An innovative process for titanium alloy package edge of aircraft engines composite fan blades

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Titanium alloy package edge provides additional strength and stiffness to the composite fan blades of aircraft engines, which can extend the service life of fan blades effectively. However, the titanium alloy package edge was traditionally manufactured by using CNC machine tools, involving a large cutting quantity and high cost. This work proposes an innovative manufacturing method for Ti-6Al-4V titanium alloy package edge. The specific process is as follows: firstly, the reverse flattening algorithm based on the equidistant surface is employed to flatten the hollow structure of the edging, obtaining the blank with a non-uniform thickness. Then, diffusion bonding of titanium alloy sheets is achieved through electrically-assisted heating method. Subsequently, pre-forming is conducted through electrically-assisted stamping. Finally, the target component is achieved through electrically-assisted hot metal gas forming. In particular, for the electrically-assisted diffusion bonding process, the experimental results indicate that the middle section of the specimen is well welded under the conditions of a current density of 5.0A/mm^2, diffusion bonding pressure of 2.5MPa, and diffusion bonding time of 30 minutes. For the electrically-assisted hot forming process, ABAQUS simulation results indicated that when the temperature is 700°C and the pressure exceeds 10MPa, titanium alloy package edge with the desired shape could be formed.

Keywords: Ti-6Al-4V; Package Edge; Diffusion Bonding; Hot Metal Gas Forming.

1. Introduction

Due to the pursuit of lightweight designs in the new generation of aircraft, composite fan blades have gained significant attention in the application of aircraft engines. Compared to metallic materials, composites offer higher specific strength, higher specific stiffness and customizable mechanical properties [1], which can significantly enhance the overall performance of the new generation of turbofan aircraft engines. However, despite these

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numerous advantages, composite blades have issues such as thin edge thickness and low strength. When composite fan blades rotate at high speeds and are subjected to impacts from birds, hail, or other debris, they are prone to damage and even breakage.

To address this issue, the metal package edge can be applied to the edges of composite fan blades. The metal package edge can absorb external impacts, thereby significantly improving the service performance of the blades. The current fan blades utilize a swept design to enhance efficiency and increase stall margin. Due to the significant twisting of the blade geometry, the package edge exhibits a complex compound bending and twisting profile. Additionally, the cross-section of the blade transitions gradually from thick to thin.

The most used manufacturing method is CNC milling. The titanium alloy package edges of the composite fan blades in GE90 and GEnx engines were machined using multi-axis CNC machines, which directly milled the excess material from the blanks [2]. Franchet et al. proposed a method to obtain metal package edges by stamping sheet metal followed by welding [3]. The study showed that this process could form complex-shaped package edges. Alexander et al. proposed a method for re-bending titanium alloy package edges [4]. The package edges could be re-cambered to improve the aerodynamic and operational performance. Zhang et al. proposed a production process for package edges based on stamping and superplastic forming [5]. The study showed that this process could form package edges with moderate curvature complexity. Han et al. proposed a package edge manufacturing technique utilizing 3D printing technology [6]. It was showed that this process could improve surface finish and form a compressive stress layer. Ruan et al. proposed a method for forming package edges using an electrically-assisted hot metal gas forming process [7]. The study indicated that this process produced relatively thin package edges. In summary, current methods for forming titanium alloy package edges suffer from high material waste, low manufacturing efficiency and high production costs. There is a need to develop a method for forming complex titanium alloy package edges with high material utilization.

Referring to the principles of titanium alloy hollow blade diffusion bonding and superplastic forming technology, a new technique for the electrically-assisted diffusion bonding/hot metal gas forming of metal package edges for composite fan blades is proposed (Fig. 1). This technique combines the high efficiency characteristics of electrically-assisted heating and gas forming. Firstly, the titanium alloy package edge model is supplemented into a closed-section part. Then, the part is unfolded based on the equidistant surface to obtain two titanium alloy blank models. The titanium alloy blank is processed and electrically-assisted heated for diffusion bonding. Next, the part is preformed using electrically-assisted heated hot stamping. The titanium alloy package edge is then formed using electrically-assisted heated hot metal gas forming. Finally, simple mechanical processing is used to obtain the titanium alloy package edge part.

