data about aircraft structure design and WAAM process.
- Develop a hybrid design method based on WAAM technology.
- Validate the developed design method through industrial case studies.

3.4 Research Scope

This research focuses on design method for WAAM including four aspects as follow:

- Domain: this research focuses on developing a design method based on WAAM technology in the aircraft industry. It is restricted by the existing WAAM technical data (e.g. WAAM features) and the available information that can be collected in this research. Experiments using the actual WAAM process for obtaining technical data are not in the research scope.

- Literature survey: there is a concentration on AM technologies, engineering design methods, design for manufacturing and design manual used to develop a design model based on WAAM technology.
- Case study: case study of this research includes one experimental design for WAAM and two real parts in the aircraft industry.

3.5 Research Methodology

3.5.1 Introduction

It is necessary to define and adopt the most appropriate research methodology to obtain the information and data for the research project. This chapter represents the research methodology of this project, which includes four stages to realize the aimed objectives.

3.5.2 Research Methodology Adopted

Figure 3-1 illustrates the structure of the research methodology, consisting of four phases. The tasks and outputs of each phase are also presented.

3.5.3 Methodology Phase Brief

3.5.3.1 Phase 1: Primary Concept of Research

The key task in phase 1 is to achieve a clear understanding of the research ambition, objectives and scope of this project, and then identify the research methods and tools. For this purpose, the literature review is focused on the areas of AM technology, classical engineering design methods, design for manufacturing and design manuals. Moreover, some valuable experience was obtained from a series of unstructured interviews with academics experts and technicians from the aircraft industry. In addition, the case study is initially chosen in this phase.

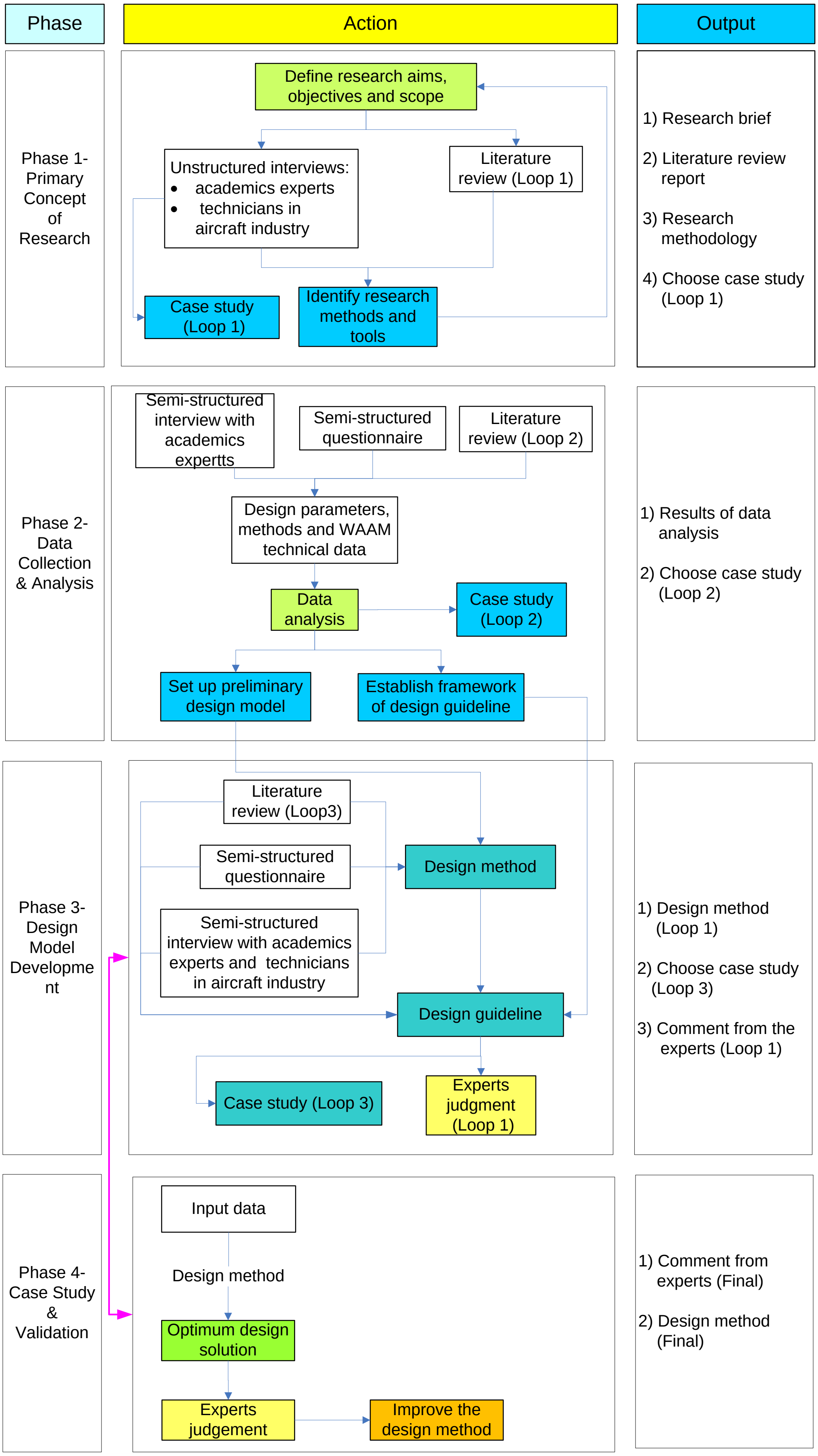


Figure 3-1 Flow chart of the research methodology

3.5.3.2 Phase 2: Data Collection & Analysis

Date collection of aircraft structure design and WAAM process is indispensable for developing a design method based on WAAM technology in the aircraft industry. The necessary data can be obtained from semi-structured interviews with academic and industrial experts, a questionnaire and a literature review. The results of the data analysis are the basis for the later research.

3.5.3.3 Phase 3: Design method Development

Phase 3 is the pivotal section of the overall research. The design method including the design model and guideline is developed in this phase. In order to guarantee its feasibility, the first judgement should be conducted in this phase. Following the experts' comments, the design method shall be modified and improved. After that, the case study shall be finally determined and two cases selected from the Chinese aircraft industry.

3.5.3.4 Phase 4: Validation

In this phase, the cases studies are carried out to verify the design model. The optimum design solution is decided through the developed design model. The next step is validation, which is conducted by academic and industrial experts. According to the expert's comments, the design model can be validated and improved.

3.6 Research Deliverables

The following deliverables have been completed in this research:

- A literature survey covering the areas of Additive Manufacturing, engineering design methods, design for manufacturing and design manual.
- A hybrid design method based on WAAM technology.

3.7 Summary

In this chapter, the aim and objectives of this research were identified. The research scope was outlined to meet the research objectives. The research methodology to follow to achieve the objectives was developed. The following chapter concentrates on data collection and analysis for WAAM technology and aircraft structure design.

4 Data Collection and Analysis

4.1 Introduction

In this chapter, data collection and analysis is introduced. The data of WAAM technology and aircraft structural design was collected and summarized by a questionnaire, literature review, and semi-structural interviews with academic and industrial experts.

4.2 Questionnaire

The questionnaire contains three sections: the respondent's general information and the design method for WAAM plus structure design objectives of the aircraft. This survey was carried out in the Chinese aircraft industry by email. 33 valid questionnaires were collected.

4.2.1 Respondent's general information

29 of all respondents are design engineers and 4 are manufacturing engineers, as shown in Figure 4-1. The work experience of these respondents is presented in Figure 4-2. The questionnaire covers young engineers and experienced engineers.

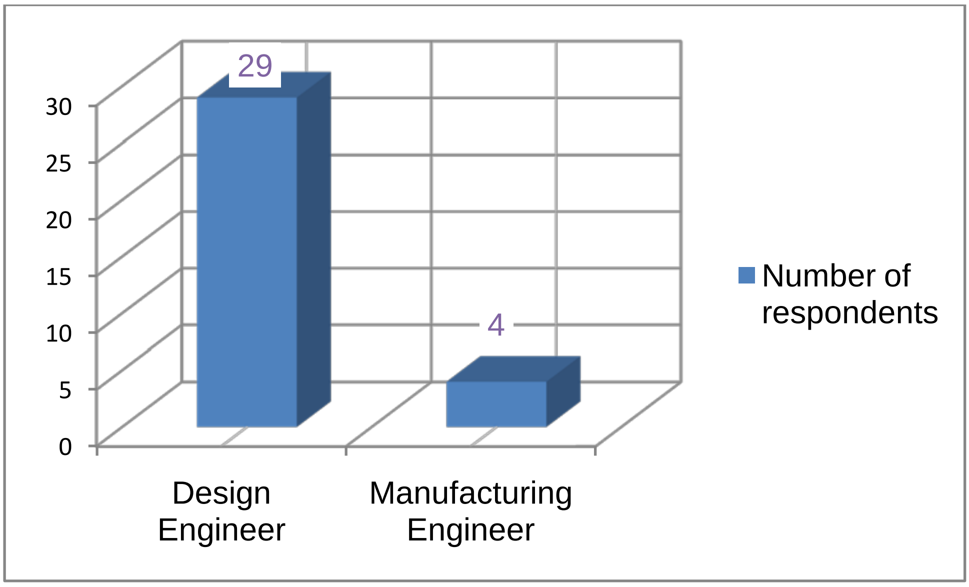


Figure 4-1 The respondents' profession

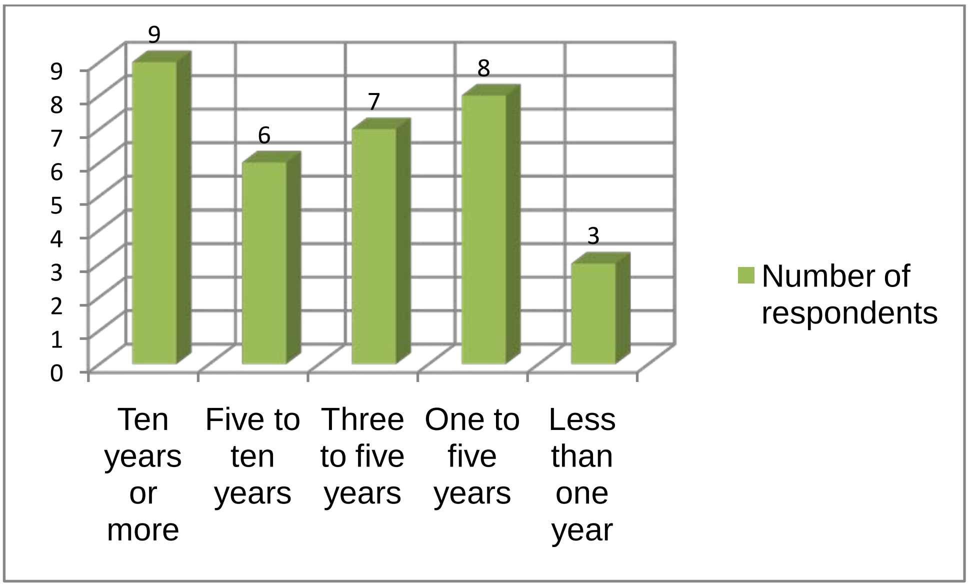


Figure 4-2 Work experience of the respondents

4.2.1.1 Design method for WAAM technology

The investigation illustrates that only 21% of respondents know about the application of additive manufacturing in their company or institute. The process typically mentioned is laser rapid prototyping based on metallic powders that is used to produce the frame of the windshield in the physical prototype.

In addition, investigation shows that 49% of respondents think it necessary to develop a design method for WAAM, while 42% of them remain unsure and the rest consider it unnecessary (as shown in Figure 4-3).

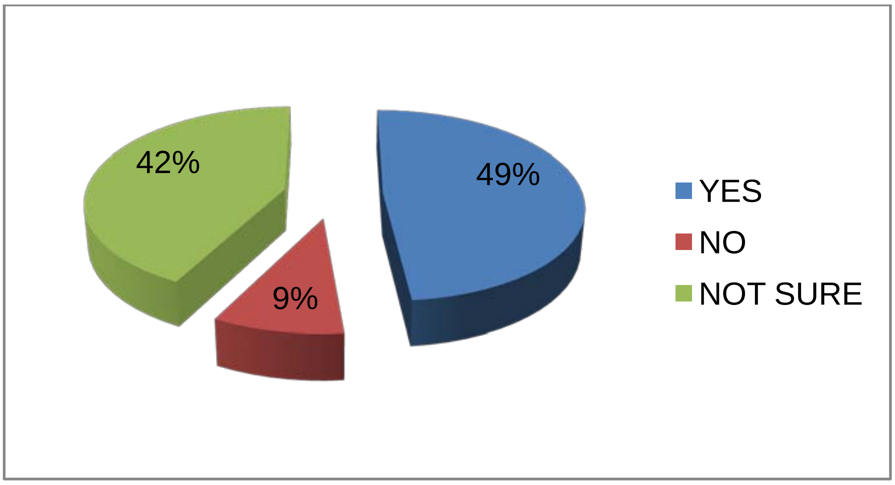


Figure 4-3 The survey result of the necessity of developing a design method for WAAM

The main reasons of "YES" are summarized as follow:

- WAAM can improve "buy-to-fly" ratio and design flexibility.
- WAAM process is quite different from conventional manufacturing processes.
- Suitable design method is necessary to take advantage of the unique advantages of WAAM.

However, 9% of respondents disapprove of this idea. They consider it too time-consuming and costly in terms of investment to develop a new design method in aviation, hence it is better to use a mature process and design method.

Figure 4-4 shows the investigation result of "How to develop a design method for WAAM technology". 67% of the respondents prefer to develop a design method for WAAM by modifying existing mature design methods. The main reason cited is that it not only lowers risk but also needs less investment. Only 18% of the respondents are in favour of developing a completely new design method. Only 9% of them consider using existing mature design method directly.

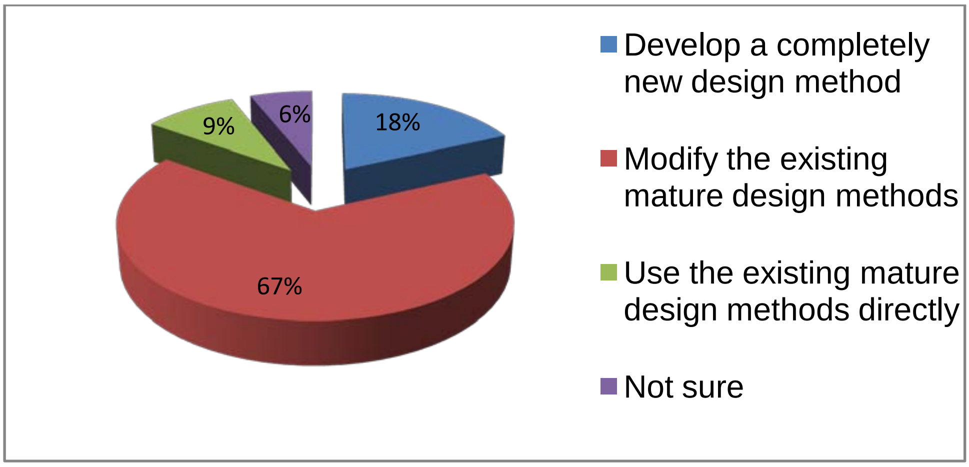


Figure 4-4 The investigation of the approach of developing a design method for WAAM technology

The questionnaire also shows that 23 respondents, 70% of the total, consider Titanium alloy to be the most suitable material for WAAM process in the aircraft industry (as shown in Figure 4-5).

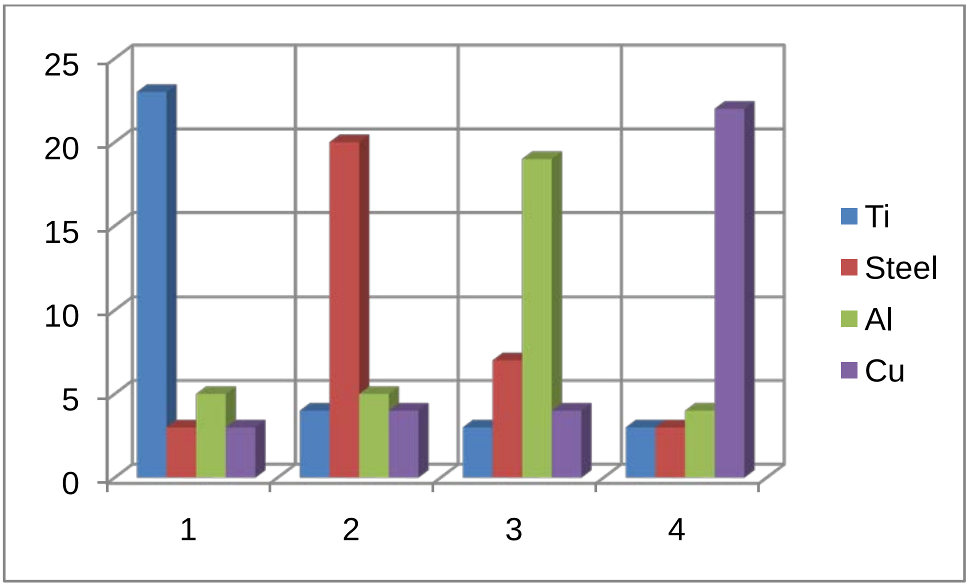


Figure 4-5 The ranking for suitable materials for WAAM process

The survey was also carried out on two design cases. Figure 4-6 presents the two different design ideas of a flap track (Kazanas, 2011). The investigation result shows that 92% of respondents prefer the “(b)” design approach which is an improved design based on WAAM process (as shown in Figure 4-7).

(a)

(b)

Figure 4-6 Flap track: (a) Manufactured by Ti-6Al-4V plate machining;

(b) Manufactured by Ti-6Al-4V plate machining (grey features) plus WAAM (green features) (Kazanas, 2011)

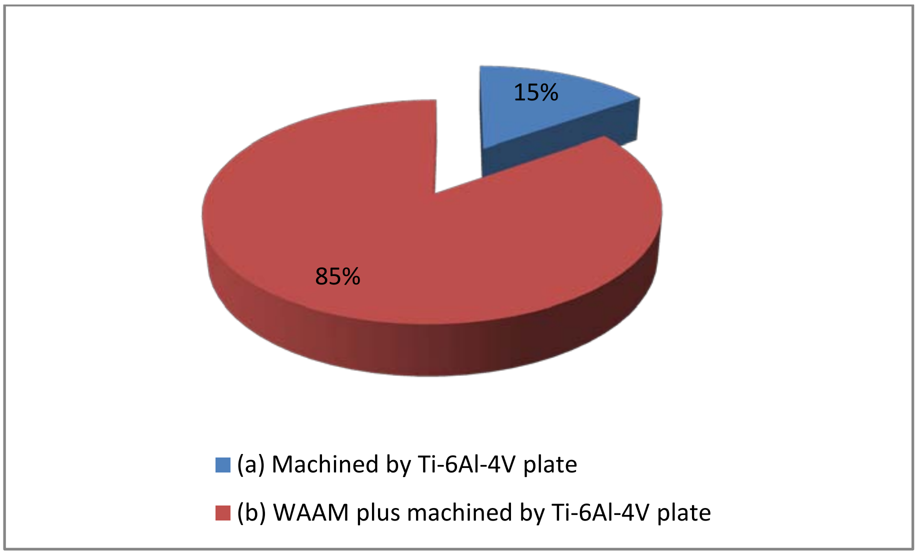
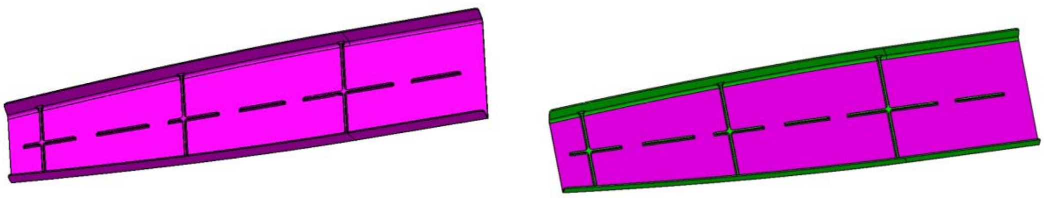


Figure 4-7 The investigation result of better design for flap track

Figure 4-8 illustrates the design ideas of a pylon bottom beam. Similar to the previous case, 85% of respondents choose “(b)” as the better design (see Figure 4-9).



(a) (b)

Figure 4-8 Pylon bottom beam: (a) Machined by Ti-6Al-4V plate; (b) Manufactured by Ti-6Al-4V plate machining (red features) plus WAAM （green features）

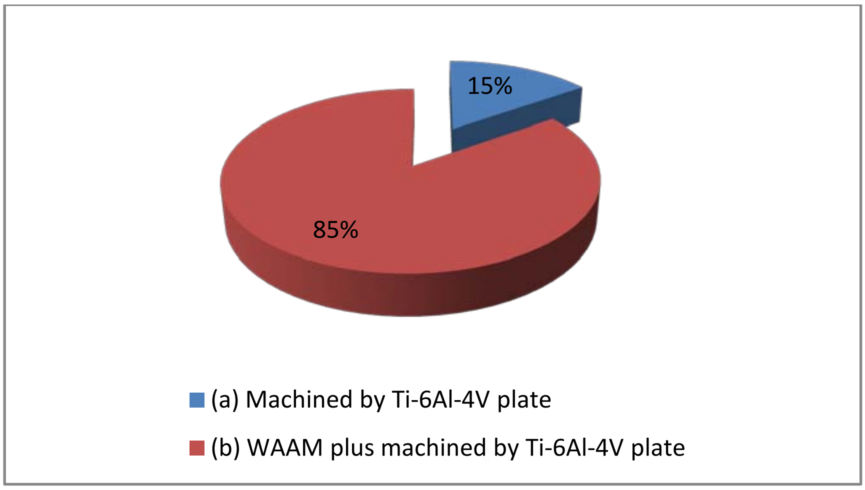


Figure 4-9 The investigation result of better design for pylon bottom beam

The key reason for such choice is that the “(b)” design leads to lower cost. Furthermore, a few engineers point out that the latter design of the flap track has better structural efficiency and less weight. However, some engineers worried about the residual stresses and the deformation during deposition, so they choose the “(a)” design. Indeed, residual stresses and deformation of WAAM process can be a big problem, which is being studied in Cranfield University (Ding, 2012).

4.2.1.2 Structural design objectives of the aircraft

In order to identify the required structural design objectives of the aircraft, investigation was carried out in the aircraft industry (as shown in Figure 4-10). All the engineers considered that “performance”, such as strength properties and functions, is the most important design objective in aircraft structure design. The “technical complexity”, “weight”, “cost” are the main objectives. However, only 24.2% of the total respondents choose the “batch size” option, which indicates that it is not important during structure design.

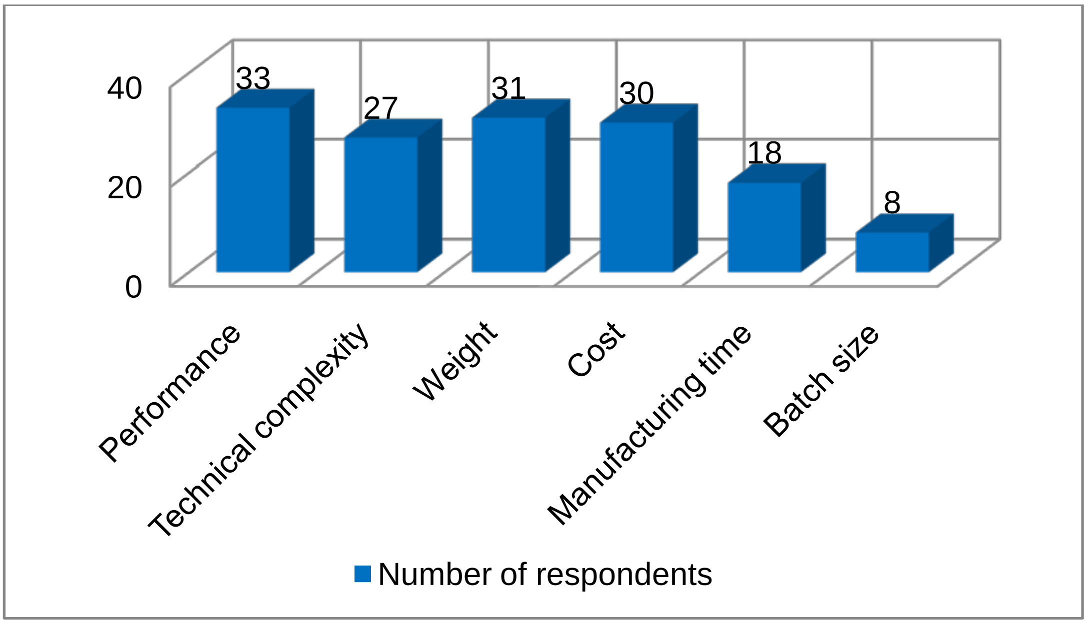


Figure 4-10 The survey result of structure design objectives

Moreover, the 33 respondents were required to give each objective a numerical value (O_{ij}) according to the degree of importance in the structure design (see Appendix C). The objective “batch size” was eliminated in the statistical process because of its low importance degree (as shown in Figure 4-10). Herein, the importance degree is identified as follows:

- Very important: 7-9.
- Important: 4-6.
- Ordinary: 1-3.

Then, the sum of all objectives (OW_j) is calculated as:

$$\mathbf{OW_j} = \sum_{\mathbf{i=1}}^{\mathbf{33}} \mathbf{O_{ij}}$$

Equation 4-1 Calculation of the sum of all objectives

The total value was calculated using Equation 4-1and listed as below (see Appendix C):

- Performance (OW_1): 289
- Technical complexity (OW_2): 167
- Weight (OW_3): 187
- Cost (OW_4): 174
- Manufacturing time (OW_5):62

The “performance” achieved the highest value that is proved to be the most important design objective. In addition, the “technical complexity”, “weight” and “cost” are considered as the main design objectives.

Finally, the weighting value of each objective (Wt_j) was calculated using Equation 4-2. The sum of all weighting valueis equals to 1.

$$\mathbf{Wt_j} = \frac{\mathbf{OW_j}}{\sum_{\mathbf{j=1}}^{\mathbf{5}} \mathbf{OW_j}}$$

Equation 4-2 Calculation of the weighting value of each objective

The weighting values were calculated as follows:

Performance:

$$\mathrm{Wt_1} = \frac{289}{289 + 167 + 187 + 174 + 62} = 0.33$$

Technical complexity:

$$\mathrm{Wt}_2 = \frac{167}{289 + 167 + 187 + 174 + 62} = 0.19$$

Weight:

$$\mathrm{Wt}_3 = \frac{187}{289 + 167 + 187 + 174 + 62} = 0.21$$

Cost:

$$\mathrm{Wt}_4 = \frac{174}{289 + 167 + 187 + 174 + 62} = 0.2$$

Manufacturing time:

$$\mathrm{Wt}_5 = \frac{62}{289 + 167 + 187 + 174 + 62} = 0.07$$

Figure 4-11shows the overall value and weighting value of each objective.

