GENERALIZED ADDITIVE MANUFACTURING BASED ON WELDING/JOINING TECHNOLOGIES

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Being in the leading position of non-conventional welding technologies R&D in China, Beijing Aeronautical Manufacturing Technology Research Institute (BAMTRI) has been involved in a number of research programs relating to generalized additive manufacturing based on welding/joining technologies. Such research programs and projects provide aviation industry a rapid response in design and trial manufacture of new products. BAMTRI, founded in 1957, is a comprehensive research institute specializing in the research of advanced aeronautical manufacturing technologies and development of related equipment as well as promoting such technologies and equipment to industrial applications. Based on its superiority in electron beam, laser beam, plasma & ion beam processing technologies, the National Key Laboratory for Power Beam Processes was established at BAMTRI in 1993. Power beam welding/joining/processing and solid state welding/joining are the two most important R and D areas at BAMTRI to solve the «unique» and «critical» problems in modern aeronautical manufacturing as well as to establish the technical basis for generalized additive manufacturing, providing frontier technologies and related machinery to aviation enterprises in China. 10 Figures.

Keywords: *survey, non-conventional welding technologies, power beam welding, additive manufacturing, aviation industry, application*

Non-conventional welding/joining technologies at BAMTRI. To meet the increasingly growing demands of the aviation industry to develop new aircrafts and aero-engines from generation to generation, continuous efforts have been made to exploit advanced welding/joining technologies. New methods and related equipments have been developed for precise and automatic material processing and structural elements forming. For the past half century, a system of non-conventional welding/joining technologies for aeronautical manufacturing has been formed at BAMTRI, which could be outlined as follows.

System of non-conventional welding/joining technologies for aeronautical manufacturing

- I Integrity of welded structures and control of stres and distortion
- II Gas shielded arc welding
- III Brazing and transient liquid phase joining (TLP)
- IV Resistance welding
- IV Power beam welding/joining/processes
  - ▲ IV-1 Electron Beam
  - ▲ IV-2 Laser Beam
  - ▲ IV-3 Plasma and Ion Beam
- V Solid state welding/joining
  - ▲ V-1 Diffusion bonding (DB) and TLP
  - ▲ V-2 Super plastic forming/diffusion bonding (SPF/DB)
  - ▲ V-3 Friction welding (FW)
    - ■ V-3-1 Inertia FW
    - ■ V-3-2 Linear FW
    - ■ V-3-3 Friction stir welding (FSW)

Among the non-conventional welding/joining technologies in this system, power beam welding/joining/processing and solid state welding/joining, as mentioned above and will be described below, are the two most important R and D areas at BAMTRI, providing tools to solve the «unique» and «critical» problems in modern aeronautical manufacturing, which are also potentially attractive and exciting for designers together with engineers to provide more creative thought and space for innovatory implementation of new products.

Power beam welding/joining/processes. Electron beam (EB) R&D activities at BAMTRI mainly involve deep penetration welding, additive manufacturing, electron beam physical vapor deposition for thermal barrier coatings (TBCs), electron beam texturing, electron beam brazing and other material processing. One of EB ma-

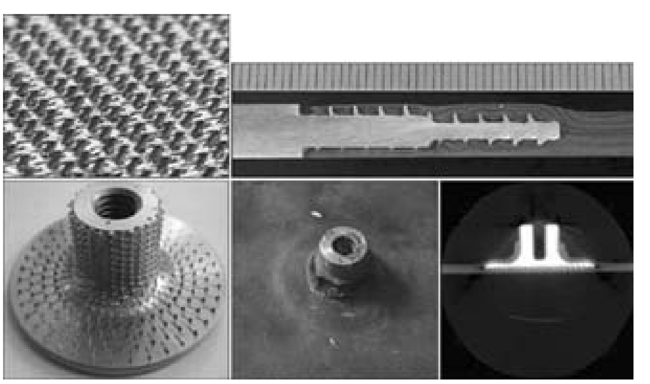

Figure 1. EB surface texturing for enhanced joining of titanium flange with composite material