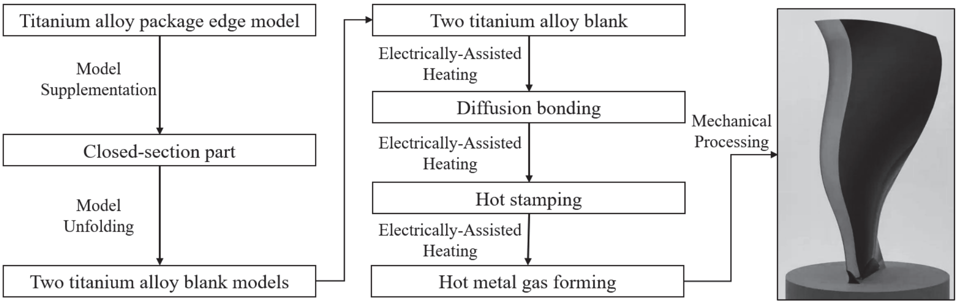

Fig. 1. Flowchart of package edge electrically-assisted diffusion bonding/hot metal gas forming process.

This paper focuses on the design of the Ti-6Al-4V package edge process model, the electrically-assisted heating diffusion bonding behavior of Ti-6Al-4V plates, and the electrically-assisted hot gas forming of Ti-6Al-4V package edges.

2. Methods

2.1. *Package edge blank model acquisition*

This study investigated the electrically-assisted diffusion bonding/hot metal gas forming process for the titanium alloy package edges of composite fan blades in a high bypass ratio turbofan aircraft engine (Fig. 2).

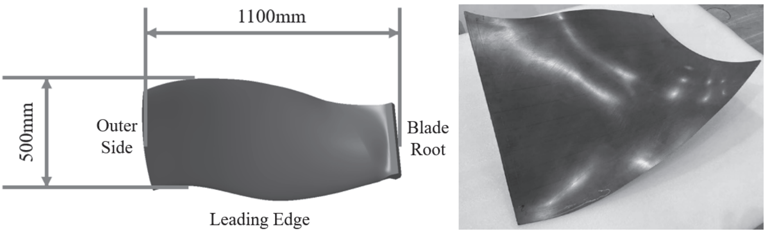

Fig. 2. 3D model and composite fan blade.

To meet the requirements of hot metal gas forming, the titanium alloy package edge part model was supplemented from a semi-closed section to a closed cavity part. Using 3D software, equidistant surface was generated on the upper and lower surfaces of the package edge model. The package edge was segmented into upper and lower entities based on the equidistant surface. In finite element software, the volume meshes of the upper and lower entities were bound to the equidistant surface. Pressure was applied to the equidistant surface using upper and lower planar molds to flatten it, causing the parts on both sides to flatten as well. This process resulted in two titanium alloy blank models.

2.2. *Electrically-assisted diffusion bonding experiment*

After obtaining the two blank models, diffusion bonding is necessary. Therefore, experimental research was conducted on electrically-assisted heating diffusion bonding of

Ti-6Al-4V plates to observe the bonding quality at different temperatures. The experimental device is shown in Fig. 3.

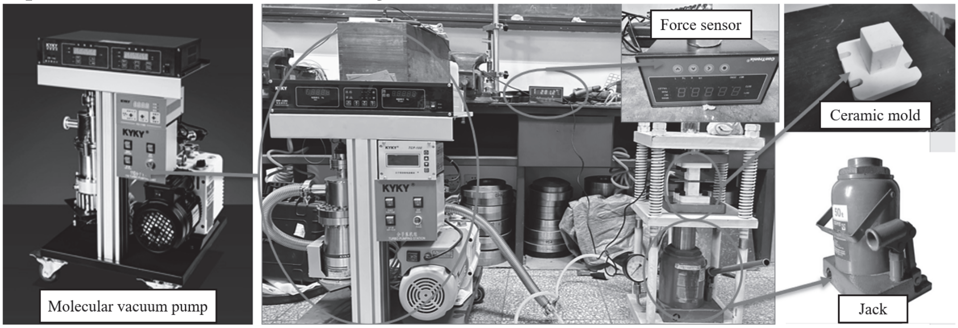

Fig. 3. Diffusion bonding device.

The experimental procedure was as follows: firstly, the ceramic mold was fixed onto the diffusion bonding device, and a force sensor was installed. The sample was mounted onto the mold, and pressure was applied using a jack. Electrodes were connected to the sample, and a vacuum pump was connected to the sample's gas valve. The vacuum pump was turned on to evacuate the internal environment of the sample to below 10^{-2} Pa to achieve vacuum conditions. Finally, the power supply was activated to heat the sample at a current density of 5.0 A/mm^2. Throughout the heating process, the pressure from the jack was adjusted to maintain a constant pressure of 2.5 MPa, and diffusion bonding was conducted for 30 minutes. When the predetermined temperature was reached, the mold was opened, and the sample's temperature was measured using a thermal imager. Based on the above method, the diffusion bonding experiments under 750°C, 850°C, and 900°C were observed.