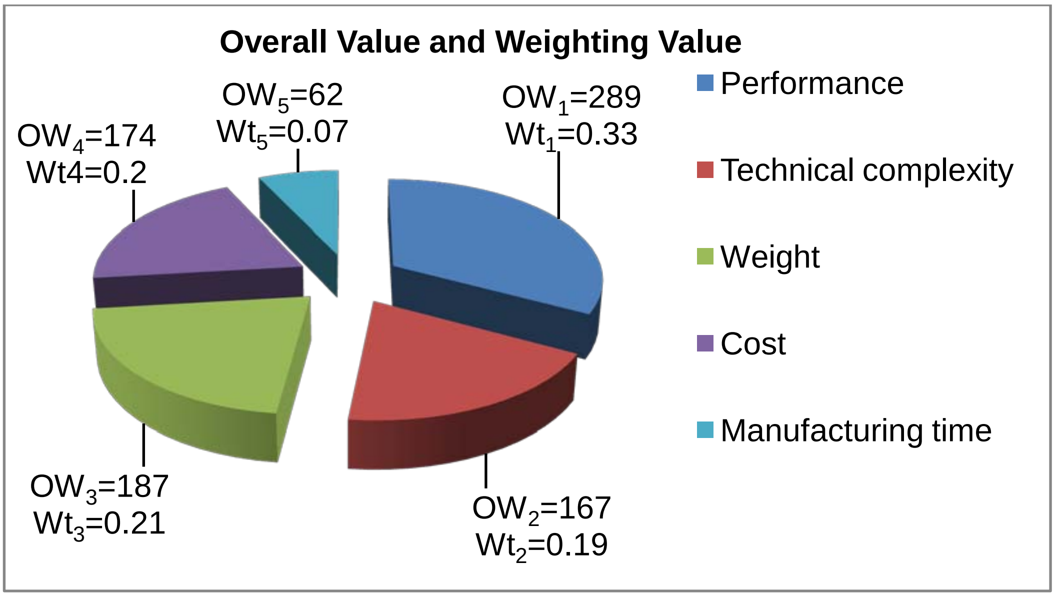


Figure 4-11 The overall value and weighting value of each objective

4.3 Literature review

4.3.1 Design method

The analysis results of the questionnaire show that it is better to develop a design method by modifying existing mature design models, such as Pahl and Beitz's design model, VDI 221 model, BS 7000 design model (Pahl and Beitz, 1999; Erbuomwan, 1996 and Cross, 2000). These methods have been widely used in various industries, which are easily adopted by engineers. The following approach takes this result into account.

4.3.2 Developed WAAM Features

Kastas (Williams, 2011) has developed a feature based design handbook of WAAM process which is structured separately for different materials.

a) Titanium alloy

Figure 4-12 illustrates the finished section of WAAM features of Ti-6Al-4V alloy. It includes welding process, feature type, geometric parameters, properties and process features.

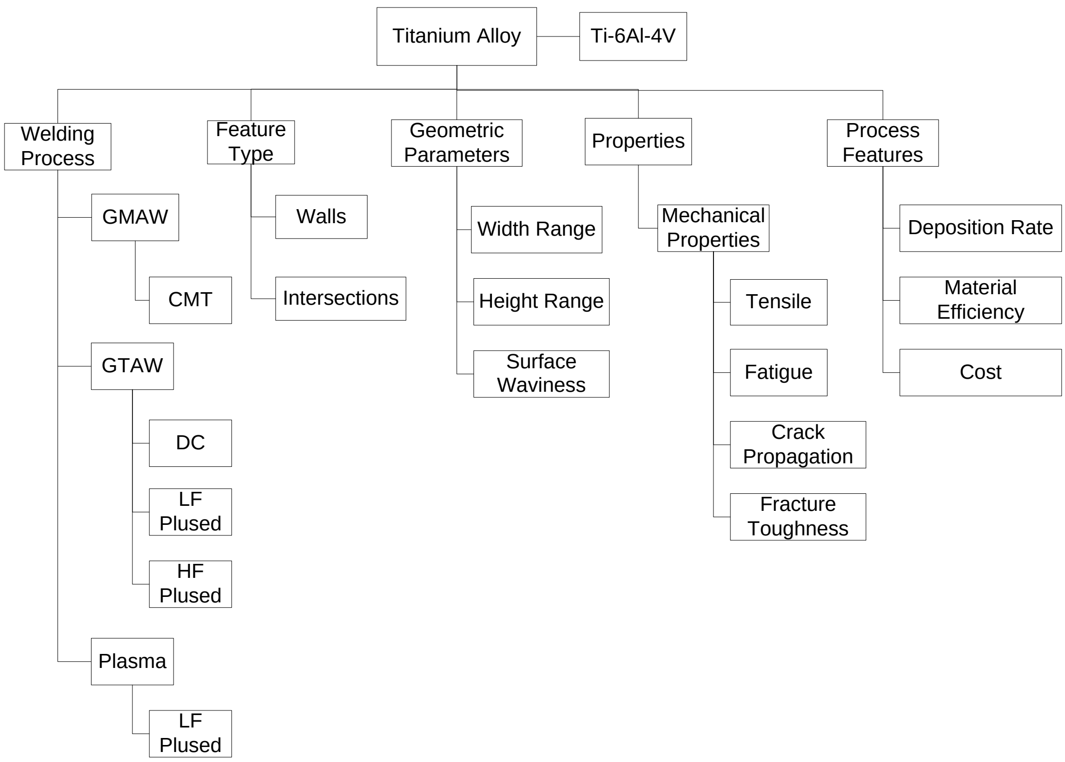


Figure 4-12 The finished section of WAAM features of Ti-6Al-4V alloy (Williams, 2011)

b) Aluminium alloy

Figure 4-13 shows the WAAM features of Aluminium alloy (Al-Si) which has currently been completed. It can be seen that there is no data of properties.

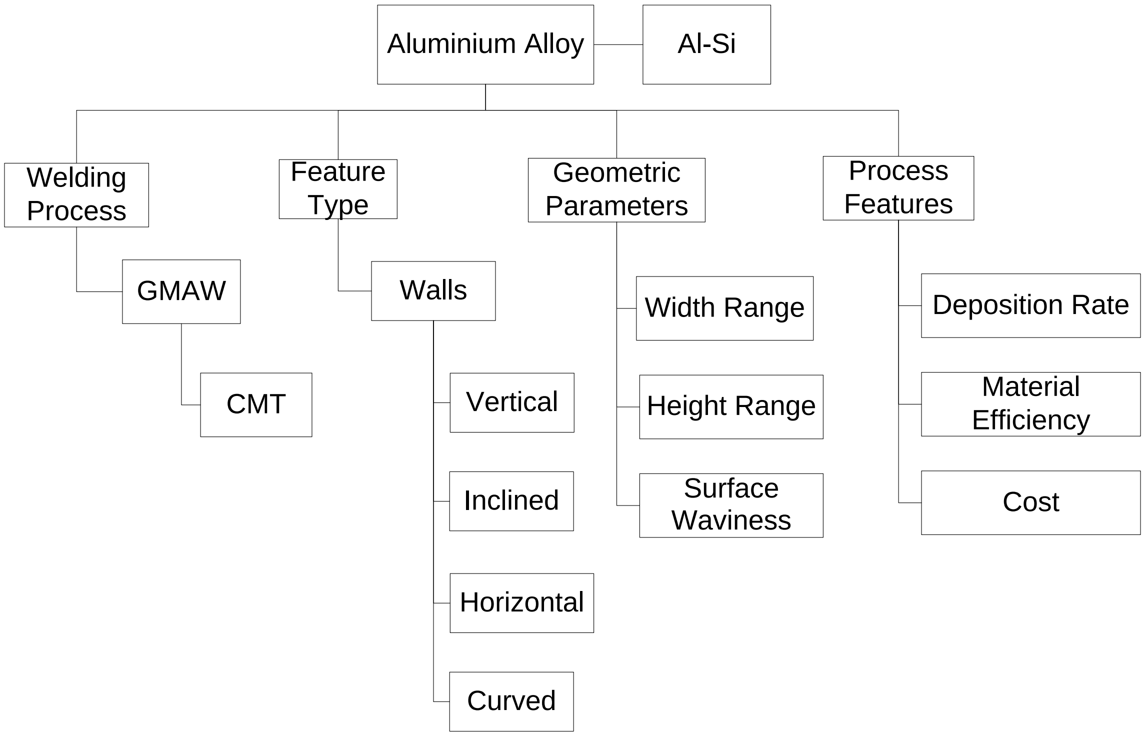


Figure 4-13 The completed section of WAAM features of aluminium alloy (Williams, 2011)

c) Steel

Figure 4-14 presents the accomplished part of WAAM features of low strength steel alloy. More features have been developed for low strength steel alloy, but only the data of residual stress has been studied.

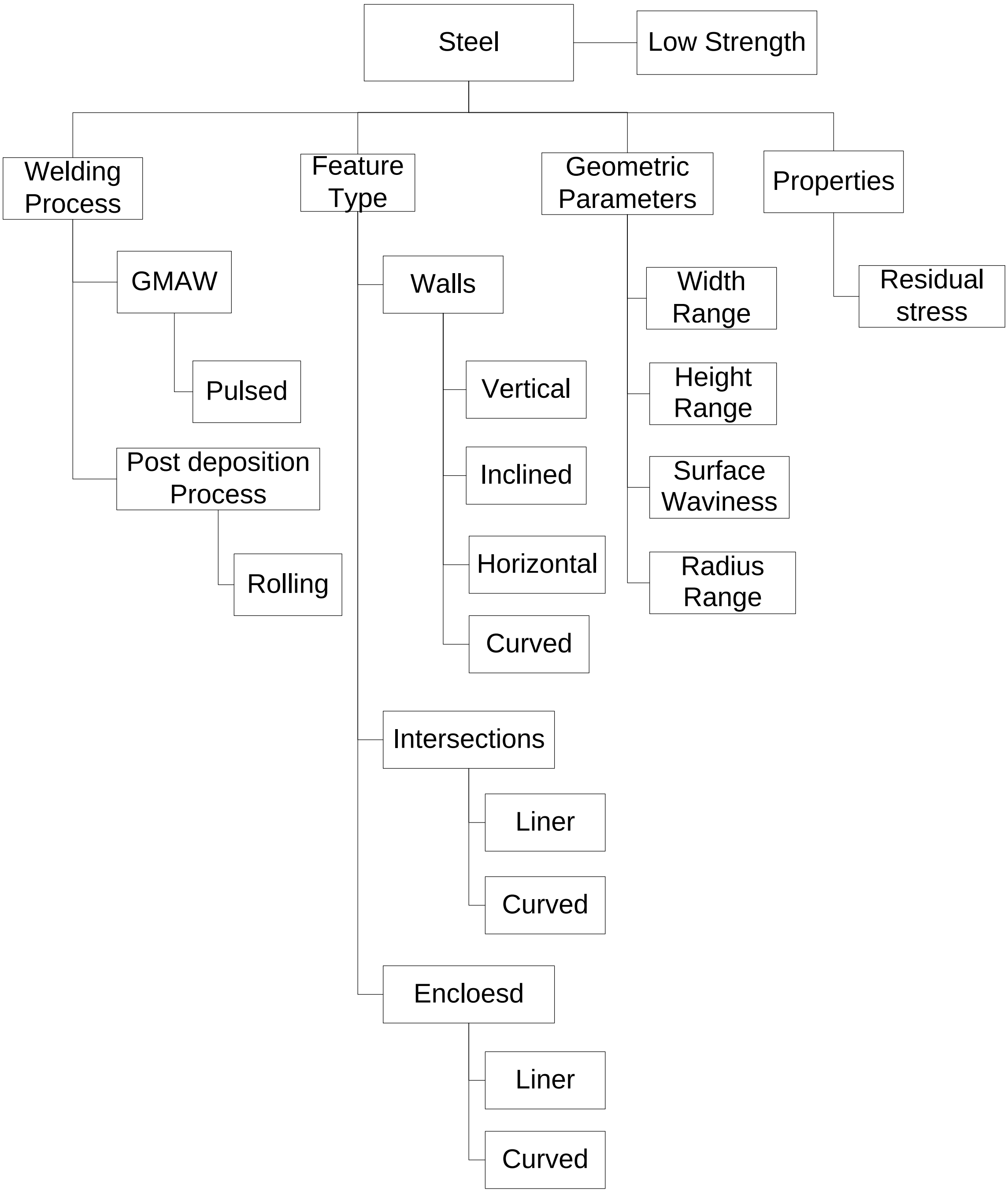


Figure 4-14 The accomplished part of WAAM features of steel (Williams, 2011)

d) Copper alloy

For copper alloys, some data of Cu-Si series alloy has been achieved (as shown in Figure 4-15).

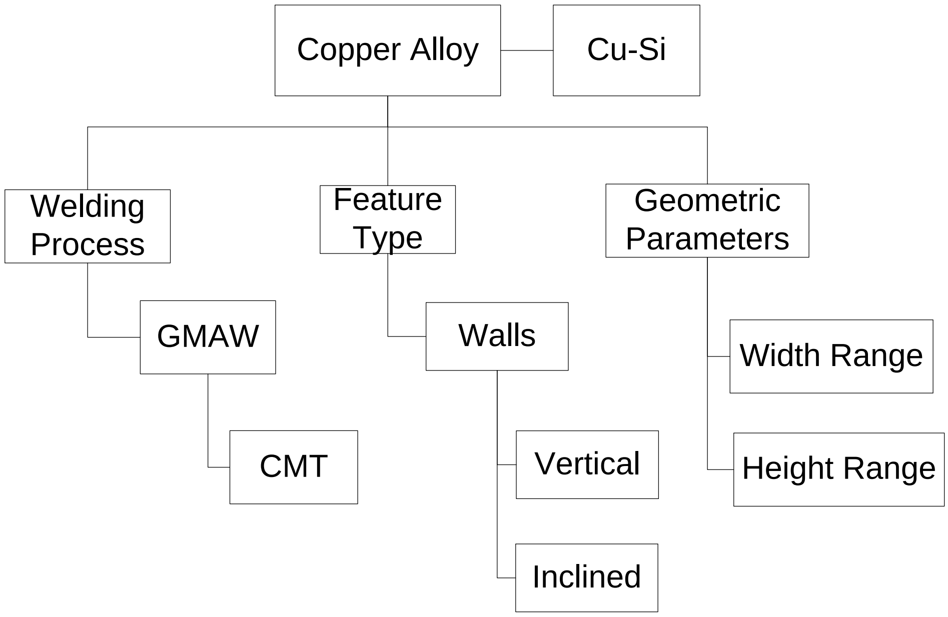


Figure 4-15 The finished part of WAAM features of copper alloy (Williams, 2011)

4.3.3 Mechanical properties of WAAM features

There is relatively complete mechanical properties data of the Ti-6Al-4V alloy wall features (as shown in Table 2-2). It is necessary for strength analysis during design.

4.4 Semi-structured interview

In order to acquire the necessary WAAM technical data for developing an effective design method, a series of semi-structured interviews were held with three academic experts and four researchers at Cranfield University.

4.4.1 Hybrid design method

Hybrid design based on WAAM technology shows huge advantages in product design. In order to properly use this concept, it is necessary to establish a WAAM feature based design guideline to support the creation of proposed hybrid design solutions. In addition, it is better to develop a suitable evaluation rule to decide the optimum hybrid design solution.

4.4.2 WAAM design parameters

The technical parameters of Ti-6Al-4V alloy WAAM features are collected and summarised in Table 4-1. The recommended welding process is Tungsten Inert Gas (TIG).The developed features are walls and intersection with a typical width from 3mm to 8mm and 1.2mm height per layer for a single bead. Other parameters, such as length, corner, surface roughness, mainly depend on design requirements and capabilities of the facility. According to statistical data, the machining allowance is 1-2mm.

Table 4-1 Design parameters of WAAM features for Ti-6Al-4V alloy

Parameters	Wall (Vertical, Inclined, Curve)	Intersection
Welding Process	TIG/GTAW (Recommended)	
Width	Single bead: 3-8mm Multiple bead: ≥8mm	
Height	Single layer: Typical 1.2mm Total height: 50mm (recommended)	
Length	Fanuc robot: Max. 1m; HiVE system: Max. 3m;	
Corner Radius	Bottom radius (recommended): 1mm,3mm	
Surface Roughness	Same as machining process, depends on final milling	
Machining allowance	1-2mm	

4.5 Summary

The required data for a design method for WAAM technology is collected through questionnaire, literature review and semi-structured interviews. The outputs of the analysis are summarized as follows.

- Design method:
    - The design method should be developed by modifying mature existing design models such as Pahl and Beitz's design model, VDI 221 model, BS 7000 design mode.
    - Hybrid design concept is accepted by most engineers in the aircraft industry because of its lower cost.

    - Titanium alloy is the most popular material for WAAM.
    - The main design objectives of aircraft structures are obtained from the survey, and the weighting value of each object is achieved which is useful for establishing an evaluation rule.
- WAAM technology:
    - A feature based design handbook of WAAM is under development. For Ti-6Al-4V alloy, the process for wall and intersection features is technically mature.
    - The mechanical properties of Ti-6Al-4V alloy WAAM features have been summarized.
    - The design parameters of Ti-6Al-4V alloy WAAM features are obtained from a semi-structural interview.

These analysis results are the foundation to realize the research objectives of this thesis. Chapter 5 focuses on the development of a hybrid design method.

5 Design Method Development

5.1 Introduction

The design model of WAAM technology is developed based on existing engineering design models: VDI 2221 model, BS 7000 design model, Pahl and Beitz's design model. This model is restricted to the structure design of the aircraft. An evaluation rule is established to decide the optimum hybrid design. The design objectives and weighting values are set according to the investigation results of the Chinese aircraft industry. Furthermore, a WAAM feature based design guideline is established to help designers create hybrid design solutions.

5.2 Design Model based on WAAM

The main function of the aircraft structure is to transmit forces or loads. The structural designer is expected to achieve this with possible minimum cost and weight (Niu, 2005). Cost savings becomes the critical factor in extremely competitive marker at present. Structure design of a new aircraft commonly experiences following phases (Chief Edition Committee of the Aircraft Design Handbook, 2000):

- Overall concept design: structural concept and layout, weight index, the application plan of new structure, material and process, risk analysis, and structural design principle.
- Preliminary design: structural layout and transmission design, material selection, weight distribution and control, initial drawings, properties analysis, and necessary tests.
- Detail design: product documents, relative tests, and manufacturability examination.

- Preproduction and production: improve the design and drawings, completely technical documents.

The aircraft structure is usually divided into several sections according to their functions, such as fuselage, wing, empennage, undercarriage and pylon. For the structural part design, the foremost thing is to make clear its design objectives and functions for the section. Then, an initial design and final detail design is to be carried out. Therefore, aircraft structure design should include: clarification of the design task, function analysis, preliminary design and detail design. Furthermore, aircraft structure design is a process of continuous iteration and compromise.

The investigation of questionnaire illustrates that it is better to develop the design method for WAAM technology based on mature existing design method. And the literature review summarized the popular engineering design method. The comparisons among these design methods and the desired design method is listed in Table 5-1. All these design models have similar design stages, but they cannot be directly used to guide hybrid design.

Among these models, the VDI 2221-systematic approach to the design of technical systems and products- is a published design guideline which is widely used in various industries (Cross, 2000). It is an iterative design model with clear output for each step. Therefore, the main structure of the VDI 2221 is used to establish the hybrid design model of the aircraft structure design. In addition, the evaluation rule in Pahl and Beitz's design model (Pahl and Beitz, 1984) is applied to develop the evaluation chart in this hybrid design model. Similarly with the BS 7000 design model (Erbuomwan, 1996), a design for hybrid manufacturing concept was added in this hybrid design model. All above makes sure that the developed hybrid design model is appropriate for aircraft structure design and easily to be accepted.

Table 5-1the comparisons among these design methods and the desired design method

Design method	Main features	Disadvantages
Pahl and Beitz's design model	Clarification of the task, conceptual design, embodiment design and detail design	General engineering design model that cannot be used directly for hybrid design in the aircraft structure
VDI 2221model	A model developed by the German association of engineers with seven stages, similar with the Pahl and Beitz's design model	General engineering design model, not suitable for hybrid design, and overly focussed on function analysis
BS 7000 design model	Derive from Pahl and Beitz design model with DFM stage	Too simple, without iterate design concept, not suitable for hybrid design
Nigel Cross's design model	A symmetrical problem-solution model with six stages, three decomposing the overall problem into sub-problems	Not suitable for hybrid design, without iterate design concept
The desired hybrid design model	Include clarification of the task, function analysis, preliminary design, analysis for hybrid and detail design	Limited to the single part design of the aircraft structure

Figure 5-1 shows the established hybrid design model according to the aircraft structure design requirements considering hybrid design concept. It contains four phases:

- Task clarification: Identify design objectives and functions.
- Conceptual design: Identify requirements and constraints, and establish preliminary 3D model.
- Embodiment design: starting from the concept, the optimum hybrid design is decided by evaluation. The output is the feature based 3D model and overall design is defined in this phase.
- Detail design: Formal engineering drawing and relative technical documents are released.

Compared with the VDI 2221model, the step of function analysis was simplified while the “analysis for hybrid design” step was introduced in this design method. The latter is the key step in this design model. An evaluation matrix chart is established in this step. Furthermore, every step in this model is not independent but interactive so as to achieve a step-by-step optimisation. This developed hybrid design model includes 7 steps:

- Step 1-clarify and define the task, establish a Design Objective Tree.
- Step 2-determine the required functions.
- Step 3-summarize the design objectives and functions into detail design requirements.
- Step 4-preliminary design including structure layout, material selection and properties analysis, etc.
- Step 5-create proposed hybrid design solutions, and then assess them using the evaluation matrix chart to achieve best design.
- Step 6-design for hybrid manufacturing, build the feature based 3D model.
- Step 7-complete final product documents.

The following sections describe the development of the hybrid design model step-by-step as well as the introductions.

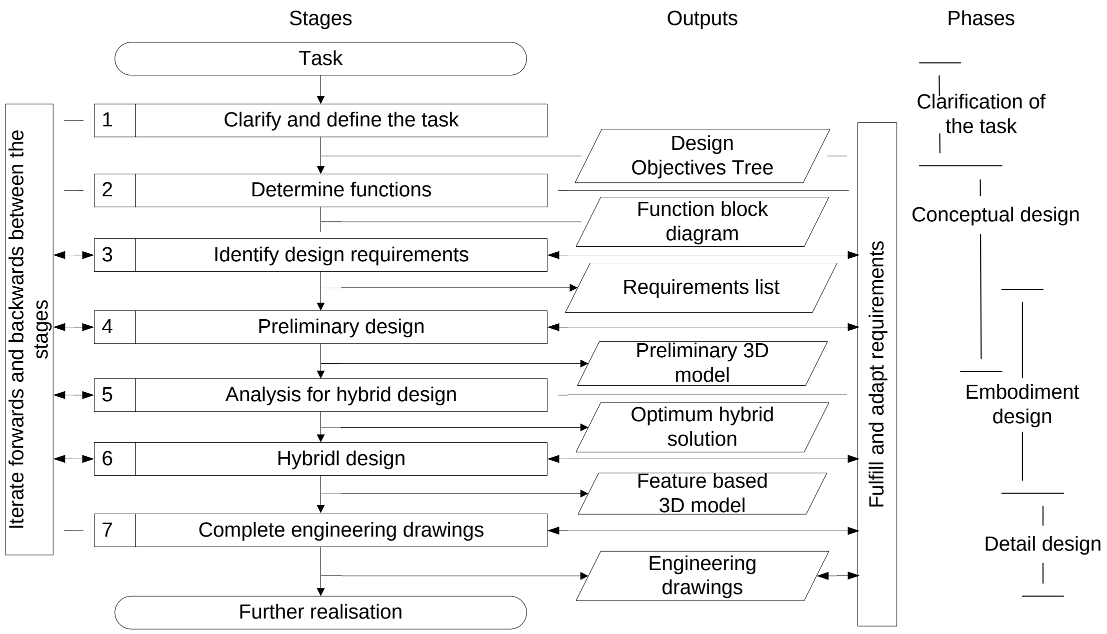


Figure 5-1 Hybrid design model based on WAAM technology

5.2.1 Clarify and define the task (step 1)

Step 1-Clarifying the design objective- is clearly the most important first step in the process. The objectives tree method is a popular approach which provides a helpful and clear formal statement of objectives. It shows the objectives systematically a diagrammatic form, which makes it easier to reach agreement between clients and designers. Figure 5-2 illustrates the procedure of the Design Objectives Tree Method.

Figure 5-2 The procedure of Objectives Tree Method

5.2.1.1 Prepare a list of design objectives

The list of design objectives are obtained from the design brief. For aircraft structure design, the main objectives are: strength properties, structure and cost. The sub-objectives of these three objectives should become increasingly specific and clear through technical negotiations or meetings.

5.2.1.2 Identify the importance degree of objective

In all listed design objectives, some objectives must be satisfied, and the others are expected to be achieved as best as possible. Therefore, it is necessary to list the principle objects at first to make the designers clear about the main design task. Actually, the principle objectives of aircraft structure design are usually related to strength properties and functions.

5.2.1.3 Draw a diagrammatic

The diagrammatic tree presents hierarchical and relationships and interconnections. Figure 5-3 shows the hierarchical diagram of relationships between objectives.

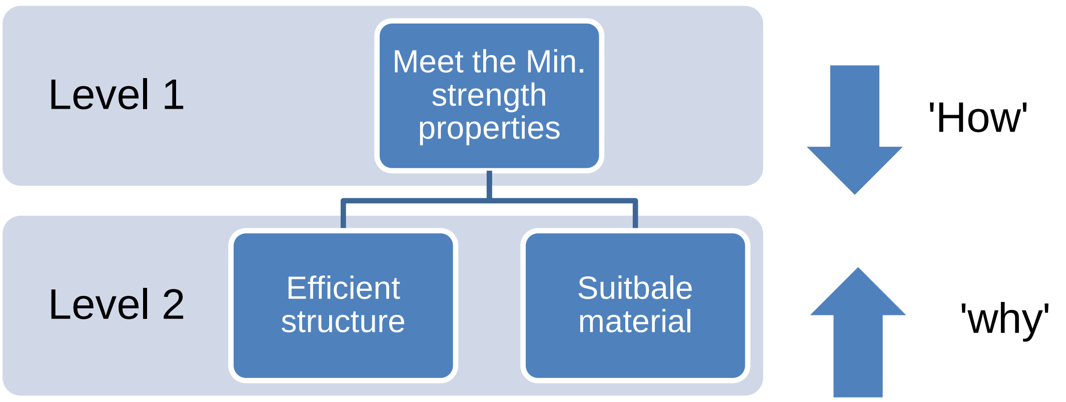


Figure 5-3 The hierarchical diagram of relationships between objectives

5.2.2 Determine functions (step 2)

Step 2 is function analysis. An important rule to assess the success of design is the fulfilment of function. The aim of function analysis is to establish the required functions of a new design. Figure 5-4 shows the procedure of the Function Analysis method.

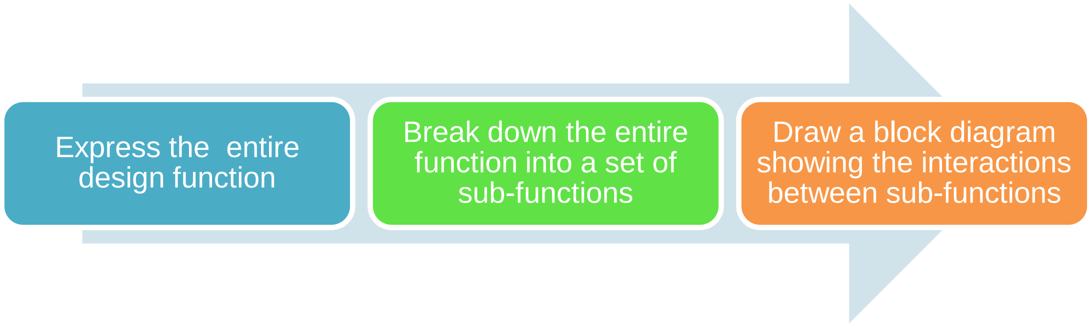


Figure 5-4 The procedure of Function Analysis method

The starting point for this method is to focus on what has to be achieved by a particular design. For a complex part, the entire function is necessarily divided into sub-functions in some cases and formalised into a block diagram to make it clear.