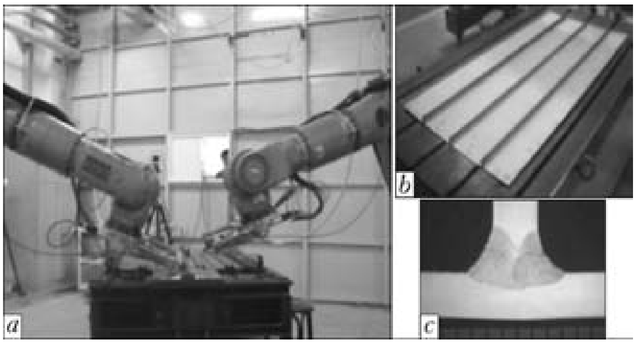

Figure 2. Dual-beam laser robotic system for welding of aluminum and titanium airframe (*a*), stiffened panels with (*b*) T-joint simultaneously from both sides of fillet welds (*c*)

chine of 150 kV, 60 kW, 85 m^3 (7.5 × 3.8 × 3 m) was built for deep penetration welding of titanium components with the thickness up to 150 mm.

The superiority of electron beam with extremely flexible scanning ability has been applied for surface texturing to obtain enhanced joining of titanium flange with polymer composite, as shown in Figure 1.

Laser Beam R&D activities at BAMTRI mainly involve welding, cutting, drilling, peening, additive manufacturing as well as hybrid laser/MIG welding, texturing and surfacing. Figure 2 illustrates an experimental set-up of dual-beam laser robotic system (Figure 2, *a*) for welding of aluminum and titanium airframe stiffened panels (Figure 2, *b*) with T-joint (Figure 2, *c*) welded simultaneously from both sides of fillet welds.

Figure 3, *a* shows an application of precise laser drilling technologies for aero-engine turbine blades. To improve fatigue life, laser peening technology is also performed on compressor blades (Figure 3, *b*).

Plasma and ion beam R&D activities at BAMTRI mainly involve plasma spraying for turbine blades with TBCs as well as nano-structured TBCs, plasma immersion ion implantation and deposition, such as TiN deposition, thin film and TiCrN multilayer film deposition on aero-engine parts.

Solid state welding/joining technologies. As mentioned above, the importance and contribution of solid state welding/joining technologies for aeronautical manufacturing are incomparable in solving specific «unique» and «critical» problems; in solid state welding/joining technologies there are no troubles and imperfections being inherent in fusion welding processes.

In the early 1980's, super plastic forming/diffusion bonding (SPF/DB) technology was firstly developed at BAMTRI for fabricating airframe titanium panels in order to reduce weight and improve structural performance. Nowadays multi-layered inner-stiffened titanium panels with complex configurations have been fabricated to meet specific requirements from aviation industry, space sector and other fields. Technical and economic benefits brought by SPF/DB are of great value for both designers and fabricators.

Linear friction welding (LFW) is an unique technique to manufacture high performance aero-engine blisks so as to replace the traditional tenon joints, achieving the weight reduction for the entire structure. Figure 4 shows a part of the as-welded blisk and macro structure of the solid

