APPLICATION RESEARCH OF LARGE-SCALED COMPLICATED FRAME-BEAM INTEGRAL COMPONENT BASED ON ELECTRON BEAM ADDITIVE MANUFACTURING

Ping Xu*, Xiangming Wang*, Shiquan Bi*, Hao Cui*
***Shenyang Aircraft Design & Research Institute of AVIC**

Keywords: Electron beam additive manufacturing, 3D Printing, Frame-beam Integral Component, Subarea Deposition, Deposition Joint.

Abstract

Due to the requirements of strength, stiffness and temperature, the main frames and beams of aircraft choose titanium alloys as the materials. Traditionally, these structures are all single plane structure because they are manufactured independently, and then are mechanically connected to an integral component. With the requirement of lightweight and the development of materials and manufacturing technology, it is gradually evolved into space structures, frame-beam integral components. In this research, a novel method of fabricating frame and beam integral components is provided by using electron beam additive manufacturing which is a kind of 3D printing. Subarea deposition and deposition joint are adopted creatively to improve the forming efficiency of the structure. The invention of conformal annealing could control structure deformation effectively. The results of the basic mechanical properties of the new structure and typical structures test indicate that electron beam additive manufacturing exhibits obvious directionality. If the T-L direction is chosen as the main force direction of a frame-beam integral component, the fatigue performance might be slightly higher according to the above results. It is proved that the whole weight of frame-beam integral component can achieve more than 10% weight benefit.

1 Introduction

Due to the requirements of strength, stiffness and temperature, many aircraft frames and beams are manufactured by titanium alloy materials. Traditionally, these in-plane airframes and beams were fabricated separately and fastened together. As the lighter aircraft structures are demanded, meanwhile with the development of new materials and advanced manufacturing technologies, It is possible that the conventional separated airframes and beams could be shaped into a three-dimensional structure even without any fasteners. The titanium alloy electron beam additive manufacturing(EBAM) provides a solution for such a large complicated structure called frame-beam integral component in this paper.

Electron beam additive manufacturing is an important branch of three-dimensional printing technologies. There are many other titles for this technology at domestic and abroad, for example, Electron Beam Freeform fabrication(EBF3)[1], Electron Beam Rapid Manufacturing(EBRM)[2], Electron Beam Additive Manufacturing (EBAM)[3]. In this article, it is unified as Electron Beam Additive Manufacturing(EBAM). EBAM is a relatively novel layer-additive manufacturing process which was developed over the past 15 years to directly fabricate complex metal components by using computer aided design (CAD) data. In a vacuum environment, a molten pool is created by electron beam on a substrate and moves along the paths designed by computer program. The metal wire is fed into the molten pool and deposited layer by layer to form a near net shape metal part[2].

the EBAM process has such superiorities as shorter depositing time than conventional casting, forging or other direct metal deposition technologies [4-6], for instance, in excess of 3500 cm3/h for titanium or aluminum alloys[7], and excellent mechanical properties might be obtained which is comparable to those of forged plate in some circumstances[8]. Together with the benefits of lower cost, lighter structure weight and less assembly time, this technology, therefore, has wide-spread potential applications for fabrication of large aircraft structures such as airframes and beams. The titanium wing beam of F-35 Lighting II Joint Strike Fighter was fabricated by this technology which size reaches 5.3m$\times$0.3m$\times$0.2m. It is estimated that the cost can be reduced by 30% to 50% [9]. Nevertheless, there remain challenges on manufacturing to large-scaled airframe-beam integral components due to its complexity and deformation.

In this paper, an innovative frame-beam integral component fabricated by EBAM is introduced which size is 2.8m$\times$0.6m$\times$0.6mm. Unlike the above wing beam, this part is very large in the other two directions which means some effective methods should be used to solve the deformation problem. In the course of research, subarea deposition and deposition joint which greatly improve the forming efficiency and deformation of the structure are adopted creatively. Conformal annealing technology controls structure deformation effectively. The results of basic mechanical properties and typical structures test indicate that the part exhibits excellent performance and obvious directionality. Compared to conventional forging components which fastened together, the whole weight of frame-beam integral component is estimated to achieve about 8% to 10% weight benefit.