5.2.3 Identify design requirements (step 3)

Statements of objectives and functions show what a design must achieve, but they are not set in terms of precise limits. It is advisable to combine them into a requirements list to define the design requirements. In setting design requirements, the main task is to establish an accurate performance specification. Figure 5-5 illustrates the recommended general method of compiling a requirements list (Pahl and Beitz, 1999). The most important point to notice is that the requirements list is a "living" document. It needs to be modified through the entire design.

Herein, "D" means Demands which must be achieved under all circumstances. Similarly, "W" means Wishes which should be taken into consideration whenever possible. In addition, quantity and quality in this list is defined as:

Quantity: data including numbers and magnitudes, such as weight, length and volume.

Quality: data including permissible variations or special requirements such as corrosion proof, temperature proof.

User		Requirements list for project. product	Issued on: Page:
Changes	D W	Requirements	Responsible
Date of change	Specify Whether item is D or W	Objective or Property with quantitative and qualitative data	Design group responsible
		Replaces issue of	

Figure 5-5 The layout of a requirements list (Pahl and Beitz, 1999)

5.2.4 Preliminary design (step 4)

Step 4-preliminary design-starts from the requirements list. Figure 5-6 presents the flow chart of the preliminary design. All design requirements should be implemented into specific aspects: loads, material section, configuration layout, connection definition, corrosion protection, etc. The preliminary 3D model is established according to these aspects as well as layout coordination with other relative structures and systems. It is an iterative process to obtain the definite design.

Generally, the Finite Element Analysis (FEA) method is used to check the performance of a design. Also, the part should be checked to ensure the satisfaction of the requirements list.

Moreover, the preferred manufacturing process is selected initially in this step, which is the basis for the following hybrid analysis.

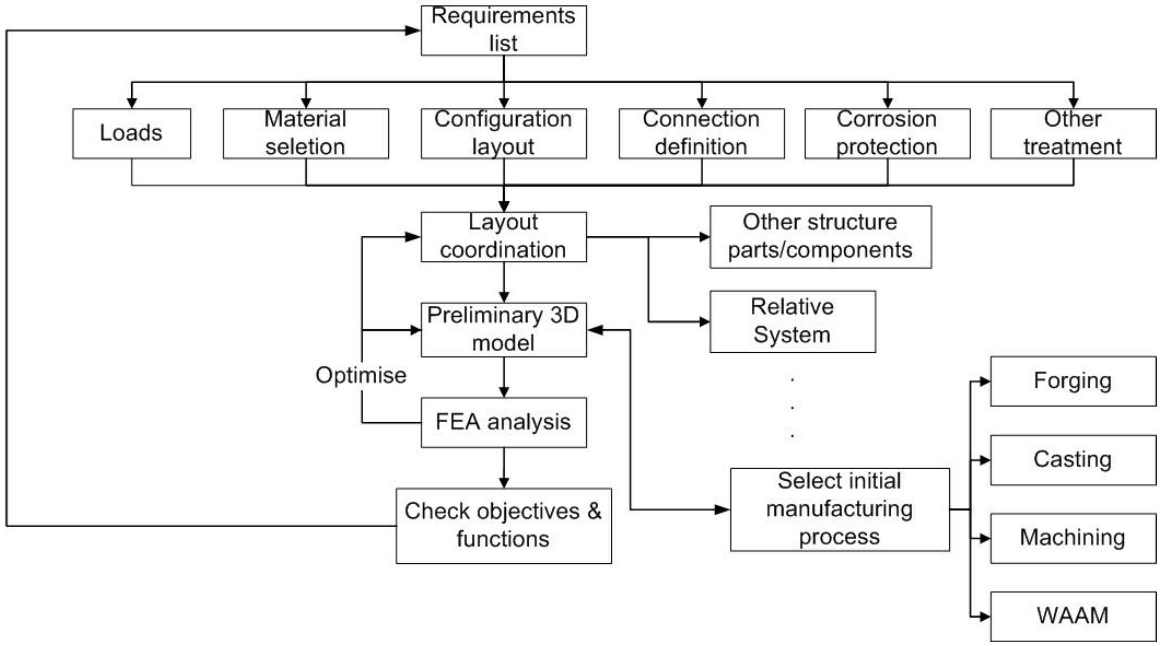


Figure 5-6 Flow chart of the preliminary design

5.2.5 Analysis for hybrid design (step 5)

Step 5 is the key to the design method which based on the preliminary design. Figure 5-7 illustrates the schematic of feature based analysis for the manufacturing process. The proposed hybrid design solutions are created according to the performance analysis as well as WAAM feature based design guideline. If necessary, optimisation, such as topology optimisation, topography optimization, can be used to create the proposed hybrid design solution. Then, the cost of each solution is to be estimated to support followed evaluation. Next, all the proposed hybrid design solutions and the preliminary design are assessed by using the developed evaluation matrix chart. Finally, the optimum hybrid design is identified according to the result of assessment.

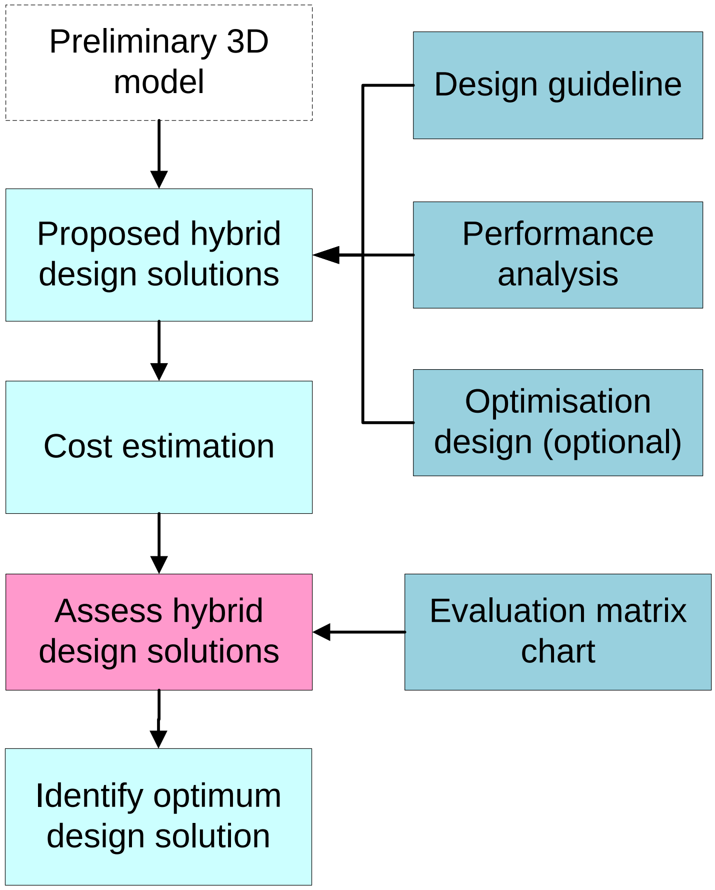


Figure 5-7 The flow chart for analysis for hybrid design solution

The following content explains how to establish the evaluation chart step by step.

5.2.5.1 Evaluation rule

In the hybrid design based WAAM technology concept, a part can be divided into several features partly made by conventional manufacturing processes, partly added by WAAM. It is not easy to decompose the features of an object and develop appropriate hybrid design solutions. The decision to select a hybrid design solution is usually affected by a number of possible variants (e.g. performance, cost, manufacturing time). Designers with different backgrounds may reach inconformity to manufacturing process. In addition, it is very hard for a designer to draw a decision after considering all the design objectives. Therefore, it is necessary to set up an evaluation rule to guide designers to create suitable hybrid design solutions and achieve the optimum design. In the following the Selection and Evaluation Method is used in this research (Pahl and Beitz, 1999).

5.2.5.1.1 Solution variants

The solution variants (V_i) are defined as proposed hybrid designs in this research. Designers are required to determine the hybrid design solutions based on the preliminary design according to a performance analysis and the WAAM feature base design guideline. The solutions developed in this stage will be evaluated to select the optimum.

5.2.5.1.2 Evaluating variants

An evaluation determines the “strength”, “usefulness” and “value” of a given objective. The evaluated variants in this research are defined as “Design Objectives”. An ideal evaluation is expected to consider all aspects in the aircraft structure design. In this research, the evaluation variants were obtained and summarized from the questionnaire and semi-structural interviews, as follows:

- **Performance:** strength properties, functions, etc.
- **Technical complexity:** manufacturing difficulty.
- **Weight:** The weight of the product.
- **Cost:** The total cost including material, manufacturing, etc.
- **Manufacturing time:** Lead time which can be obtained from the suppliers (the time interval between the initiation and the completion of a production process).

5.2.5.1.3 Weighing Evaluation

To set up evaluation criteria, the selected objectives must be assessed on their contribution to the whole value of the solution. After that, each objective is given a “weighing factor”, which presents the degree of importance of the objective. In this research, the weighting value of each objective is obtained and calculated by a questionnaire.

Figure 5-8 shows the procedure of decomposing weighting factors. The sum of all weighting values must be equal to 1.

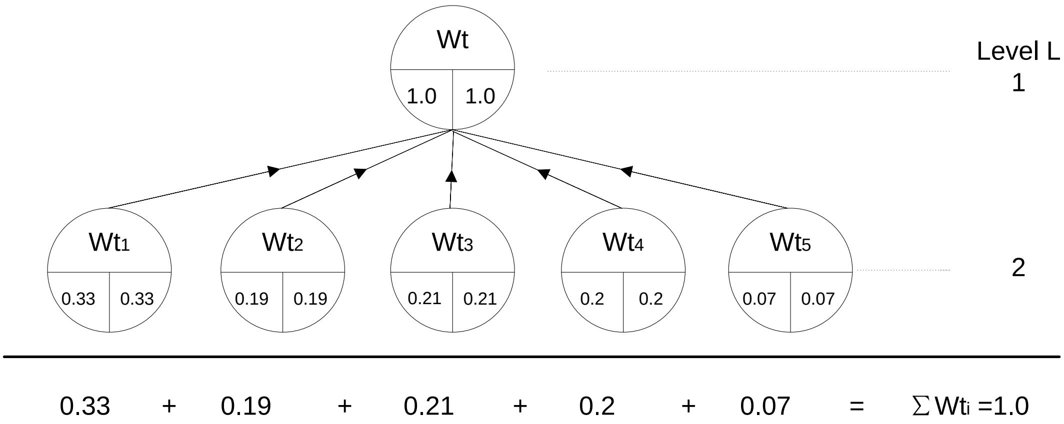


Figure 5-8 Evaluation variants tree with weighting value

5.2.5.1.4 Compiling evaluation chart

The solution variants and evaluation variants are compiled in a matrix chart, (as shown in Figure 5-9).

Evaluation Criteria			Variant V_1 (Preliminary)		Variant V_2 (Proposed Hybrid design 1)		Variant V_3 (Proposed Hybrid design 2)		Variant V_n (Proposed Hybrid design n)	
			Value	Weighted value	Value	Weighted value	Value	Weighted value	Value	Weighted value
No.	Objectives	Wt.	V_{i1}	WV_{i1}	V_{i2}	WV_{i2}	V_{i3}	WV_{i3}	V_{in}	WV_{in}
1	Performance	0.33								
2	Technical complexity	0.19								
3	Weight	0.21								
4	Cost	0.20								
5	Manufacturing time	0.07								
		$\sum_{i=1}^{5} W_i = 1$	V_1 R_1	OWV_1 WR_1	V_2 R_2	OWV_2 WR_2	V_3 R_3	OWV_3 WR_3	V_n R_n	OWV_n WR_n

Figure 5-9 The evaluation matrix chart

5.2.5.1.5 Assessing values

The assessing value scale is presented in Table 5-2. The scale of "performance" is different with other objectives because aircraft structure design must fully meet the performance requirement without any compromise.

In Advisory Circular (AC) No. 25.571-1D (2011) of the Federal Aviation Administration, "principal structural element (PSE)" is emphasized and defined as follow:

"Principal structural element, PSE, is an element that contributes significantly to the carrying of flight, ground, or pressurization loads, and whose integrity is essential in maintaining the overall integrity of the airplane."

(Federal Aviation Administration, 2011)

In the Chinese aircraft industry, the Margin of Safety (MS) value of the PSE is require to be greater than 0.15. For Ti alloy, the mechanical properties of WAAM features are close to machining features. WAAM is a new manufacturing process with no track record in the Chinese aircraft industry. Therefore, WAAM using on PSE defines "low risk" in this research to make sure safety of the design.

The values V_{ij} of each solution should be decided by the designer and entered in the evaluation chart (see Figure 5-9).

For each solution variant, WV_{ij} is calculated by multiplying the sub-value V_{ij} and the weighting factor W_i:

$$WV_{ij} = V_{ij} \times W_i$$

Equation 5-1 Calculation of the weighted value of each objective

5.2.5.1.6 Determining the overall value

After the values of V_{ij} and WV_{ij} have been determined, the overall value of each solution j is calculated.

Un-weighted:

$$OV_j = \sum_{i=1}^{5} V_{ij}$$

Equation 5-2 Calculation of the sum of un-weighted value

Weighted:

$$OWV_j = \sum_{i=1}^{5} W_i \cdot V_{ij} = \sum_{i=1}^{5} WV_{ij}$$

Equation 5-3 Calculation of the sum of weighted value

Table 5-2 Points awarded for evaluation analysis

	Assessing Value Scale		
Objectives	Points	Meaning	Remarks
(1) Performance	0	Useless solution	MS＜0 (for PSE, MS＜ 0.15) or function is unsatisfied
	7	Good solution with low risk	MS＞0.15 and function is satisfied (only for WAAM using on PSE)
	10	Good solution	MS＞0 (for PSE, MS＞ 0.15) and function is satisfied
(2)Technical complexity (3) Material cost (4)Manufacturing time (5)Manufacturing cost	0	Absolutely useless solution	-
	1	Very inadequate solution	-
	2	Weak solution	-
	3	Tolerable solution	-
	4	Adequate solution	-
	5	Satisfactory solution	-
	6	Good solution with few drawbacks	-
	7	Good solution	-
	8	Very good solution	-
	9	Solution exceeding the requirement	-
	10	Ideal solution	-

5.2.5.1.7 Comparing solution variants

Due to the summation rule, the following two methods are used to assess solution variants.

- Determining the maximum overall value: that variant is judged best which has the maximum overall value:

$$\mathbf{OV_j \rightarrow max} \text{ or } \mathbf{OWV_j \rightarrow max}$$

- Determining the rating value: if above OV_j and OWV_j is insufficient to decide the best solution, then the rating value has to be calculated.

Un-weighted:

$$\mathbf{R_j = \frac{OV_j}{V_{max} \cdot n} = \frac{\sum_{i=1}^{5} V_{ij}}{V_{max} \cdot n}}$$

Equation 5-4 Calculation of the un-weighted value

Weighted:

$$\mathbf{WR_j = \frac{OWV_j}{V_{max} \cdot \sum_{5}^{i=1} W_i} = \frac{\sum_{i=1}^{5} W_i \cdot V_{ij}}{V_{max} \cdot \sum_{i=1}^{5} W_i}}$$

Equation 5-5 Calculation of the weighted value

5.2.6 Hybrid design (Step 6)

Step 6-hybrid design-is to establish the feature based 3D models. Hybrid design is developed from the Design For Manufacturing (DFM) concept. Figure 5-10 shows the concept of hybrid design. In this research, it contains design for forging, casting, machining and for WAAM. In addition, FEA is applied to check the performance of the hybrid design.

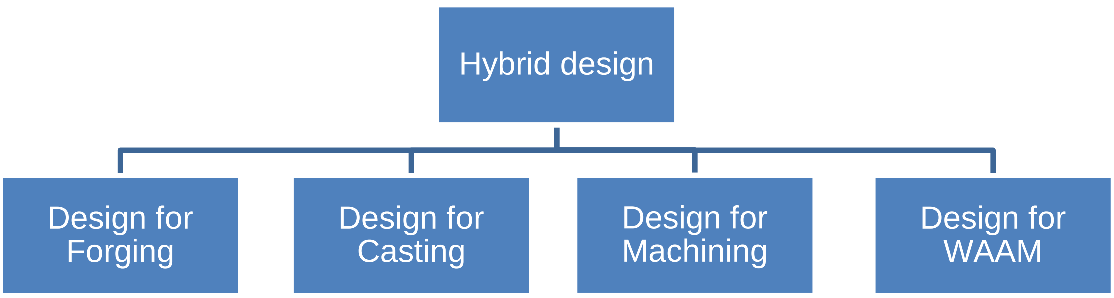


Figure 5-10 The concept of hybrid design

5.2.7 Complete engineering drawings (step 7)

The final step in this design model is to complete engineering drawings for production. The style of engineering drawings depends on the requirements of the industry standard. However, the most important and common thing is that the engineering drawings must be complete. As the only basis for manufacturing, they must cover the all technical data and requirements.

5.3 WAAM Feature based Design Guideline

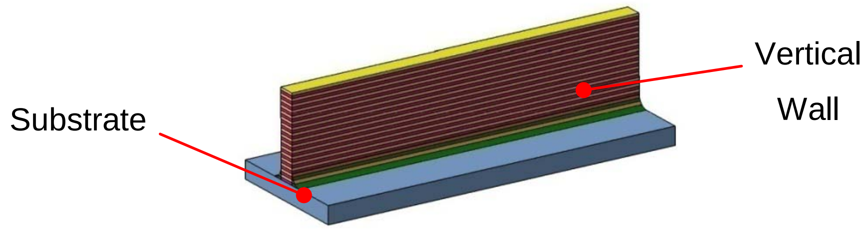
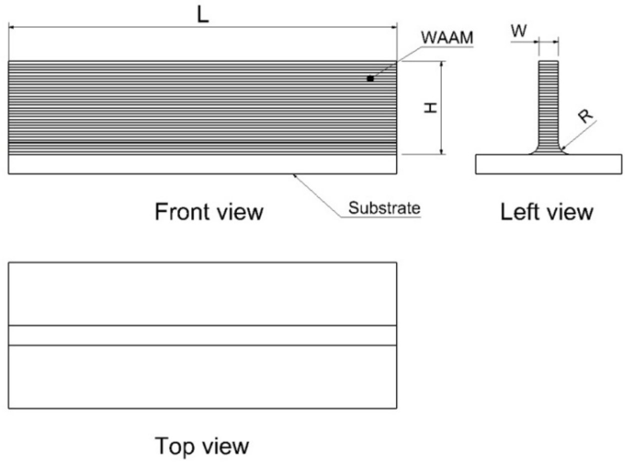
The WAAM feature based design guideline aims to help the designer to create proposed hybrid design solutions and build the feature based 3D model. This design guideline includes three aspects: Ti alloy WAAM features, recommended design approach and design consideration.

5.3.1 Ti alloy WAAM features

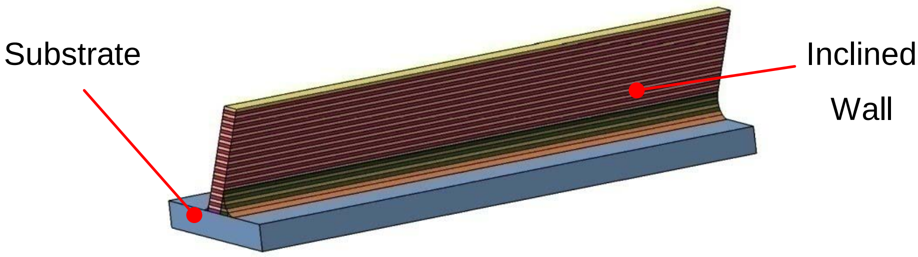
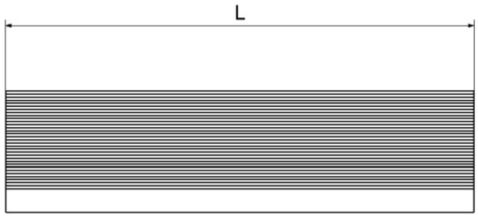
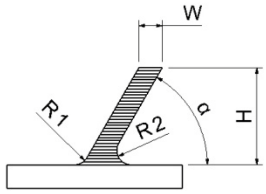
As the above analysis indicated, this research should focus on Ti alloy parts. The developed Ti alloy features are walls-vertical, inclined, and curved- and intersection.

5.3.1.1 Wall features

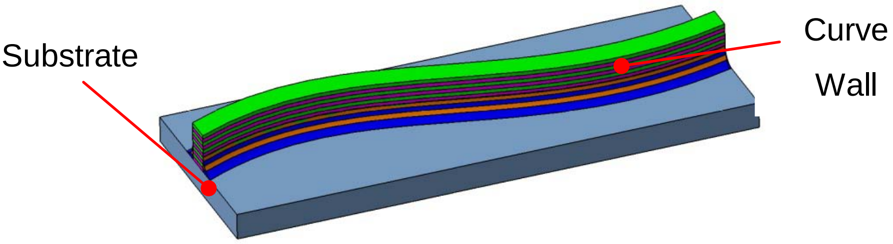
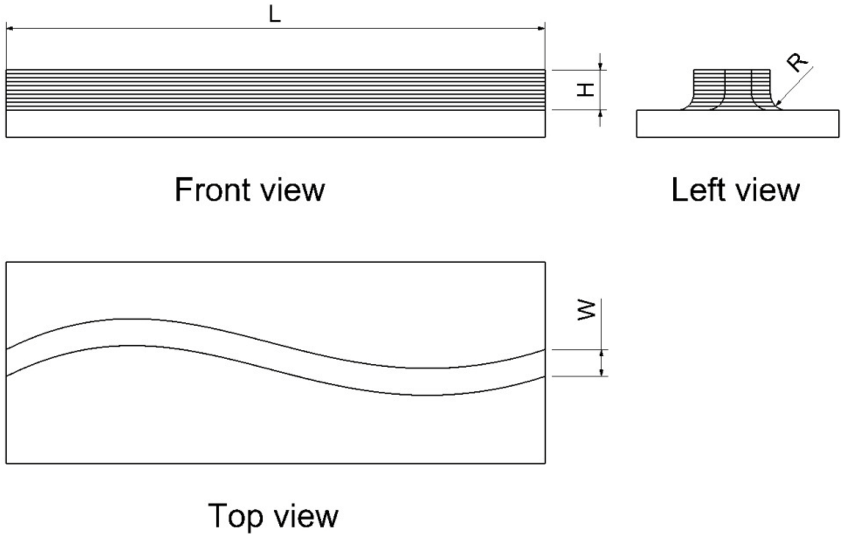
Figure 5-11 shows the design parameters of WAAM wall features. It covers 3D model, three view drawing, basic design parameters, material and welding process.

Vertical Wall				
3D Model				
Three View Drawing				
Basic Design Parameters	W, mm	H, mm	L, mm	R, mm
	Single bead: 3-8mm Multiple bead: ＞8mm	Recommended: 50mm	Fanuc robot: Max. 1m; HiVE system: Max. 3m	Recommended: 1mm, 3mm
Material	Ti-6Al-4V			
Welding Process	GTAW: Gas Tungsten Arc Welding (Recommended) GMAW: Gas Metal Arc Welding			

(a)

Inclined Wall						
3D Model						
Three View Drawing	 Front view  Left view  Top view					
Basic Design Parameters	W, mm	H, mm	L, mm	R1, mm	R2, mm	α
	Single bead: 3-8mm; Multiple bead: ＞8mm	Recommended: 50mm	Fanuc robot: Max. 1m; HiVE system: Max. 3m	Recommended: 1mm, 3mm		From 15° to 90°
Material	Ti-6Al-4V					
Welding Process	GTAW: Gas Tungsten Arc Welding (Recommended) GMAW: Gas Metal Arc Welding					

(b)

Curve Wall				
3D Model				
Three View Drawing				
Basic Design Parameters	W, mm	H, mm	L, mm	R, mm
	Single bead: 3-8mm; Multiple bead: ＞8mm	Recommended: 50mm	Fanuc robot: Max. 1m; HiVE system: Max. 3m	Recommended: 1mm, 3mm
Material	Ti-6Al-4V			
Welding Process	GTAW: Gas Tungsten Arc Welding (Recommended) GMAW: Gas Metal Arc Welding			

(c)

Figure 5-11 Design parameters of WAAM wall features: (a) Vertical wall; (b) Inclined wall; (c) Curve wall

5.3.1.2 Intersection feature

Figure 5-12 presents the design parameters of a WAAM intersection feature. Actually, an intersection is a variant of the wall feature. However, WAAM intersections need special consideration as joining of walls is not straight forward due to various technical reasons (e.g. avoiding of material accumulation at the cross point, sharp corners, etc.).

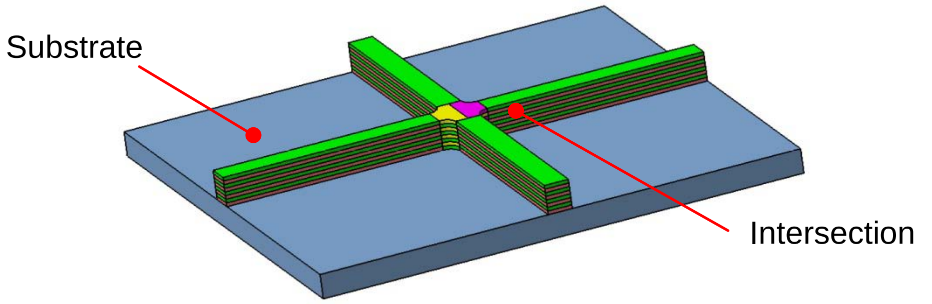
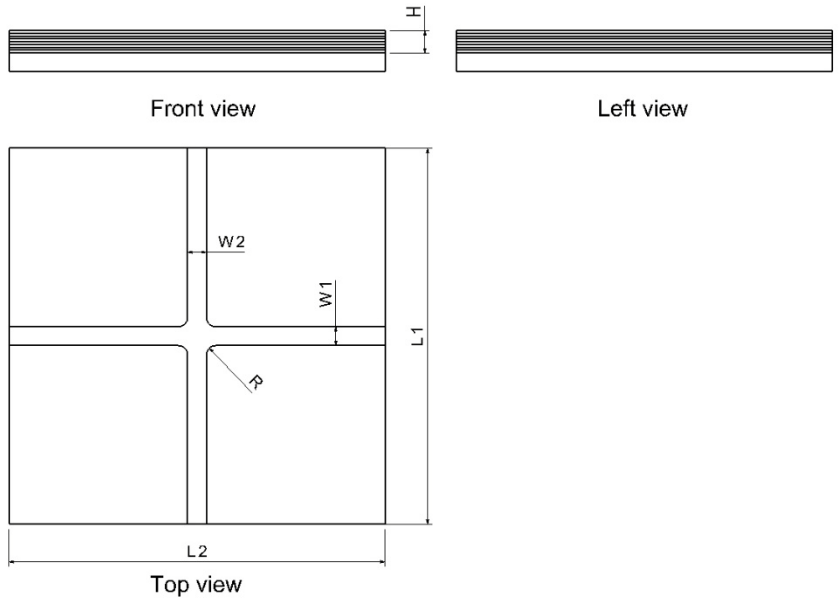
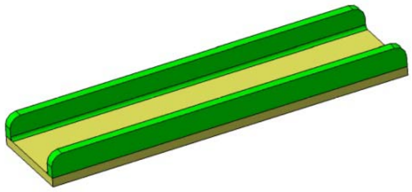
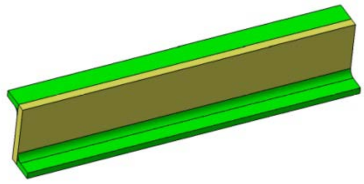
<table>
<tr><th colspan="7">Intersection</th></tr>
<tr><td>3D Model</td><td colspan="6">
</td></tr>
<tr><td>Three View Drawing</td><td colspan="6">
</td></tr>
<tr><td rowspan="2">Design Parameters</td><td>W1, mm</td><td>W2,mm</td><td>H, mm</td><td>L1, m</td><td>L2,m</td><td>R, mm</td></tr>
<tr><td colspan="2">Single bead: 3-8mm
Multiple bead: ＞8mm</td><td>Recommended: 50mm</td><td colspan="2">Fanuc robot: Max. 1m;
HiVE system: Max. 3m</td><td>Recommended: 1mm, 3mm</td></tr>
<tr><td>Material</td><td colspan="6">Ti-6Al-4V</td></tr>
<tr><td>Welding Process</td><td colspan="6">GTAW: Gas Tungsten Arc Welding (Recommended)
GMAW: Gas Metal Arc Welding</td></tr>
</table>

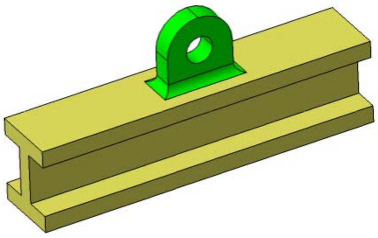
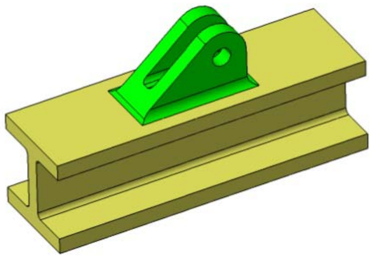
Figure 5-12 Design parameters of WAMM intersection features

5.3.2 Recommended design approach

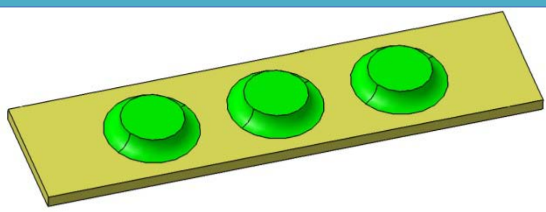
Hybrid design is a design concept where WAAM parts are combined with prefabricated parts. There are several recommended design ideas for hybrid design based on WAAM features (as shown in Figure 5-13).