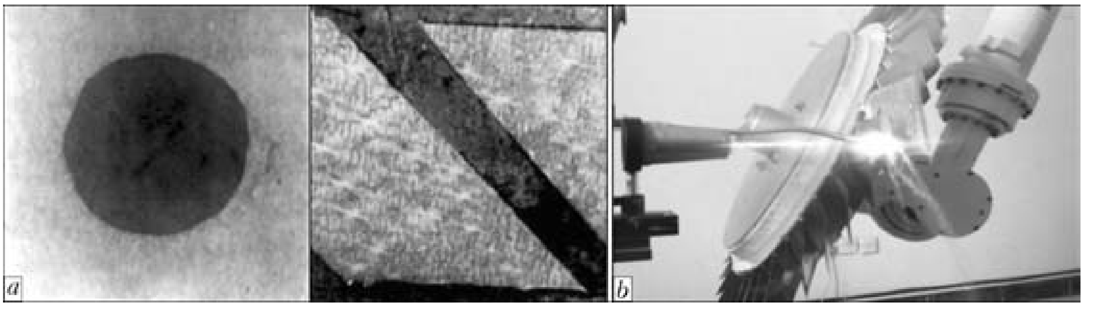

Figure 3. Laser drilling for turbine blades (*a*) and laser peening for compressor blades (*b*)

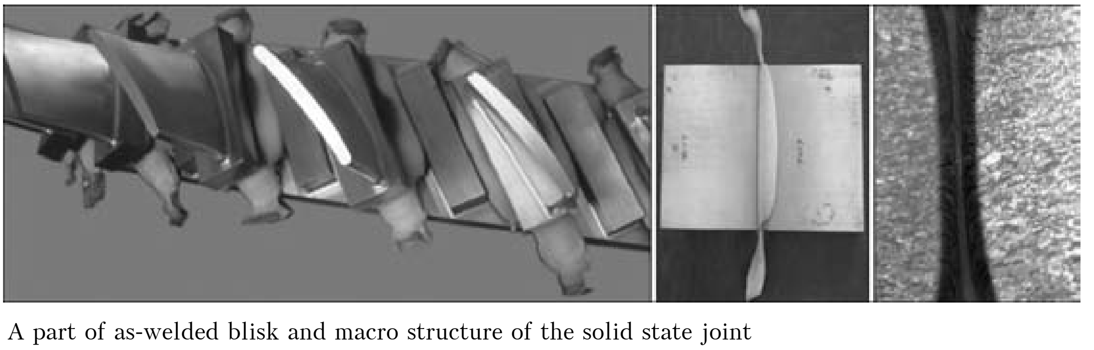

Figure 4. A part of as-welded blisk and macro structure of the solid state joint

state joint. LFW can be considered as a block joining process in solid state additive manufacturing that will be described below.

Moreover, friction stir welding (FSW), which is also a solid state welding process, has been developed at BAMTRI for over fifteen years, and this development is ongoing. As a great alternative choice, FSW has attracted more attentions to be used instead of the traditional fusion welding in the area of aluminum structure joining. Similar to the LFW, FSW is also a powerful block joining process in solid state additive manufacturing.

Understanding of generalized additive manufacturing. Additive manufacturing is different from the traditional material removal machining/cutting reduction manufacturing. In additive manufacturing, structural elements are formed usually by metal melting deposition. Such deposition is generally performed layer-by-layer with CAD/CAM techniques which is based on wire/powder feeding and melting using electron beam or laser beam. In generalized additive manufacturing, structural elements could also be produced by block joining using allied energy sources for welding/joining technologies, such as mechanical friction heating etc.

The disadvantages of traditional material removal machining/cutting reduction manufacturing techniques include low effectiveness, high material cost, and relatively long manufacturing cycle while a great portion of valuable material is turned into undesirable metal chips.

Compared with traditional techniques, additive manufacturing has many advantages and benefits, such as free forming, near net shape fabrication, material and time saving, flexibility and ability in controlling and optimizing performances of products.

Besides laser beam and electron beam, other allied energy sources are also applicable for generalized additive manufacturing, such as: chemical, electro-chemical, mechanical etc., especially pile-up forming could be performed applying block joining to produce directly integrated monolithic metallic structural elements.

From a welding researcher' s point of view the original formation of generalized additive manufacturing is buildup cladding by manual metal arc welding, or using gas tungsten arc welding as well as micro-plasma welding with wire feeding for surfacing and repair work. Although these heat sources do not possess the suitable flexibility and advantages as electron beam and laser beam used for modern additive manufacturing, all the heat sources for fusion welding are applicable for additive manufacturing, provided computer aided automation is entrusted to them. Besides, block joining processes using mechanical friction heating like linear friction welding are also considered as the solid-state additive manufacturing.