2.3. *Electrically-assisted hot gas forming simulation*

ABAQUS is used to study hot forming of the titanium alloy package edge. Firstly, it is necessary to simulate electrically-assisted heating of Ti-6Al-4V package edges. The blank model was imported into ABAQUS. A specified current density was applied at one end of the part, and the other end was designated as a zero potential region. The temperature distribution results were inherited in the form of a temperature field for subsequent simulations.

The blank hot stamping model was established. The flattened blank model was imported, and according to actual production process, it was heated to 700°C using a current density of 4 A/mm^2.

The numerical model obtained after hot stamping forming was imported into ABAQUS through an ODB file for hot metal gas forming simulation. The tetrahedral element mesh was inherited from the hot stamping process. The mold for hot metal gas forming was imported in IGS format. During the hot metal gas forming process, the positions of the upper and lower dies remained fixed, and fixed constraints were applied to the two short edges of the part, while the remaining positions remained free. The contact constraint was defined between the part surface and the mold, with the friction coefficient empirically set to 0.2. A uniformly distributed load was applied to the inner surface of the part to simulate the pressure exerted by high-pressure gas on the inner wall of the part during the forming process. The effects of hot metal gas forming pressure and temperature on the forming results were studied by selecting five forming pressures: 2.5 MPa, 5 MPa, 7.5 MPa, 10 MPa, and 12.5 MPa, and three forming temperatures: 600°C, 700°C, and 750°C.

3. Results and Discussion

3.1. *Electrically-assisted diffusion bonding experiment*

The bonding quality was evaluated from grain structure and welding strength. The grain structure was observed using a field emission SEM/EBSD (7200F) electron microscope, and the welding strength of the samples was measured using a THV-50DP computer-controlled Vickers hardness tester.

Three samples measuring 10×5 mm were taken from the specimen, starting from the center to one edge, and were labeled with numbers 1 to 3. The temperatures of three samples, as measured by the thermal imager, were 750°C, 850°C, and 900°C. Similarly sized sample was cut from the specimen before diffusion bonding, labeled as 0, and observed using SEM for comparison. This allowed for the observation of the bonding ratio after diffusion bonding, the changes in grain size before and after diffusion bonding, and the hardness at the weld seam after diffusion bonding. The SEM micrographs of the samples before and after diffusion bonding were shown in Fig. 4.

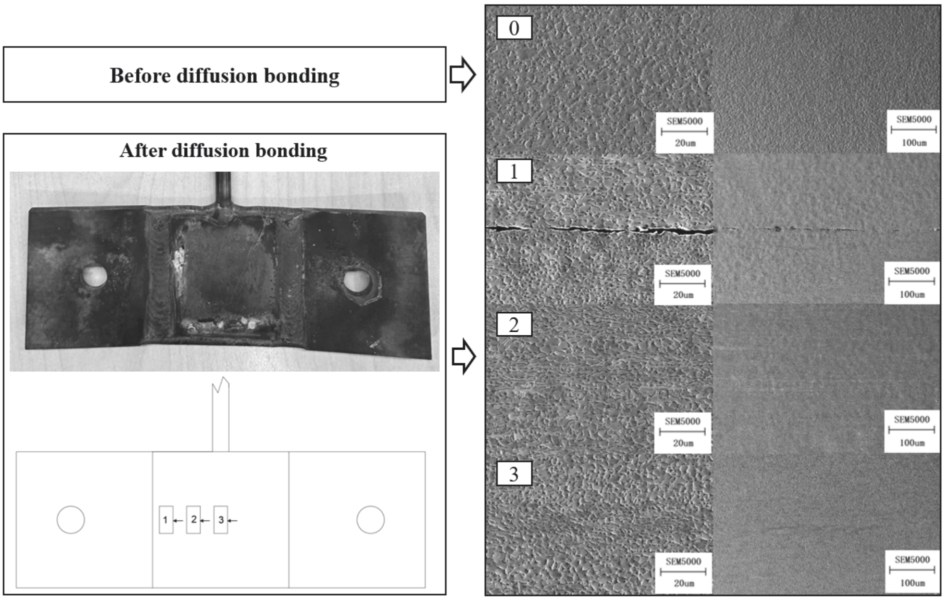

Fig. 4. Sampling positions after diffusion bonding and SEM micrographs of the samples

As shown in Fig. 4, the welding at 750°C was poor, with a bonding ratio of approximately 20%. Sample 2 and 3 had higher temperatures, and the weld seams were essentially not visible, indicating complete bonding. This ensured the gas tightness of the part during the hot metal gas forming process. Before experiment, the surface hardness averaged 309 HV. After diffusion bonding, the hardness at the weld seam reached 360.2 HV and gradually decreased along both sides of the weld. At 0.8 mm from the weld on either side, the hardness gradually decreased to the pre-test hardness, thereby ensuring that the requirements for package edge formation in hot metal gas forming.