Flange		
Examples	 “C” Type	 “Z” type
Design Method	Conventional design	Hybrid design
	• Machining • Extrusion	• Green part: WAMM • Yellow part: conventional process
WAMM Feature	–	• Vertical wall • Inclined wall • Curve wall

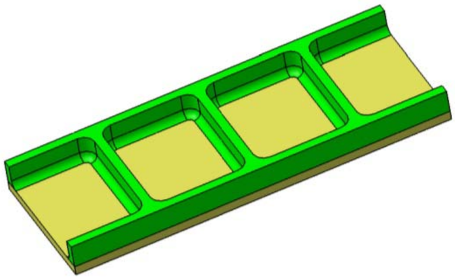
(a)

Lug		
Examples	 Single Lug	 Double Lug
Design method	Conventional design	Hybrid design
	• Machining • Casting • Forging	• Green part: WAMM • Yellow part: conventional process
WAMM Feature	–	• Vertical wall • Inclined wall

(b)

Lug boss		
Example	 columnar lug boss	
Design method	Conventional design	Hybrid design
	• Machining • Casting • Forging	• Green part: WAMM • Yellow part: conventional process
WAMM Feature	–	• Vertical wall • Curve wall

(c)

<table>
<tr><th colspan="3">Stiffener & Rib</th></tr>
<tr><td>Example</td><td colspan="2">
Stiffener</td></tr>
<tr><td rowspan="2">Design method</td><td>Conventional design</td><td>Hybrid design</td></tr>
<tr><td>• Machining
• Casting
• Forging</td><td>• Green part: WAMM
• Yellow part: conventional process</td></tr>
<tr><td>WAMM Feature</td><td>–</td><td>• Vertical wall
• Inclined wall
• Curve wall
• Intersection</td></tr>
</table>

(d)

Figure 5-13 Recommended design ideas for hybrid design based on WAAM features: (a) Flange; (b) Lug; (c) Lug boss; (d) Stiffener & Rib

5.3.3 Design consideration

In civil aircraft structure design, the safety coefficient of 1.5 must be applied to limit load unless otherwise specified. Detail rules are as follows (Niu, 2005):

- Ultimate load=1.5×limit load.
- Support ultimate loads without failure.
- Support limit loads without detrimental permanent deformation.

The Margin of safety (MS) of a structure is required to equal to zero or greater. Following state the calculation steps to meet airworthiness requirements:

a) First step-under the ultimate load case:

$$\mathbf{MS}_{(\mathbf{x})} = \frac{\mathbf{F}}{\mathbf{f}} - \mathbf{1} \geq \mathbf{0}$$

Equation 5-6 Calculation of the MS under ultimate load (Niu, 2005)

Where: F- allowable stress (F), moment (M), load (P), etc.

f- applied ultimate stress (f), moment (m), load (p), etc.

(x)- Critical condition, i.e.: tension, compression, shear, buckling, bearing, fastener, etc.

b) Second step-check material yield conditions:

$$\mathbf{MS}_{(\mathbf{yield})} = \frac{\mathbf{F}_{\mathbf{yield}}}{\mathbf{f}_{\mathbf{limit}}} - \mathbf{1} \geq \mathbf{0}$$

Equation 5-7 Calculation of the MS under material yield (Niu, 2005)

where: F_{yield}- allowable stress (F), moment (M), load (P), etc.

f_{limit}- applied limit stress (f), moment (m), load (p), etc.

c) Third step-the final MS is the smaller MS from either a) or b)

5.4 Summary

This chapter introduces the development of a hybrid design method based on WAAM technology consisting of a design model and guideline. The design model is developed by modifying existing mature design models which is used to guide designers to create hybrid design solutions step-by-step and achieve final optimum hybrid design solution. The whole design process was divided into seven steps. An evaluation matrix chart was compiled to assess the proposed hybrid design solutions.

Furthermore, design parameters of WAAM process of Ti-6Al-4V alloy were summarized as a WAAM feature based design guideline. The guideline includes design parameters of wall and intersection features, recommended hybrid design approaches and design consideration. It aims to help designers decompose the features of an object and create suitable hybrid design solutions.

6 Case study and Validation

6.1 Introduction

In the last chapter, a hybrid design method has been established for WAAM technology. In this chapter, three case studies were carried out to test and verify the developed design method. Furthermore, validation was done by academic and industrial experts.

6.2 Integral Panel

The integral panel is widely used in aircraft design. An experimental design was implemented to test the design model and guideline as well as to learn the design method of the integral panel.

6.2.1 Clarify and define the task

The task is to design an elastic panel with unflanged integral stiffeners. The panel is to be 1000 mm square that is made of Ti-6Al-4V alloy. The following dimensional restrictions should be met: height (h) ⩽50mm, stiffener pitch (b)⩾ 100mm, thickness of stiffener (t_s)⩽8mm ,thickness of skin (t)⩾3 (as shown in Figure 6-1). These constrains are set up according to the recommended design parameters in WAAM feature based design guideline.

The applied load is 2MN which is simply supported on all four sides. The design objective is to achieve less weight and cost. Figure 6-2 shows the Design Objectives Tree of this integral panel.

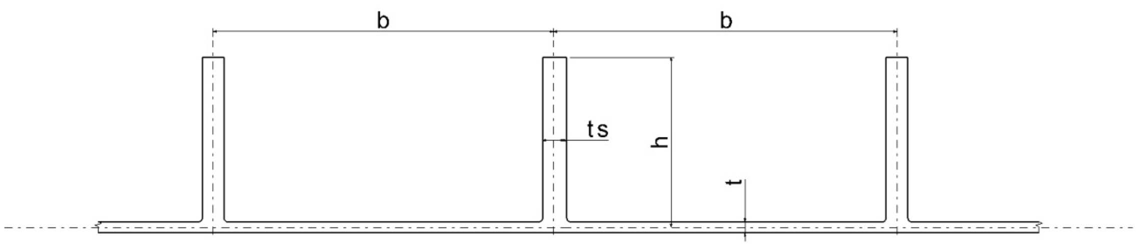


Figure 6-1 Design parameters of integral panel

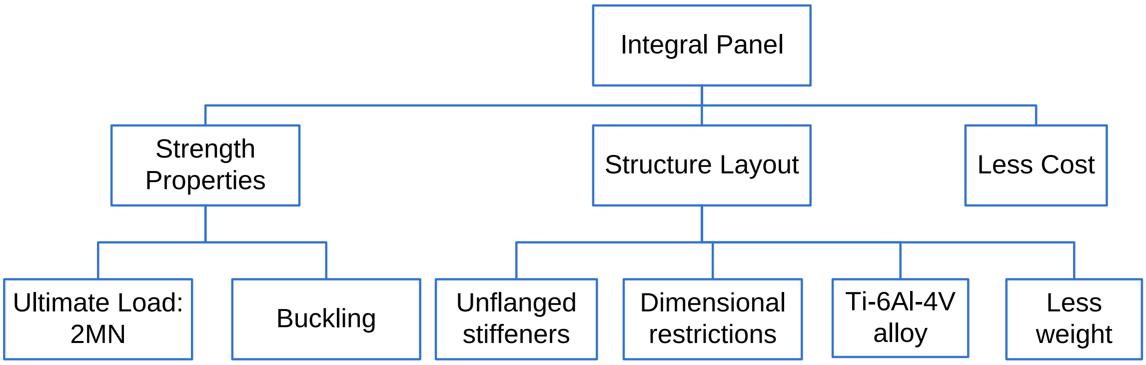


Figure 6-2 Design Objectives Tree of the integral panel

6.2.2 Determine functions

The function of the integral panel is to withstand compression load and seal the internal structure (as shown in Figure 6-3). It is mainly decided by the skin thickness, and stiffener geometry such as thickness, height and pitch.

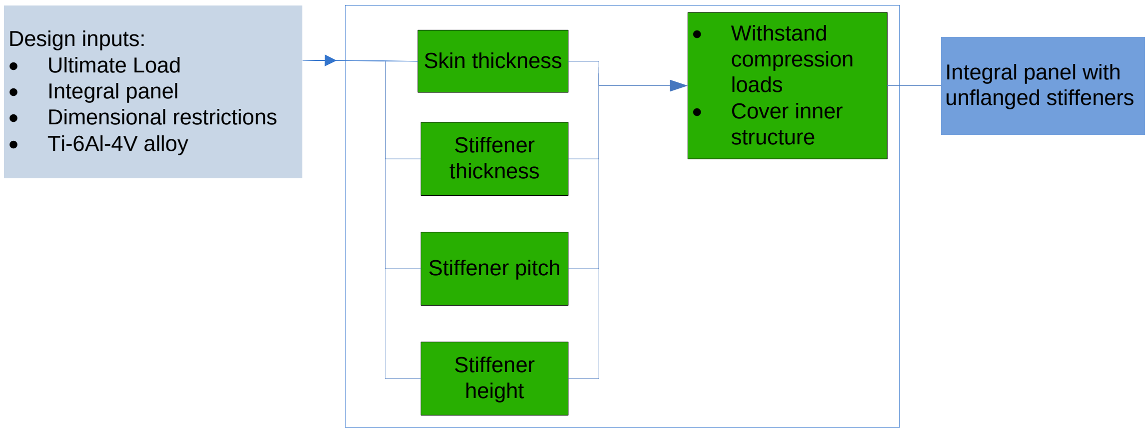


Figure 6-3 Function analysis of the integral panel

6.2.3 Identify design requirements

Design requirements list is shown in Figure 6-4. It covers structure layout, tolerance, weight, strength, material and cost.

		Requirements list for Pylon bottom beam	Issued on:10/09/2012 Page:2
Changes	D W	Requirements	Responsible
10.09.12	 D D	1. Structure layout: ● integral panel with unflanged stiffeners ● dimensional restrictions: h≤50mm, b≥100mm, t_s≤8mm , t≥3 ● cover inner structure	JIAN CHEN
	D	2. Tolerance: ● surface tolerance=Ra 3.2	
	D W	3. Weight: ● weight ≤28kg ● control the weight below 27kg	
	D D	4. Strength: ● withstand compression load ● ultimate Load=2000000N ● no buckling	
	D	5. Material ● Ti-6Al-4V alloy	
	W W	6. Cost: ● low manufacturing cost ● high material utilization	
		Replaces issue of	

Figure 6-4 Requirements list of the integral panel

6.2.4 Preliminary design

This integral panel is designed according to ESDU 70007 which meets the dimension constrains with least weight. Table 6-1 has been compiled to show the calculation process. It typically contains 10 steps. Figure 6-5 has been constructed from Table 6-1. The restriction h≤50mm is introduced. The maximum f is 317 MN/m^2 (317MPa) within this range. The panel dimensions are b=100mm, t=3.2mm, t_s=6.3mm and h=50mm (as shown in Figure 6-6).

The panel cross-sectional area per unit width is:

$$\frac{0.0032 \times 0.100 + 0.0063 \times 0.05}{0.1} = 0.00635\text{m}^2/\text{m}$$

Checking the panel stress, $\text{f} = \frac{2}{0.00635}$ =315M/N^2 (MPa)

Based on the above, the 3D model is built by using CATIA V5 R20 for the machining process (as shown in Figure 6-7). It is made of Ti-6Al-4V alloy and the weight of this part is 26.344kg. Figure 6-8 shows the Finite Element Model and Figure 6-9 illustrates the VonMise stress distribution nephogram. It can be seen that the maximum stress is 486.8 MPa.

Using Equation (5-7) and Equation (5-8) calculate the MS value :

$$\text{MS}_{(\text{ultimate load})} = \frac{\text{F}}{\text{f}} - 1 = \frac{896.35}{486.8} - 1 = 0.84 > 0$$

$$\text{MS}_{(\text{yield})} = \frac{\text{F}_{\text{yield}}}{\text{f}_{\text{limit}}} - 1 = \frac{786 \times 1.5}{486.8} - 1 = 1.42 > 0$$

Herein, F=896.35MPa, F_{yield}= 813.61MPa (Richard et al., 2003) and safe coefficient is 1.5.

Therefore, MS=0.84. The preliminary design is proven to meet the strength properties. Furthermore, it fulfils the requirements of function.

Table 6-1 Results of the calculation process

		f/f_L	f/f_E	f_{0e}	t_{0e}	t_{s0}	b_0	h_0	T≥	B≥	Highest F	f	Ts	H	B	T	t_{se}	h_e	t_e	b_e
Case (a) $f=f_E \le f_L$	Step No.			(ii)					(iii)		(iv)									
	(i)	1.0	1.0	336	2.5	5.6	110.4	68.7	1.203	0.906	0.9875	332	1	1.01	1.1	1.203	5.6	69.3	3.0	121.4
	(v)	0.6	1.0	336	2.5	5.6	85.5	53.2	1.203	1.170	0.987	332	1.065	1.005	1.17	1.203	5.9	53.4	3.0	100.0
	(vi)	0.9	1.0	336	2.5	5.6	104.7	65.1	1.203	0.955	0.9875	332	1	1.01	1.1	1.203	5.6	65.8	3.0	115.2
		0.8	1.0	336	2.5	5.6	98.7	61.4	1.203	1.013	0.9875	332	1	1.01	1.1	1.203	5.6	62.0	3.0	108.6
		0.7	1.0	336	2.5	5.6	92.4	57.4	1.203	1.083	0.9875	332	1	1.01	1.1	1.203	5.6	58.0	3.0	101.6
	Step No.								(vii)		(ix)									
	(vii)	0.5	1.0	336	2.5	5.6	78.1	48.6	1.203	1.281	0.902	303	1.18	0.984	1.281	1.4	6.6	47.8	3.5	100.0
	(x)	0.4	1.0	336	2.5	5.6	69.8	43.4	1.203	1.433	0.8125	273	1.48	0.94	1.433	1.6	8.3	40.8	4.0	100.0
Case (b) $f=f_L \le f_E$	Step No.			(ii)					(iii)		(iii) and (iv)									
	(ii)	1.0	0.8	336	2.5	5.6	110.4	68.7	1.203	0.906	0.936	315	1.06	1.095	1.115	1.203	5.9	75.2	3.0	123.1
	(iv)	1.0	0.6	336	2.5	5.6	110.4	68.7	1.203	0.906	0.875	294	1.14	1.213	1.26	1.203	6.4	83.3	3.0	139.1
		1.0	0.4	336	2.5	5.6	110.4	68.7	1.203	0.906	0.795	267	1.23	1.41	1.3	1.203	6.9	96.8	3.0	143.5
															Restriction are		$t_s \le 8$	h≤50	t≥3	b≥100

f-average compressive stress in panel failure, N/m^2 (Pa)

f_E-overall buckling stress of panel, N/m^2 (Pa)

f_L-local buckling stress of panel, N/m^2 (Pa)

0-suffix added to b, f, h, t and t_s when they relate to panel of least weight having no dimensional restrictions

e-suffix added to b, f, f_L, f_E, h, t and t_s indicating that they are calculated on assumption that panel is elastic

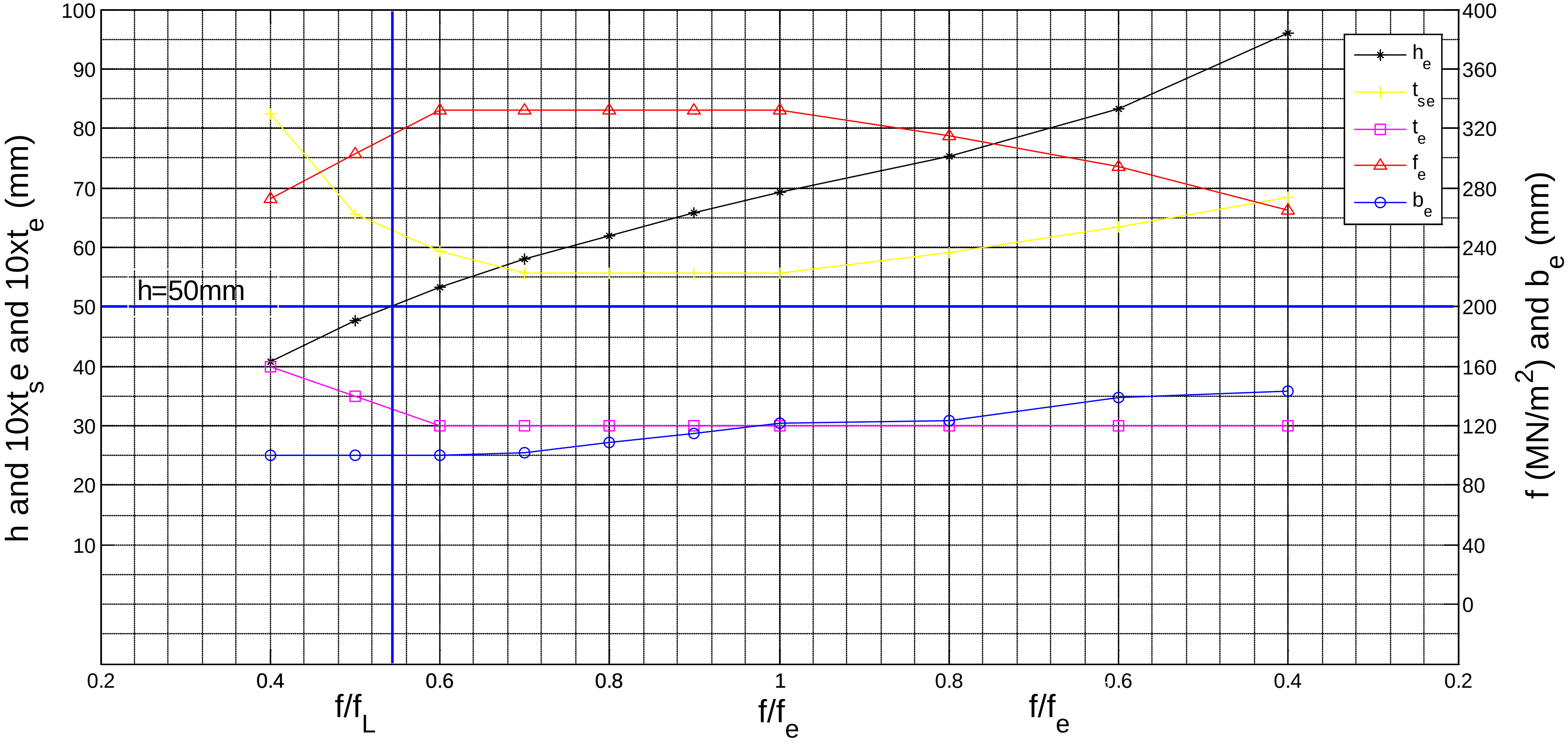


Figure 6-5 Curves of f_e, b_e, h_e, t_{se} and t_e

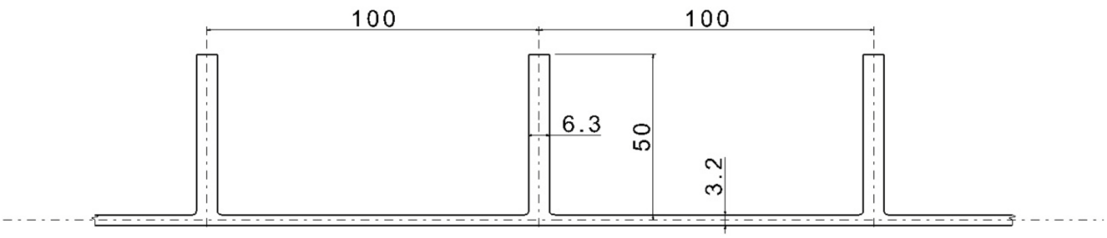


Figure 6-6 the dimensions of the integral panel

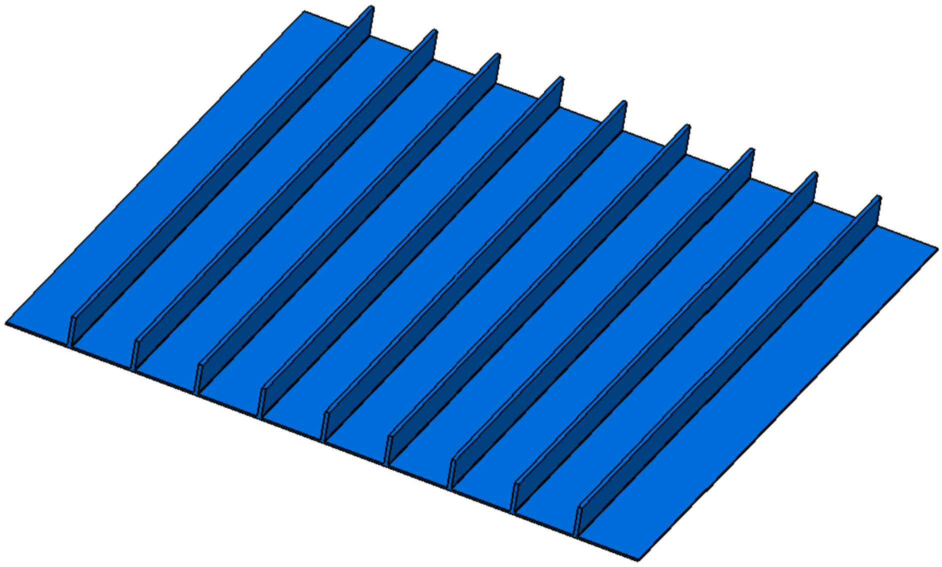


Figure 6-7 3D model of the integral panel for machining

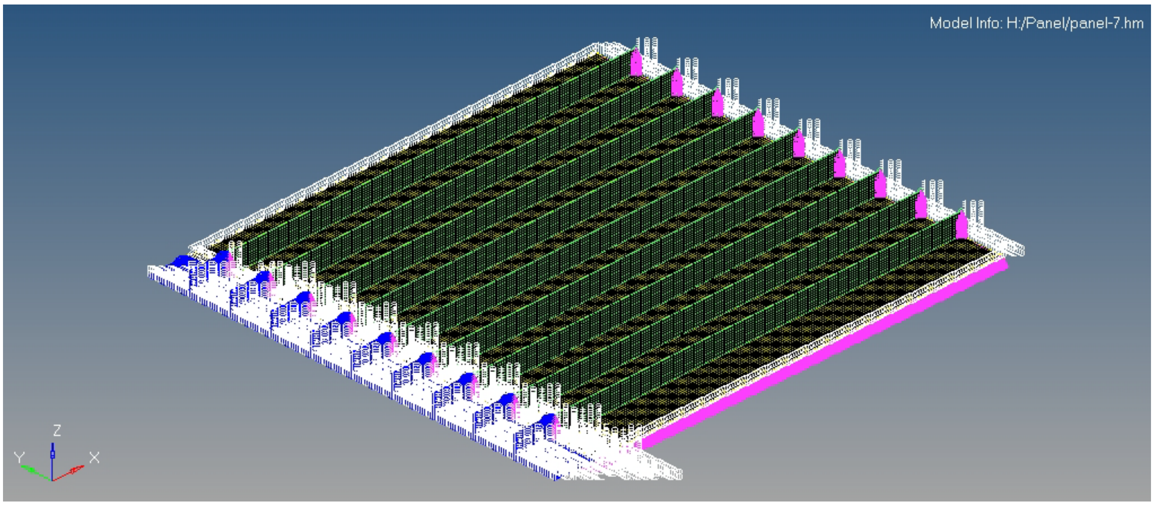


Figure 6-8 Finite Element Model

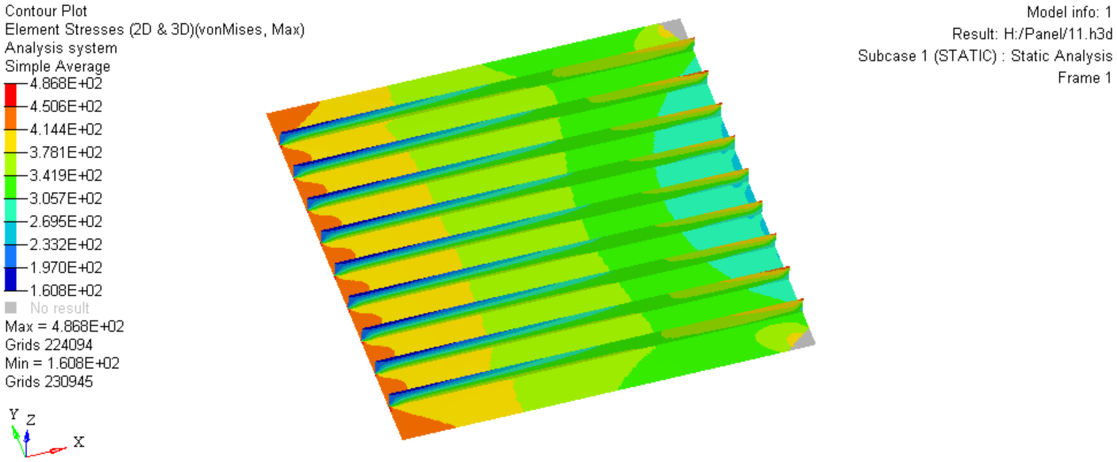


Figure 6-9 VonMise stress distribution nephogram under compression load

6.2.5 Analysis for hybrid design

According to developed design guideline, the stiffeners can be realized by vertical wall features of WAAM. And the skin can be machined by Ti-6Al-4V alloy plate.