2 Materials and methods

According to the characters of EBAM, a lot of aircraft parts which cannot be made if using traditional methods are fabricated. Shown in Fig.1 are two joined structures applied to connect three aircraft products containing sophisticated outer surfaces. And the sizes of these two structures are approximate 250mm$\times$200mm$\times$140mm. Illustrated in Fig.2 is a self-balancing beam whose dimension is about 1050mm$\times$10mm$\times$70mm. Fig.3 presents one part of an airframe which has a size of 1400mm$\times$450mm$\times$80mm. Such an EBAM structure saves about 8% of weight compared with the traditional one fastened through three subcomponents.

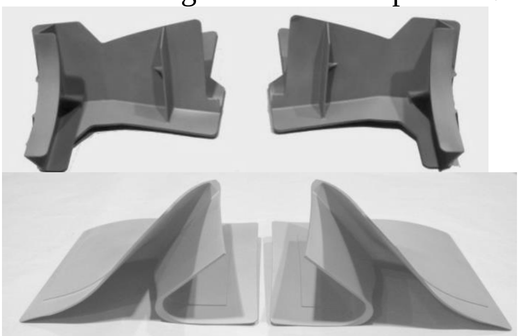


Fig.1. Upper and lower lip joint of air inlet

Fig.2. Self-balancing beam

Fig.3. One part of an airframe

Based on the above investigations, much more complicated large-scaled frame-beam integral component is studied and manufactured. The traditional airframe and beam are combined together, which excludes connecting box and fasteners. There, consequently, are more than 10% of weight saving achieved. Fig.4 and Fig.5 demonstrate the technical design schemes and prototype parts respectively.

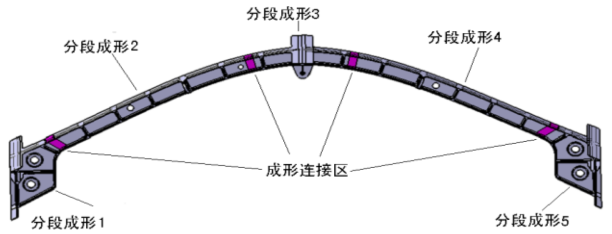


Fig.4. Technical design schemes of a large-scaled frame-beam integral component

Fig. 5. Prototype parts of a large-scaled frame-beam integral component

Because of the large dimension which is up to almost 2840mm × 600mm × 610mm, four main researches are applied for the manufacturing scheme.

The first one is subarea deposition for efficiency-improving. EBAM equipment is able to achieve the synchronous deposition of different partitions in the same heat source. The deposition efficiency, therefore, could be improved significantly via portioning the large-scaled component into 5 parts.

Secondly, there is possibility of fabricating oversized sophisticate frame-beam component through joining the rough parts made from the subarea deposition process which is called deposition joint.

Thirdly, conformal annealing can be done to control the deformation. This process is obtained utilizing the large-power electron to scan the forming parts online repeatedly, which can eliminate the residual stresses. Therefore, the deformation of frame-beam component is restrained, and HIP treatment obviously improving the inner quality by decreasing micro-defects and improving fatigue performance.

Finally, EBAM has the capability of feeding the wires from several channels, and the wires' materials can be different in every channel. According to the application requirements, the part of airframe utilizes TC4, and the material of attachment lug chooses TC11. Consequently, this graded structure[10] can meet the demands of strength, fatigue and damage tolerance. The deformation of the deposited frame-beam integral structure is less than 5mm/m, when it is checked through lineation detection in the N C machine.

3 Results and discussion

Performance researches of TC4 EBAM frame-beam integral component contains basic mechanical properties, dissection performance and the assessments of typical structural components.