3.2. *Electrically-assisted hot gas forming simulation*

The forming pressure and forming temperature both influenced the forming accuracy of parts. Figure 5 showed that under the same temperature, increasing the forming pressure from 2.5 MPa to 12.5 MPa could reduce the maximum distance between the formed part and the mold surface. Under the same forming pressure, increasing the temperature from 650°C to 750°C resulted in decreases in the maximum distance between the formed part and the mold surface by 1.307 mm, 0.752 mm, 0.768 mm, and 0.252 mm respectively.

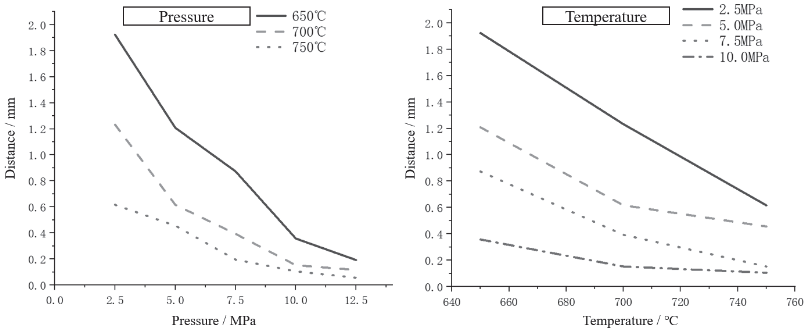

Fig. 5. The influence of forming pressure and forming temperature on the maximum distance between the part and the mold surface.

At 700°C and 10 MPa, the simulation results for the distances between the part and the mold before and after hot metal gas forming were as Fig. 6: after forming, the maximum distance between the upper side of the part and the mold was 0.091 mm, and between the lower side of the part and the mold was 0.152 mm. Both distances were less than 0.2 mm, satisfying the shape requirements for titanium alloy package edge.

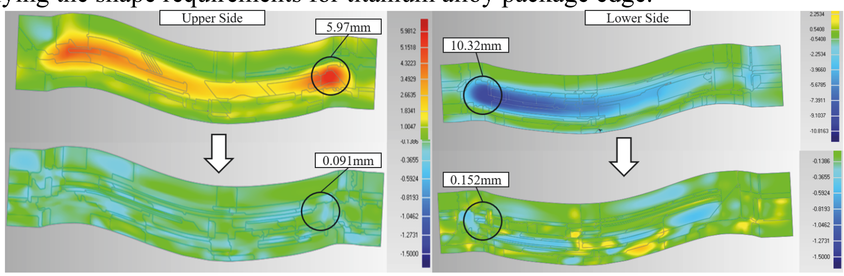

Fig. 6. The distance between the part and the mold surface.

Through analyzing the influence of different forming temperatures and pressures on the forming accuracy of parts, it was found that higher forming pressures and temperatures lead to higher forming accuracy of titanium alloy package edges after hot metal gas forming. When the forming temperature is 700°C, the distance between the part and the mold surface will be below 0.2 mm under pressures exceeding 10.0 MPa. Similarly, at 750°C, the distance will also be below 0.2 mm under pressures exceeding 7.5 MPa, resulting in the part achieving its desired shape.

4. Conclusions

The main conclusions drawn from this paper are as follows:

(1) Ti-6Al-4V titanium alloy electrically-assisted diffusion bonding experiments were conducted. The results indicated that under conditions of 5.0A/mm² current density, 2.5 MPa diffusion pressure, and 30 minutes bonding time, the central part of the specimens was effectively welded. At the weld seam, the hardness reached 360.2 HV, meeting the requirements for hot metal gas forming.

(2) Using ABAQUS, a simulation study on the overall process of electrically-assisted hot forming of Ti-6Al-4V titanium alloy package edge was conducted. The simulation results indicated that at a temperature of 700°C, the titanium alloy package edge could achieve the desired shape when the pressure exceeds 10 MPa. Increasing the forming pressure and raising the temperature are effective methods to improve forming accuracy.

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