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An investigation on adaptively machining the leading and tailing edges of an SPF/DB titanium hollow blade using free-form deformation

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Abstract Titanium hollow blades are characterized with lightweight and high structural strength, which are widely used in advanced aircraft engines nowadays. Superplastic forming/diffusion bonding (SPF/DB) combined with numerical control (NC) milling is a major solution for manufacturing titanium hollow blades. Due to the shape deviation caused by multiple heat and pressure cycles in the SPF/DB process, it is hard to manufacture the leading and tailing edges by the milling process. This paper presents a new adaptive machining approach using free-form deformation to solve this problem. The actual SPF/DB shape of a hollow blade was firstly inspected by an on-machine measurement method. The measured point data were matched to the nominal SPF/DB shape with an improved ICP algorithm afterwards, by which the point-pairs between the measurement points and their corresponding points on the nominal SPF/DB shape were established, and the maximum modification amount of the final nominal shape was constrained. Based on the displacements between the point-pairs, an accurate FFD volume was iteratively calculated. By embedding the final nominal shape in the deformation space, a new final shape of the hollow blade was built. Finally, a series of measurement and machining tests was performed, the results of which validated the feasibility of the proposed adaptive machining approach.

1. Introduction

Titanium hollow blades are very popular in aerospace application with the advantages of lightweight and high damping level, which have been a pivotal option for high thrust-to-weight turbine engines.[1–4] Because of their hollow structures, traditional machining technologies such as forging, casting, and milling, cannot be used to manufacture this kind of blades. Superplastic forming and diffusion bonding (SPF/DB) is a

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technique allowing for manufacturing hollow metallic sandwich parts with an internal structure, which is based on the superplasticity and bondability of metal materials.[5–7] Since titanium alloys exhibit great performance of superplasticity and diffusion bondability, titanium hollow blades are formed by the SPF/DB process nowadays.[8,9] However, a critical problem occurs in this process. Although the SPF/DB process can form the desired internal structure of a blade, it is hard to form the leading and tailing edges simultaneously, which are circle arc lines or quadratic curves with a high requirement of machining accuracy. Thus, a numerical control (NC) milling operation is often employed after the SPF/DB process to manufacture the leading and tailing edges.[10,11] SPF/DB is a hot-forming process in which titanium alloys undergo multiple cycles of high temperature and pressure, leading to a global deformation of the hollow blade. Because the leading and tailing edges have a small allowance to be removed in the NC milling operation, the heat-induced global deformation makes it impossible to manufacture the edges depending on the original nominal CAD model of the blade. Although this global deformation problem is inevitable for SPF/DB, it has a small effect on the aerodynamic performance of the hollow blade. Hence, if the nominal CAD model of the blade can be slightly and correctly modified, like twisting and scaling, to adapt to the actual deformed shape of the hollow blade, it can dramatically reduce the rejection rate and save the production cost. This paper attempts to propose a quick and convenient approach to adaptively manufacture the leading and tailing edges of a hollow blade previously formed by the SPF/DB process.

The critical issue in adaptively machining the leading and tailing edges of a hollow blade is how to reconstruct a new nominal CAD model fitted to the deformed shape. Many previous works have been carried out in geometric reconstruction of blades. Lin et al.[12] presents a geometric reconstruction approach for solving the disconnection problem between the actual surface of a blade and the theoretical model in the areas of the leading and tailing edges. They dealt with modifying each cross-section of a turbine blade separately by searching new arc radii and center points as well as fitting lines around the connection area. Wang et al.[13] put forward a method to remanufacture and repair damaged blades, in which the point cloud of broken blades was obtained and processed and a 3D digital model was built on the boundary section curves extracted from the point cloud. Piya et al.[14] used sectional Gauss sections to generate a series of prominent cross sections to rebuild a CAD model for remanufacturing gas turbine blades. Mavromihales et al.[15] obtained the point cloud of a hollow fan blade with a five-axis center, which was imported into reverse engineering software for CAD model reconstruction. Gao et al.[16] scanned a worn blade and loaded the scanned data into the reverse engineering software of Polyworks for tip reconstruction.

As described above, previous related works have mainly focused on the geometric reconstruction of worn blades for remanufacturing or repairing. Besides, the reconstructed geometry was fitted from a large number of scanned points. Scanning, processing of points data, and geometric fitting are all time-consuming and labor-intensive. Free-form deformation (FFD) is a modelling technique for quickly reshaping an object by warping the surrounding space[17], which is widely used in computer graphics and film animation. FFD was firstly proposed by Sederberg and Parry[18], which deforms a solid geometric model in a free-form manner based on trivariate Bernstein polynomials. Coquillart[19] extended FFD in which arbitrarily-shaped bumps can be designed and surfaces can be bent along arbitrarily-shaped curves. Kobayashi and Ootsubo[20] presented a t-FFD method, by which the original shape of a polygonal mesh or point cloud is deformed using a control mesh. Up to now, volume-based, surface-based, curve-based, and point-based FFD technologies have been developed to satisfy different requirements from a user-centered perspective.[17]

This paper intends to find a quick and convenient approach for adaptively machining hollow blades using an improved ICP algorithm and an FFD volume based on on-machine measurement point data, by which the final nominal shape can be accurately modified in a controllable amount to make the leading and tailing edges be manufactured successfully. The rest of this paper is organized as follows. The problem description and solving methodology are given in Section 2. Section 3 details the implementation of the proposed adaptive machining method. The results of a case study and some related discussion are presented in Section 4. Finally, conclusions are summarized in Section 5.

2. Problem description and solving methodology

2.1. Problem description

In traditional NC machining, the nominal shape of a part is the shape finally wanted by designers or manufacturers, which plays an indispensable role in multi-axis NC programming. It is necessary for a blank with a non-negative allowance to be removed from the final nominal shape of the part. Fig. 1 schematically illustrates the relation between nominal and actual SPF/DB shapes, and the final nominal shape for a milling operation. It can be seen that the actual SPF/DB shape has a deviation compared to the nominal SPF/DB shape. Because the nominal SPF/DB shape only has a slight allowance in the areas around the leading and tailing edges, the deviation between the actual and nominal SPF/DB shapes causes that the final nominal shape cannot be totally enveloped by the actual SPF/DB shape. In other words, the actual SPF/DB shape has a negative allowance, which is impossible for traditional NC machining to manufacture the leading and tailing edges of the hollow blade. This problem results in a high rejection rate and an expensive production cost, which limit the application of hollow blades in aerospace engineering. Besides, it can be seen from Fig. 1 that only the areas around the leading and tailing edges (Zones A and C) are manufactured with the NC milling process, while Zone B will be polished using multi-axis belt grinding after NC milling. A disconnection problem will occur in the adjacent areas between Zones A and B and Zones B and C, which also cannot be solved by the following belt grinding process. This problem will be discussed in our future papers.

2.2. Solving methodology

Since the traditional NC machining process cannot solve this problem, a new machining approach should be developed. Fig. 2 presents the flowchart of the adaptive machining approach proposed in this paper. Firstly, on-machine