6.2.5.1 Proposed hybrid design

The integral panel can be cut into two individual sections: one plate and nine stiffeners. Figure 6-10 shows the hybrid design solution. 9 green stiffeners are to be added on the yellow substrate and then the final part is to be finished by machining.

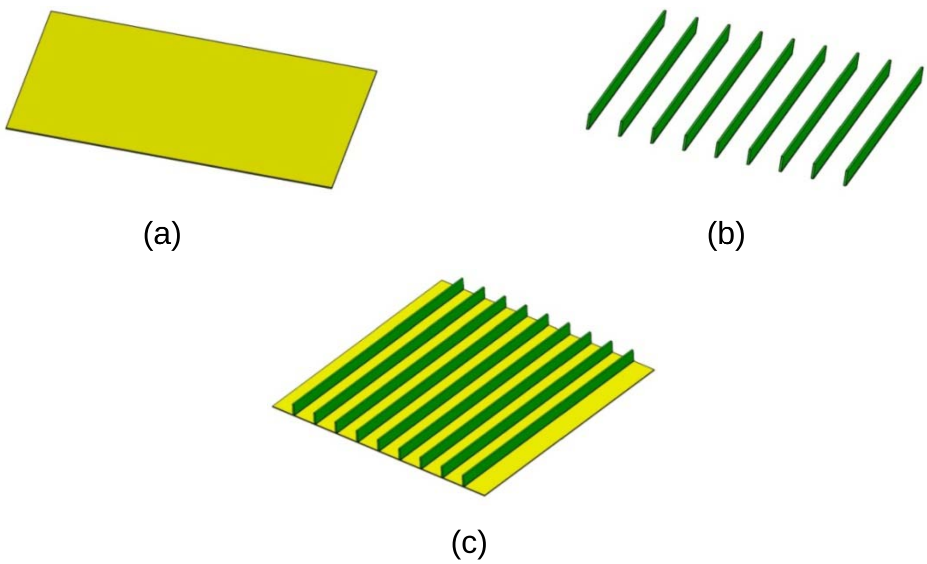


Figure 6-10 The schematic of proposed hybrid design of the integral panel:
(a) substrate; (b) stiffeners added by WAAM; (c) final part finished by machining

6.2.5.2 Evaluation

The cost estimation of the machining solution and the hybrid solution is listed in Table 6-2, which is calculated by the cost model (Zhai, 2012). The hybrid design is expected to save more than ￡10000 per piece.

Table 6-2 Cost estimation

	Preliminary design	Proposed hybrid design
Manufacturing Time, h	14.42	24.1
“Buy-to-fly” ratio	9.2	1.1
Material Cost, ￡	15601.48	3697.63
Set-up Cost, ￡	170.08	184.31
Non-productive Cost, ￡	21.42	110.57
Welding Cost	-	2104.26
Machining Cost, ￡	1634.70	688.324
Shielding Gas Cost, ￡	-	0.5892
Wire Change Cost, ￡	-	18.07
Total Cost, ￡	17427.68	6803.74

Using the evaluation matrix chart to assess these two solutions, the evaluation values are presented in Figure 6-11.The result of the evaluation indicates that the hybrid design solution is superior.

6.2.6 Hybrid design

According to design parameters of WAAM features developed within design guideline, a feature based 3D model was built (as shown in Figure 6-12). The yellow section is the substrate made by a machining process while the green one is manufactured by WAAM process.

Evaluation Criteria			V1 (Preliminary design)		V2 (Proposedhybrid solution)	
			Value	Weighted value	Value	Weighted value
No.	Objectives	Wt.	V_{i1}	WV_{i1}	V_{i2}	WV_{i2}
1	Performance	0.33	10	3.3	10	3.3
2	Technical complexity	0.19	7	1.33	8	1.52
3	Weight	0.21	7	1.47	7	1.47
4	Cost	0.20	3	0.6	9	1.8
5	Manufacturing time	0.07	7	0.49	4	0.28
		$\sum_{i=1}^{5} W_i = 1$	V_1=34 R_1=0.68	OWV_1=7.19 WR_1=0.72	V_2=38 R_2=0.76	OWV_2=8.37 WR_2=0.84

Figure 6-11 The evaluation matrix chart of the integral panel

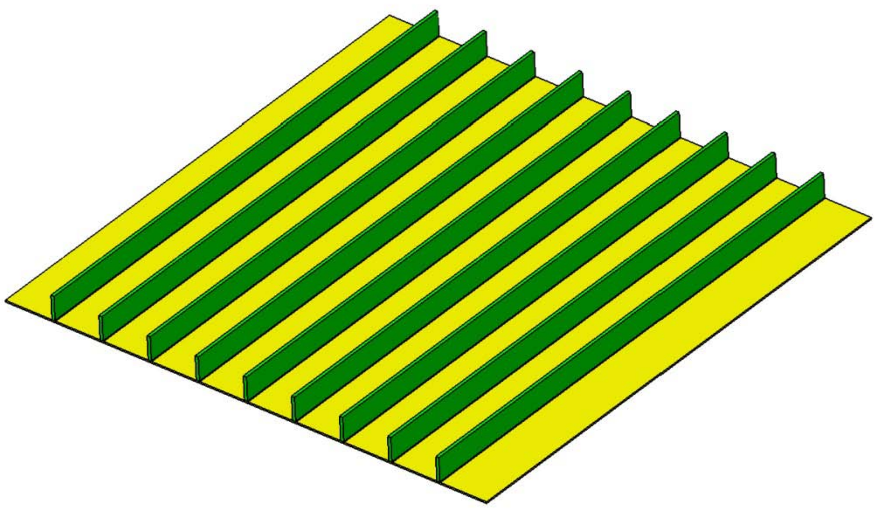


Figure 6-12 Feature based 3D Model of the integral panel

Using Equation (5-7) re-check the properties:

- Machining part:

$$MS_{(ultimate\ \ load)} = \frac{F}{f} - 1 = \frac{923.93}{486.8} - 1 = 0.90 > 0$$

Herein, F=923.93MPa (Richard et al., 2003)

- WAAM part:

$$MS_{(ultimate\ \ load)} = \frac{F}{f} - 1 = \frac{923}{486.8} - 1 = 0.90 > 0$$

Therefore, the MS value of the hybrid design is 0.90 which meets the properties' requirement.

6.3 Pylon Frame

Case study 2 is the pylon frame. All input design data including design load, dimensions and constraints was provided by the Chinese aircraft industry.

6.3.1 Clarify and define the task

It is a wing hanging transport airplane. The pylon connects the wing and engine, which transmits all loads from engine to wing structure. The pylon frame participates in force and provides support stiffness and, the working temperature is about 120℃-150℃. The critical condition of the pylon frame is -6G, Y axial direction, and -1.5 times Max. take off thrust, both applied on centre gravity of the engine. In addition, it needs a connection to support inner systems and leaves enough space for passing systems. Furthermore, the frame should meet the limitation of weight and dimensions. The material and manufacturing cost of this part is as low as possible. Figure 6-13 shows the Design Objectives Tree.

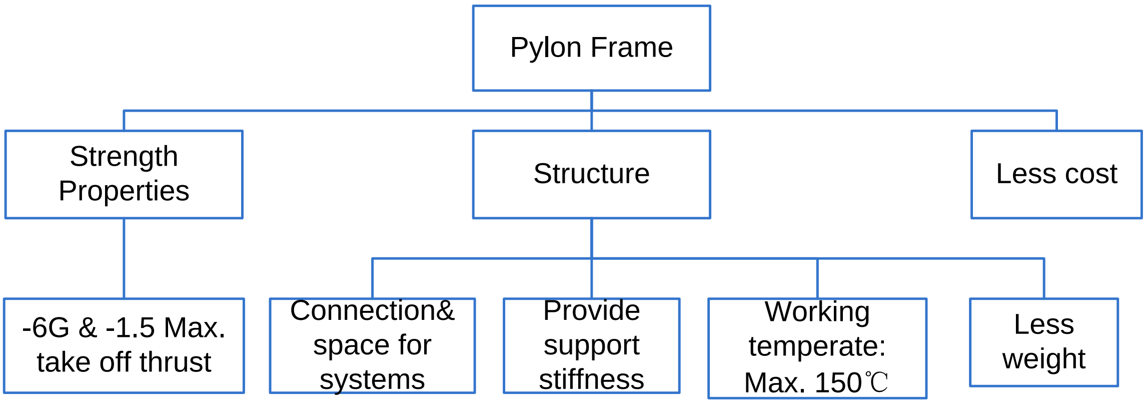


Figure 6-13 Design Objectives Tree of the pylon frame

6.3.2 Determine functions

As a structural part, the pylon frame is mainly expected to provide support stiffness for the pylon. Figure 6-14 presents the functional analysis. The main structural features (e.g. flange, stiffener and lug) and material were decided in this step to meet the functional requirements.

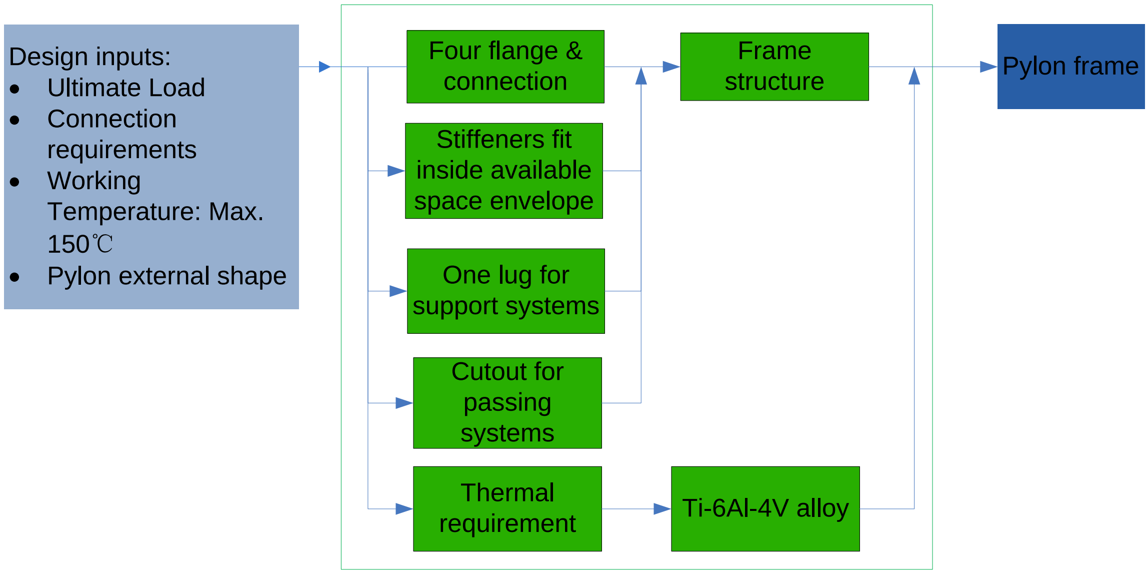


Figure 6-14 Function analysis of the pylon frame

6.3.3 Identify design requirements

Design requirements of the pylon frame were summarized from the above (as shown in Figure 6-15). It contains structure layout, tolerance, weight, strength, material, quality control and cost.

		Requirements list for Pylon Frame	Issued on:19/07/2012 Page:2
Changes	D W	Requirements	Responsible
19.07.12		1. Structure layout:	Pylon structure design team
	D D	● four flanges for connecting panels by using Hi-lock bolts	
	D	● stiffeners for support stiffness	
	D	● one lug for connecting systems	
		● external shape of pylon used to limit the dimensions	
		2. Tolerance:	
	D	● surface tolerance=Ra 3.2	
	D	● contour tolerance=0.2mm	
		3. Weight:	
	D	● weight ⩽3.4kg	
	W	● weight controlled below 3kg	
		4. Strength:	
	D D	● ultimate Load: -6G (Y axial direction) and -1.5 times Max. take off thrust (X axial direction)	
		● Margin of Safety (MS) > 0	
	D D	● safety coefficient for allowable tensile strength is 0.9 considered temperature effect	
		5. Material	
	D	● Ti-6Al-4V alloy	
		6. Quality control	
	D	● sample inspection in production	
		7. Cost:	
	W	● low manufacturing cost	
	W	● high material utilization	
		~~Replaces issue of~~	

Figure 6-15 Design requirements list of the Pylon frame

6.3.4 Preliminary design

6.3.4.1 3D model

Figure 6-16 illustrates 3D model of the preliminary design. It is made of Ti-6Al-4V alloy. The weight of this part is 2.962kg and it is machine manufactured. Figure 6-17 illustrates the 2D views of the preliminary design. The maximum size of this part is 384mm by 435mm. The thickness of the stiffeners is 4mm.

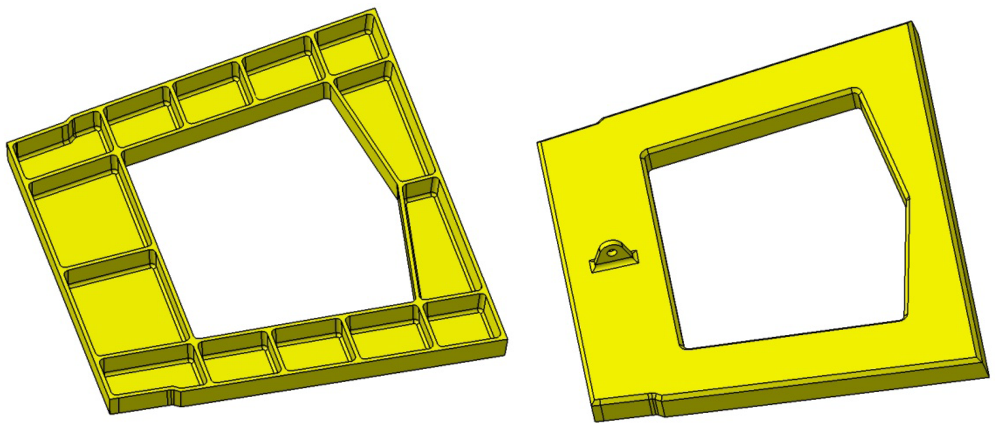


Figure 6-16 3D model of the preliminary design

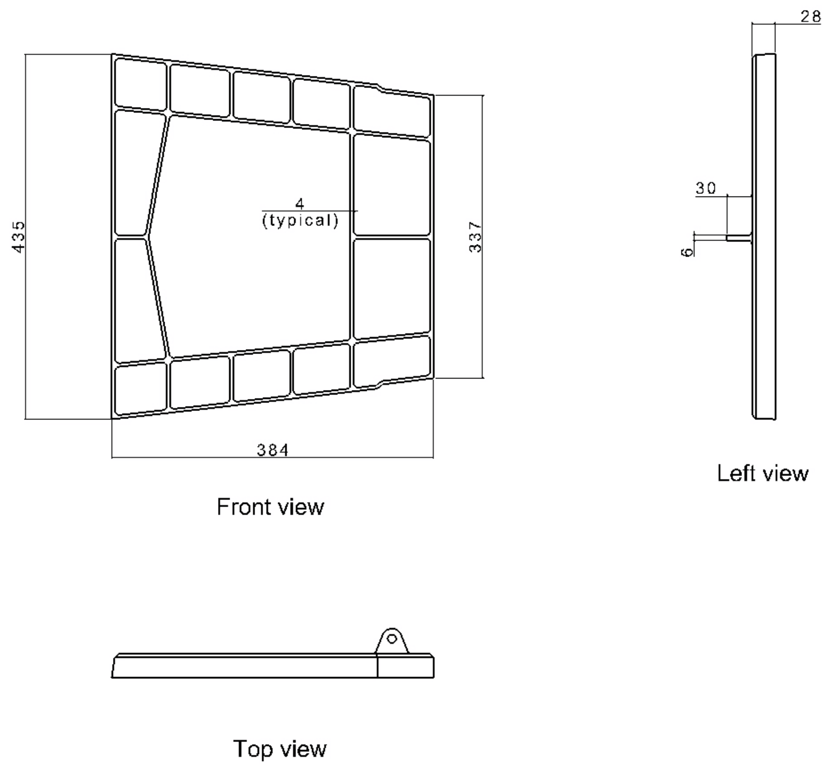


Figure 6-17 2D views of the preliminary design

6.3.4.2 Check performance

The ultimate Load was applied on the pylon component, and then the load on the pylon frame was taken out from the whole pylon component to build the Finite Element Model. Figure 6-18 shows VonMise stress distribution nephogram of the Pylon frame. The maximum stress is 365.2Mpa.

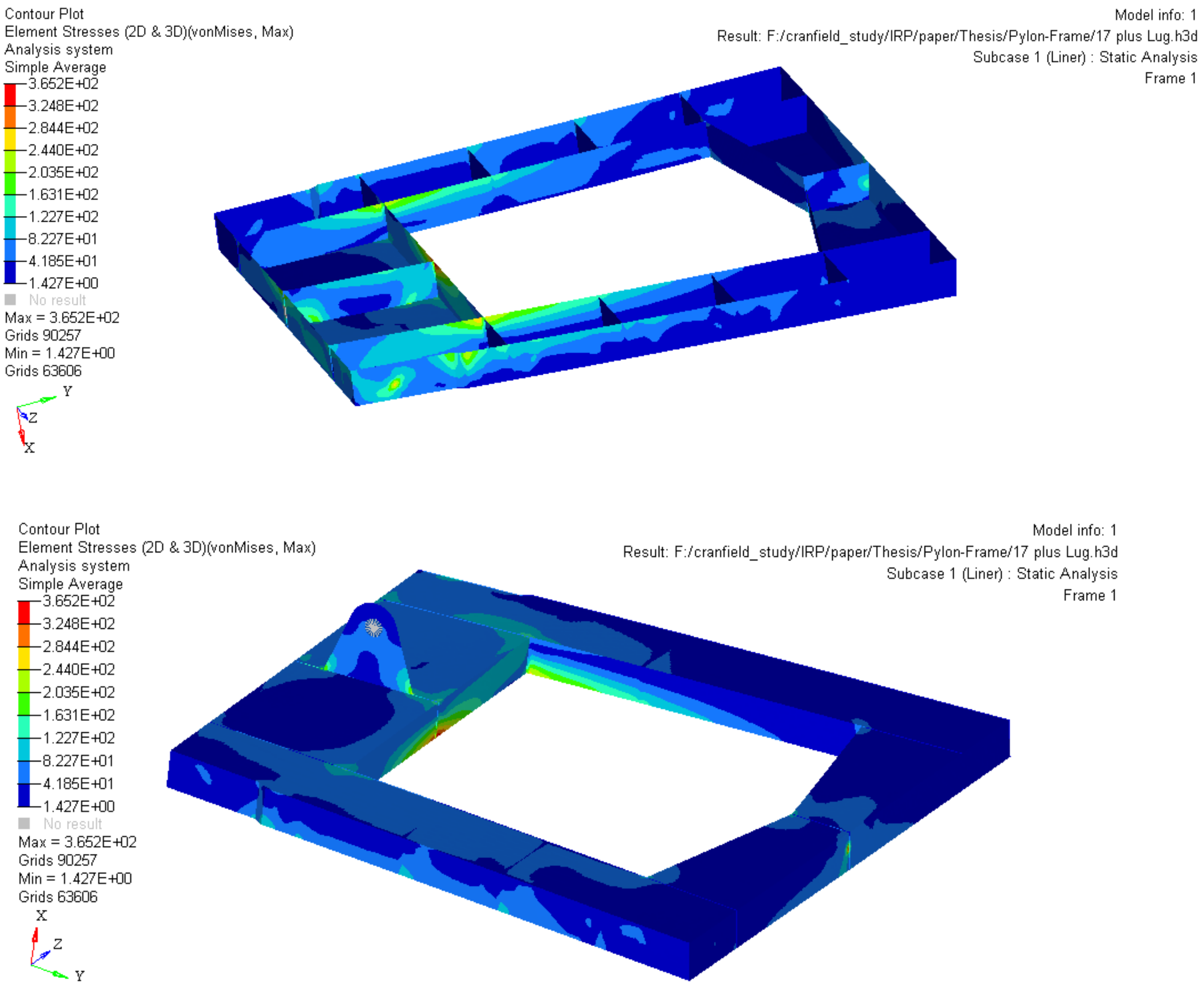


Figure 6-18 VonMise stress distribution nephogram of the Pylon frame

Using Equation (5-7) and Equation (5-8) calculate the MS value:

$$MS_{(ultimate\ \ load)} = \frac{F}{f} - 1 = \frac{0.9 \times 896.35}{365.2} - 1 = 1.21 > 0$$

$$MS_{(yield)} = \frac{F_{yield}}{f_{limit}} - 1 = \frac{0.9 \times 813.61 \times 1.5}{365.2} - 1 = 2 > 0$$

Herein, F=896.35MPa, F_{yield}=813.61MPa (Richard et al., 2003), temperature effect coefficient is 0.9 and safe coefficient is 1.5.

Therefore, MS=1.21. The preliminary design is proven to meet the strength properties. Furthermore, it fulfils the requirements of function.

6.3.5 Analysis for hybrid design

According to developed design guideline, the lug and stiffeners can be realized by vertical wall features of WAAM. Consequently, feasible and reasonable hybrid design solutions can be established and evaluated.

6.3.5.1 Proposed hybrid design

Two hybrid design solutions were decided as follows:

a) Proposed hybrid design 1

According to the recommended hybrid design approach in the design guideline, the lug can be added by WAAM. Figure 6-19 shows the schematic of hybrid design 1. The main structure is machined except the lug which is manufactured by WAAM. The final part is finished by machining.

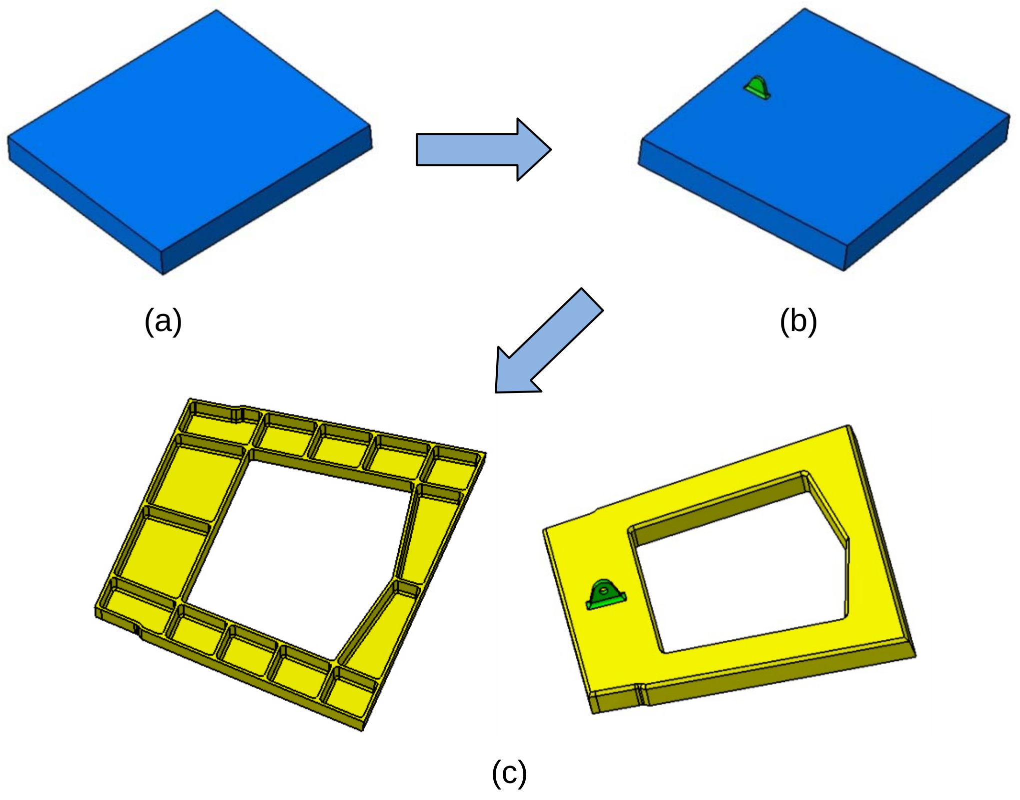


Figure 6-19 The schematic of proposed hybrid design 1: (a) substrate; (b) lug added by WAAM; (c) final part by machining

b) Proposed hybrid design 2

Figure 6-20 shows the schematic of hybrid design 2. The stiffeners and lug can be added by WAAM according to the design guideline. The final part is finished by machining.

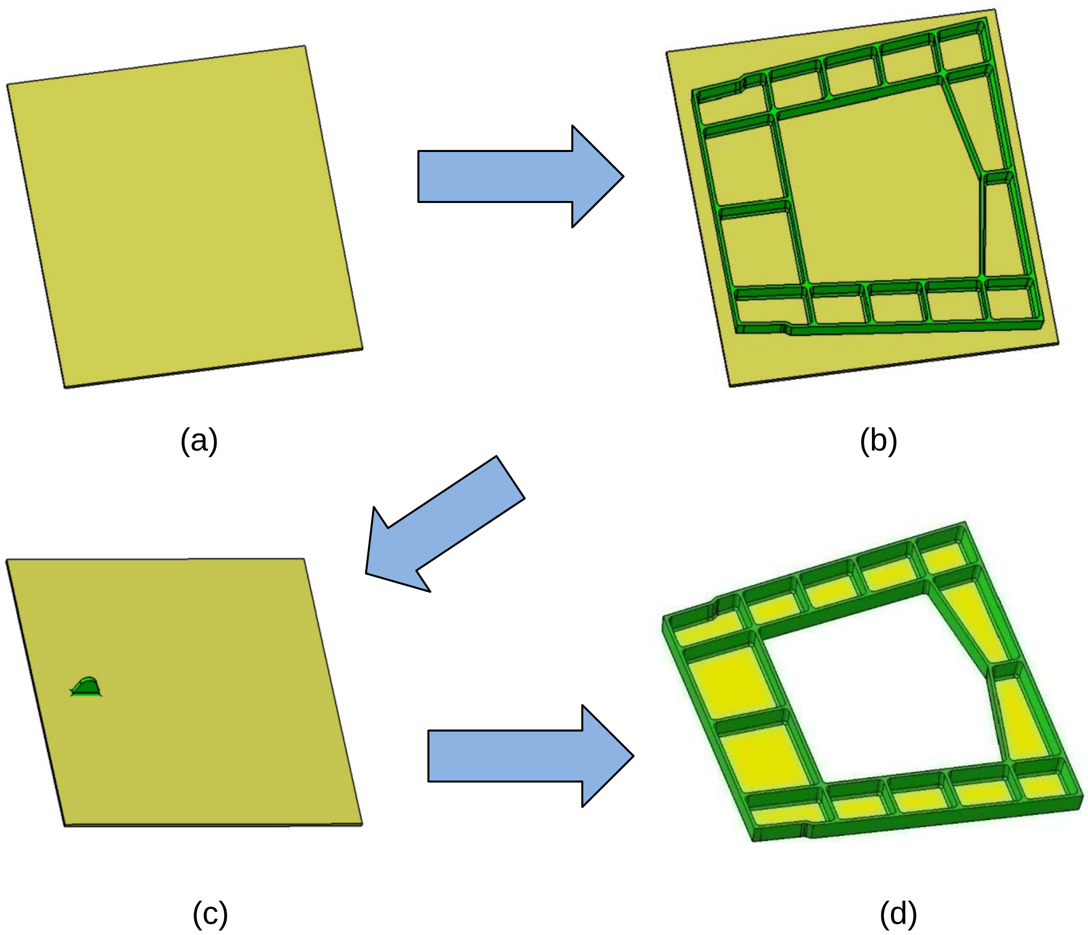


Figure 6-20 The schematic of proposed hybrid design 2: (a) substrate; (b) flanges and stiffeners added by WAAM; (c) lug added by WAAM; (d) final part by machining

c) Proposed hybrid design 3

Topology optimisation is applied in the proposed hybrid design 3. Figure 6-21 shows the topology optimisation analysis of the pylon frame. According to results of analysis, the pylon frame structure was re-designed (as shown in Figure 6-22). The weight of this part is 2.238kg which is reduced by 24.4%. In addition, a 6mm Ti-6Al-4V plate is used as a substrate considering the decrease of deformation during WAAM process. Figure 6-23 illustrates the schematic of hybrid design 3.