3.1 Basic mechanical properties

Since the mechanics performs directional features based on the deposition routes of EBAM, the basic mechanical properties are investigated. And it is defined that the longitudinal direction (L) is in-plane scanning path of the electron gun, while the transverse one (T) is in the same plane and perpendicular to L direction. Clearly, the short transverse direction (ST) is along the thickening path. Table. 1 provides the tensile strength, impact ductility and fracture toughness under room temperature. Illustrated in Table.2 is the fatigue data under axial loading.

Table 1
Basic mechanical properties of EBAM under room temperature

	L	T	ST
Tensile strength σ_b(MPa)	942 ~ 975 958	955 ~ 975 965	885 ~ 898 886
Impact ductility a_{kU}(J/cm^2)	71 ~ 83 76	66 ~ 74 70	71 ~ 74 72
Fracture toughness K_{IC}(MPa·$m^{1/2}$)	L-T	T-L	——
	124,121,122	135,138, 139	

Table 2
Fatigue data under axial loading

	Stress concentration coefficient	Stress ratio	$N=10^7$ Fatigue limit
L	K_t=1	R=0.06	σ_D=626MPa
L	K_t=3	R=0.06	σ_D=288MPa
L	K_t=5	R=0.06	σ_D=171MPa

It can be concluded from Table 1 that there is little difference of tensile strength between L and T direction, however, ST direction's strength is just below 70 MPa. In terms of impact ductility in the room temperature, these three directions are almost the same while the fracture toughness of T is a bit better than L direction.

3.2 Mechanics performance of dissections

Anatomic sampling is complete from non-graded compound zones of the large-scaled frame-beam integral structure, and the mechanical properties are tested. The samples contain L, T, ST directions of bases, L direction of deposition joint, as well as the interface zones (The intersection of frame and beam). Based on the above samples, the tensile strength, impact ductility and fracture toughness under room temperature are measured, shown in Table 3. Table 4 summarizes the high-cycle fatigue testing results.

Table 3
Tensile strength, impact ductility and fracture toughness under room temperature under room temperature

	L	T	ST	L of deposition joint	Interface zones
Tensile strength σ_b(MPa)	946 ~ 970 958	948 ~ 975 962	885 ~ 898 890	949 ~ 968 958	873 ~ 882 878
Impact ductility a_{kU}(J/cm^2)	69 ~ 83 76	65 ~ 81 74	71 ~ 76 74	63 ~ 71 67	65 ~ 72 68
Fracture toughness K_{IC}(MPa·$m^{1/2}$)	T-L	L-T	——	——	——
	129,133	116,120			

Table 4
High-cycle fatigue testing results

	Stress concentration coefficient	Stress ratio	$N=10^7$ Fatigue limit
L	K_t=1	R=0.06	σ_D=609MPa
L	K_t=3	R=0.06	σ_D=284MPa
L of deposition joint	K_t=1	R=0.06	σ_D=494MPa
Interface zones	K_t=1	R=0.06	σ_D=580MPa

The above two tables present that the tensile strength in L, T directions is more excellent than ST direction, while the tensile strength at deposition joint and interface zones are separately equivalent to L and ST direction. Few distinctions in the impact ductility of different directions can be found. Besides, high-cycle fatigue property in the deposition joint is relatively low, which should be payed attention when it is applied to the structures which requiring long fatigue lives.

3.3 Assessment of typical structures

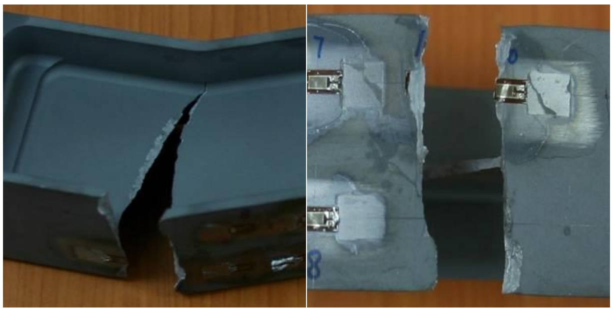
In order to assess the influences on loading capability of the structures fabricated from different deposition directions, four-point bending beams, as well as attachment lugs in L and T directions are manufactured and examined through static and fatigue tests and the data are shown in Table 5.