For the past two decades, the technical basis for rapid development of additive manufacturing has been attributed to the extreme flexibility of power beams like electron beam and laser beam (such as power control, focusing control, deflection capability, scanning control, long focused active zone) combined with CAD/CAM technologies. At the same time, additive manufacturing has been more and more applied for direct metal free forming fabrication.

In general, modern advanced generalized additive manufacturing could be classified into three categories: 1) direct metal free forming fabrication; 2) non-metallic parts direct manufacturing; 3) rapid bio-model direct forming.

Figure 5 shows the distinctions between additive manufacturing in a narrow sense (inner circle) and additive manufacturing in a broad sense (outer ellipse). The inner circle represents the additive manufacturing in a narrow sense

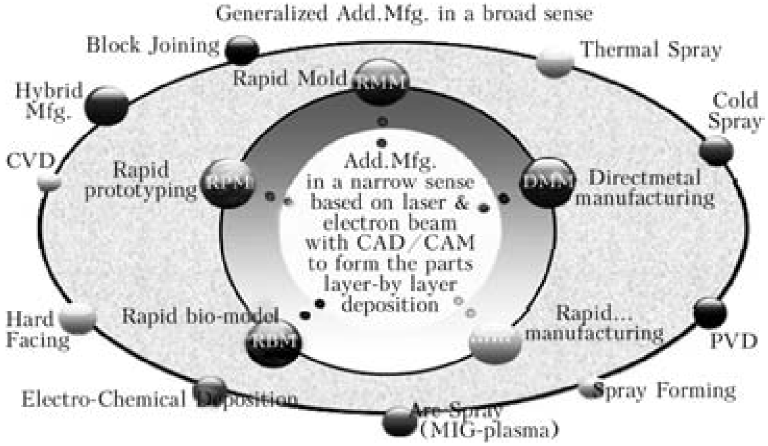

Figure 5. Distinctions between Add. Mfg. in a narrow sense (inner circle) and Add. Mfg. in a broad sense as generalized Add. Mfg. (outer ellipse)

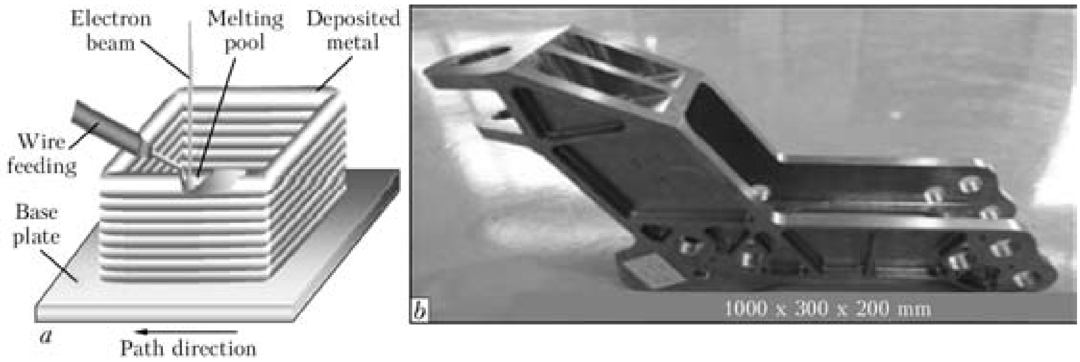

Figure 6. Principle of (*a*) Add. Mfg. based on EB with wire feeding and (*b*) deposited titanium structural element after machining

based on laser and electron beams with CAD/CAM to form the parts by deposition layer-by-layer. The outer ellipse gives an idea to understand the generalized additive manufacturing based on allied energy sources such as electrical arc and plasma for melting deposition, light sources for photo curing stereo-lithography, electro-chemical sources for deposition in liquid phase, and mechanical friction heating sources for block joining etc.