The flanges are added on the substrate by WAAM and the final part is finished by machining.

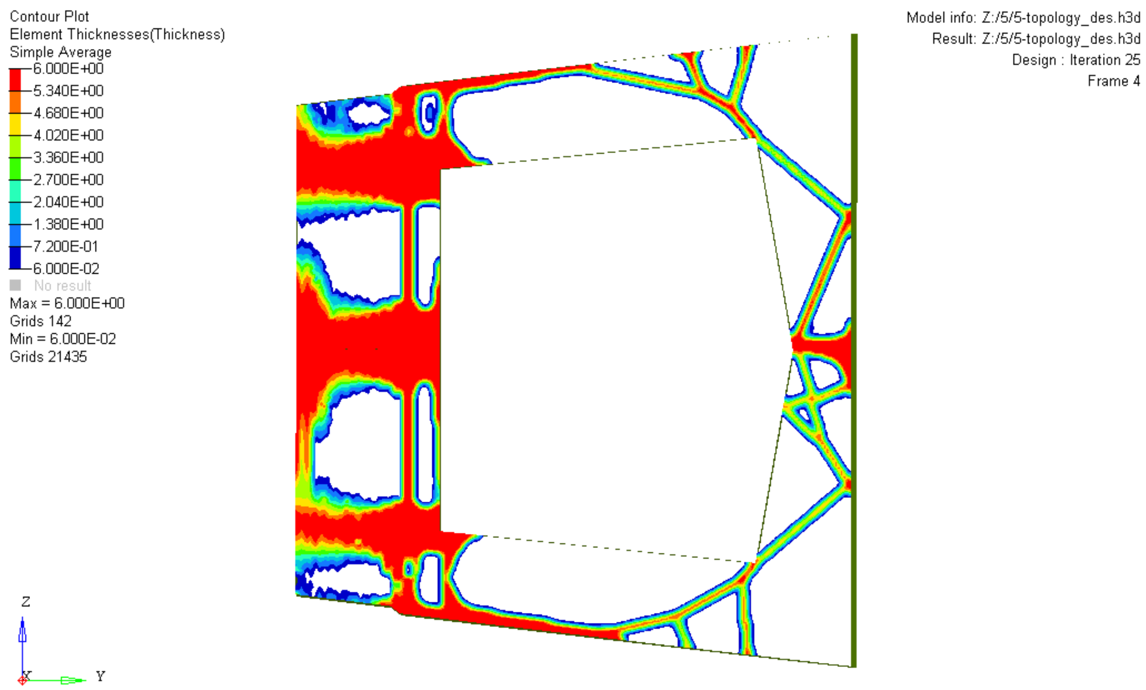


Figure 6-21 Topology optimisation analysis of the pylon frame

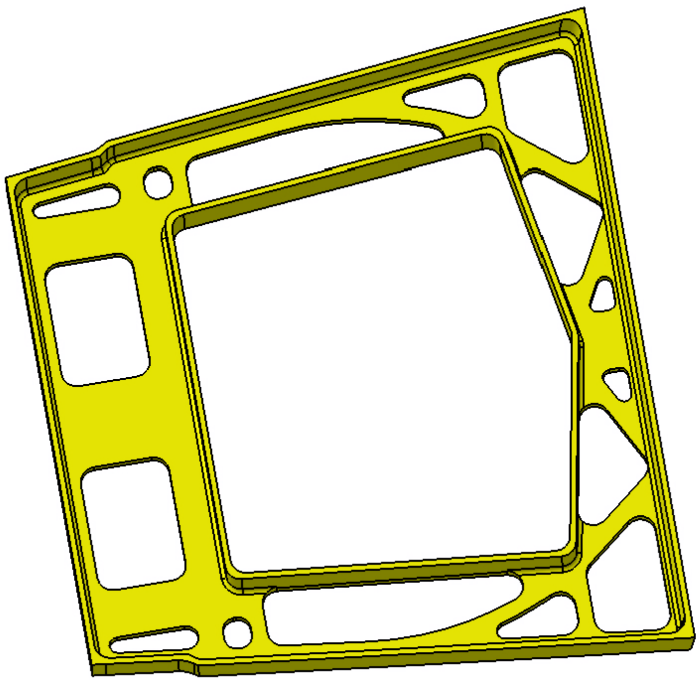


Figure 6-22 The pylon frame structure after optimisation

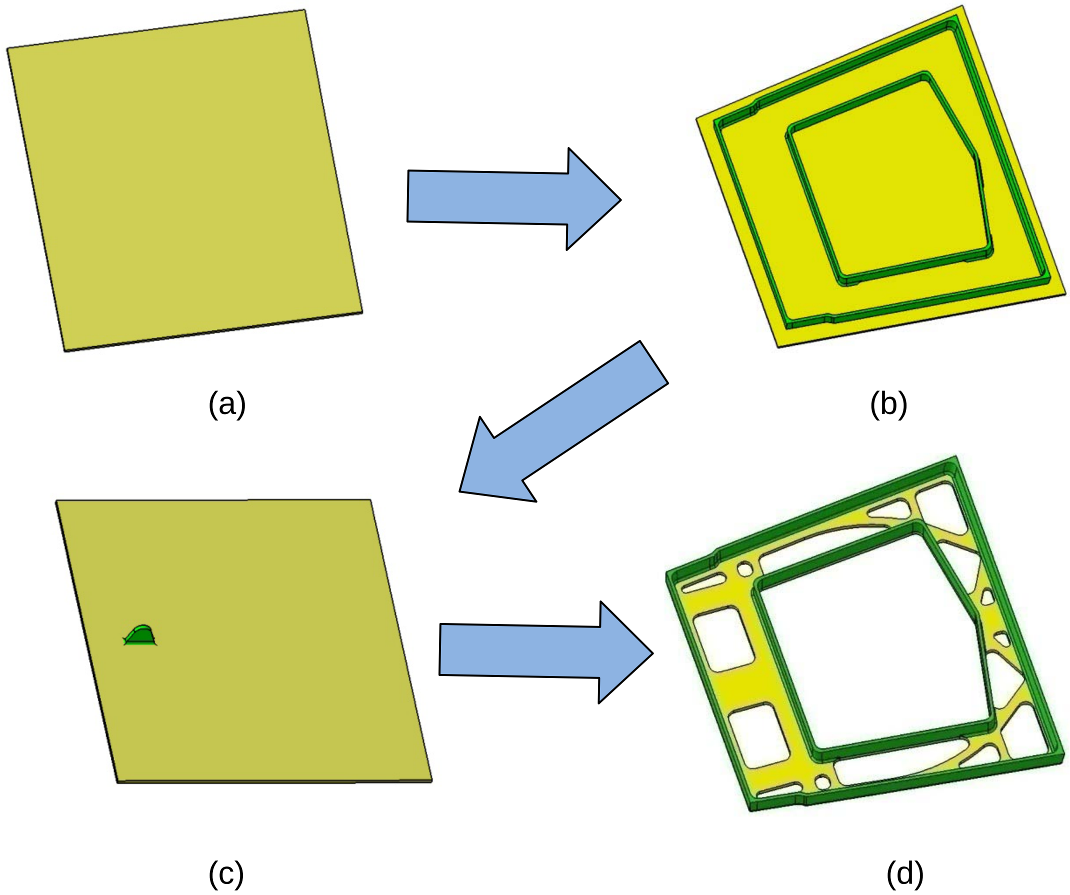


Figure 6-23 The schematic of proposed hybrid design 3: (a) substrate;
(b) flanges added by WAAM; (c) lug added by WAAM; (d) final part by machining

6.3.5.2 Evaluation

The first batch of this part is 40 pieces (2 pieces per airplane).The cost of the preliminary design and the proposed hybrid designs were estimated by the cost model (Zhai, 2012), see Table 6-3. Compared with the preliminary design (￡3656.49), proposed hybrid design 1 reduces the cost by 42.3% while the cost of proposed hybrid design 2 is decreased by 72.3%. Moreover, the cost of proposed hybrid design 3 is only ￡829.32 which is reduced by 77.3%

Table 6-3 Cost estimation

	Preliminary design	Proposed hybrid design 1	Proposed hybrid design 2	Proposed hybrid design 3
Manufacturing Time, h	3.03	2.9	3.54	2.49
“Buy-to-fly” ratio	17	10	2	2.7
Material Cost, £	3289.78	1744.83	554.54	496.57
Set-up Cost, £	4.25	8.86	8.86	8.86
Non-productive Cost, £	21.42	27.15	52.83	44.3
Welding Cost	-	3.71	260.56	175.29
Machining Cost, £	344.04	324.3	133.84	102.74
Shielding Gas Cost, £	-	0.0010	0.073	0.0491
Wire Change Cost, £	-	0.03	2.24	1.50
Total Cost, £	3656.49	2108.88	1012.93	829.32

The preliminary design is regarded a benchmark, the value of each objective for each solution is added to the evaluation matrix chart (as shown in Figure 6-24). It can be seen that hybrid design 3 is the best solution which achieves the highest score.

Evaluation Criteria			V_1 (Preliminary design)		V_2 (proposed hybrid design 1)		V_3 (proposed hybrid design 2)		V_4 (proposed hybrid design 3)	
			Value	Weighted value	Value	Weighted value	Value	Weighted value	Value	Weighted value
No.	Objectives	Wt.	V_{i1}	WV_{i1}	V_{i2}	WV_{i2}	V_{i3}	WV_{i3}	V_{i4}	WV_{i4}
1	Performance	0.33	10	3.3	10	3.3	10	3.3	10	2.62
2	Technical complexity	0.19	7	1.33	6	1.14	5	0.95	6	1.14
3	Weight	0.21	5	1.05	5	1.05	5	1.05	7	1.47
4	Cost	0.20	3	0.6	5	1	7	1.4	9	1.8
5	Manufacturing time	0.07	7	0.49	7	0.49	6	0.42	8	0.56
		$\sum_{i=1}^{5} W_i = 1$	V_1=32 R_1=0.64	OWV_1=6.77 WR_1=0.68	V_2=33 R_2=0.66	OWV_2=6.98 WR_2=0.70	V_3=33 R_3=0.66	OWV_3=7.12 WR_3=0.71	V_4=40 R_4=0.8	OWV_3=8.27 WR_3=0.83

Figure 6-24 The evaluation matrix chart of the pylon frame

6.3.6 Hybrid design

6.3.6.1 3D model

A feature based 3D model was built according to the design guideline and published machining design manuals, (as shown in Figure 6-25). The yellow section is made by machining while the green section is manufactured by WAAM process. The total weight is 2.238kg.

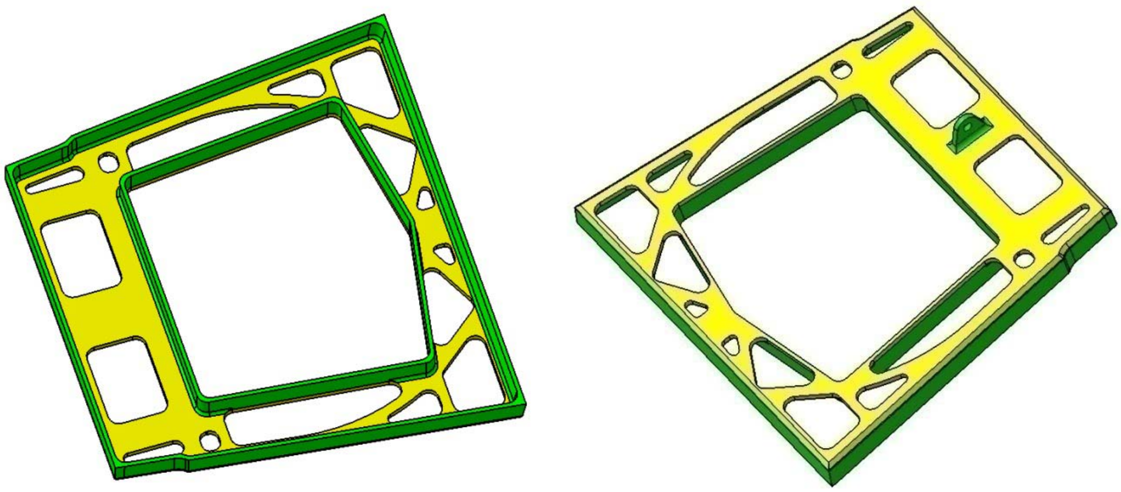


Figure 6-25 Feature based 3D model of the Pylon frame

6.3.6.2 Check Performance

The VonMise stress distribution nephogram of the final design is shown in Figure 6-26. The maximum stress is 580.6Mpa.

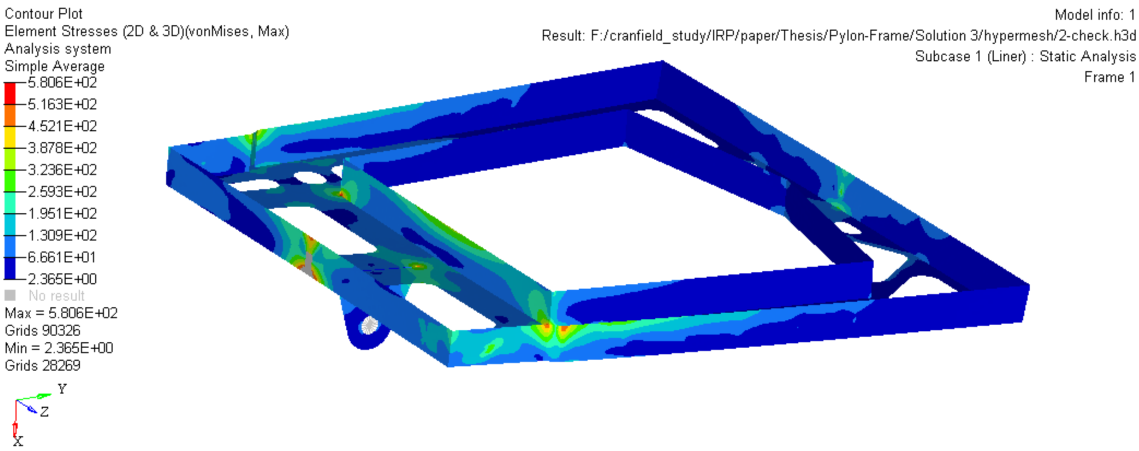


Figure 6-26 VonMise stress distribution nephogram of final design

Using Equation (5-7) re-check the properties:

- Machining part:

$$\mathrm{MS}_{(\mathrm{ultimate\ \ load})} = \frac{\mathrm{F}}{\mathrm{f}} - 1 = \frac{0.9 \times 923.93}{580.6} - 1 = 0.43 > 0$$

Herein, F=923.93MPa (Richard et al., 2003), temperature effect coefficient is 0.9.

- WAAM part:

$$\mathrm{MS}_{(\mathrm{ultimate\ \ load})} = \frac{\mathrm{F}}{\mathrm{f}} - 1 = \frac{0.9 \times 923}{580.6} - 1 = 0.43 > 0$$

Therefore, the MS value of the hybrid design is 0.43 that meets the properties requirement.

6.4 Forward Fitting

Case study 3 is a forward fitting of the pylon. All input design data including design load, dimensions and constrains was provided by the Chinese aircraft industry.

6.4.1 Clarify and define the task

The pylon connects the wing and engine, which transmits all loads from engine to wing structure. The forward fitting is mainly required to transmit lateral force, vertical force and torque load form engine. Moreover, this part is required to meet fail-safe design. The critical condition of the forward fitting (ultimate load) is 8G, Y axial direction.

As far as the structure design is concerned, four points for connecting engine and one extra connection points for fail-safe design should be considered. Moreover, connection structure with other parts must be carefully considered. The structure should also be efficient to satisfy the weight and dimension limitation. Finally, the working temperature of this fitting is 300℃.

In addition, the material and manufacturing cost of this part is as low as possible.

In conclusion, the principle objectives of forward fitting are strength properties and structure. All design objectives are listed as follows:

a) Strength properties

- Ultimate load: 8G, Y axial direction.
- Fail-safe design.

b) Structure

- 4 connection points for engine.
- 1 extra connection points for fail-safe design.
- Connection structure with other parts.
- Less weight.
- Working temperature: 180℃.
- Fail-safe design

c) Cost

- Low manufacturing cost.
- Low material cost.

Figure 6-27 illustrates the Objectives Tree of this part.

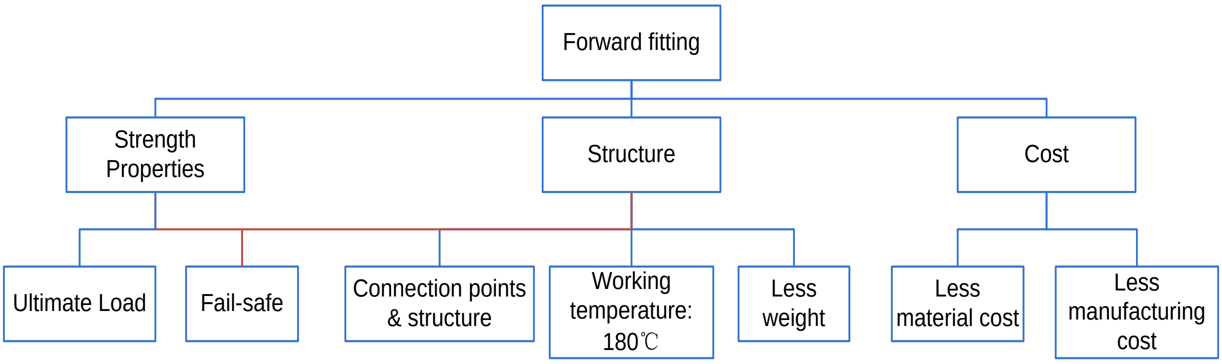


Figure 6-27 Design Objectives Tree of the forward fitting

6.4.2 Determine functions

According to functions analysis method, the functions of forward fitting are identified. Figure 6-28 presents the process of functions analysis. The main structural requirements of the forward fitting were decided as well as the material.

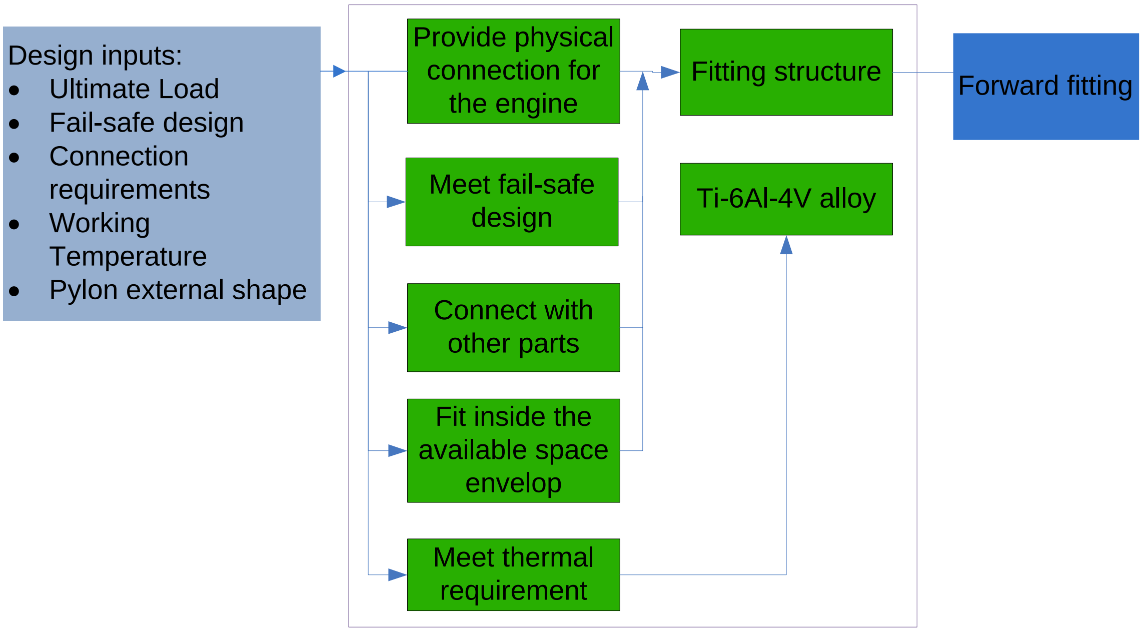


Figure 6-28 Functions analysis of the forward fitting

6.4.3 Identify design requirements

The design objectives and functions of the forward fitting were summarized in the requirements list (as shown in Figure 6-29). It contains 7 items: structure layout, tolerance, weight, strength, material, quality control and cost.

	Requirements list for forward fitting	Issued on:19/05/2011 Page:2	
Changes	D W	Requirements	Responsible
19.05.11		1. Structure layout:	Pylon structure design team
	D	● 4 lugs for connecting engine	
	D	● 1 extra lug for fail-safe design	
	D	● use Hi-lock bolts to joint other structures	
	D	● use external shape of engine and pylon to limit the fitter dimensions	
		2. Tolerance:	
	D	● surface tolerance=Ra 3.2	
	D	● contour tolerance=0.2mm	
		3. Weight:	
	D	● weight ≤21kg	
	W	● control the weight below 20kg	
		4. Strength:	
	D	● fail-safe design	
	D	● ultimate Load=8G (Y axial direction, applied on centre gravity of engine)	
		● Margin of Safety (MS) ＞0	
	D D	● safety coefficient for allowable tensile strength is 0.8 considered temperature effect	
		5. Material	
	D	● Ti-6Al-4V alloy	
		6. Quality control	
	D	● first article inspection	
	D	● sample inspection in production	
		7. Cost:	
	W	● Low manufacturing cost	
	W	● High material utilization	
	Replaces issue of		

Figure 6-29 Requirements list of the forward fitting

6.4.4 Preliminary design

6.4.4.1 3D model

The result of the preliminary design is shown in Figure 6-30 and Figure 6-31. It is made of Ti-6Al-4V alloy and the weight is 19.287kg. The initial manufacturing process is machining. The maximum size is 814mm by 158mm.

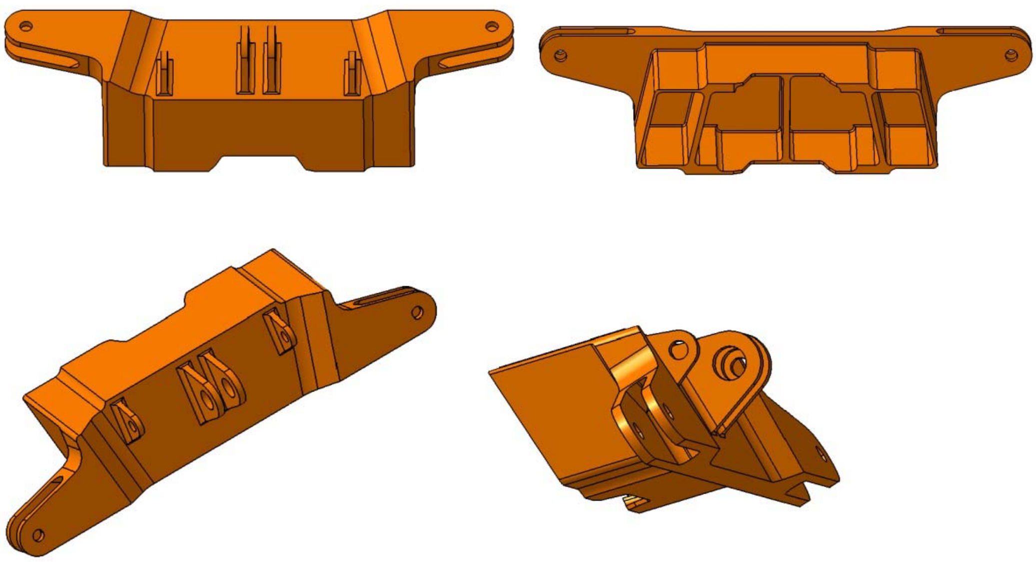


Figure 6-30 3D model of the preliminary design

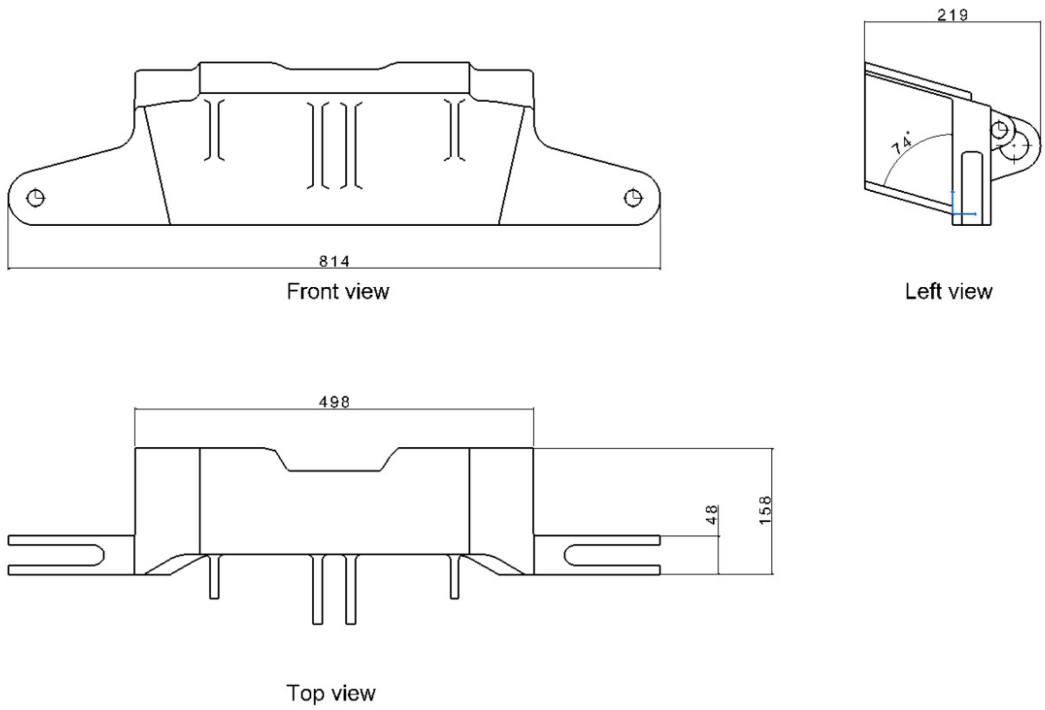


Figure 6-31 2D views of the preliminary design

6.4.4.2 Check performance

In order to check the performance, Finite Element Analysis method is carried out by using Hyperwork software. The results are presented in Figure 6-32 and Figure 6-33. The maximum stress of ultimate load condition is 587.9Mpa, and the maximum stress of fail-safe condition is 457.5Mpa. Therefore, the maximum stress is 587.9Mpa. The areas of lug A and lug B are the most dangerous locations (as shown in Figure 6-32).