Table 5
Results of static and fatigue tests

Type of specimen		Collapsing load（kN）	Fatigue lives $N_{95,95}$(cycles)
Four-point bending beams	L	124.04	8323
	T	126.68	12896
Attachment lugs	L	227. 67	19329
	T	231. 98	25684

The failure modes demonstrated in Fig. 6 of four-point bending beam is the flange of T direction is compressed into buckling, while the flange of L direction beam is pulled into fracture. In addition, the collapsing load of T direction beam is a little bigger than L, which means T direction specimen owns stronger fracture resistance. As for the fatigue life of four-point bending beams, T direction is a bit better than L one. And the specific reason need to be further studied.

Fig.6. Failure modes of four-point bending beam



There is almost no difference in the static results of attachment lugs between T and L directions, while the T direction specimen performs better fatigue property than L one.

4 Conclusions

Four conclusions can be summarized from the above researches:

(1) EBAM is able to control the parts deformation and quality, which is pretty suitable for the large-scaled frame-beam integral component.

(2) The performances of EBAM component indicate the technology's directional. Although the basic mechanical properties of L and T directions are the same, the typical structures formed in T direction have a little better fatigue performance than L. And the specific reason need to be further studied.

(3) It is worth noticing that the fatigue performance at deposition joint is relatively low, which should be taken seriously in structural design and manufacturing.

(4) EBAM provides a possibility for fabricating large-scaled complex components, therefore, it endows a broad application prospects in aviation industry.

References

[1] Taminger K. M. B. and Hafley R. A. *Characterization of 2219 Aluminium Produced by Electron Beam Freeform Fabrication[C]*. in Proceedings of 13th SFF Symposium.Austin., 2002: 482-489.

[2] Suo H. B., Liu J. R., Gong S. L., et al. *Microstructure and Mechanical Properties of Ti-6Al-4V Fabricated by Electron Beam Rapid Manufacturing[J]*. Rare Metal Materials and Engineering, 2014, 43(4): 0780-0785.

[3] Stecker S., Lachenberg K. W., Wang H., et al. *Advanced Electron Beam Free Form Fabrication Method &Technology[C]*. Society of Manufacturing Engineers Technical Conference Session, 2006, 2: 35-46.
[4] Taminger K M B, Hafley R A, Dicus D L. *2002 International Conference on Metal Powder Deposition for Rapid Manufacturing*[C]. San Antonio, TX: Metal Powder Industries Federation, 2002: 51

[5] Stecker S, Lachenberg K W, Wang H *et al*. *Society of Manufac- turing Engineers Technical Conference*[C]. SME, TP06PUB111, 2006

[6] Karen M B Taminger , Rober A Hafley. *AeroMat 2005*[C]. Or- lando, 2005

[7] Taminger K M B. *Advanced Materials & Processes*[J], 2008, 166: 25
[8] Taminger K M B, Hafley R A. *The 3rd Annual Automotive Composites Conference*[C]. Troy MI: Society of Plastics Engineers, 2003

[9] Guan Qiao *3D Printing & Generalized Additive Manufacturing* Mianyang International Manufacturing Conference, 2015

[10] Ting-ting QIAN, Dong LIU, Xiang-jun TIAN, Chang-meng LIU, Hua-ming WANG *Microstructure of TA2/TA15 graded structural material by laser additive manufacturing process* Trans. Nonferrous Met. Soc. China 24(2014) 2729−2736

5 Copyright Issues

Contact Author Email Address

e-mail: zhxpzzx@sina.com

Copyright Statement