It should be stressed that in past years the enthusiasm to promote 3D printing is mostly related to non-metallic part direct fabrication. But nowadays direct metal free forming manufacturing is expected to be the follow-up upsurge of additive manufacturing to change gradually the traditional manufacturing mode from mass production to customized product made to order. Another breakthrough in bio-model direct forming as generalized additive manufacturing is predictable in the near future.

Potential application of generalized additive manufacturing. *Additive manufacturing based on electron beam.* Figure 6 shows the principle of additive manufacturing process based on electron beam with wire feeding. In vacuum chamber the wire fed to welding pool is melted by CAD controlled focused scanning electron beam, layer-by-layer deposition path is directed according to the CAD model (Figure 6, *a*); a typical deposited titanium structural element after machining of 1000 × 300 × 200 mm is also shown in Figure 6, *b*.

In the past few years, EB additive manufacturing titanium alloy wire composition system made to custom-order has been developed at BAMTRI to meet the required properties and structural performance. Technologies for deposition path control, parameter optimization, as well as post treatment are utilized to avoid possible emergence of imperfections and distortion. In general, mechanical properties of the deposited elements are compatible with forged parts.

Up to now the largest-sized facility for electron beam additive manufacturing with wire feeding system has been set up at BAMTRI. It is capable to fabricate structural elements with dimensions of 1500/800/3000 mm.

Additive manufacturing based on selective powder melting using electron beam is also implemented in a vacuum chamber. Metal powder spread on the powder bed is melted layer-by-layer by scanning electron beam following the CAD model paths.

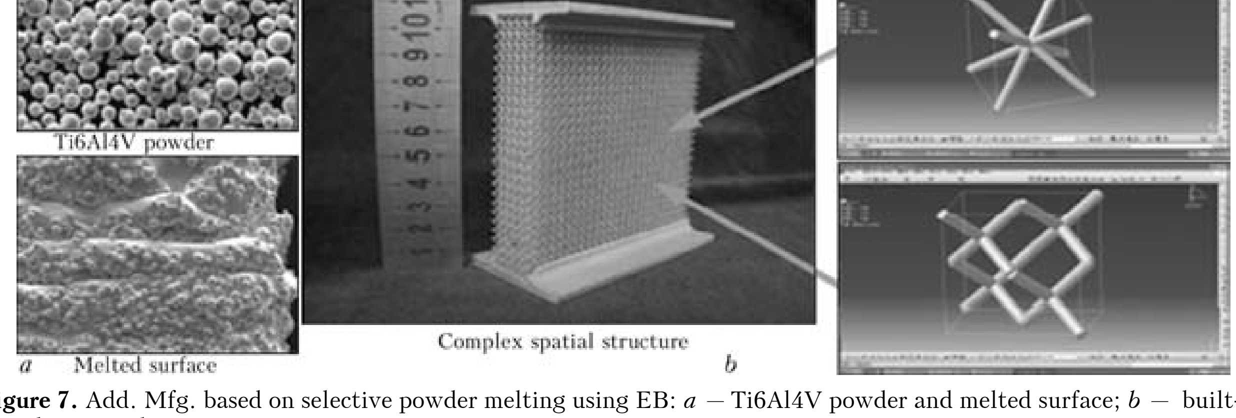

Figure 7. Add. Mfg. based on selective powder melting using EB: *a* — Ti6Al4V powder and melted surface; *b* — built-up complex spatial structure

In Figure 7 Ti6Al4V powder and melted deposition surface are shown (Figure 7, *a*); in this way complex spatial structure (Figure 7, *b*) can be built-up easily.

Additive manufacturing based on laser beam. Using laser beam, additive manufacturing could be implemented based on either direct laser melting deposition with coaxial feeding powder or selective laser melting with spread powder on bed layer-by-layer. Besides, laser beam additive manufacturing based on wire feeding is also explored at BAMTRI.