Using Equation (5-7) and Equation (5-8) calculate the MS value:

- Ultimate load condition:

$$\mathrm{MS}_{(\mathrm{ultimate\ \ load})} = \frac{\mathrm{F}}{\mathrm{f}} - 1 = \frac{0.8 \times 862}{587.9} - 1 = 0.173 > 0$$

$$\mathrm{MS}_{(\mathrm{yield})} = \frac{\mathrm{F_{yield}}}{\mathrm{f_{limit}}} - 1 = \frac{0.8 \times 786 \times 1.5}{587.9} = 0.6 > 0$$

- Fail-safe condition

$$\mathrm{MS}_{(\mathrm{ultimate\ \ load})} = \frac{\mathrm{F}}{\mathrm{f}} - 1 = \frac{0.8 \times 862}{457.5} - 1 = 0.507 > 0$$

$$\mathrm{MS}_{(\mathrm{yield})} = \frac{\mathrm{F_{yield}}}{\mathrm{f_{limit}}} - 1 = \frac{0.8 \times 786 \times 1.5}{457.5} = 1.06 > 0$$

Herein, F=862MPa, F_{yield}= 786MPa (Richard et al., 2003), temperature effect coefficient is 0.8 and safe coefficient is 1.5.

Therefore, MS=0.173. The preliminary design is proven to meet the strength properties. Furthermore, it fulfils the requirements of function.

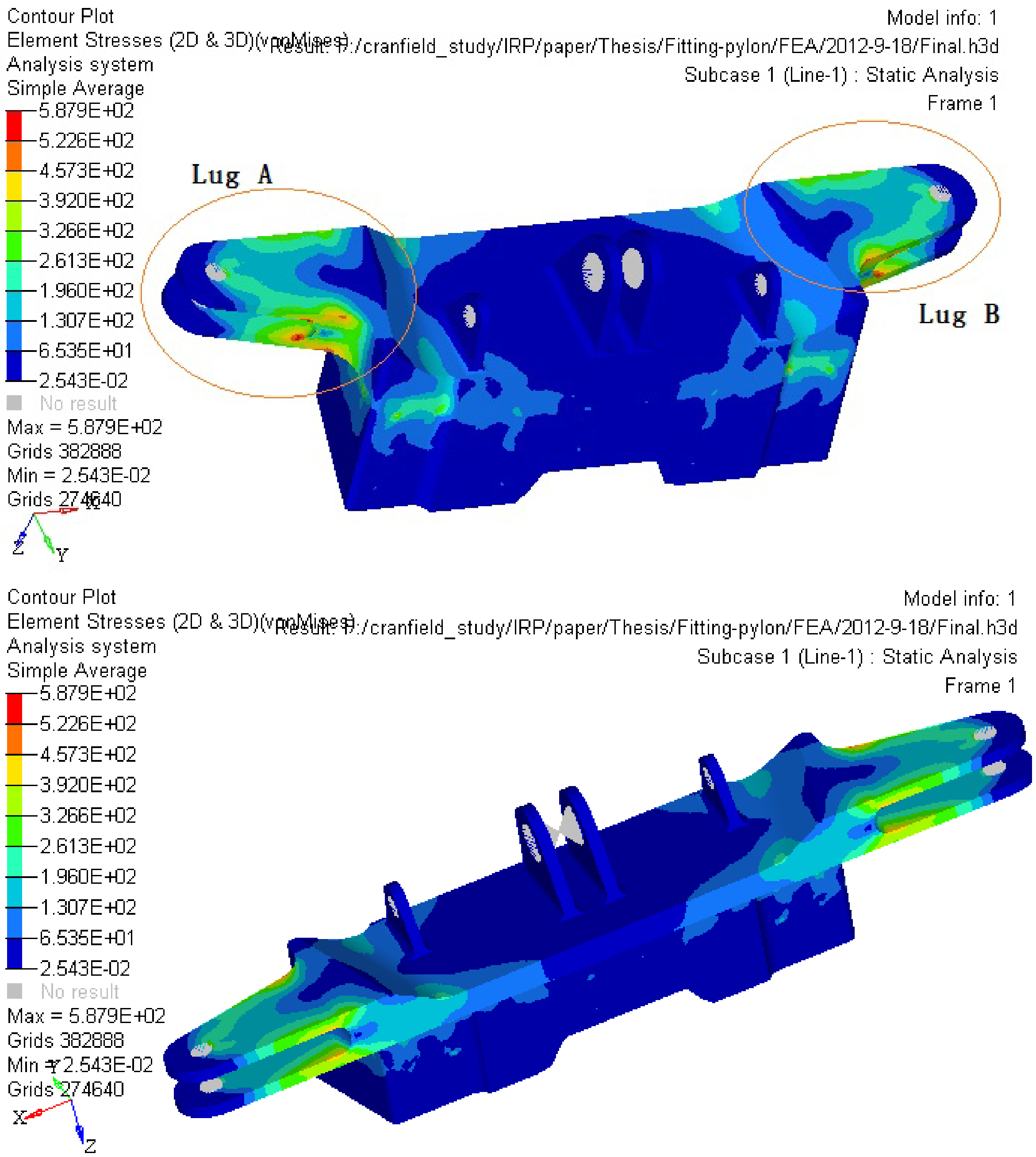


Figure 6-32 VonMise stress distribution nephogram under the ultimate load condition

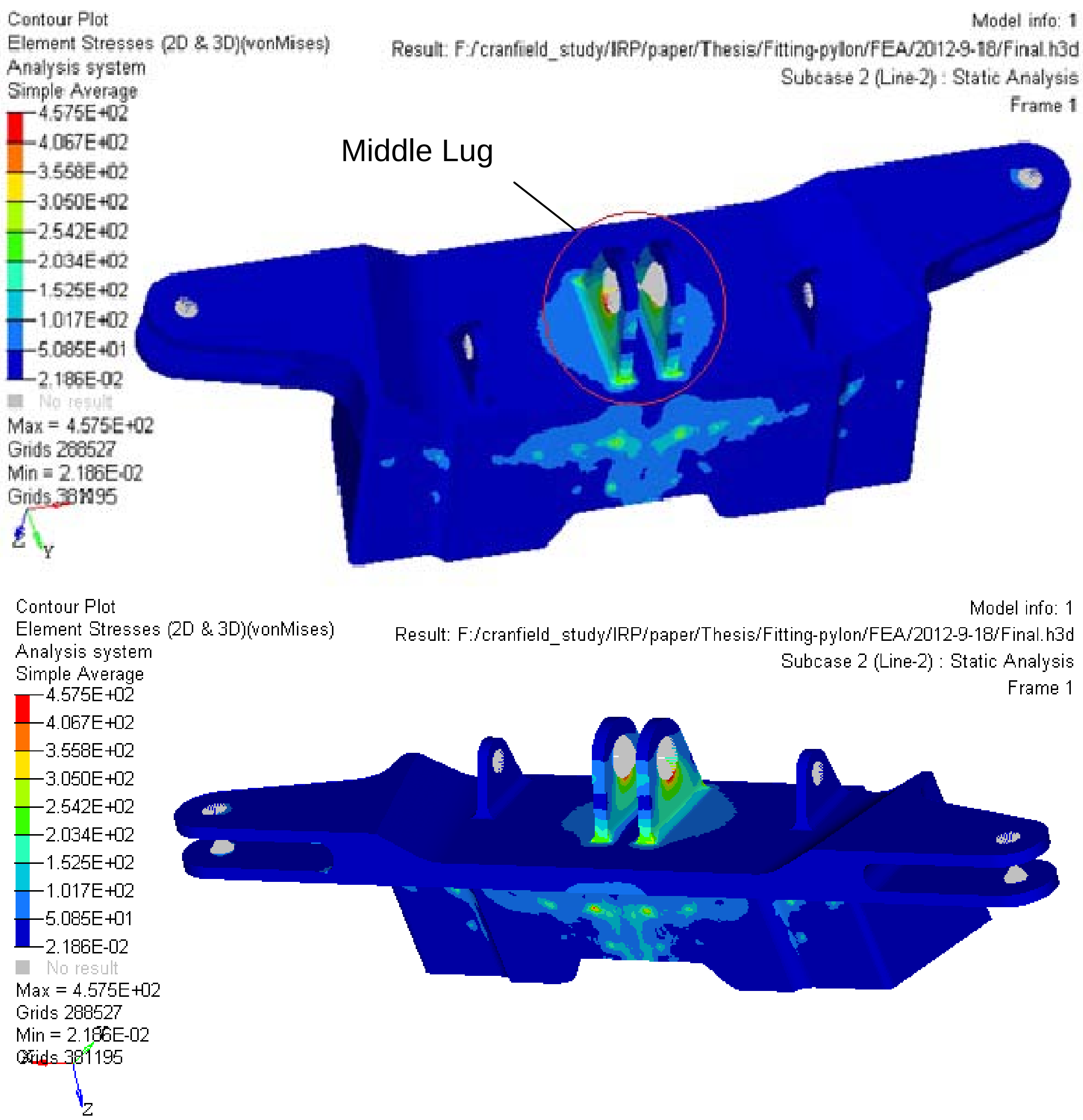


Figure 6-33 VonMise stress distribution nephogram under the fail-safe condition

6.4.5 Analysis for hybrid manufacturing

According to developed design guideline, the lugs and stiffeners can be realized by vertical and inclined wall features of WAAM. Consequently, feasible and reasonable hybrid design solutions can be developed and then applied to the evaluation matrix chart to decide the optimum design.

6.4.5.1 Proposed hybrid design

For the forward fitting, three hybrid solutions have been created.

a) Proposed hybrid design 1

According to the design guideline, the lugs and stiffener can be added by WAAM.

Figure 6-34 shows the schematic of proposed hybrid design 1. The green section is to be added on the blue substrate by WAAM. The final part is finished by machining.

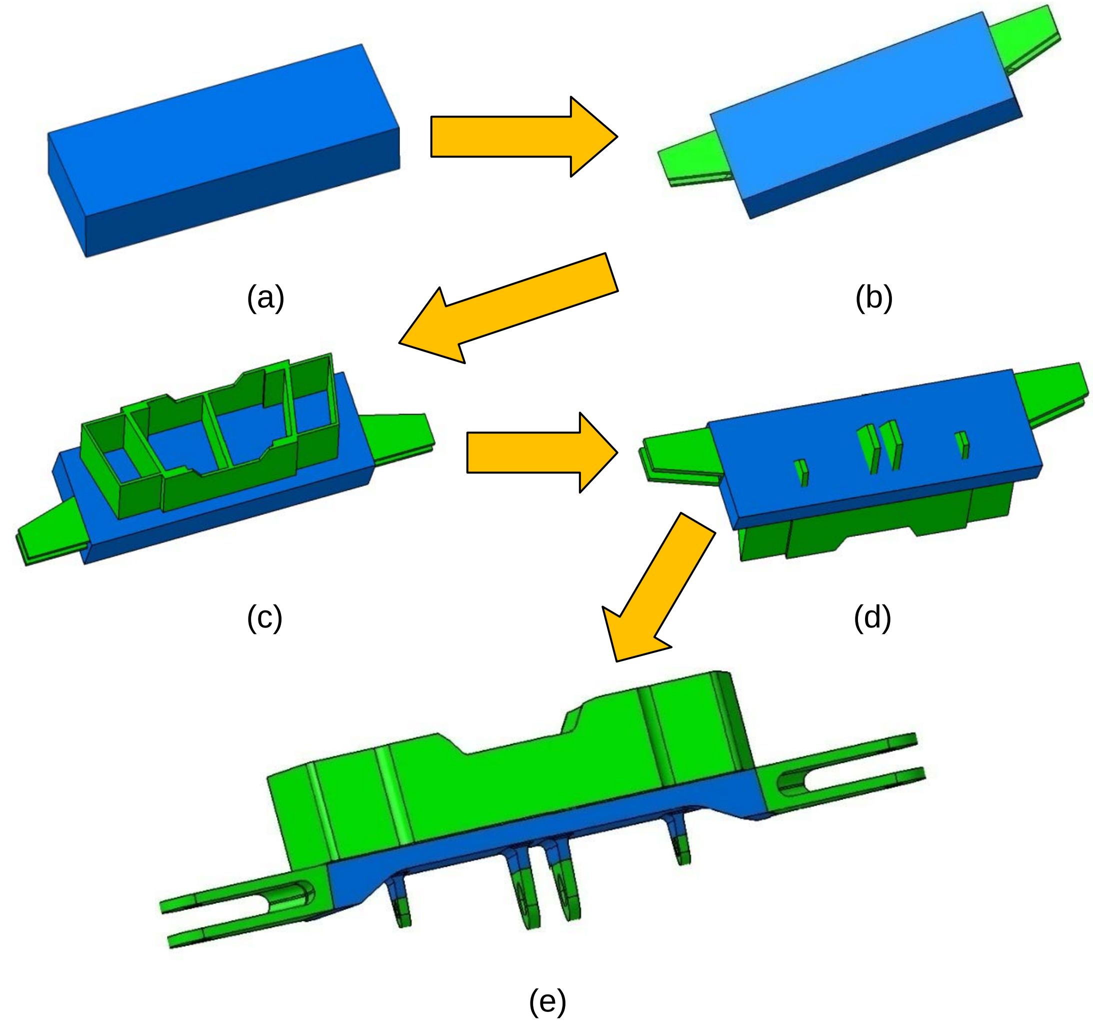


Figure 6-34 The schematic of proposed hybrid design 1: (a) substrate; (b) lugs added by WAAM; (c) stiffeners and lugs added by WAAM; (d) lugs added by WAAM; (e) final part finished by machining

b) Proposed hybrid design 2

Figure 6-35 shows the schematic of proposed hybrid design 2. The green part is added by WAAM. The final part is finished by machining.

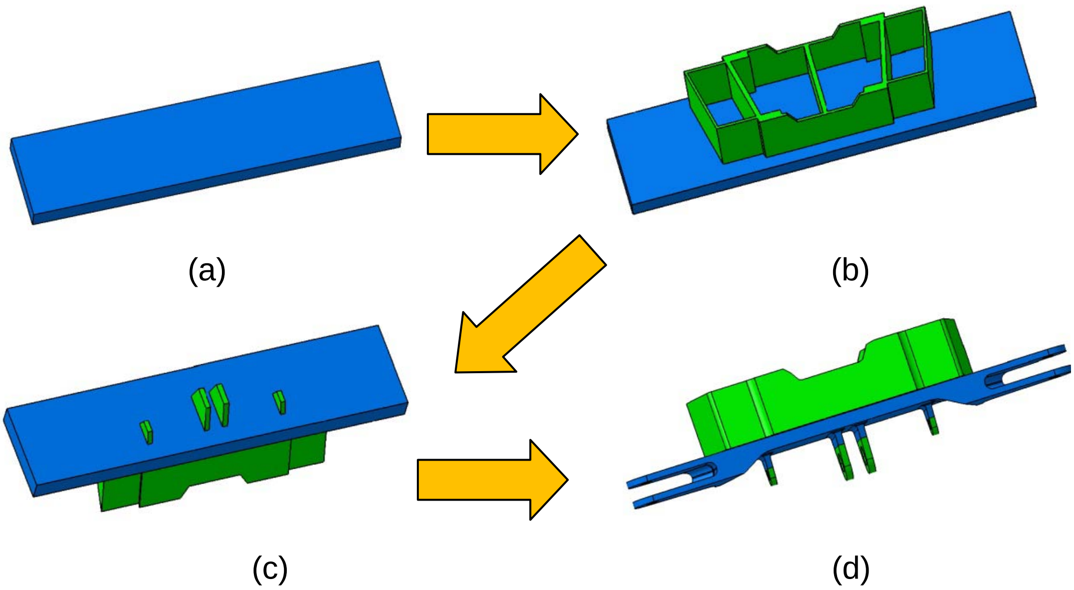


Figure 6-35 The schematic of proposed hybrid design 2: (a) substrate; (b) stiffener added by WAAM; (c) lugs added by WAAM; (d) final part finished by machining

c) Proposed hybrid design 3

Optimisation design was used in proposed hybrid 3. Figure 6-36 shows the topology optimisation analysis of the forward fitting. The optimisation objective is minimum weight.

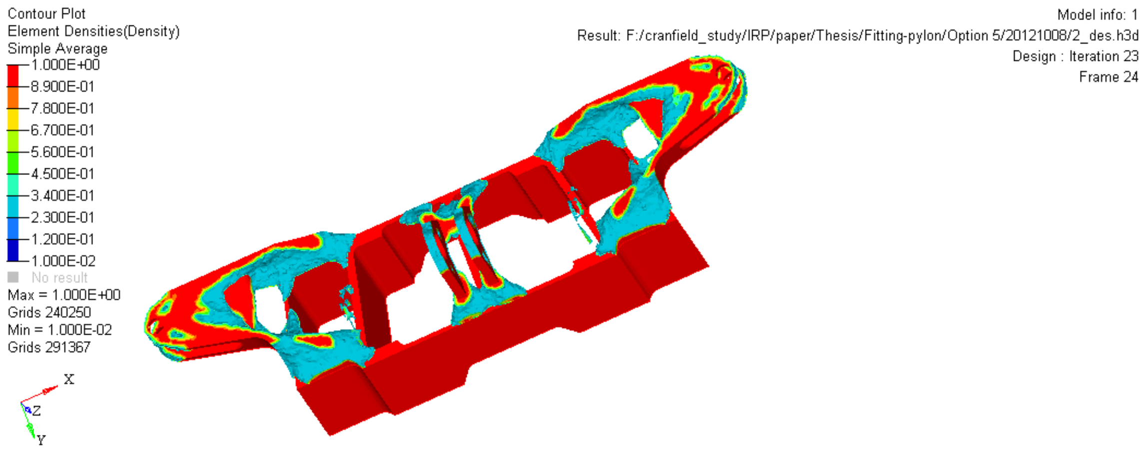


Figure 6-36 Topology optimisation analysis of the forward fitting

According the analysis result, the fitting was re-designed (as shown in Figure 6-37). The weight of this part is 17.744kg which is reduced by 1.543kg. The external plate was reserved due to the fireproof requirement of this fitting. The thickness of some areas was decreased to reduce weight on the basis of the optimisation result. The proposed hybrid design for this part is shown in Figure 6-38. The green part is added on the blue substrate by WAAM, and finally the part is finished by machining.

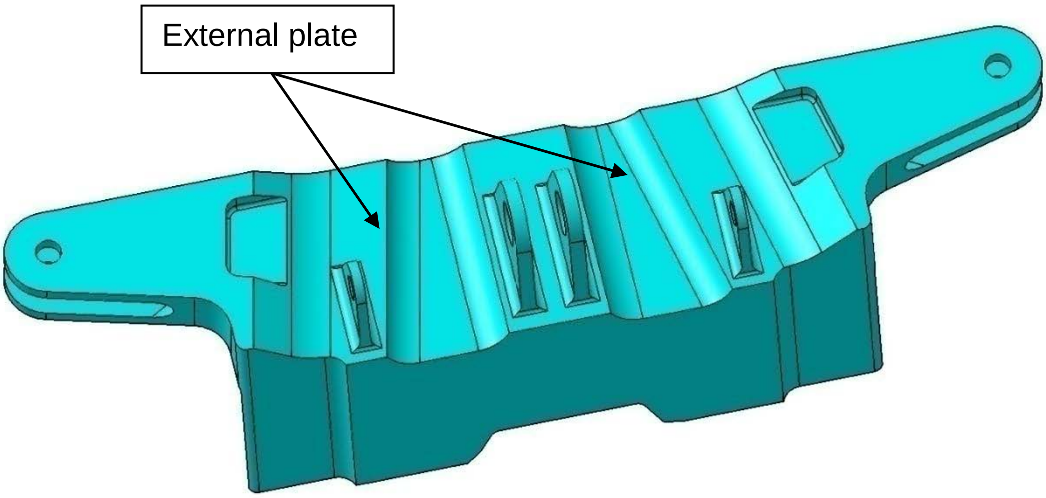


Figure 6-37 Design of the forward fitting after optimisation

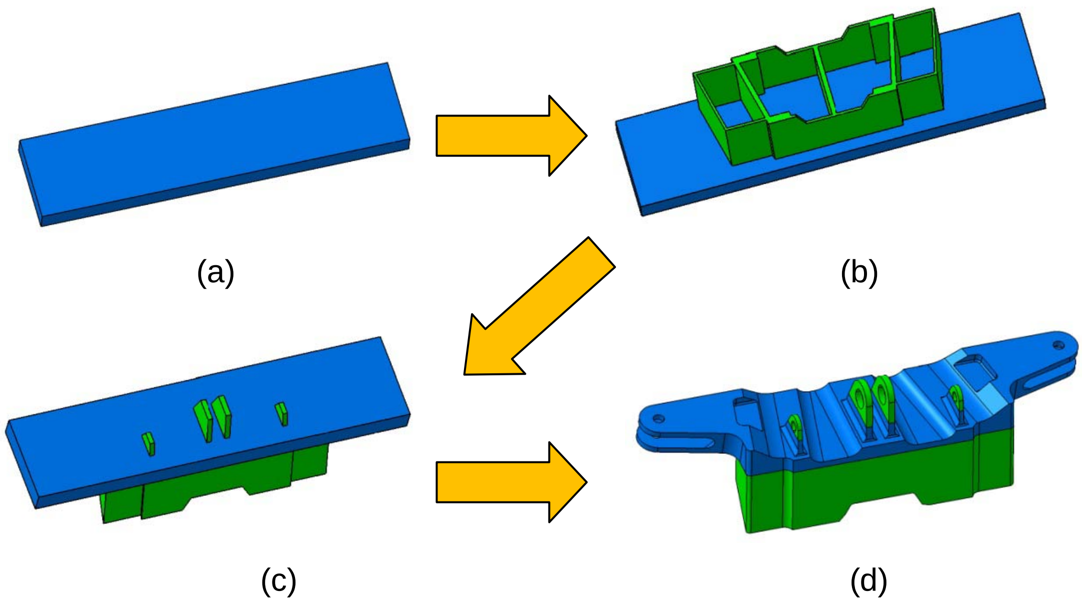


Figure 6-38 The schematic of proposed hybrid design 3: (a) substrate; (b) stiffener added by WAAM; (c) lugs added by WAAM; (d) final part finished by machining

6.4.5.2 Evaluation

The first batch of this part is 40 pieces (2 pieces per airplane). The manufacturing time, material and manufacturing cost were estimated by the cost modelling (Zhai, 2012), see Table 6-4. The cost of the hybrid designs can be reduced by about 50% compared with that of the preliminary design.

Table 6-4 Cost estimation

	Preliminary design	Proposed hybrid design 1	Proposed hybrid design 2	Proposed hybrid design 3
Manufacturing Time, h	6.92	16.03	12.21	12.27
"Buy-to-fly" ratio	7.1	1.6	2.1	2.3
Material Cost, £	8845.16	3191.86	3413.54	3413.54
Set-up Cost, £	4.25	8.86	8.86	8.86
Non-productive Cost, £	21.42	185.14	130.74	130.74
Welding Cost	-	1583.66	1039.68	1039.68
Machining cost, £	784.41	193.57	319.4	327.62
Shielding Gas Cost, £	-	0.4434	0.2911	0.2911
Wire Change Cost, £	-	13.60	8.93	8.93
Total Cost, £	9655.24	5177.14	4921.44	4929.66

The value of each objective is decided and added to the evaluation matrix chart which regards the preliminary design as the benchmark (as shown in Figure 6-39).

As analysed before, Lug A and Lug B (as shown in Figure 6-32) are the principle structural element (PSE), and its MS value is 0.173 without high residual strength. It will be low risky to use WAAM features on this area technically. For the middle lug, it will not participate in force unless Lug A or Lug B fail under the ultimate load condition (see Figure 6-33). And what is more, the highest stress for the middle lug is 457.5 MPa and its MS value is 0.507 which occurs in the fail-safe condition. Hence, it has enough residual strength. Finally, as a fail-safe design structure, this lug is supposed to be used only once. Consequently, there is no risk to use WAAM features in this area. Therefore, the assessing value of "Performance" is 7 for proposed hybrid design 1 and that of proposed hybrid design 2 and 3 are 10.

As can be seen from the chart, the "OWV" and "WR" of the proposed hybrid design 3 is the highest, so it is the best design among all solutions.

Evaluation Criteria			V_1 (preliminary design)		V_2 (proposed hybrid design 1)		V_3 (proposed hybrid design 2)		V_4 (proposed hybrid design 3)	
			Value	Weighted value	Value	Weighted value	Value	Weighted value	Value	Weighted value
No.	Objectives	Wt.	V_{i1}	WV_{i1}	V_{i2}	WV_{i2}	V_{i3}	WV_{i3}	V_{i4}	WV_{i4}
1	Performance	0.33	10	3.3	7	2.31	10	2.3	10	2.3
2	Technical complexity	0.19	6	1.14	5	0.95	7	1.54	7	1.54
3	Weight	0.21	5	1.05	5	1.05	5	1.28	8	1.28
4	Cost	0.20	4	0.8	7	1.4	7	0.84	7	0.84
5	Manufacturing time	0.07	7	0.49	4	0.28	5	0.7	5	0.7
		$\sum_{i=1}^{5} W_i = 1$	V_1=32 R_1=0.64	OWV_1 =6.78 WR_1 =0.68	V_3=28 R_3=0.56	OWV_2 =5.99 WR_2 =0.60	V_4=34 R_4=0.68	OWV_3 =7.43 WR_3 =0.74	V_4=37 R_4=0.74	OWV_4 =8.06 WR_4 =0.81

Figure 6-39 The evaluation matrix chart of the forward fitting

6.4.6 Hybrid design

According to design parameters of WAAM features developed within design guideline and published machining design manuals, a feature based 3D model was built. Figure 6-40 illustrates the feature based 3D model of the forward fitting. The brown section is made by machining process while the green section is added by WAAM process. The whole weight of this part is 17.744kg. Figure 6-41 shows the VonMise stress distribution nephogram of the final design. The maximum stress of the machining part is 587.9Mpa and that of the WAAM part is about 392Mpa.