Figure 8 shows the universal laser beam additive manufacturing robot facility at BAMTRI for direct laser deposition melting, selective laser melting deposition as well as wire feeding laser melting deposition (chamber with dimension of 3 × 3 × 2.5 m).

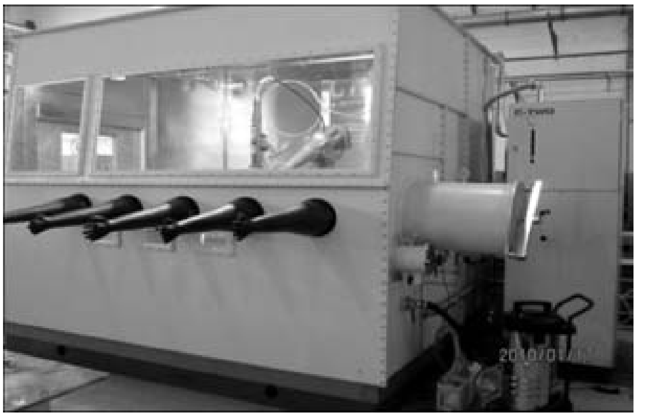

Figure 8. Universal laser beam additive manufacturing robot facility at BAMTRI for direct laser melting, selective laser melting as well as wire feeding laser melting

Technological procedures for laser beam additive manufacturing almost the same as for electron beam additive manufacturing. Material system with either wire or powder composition preparation made to custom-order also has been developed to meet the required properties and structural performance.

For more precise deposition forming (e.g. surface roughness Ra: 10 ~ 30 μm), high performance laser beam, fine granulated powder layer thickness should be matched. Subsequently, it is undoubtedly logical that the as deposited parts will be the final products or just finished surface polishing is needed.

Generalized additive manufacturing based on block joining. For high performance aero-engine, the compressor weight reduction can be reached up to 50 % if the traditional tenon joining of blades to disk can be replaced by blisk (blades to be welded to disk). Solid state additive manufacturing based on block joining by linear friction welding to produce integrated monolithic welded blisk is an effective tool for achieving the above mentioned idea.

Figure 9 exhibits the weight reduction for aero-engine tenon joining replaced by welded integrated monolithic blisk (Figure 9, *a*) using linear friction welding (Figure 9, *b*) as solid state additive manufacturing.

Low effectiveness in material saving and time saving of traditional material removal reduction manufacturing based on machining & cutting is fully reflected on monolithic stiffened airframe panel fabrication. Nowadays friction stir welding (FSW) turns the tide and brings about a radical change in the situation of block joining additive manufacturing of aluminum monolithic stiffened airframe panels. Stiffening ribs are assembled and welded to skin sheets using FSW for aluminum monolithic stiffened airframe panel fabrication. The name of solid state block joining additive manufacturing by FSW matches the reality.

In the case of titanium alloy, monolithic stiffened airframe panel fabrication can be achieved