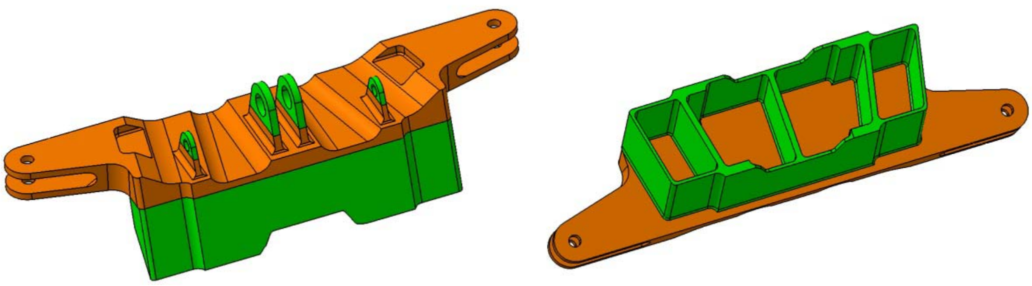


Figure 6-40 Feature based 3D model of the forward fitting

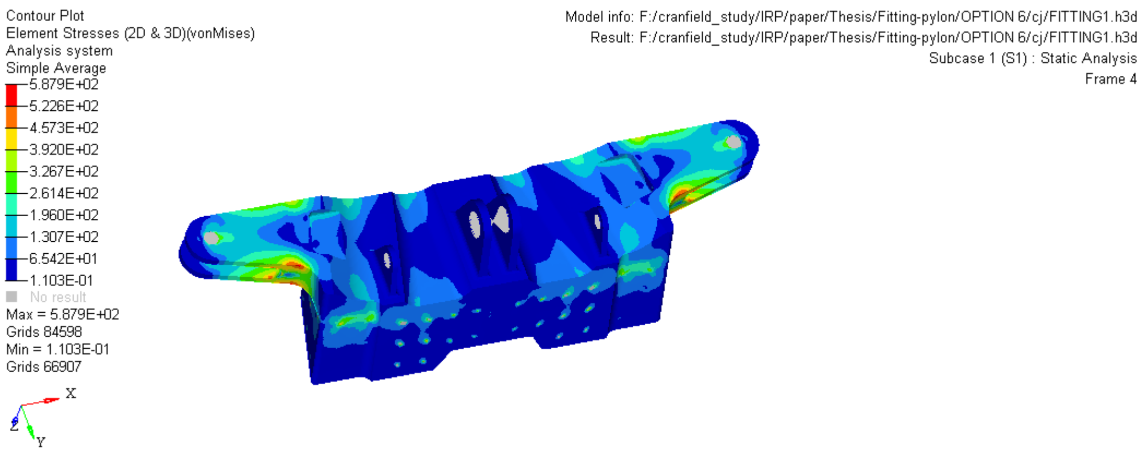


Figure 6-41 VonMise stress distribution nephogram of the final design

Using Equation (5-7) re-check the properties:

- Machining part:

$$MS_{(\text{ultimate load})} = \frac{F}{f} - 1 = \frac{896.35 \times 0.8}{587.9} - 1 = 0.22 > 0$$

Herein, F=896.35MPa (Richard et al., 2003)

- WAAM part:

$$MS_{(ultimate\ \ load)} = \frac{F}{f} - 1 = \frac{923 \times 0.8}{392} - 1 = 1.24 > 0$$

Therefore, the MS value of the hybrid design is 0.22 which meets the properties requirement.

6.5 Validation

6.5.1 General information of experts

The general information of experts who participated in the judgement is listed in Table 6-5. Two of them are university professors and the others are from COMAC.

Table 6-5 General information of the experts

Title	Company/Institute	Main Research area
Professor	Zhejiang University	Feature based CAD/CAM, Virtual design and processing
Professor	Nanjing University of Aeronautics and Astronautics	Mechanical and electrical products innovation design and development
Expert	COMAC	Over 30 years on aircraft manufacturing process
Expert	COMAC	Over 40 years on metal material and manufacturing process
Senior designer	COMAC	Over 10 years on aircraft structure design

6.5.2 Experts' judgement

6.5.2.1 Research aim and methodology

The research aim is explicit and realized well in this MSc project. The whole project was implemented step-by-step according to the research methodology.

6.5.2.2 Design method

All experts considered the design model is to be good and able to guide the design step by step to achieve an optimum design solution. Furthermore, the evaluation chart works well. It provides a good concept that different industries can develop based on their particular requirements.

In addition, experts from COMAC proposed that it is necessary to decide the design objectives and weighting value more rationally. For example, it is better to increase the weighting value of “Performance” in the aircraft industry because the foremost design objective is to ensure the safety of the passengers. Moreover, it is necessary to consider the deformation of welding process during the creation of hybrid design solutions.

The developed design guideline is acceptable. However, with the development of WAAM process it can be improved to add more features that could show its superiority of manufacturability. Furthermore, the COMAC expert highlighted the importance of guaranteeing the stability of WAAM process parameters and accumulating data during real production to obtain approval of airworthiness from the appropriate authorities.

6.5.2.3 Case study

The case studies effectively verify the design model and guideline. The integral panel is popularly used in the aircraft structure and the hybrid design method similarly impresses as it leads to significantly low cost. The case 2 and case 3 are typical parts in the pylon. The cost and weight were reduced significantly. WAAM is an ideal process for Ti alloy parts with high “buy-to-fly” ratio. The FEA method ensures that the final design meets the performance requirement. Furthermore, the academic experts considered it possible to use this hybrid design method in the aircraft structure, such as the wing and fuselage, while the experts from COMAC suggested that it can be firstly used in non-critical structures and some difficult machined parts, such as system bracket and unpressurized floor structure.

6.6 Summary

Three case studies have been carried out in this chapter. The case study was presented step by step according to the hybrid design guideline. The design solutions were decided based on the WAAM feature in accordance with the design guideline and the results of Finite Element Analysis. Furthermore, the evaluation matrix chart works well to identify the optimum design solution.

Validation was achieved through academic and industrial experts. The design model and feature based design guideline can acceptably be used in aircraft structural design. In addition, the evaluation matrix chart was improved in accordance with the suggestions from experts.

7 Discussion and Conclusions

7.1 Introduction

A hybrid design method based on WAAM technology has been developed. Proposed hybrid design solutions can be created step-by-step. The evaluation matrix chart is applied to assess the created hybrid design solutions to achieve the optimum design. This hybrid design method combines conventional processes with WAAM process which aims to achieve less cost. Furthermore, Finite Element Analysis is introduced to check stress distribution and help to decide the rational hybrid design. The key findings of this research are summarized in this chapter. The contributions of knowledge, limitations of the research and future work are also emphasized here, together with the conclusions.

7.2 Key Findings

WAAM is a developing rapid prototyping and manufacturing technology. Compared with other additive manufacturing, the remarkable advantages of WAAM technology are high deposition rate, large component scale and low cost. The developed hybrid design method based on WAAM technology was validated to decide the hybrid design solution effectively that can take advantage of these superiorities very well. The research aim and objectives have been achieved by this research. Findings of this research are summarized as follows.

7.2.1 Literature review

As a new process, there is little publication of WAAM technology, especially the design aspect. Therefore, in order to obtain a fully rounded understanding of WAAM technology and current design concept, the literature review of this research covers four areas: additive manufacturing, engineering design methods, design for manufacturing and design manual. The fundamental knowledge about WAAM technology and engineering design method was gained as follows.

- **The characteristics of WAAM technology:** compared with Laser Additive Manufacturing and Electron Beam Melting, the main advantages of WAAM are high deposition rate, large component scale, low cost of equipment installation and maintenance. Therefore, WAAM process has no advantages in terms of manufacturing high-precision and complex parts such as small functional parts, airborne structures, and biological bones. However, WAAM demonstrates the huge superiority in making larger structural parts that meets the demand of the aircraft industry.

- **WAAM process:** WAAM can use all existing wire based welding processes and weld able materials. The systems can be built by integrating the common motion system and the commercial welding equipment, but also by refitting the existing welding machines, which is easier for batch production.
- **Engineering design method:** The engineering design methods have already developed maturity, and have also been applied to actual projects. Adding a hybrid design concept into existing mature design method will be a meaningful effort.
- **Design manual:** The design manual is a necessary tool for guiding design. It is useful to develop a design manual for WAAM process according to the needs of the designer.

Furthermore, the research gaps were summarised through the literature review that verified the research motivation and drove the author to focus on the development of design method based on WAAM technology.

7.2.2 Data collection and analysis

An investigation into the application of additive manufacturing and aircraft structure design was conducted with 33 engineers in the Chinese aircraft industrial by use of a questionnaire. The results indicated that no parts made by additive manufacturing have been applied to the Chinese aircraft industry. The only attempt is the windshield framework of a physical prototype made by laser additive manufacturing. Therefore, it is not easy to spread the application of WAAM technology in the aircraft industry. Through this survey, the main structural design objectives have been obtained. The “performance” is the key objective among structure design objectives of the aircraft.

Furthermore, this research summarized the technical data of WAAM technology through the literature review and semi-structural interviews with academic experts. It is really important to analyse and accumulate data of process and properties and formalize them as industry specifications or standards. It is the most basic condition for the application in the aircraft industry. The technical data should include process parameters, dimension parameters, mechanical properties, raw material specification and inspection standard.

7.2.3 Design method development

A step-by-step design model based on WAAM technology has been established, which can guide the designer to create and assess proposed hybrid designs to achieve the optimum hybrid design. In addition, the design parameters of Ti alloy WAAM features were summarized and compiled as a WAAM feature based design guideline. It can help designers to decompose the features of object and decide the hybrid design solutions based on WAAM features.

The advantages of the design model are listed below:

- It combines conventional manufacturing process and WAAM process in design that leads to less cost.
- The evaluation method in design model is extendable. It can be modified to adapt the product design of various industries.
- The creation of design solutions is flexible and free that will not restrict the creative thinking of designers.
- The evaluation process is based firstly on the performance analysis so as to guarantee the feasibility of proposed hybrid design solutions.

The disadvantages of the design model are summarized as follows:

- The obtained data for Ti alloy WAAM is limited to walls and intersection features, so WAAM process can be only used to produce these features in this research.

- It is not easy to decide the design objectives and their weighting value which significantly affects the final decision. It is better for a specific user to identify these items based on large data analysis in their own industry.

- The evaluation process is a qualitative analysis regarded the preliminary design as benchmark.

The “performance” is the most important objective in the aircraft structure design. In the evaluation chart, it uses the assessing value criteria rather than the pass/fail criteria, which defines WAAM using on the PSE as “low risk”. The pass/fail criteria are easier for the designer to make a decision. A creative design may usually bring risk in the aircraft structure design. However, technology innovation is necessary for the development of the aircraft industry. Therefore, it is not simply “yes” or “no”. It is useful to measure the risks and benefits when making a decision in the initial application stage. After the WAAM technology is maturely used in the aircraft industry, the pass/fail criteria will be the best choice.

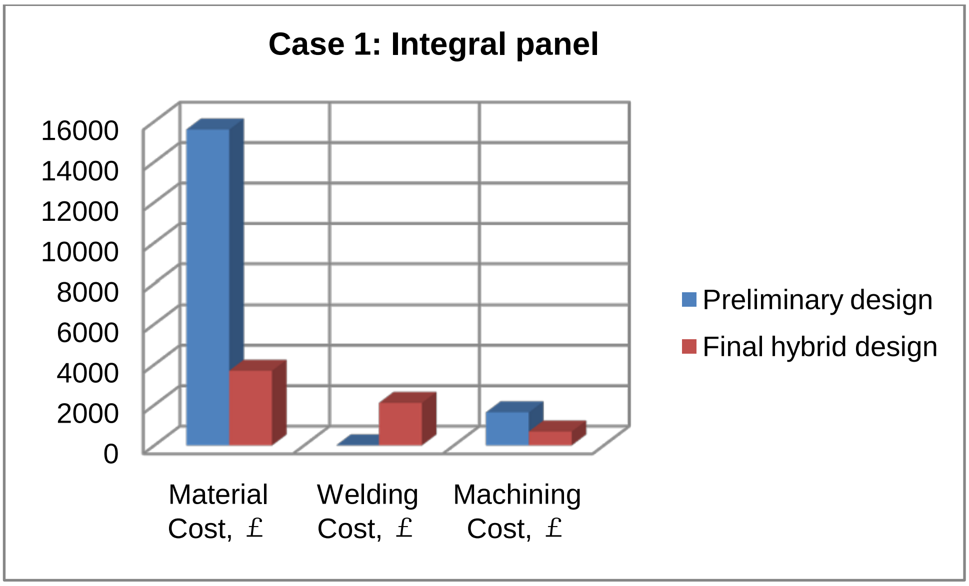
7.2.4 Case studies

The design constraints of the first case study were set according to the recommended design parameters of Ti alloy WAAM features. It shows a typical design for WAAM process.

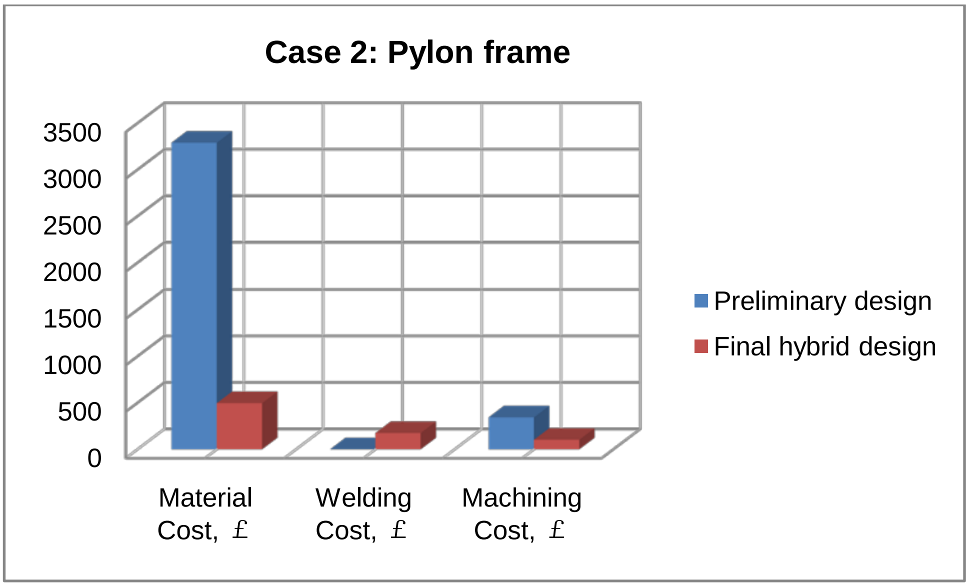
Case 2 &3 are real industrial parts. The hybrid designs of these two parts lead to significantly reduced cost as well as lower weight, which show that the hybrid design method can theoretically bring great benefits to the aircraft industry. Furthermore, it makes the designers in the Chinese aircraft industry familiar with the WAAM technology and hybrid design concept and offers them another choice to design the part with less cost and weight. However, as a novel manufacturing process, it must be careful to use the WAAM process in the critical aircraft structure. Comprehensive analysis and test is necessary before actual use. It is better to first use the developed hybrid design method in non-critical areas of the aircraft, and then expand gradually to the key components

Figure 7-1 presents cost distribution of the preliminary and the final hybrid design. It can be seen that, the material cost of the hybrid design is reduced significantly compared with the preliminary design, while the manufacturing cost of the hybrid design is increased a little due to the addition of welding process. Therefore, the total cost is decreased significantly owing to the effective material utilization that really presents the superiority of the WAAM process. The cost estimation of case 1 is reduce by 61% compared with the preliminary design, and that of case 2 and case 3 are decreased by 77.3% and 48.9% respectively. In addition, it also demonstrates that the WAAM process is appropriate for large sizes parts.

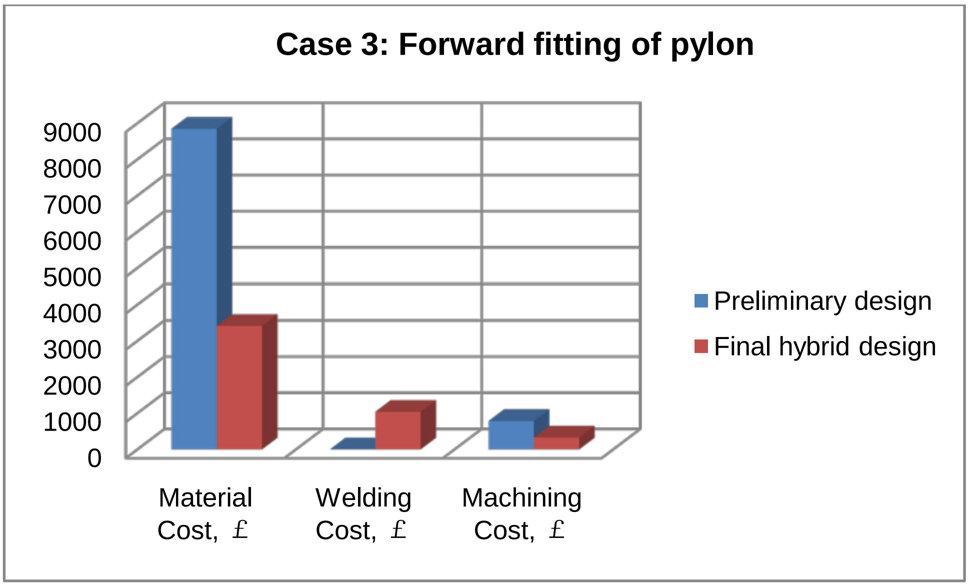
Finite Element analysis and topology optimisation are introduced in this hybrid design method, which contribute great to performance analysis and design improvement. Weight of the pylon frame is reduced by 24.4% while that of the forward fitting is decreased by 8%.



(a)



(b)



(c)

Figure 7-1 Cost distribution of the preliminary and the final hybrid design:

(a) integral panel; (b) pylon frame; (c) forward fitting

7.3 Contribution to Knowledge

The developed hybrid design method based on WAAM technology is the main contribution to knowledge in this research. In detail, the following contributions are most relevant:

- **Summary of WAAM technical data:** The technical data of Ti alloy of the WAAM process is summarised in this research, such as welding process, geometry parameters, materials and mechanical properties.

- **Hybrid design method based on WAAM technology:** An effective step-by-step hybrid design method was developed, which aims to guide the designers to create and assess the hybrid design solutions based on WAAM technology.

- **The investigation of WAAM process in the aircraft industry:** Questionnaires and interviews have been carried out in the aircraft industry. It not only collected numerous constructive suggestions on developing the hybrid design method, but also enabled the industrial technicians to become familiar with WAAM technology and the hybrid design concept. Furthermore, two industrial case studies were carried out in this research and validated by three industrial experts.

7.4 Limitations of the Research

There are a number of limitations which are listed below:

- **The evaluation chart:** The design objectives and weighting values were collected and summarized through a questionnaire. There could be some design objectives that have not been considered. The weighting value may also need to be set with more rational.

- **WAAM feature based design guideline:** The WAAM feature based design guideline only contains the wall and intersection features of Ti-6Al-4V alloy. More WAAM features and technical data, especially mechanical properties, should be developed in WAAM process.

- **Case study:** The case studies were not conducted with real manufacturing owing to the limitation of research time.

7.5 Future Work

The research introduced in this thesis can be further extended into following possible research areas:

- Build real parts and validate the evaluation matrix and weighting factors. Weighing objectives and values can be improved or modified. Moreover, check the accuracy of the cost model as well as the benefits simultaneously.

- Develop typical WAAM features that are difficult for conventional subtractive manufacturing, such as complex double curved features and closed angle structures; and establish whole technical database of these features step by step.

- Cooperate with the aircraft industry to build real parts and do comprehensive mechanical and fatigue properties tests, accumulate technical data (e.g. tensile properties, fatigue crack growth rate, fracture toughness, density and

Young modulus) which are necessary for aircraft structure design. Furthermore, the process parameters should be fixed, and then develop an industrial process standard.

- The evaluation method developed in this research is significantly affected by the knowledge background of the user. The solution is to set up an expert system to help the designer select optimum design solutions automatically. In order to realize this ambition, a comprehensive database of WAAM features catalogue is necessary. Furthermore, a lot of work should be done to establish an expert knowledge database about manufacturing difficulty. The cooperation with the aircraft industries is essential to achieve this goal.

7.6 Conclusions

This thesis has developed a hybrid design method based on WAAM technology in the aircraft industry, which is a necessity for promoting the application of WAAM technology. A literature review, questionnaire and semi-structured interviews with academic and industrial experts were carried out to achieve the research objectives. The developed method is proven to be a helpful and effective approach for guiding designers to obtain the optimum hybrid design. The results of this research are summarised as follows:

- The knowledge of WAAM technology has been systematically analysed and well understood and incorporated into the hybrid design method.

- The hybrid design method based on WAAM technology effectively combines the conventional subtractive process and WAAM process leading to less cost by reducing the material cost.

- The evaluation method is proven to be useful and effective to decide the optimum hybrid design through case studies.

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APPENDICES

Appendix A **Questionnaire**

Hybrid design based on Wire and Arc Additive Manufacturing in the aircraft industry

This questionnaire is part of MSc research project entitled "Hybrid design for WAAM in the aircraft industry". This research implies the analysis of efficient ways of making hybrid parts which are partially made by Additive Manufacturing and partly made by conventional means.

This questionnaire is aim to collect information about design method in the aircraft industry. With the collected information, a Hybrid Design Method will be developed aiming to guide design.

Thanks for participating this research. If, required, the analysis results can be sent to you. In addition, the collected data will be treated confidentially. The original records will be destroyed after the thesis is finished and not be spread to any other organization or person.

Note: Please write the letter of your choice(s) (e.g. A, B, or C …) in the box or write your answer on the line below the question. If other, please list it out.

Name(optioned): ____________________________________

Company/Institute (optioned): ____________________________________

1 Respondent's general information

1.1 Please choose the type of your company/Institute? (Please choose the most suitable option)

A.	Aircraft manufacturing company	B.	Aircraft R&D Institute
C.	University	D.	Other

Other: ______________________________

1.2 What is your job? (Please choose the most suitable option.)

A.	Design engineer	B.	Manufacturing engineer
C.	Researcher	D.	Student
E.	Other		

Other: ______________________________

1.3 How long have you worked at this job?

A.	Ten years or more	B.	Five to ten years
C.	Three to five years	D.	One to three years
E.	Less than one year		

2 Design Method for WAAM

2.1 Has your company/institute used additive manufacturing technology? （e.g. Laser power Fabrication）

Yes	Not sure	No

If yes, please list the additive manufacturing technology and the types of the parts or the names of the parts.

___

2.2 From your experience, is it necessary to develop a design method for WAAM?

Yes	Not sure	No

Please give reasons:

___

___

___

2.3 Which approach do you think is the best choice to develop the design method for WAAM? (Please choose one option)

A. Develop a completely new design method for additive manufacturing

B. Develop a method by modifying existing mature design method

C. Use the existing mature design method directly

D. Not sure

Other: ___

Please give reasons:

___

___

2.4 Considering the manufacturing cost, which material do you think is more suitable for WAAM in the aircraft industry? Please rank the materials from high to low.

A. Titanium alloy

B. Steel

C. Aluminium alloy

D. Copper alloy

E. Not sure

Other:

2.5 What are the challenges of using WAAM technology in aircraft industry? (Multiple-choice)

A. Airworthiness

B. Design method

C. Design Handbook

D. Devices

E. Process

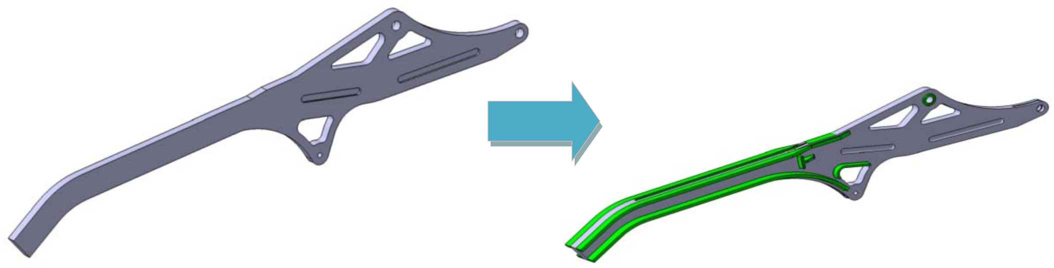
F. Properties

Other:

2.6 Supposed following two designs both meet the requirements of function and strength properties, which design do you think is the better one?

A. Manufactured by Ti-6Al-4V plate machining (Kazanas, 2011)

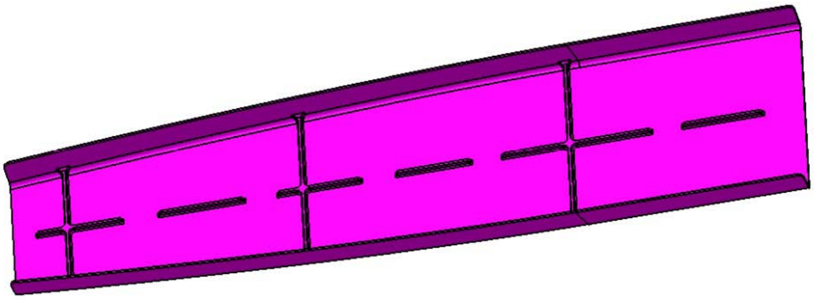
B. Manufactured by Ti-6Al-4V plate machining (Grey feature) and WAAM (Green features) (Kazanas, 2011)



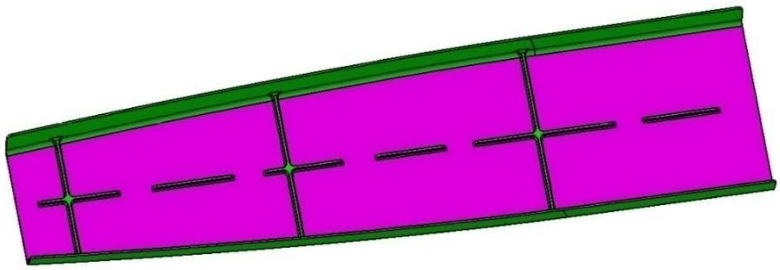
Other: ______________________________

2.7 Supposing following two designs both meet the requirements of function and strength properties, which design do you prefer to use?

A. Manufactured by Ti-6Al-4V plate machining



B. Manufactured by Ti-6Al-4V plate machining (Red features) and WAAM （Green features）



Other: ______________________________

3 Structure design objectives of the aircraft

3.1Please choose the main design objectives in the aircraft structure design. (Multiple-choice)

A. Performance   B. Technical complexity   C. Weight

D. Cost   E. Manufacturing time   F. Batch size

G. Other

Other: ____________________

3.2 Please rank the following items and give each item a numerical value according to the degree of importance in the aircraft structure design.

Rank order：（e.g. A B D C E F）

____

Notes:

Very important: 7-9;

Important: 4-6;

Ordinary: 1-3

A. Performance ☐

B. Technical complexity ☐

C. Weight ☐

D. Cost ☐

E. Manufacturing time ☐

F. Batch size ☐

G. Other

______________________ ☐

Please write down any words you would like to give this project. (Suggestion or comment)

Suggestion :

End of the questionnaire.

Thank you for the participation.

E-mail: j.chen@cranfield.ac.uk

Appendix B Questions for validation

B.1 Questions for the design method

1) What do you think of the developed hybrid design model? If possible, please give your suggestions?
2) What do you think of the evaluation method of “Analysis for hybrid design”? If possible, please give your suggestions?
3) What do you think of the developed design guideline? If possible, please give your suggestions?

B.2 Questions for the design method

1) What do you think of the case studies? If possible, please give your suggestions?

2) Would you consider using this hybrid design method? Why?

3) In your opinion, what kind of part in the aircraft industry is suitable for hybrid design based on WAAM technology?

Appendix C The calculation of the weighting values

Respondents	Performance (T_1)	Technical complexity (T_2)	Weight (T_3)	Cost (T_4)	Manufacturing time (T_5)
1	9	6	5	5	2
2	9	7	6	5	2
3	9	4	5	4	1
4	9	5	5	5	2
5	8	3	6	4	1
6	9	8	7	2	1
7	9	6	5	5	1
8	9	7	6	4	2
9	9	6	7	6	1
10	8	5	6	6	2
11	8	4	6	6	1
12	9	2	5	4	2
13	9	6	5	5	2
14	9	6	6	7	1
15	9	6	5	8	5
16	9	6	7	3	3
17	8	5	6	6	2
18	9	5	4	4	1
19	9	5	4	4	1
20	9	3	7	7	1
21	9	4	6	6	3
22	9	6	4	7	1
23	9	6	6	4	2
24	8	6	7	7	2
25	9	5	5	5	1
26	8	4	5	5	4
27	9	4	6	5	2
28	8	3	4	5	1
29	9	4	7	7	2
30	9	5	7	6	4
31	9	6	6	6	2
32	8	4	5	6	3
33	9	5	6	5	1
$W_j = \sum_{i=1}^{33} O_{ij}$	289	167	187	174	62
$Wt_j = \frac{W_j}{\sum_{j=1}^{5} W_j}$	0.33	0.19	0.21	0.2	0.07