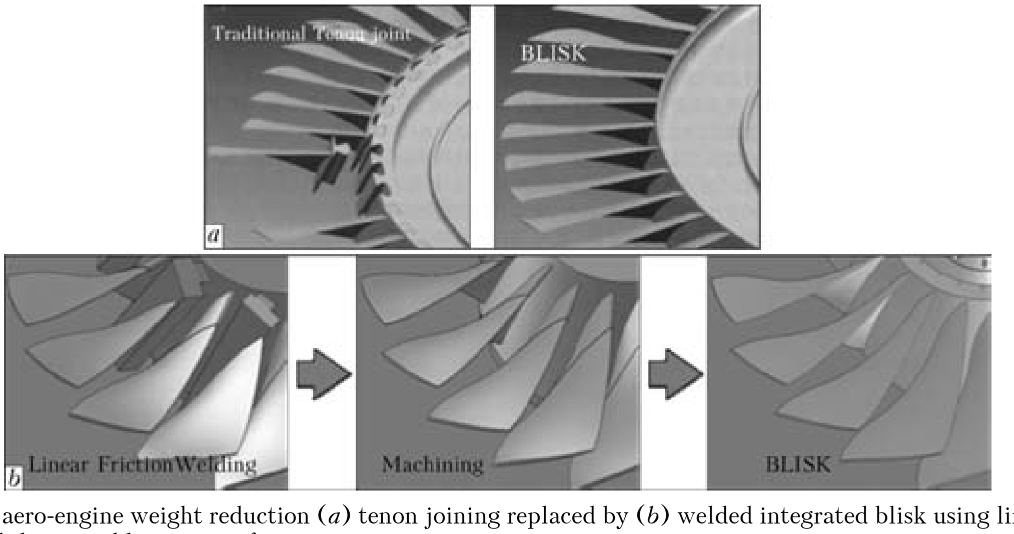

Figure 9. For aero-engine weight reduction (*a*) tenon joining replaced by (*b*) welded integrated blisk using linear friction welding as solid state additive manufacturing

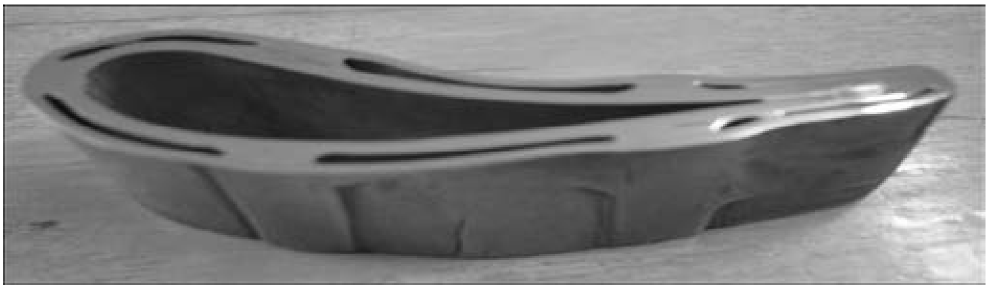

Figure 10. Turbine blade with complicated inner cooling gas channeling to be fabricated by additive manufacturing using electron beam physical vapor deposition (EB-PVD)

by block joining additive manufacturing using laser welding; titanium stiffening ribs are assembled and welded to titanium skin sheets using dual-beam laser robotic system as already shown in Figure 2.

Generalized additive manufacturing based on other energy sources. The variations of generalized additive manufacturing based on other applicable allied energy sources have been shown above in Figure 5.

As a typical application shown in Figure 10, an example is given to electron beam physical vapor deposition (EB-PVD) for additive manufacturing of turbine blade with complicated inner cooling gas channeling.

Technology and material composition of the blades made to custom-order for electron beam physical vapor deposition (EB-PVD) are selected to match the required properties and structural performance. In the vacuum chamber either a single electron beam gun or multiple electron beam guns can be used to form the blades by depositing different materials. It is expected that EB-PVD will be full of promise in additive manufacturing of newly designed aero-engine parts.

Conclusions

1. In terms of market pull there is very strong interest in additive manufacturing (particularly using power beams: electron beam & laser beam) from the aviation industry, especially for airframe and aero-engine applications as strategically important. BAMTRI has been involved in a number of research programs for aviation companies to provide a rapid response in design and trail manufacturing of new products.

2. For generalized additive manufacturing other allied energy sources are also applicable such as electrical, chemical, electro-chemical, mechanical etc. Especially pile-up forming could also be performed applying block joining (e.g. friction welding) to produce directly integrated monolithic metallic structural elements including aero-engine blisks and airframe stiffened panels.

3. Generalized additive manufacturing based on block joining (particularly friction welding) offer the potential for solid-state joining to build up near net shape elements by assembling of relatively simple parts. BAMTRI has been developing this solid state additive manufacturing technology for aero-engine parts as well as for airframe stiffened panels fabrication, demonstrating high value applications in other industry sectors.

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