Int J Adv Manuf Technol (2008) 36:1170–1179
DOI 10.1007/s00170-006-0923-6

ORIGINAL ARTICLE

An integrated adaptive repair solution for complex aerospace components through geometry reconstruction

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Received: 17 February 2006 / Accepted: 27 December 2006 / Published online: 3 February 2007

Abstract The repair of worn parts is of great interest for aerospace industries to extend the life cycle of aerospace parts. Due to the distortion and defects of a worn part, the nominal CAD model from the design stage is no longer suitable for the use of the repairing process, which causes the main problem for precisely repairing complex components. In this paper, an integrated repair solution adaptive to worn component geometry is proposed and developed for aerospace industries. Based on the scanned repair model with different defects, a reverse engineering(RE)-based geometry reconstruction method is developed for the normal model creation of a worn component. This is a crucial procedure for precisely repairing individual component. Based on the nominal model reconstructed, tool paths used for the build-up and machining process can then be generated to implement the repairing work. In this study, repairing complex blades from aerospace engines were considered and practised. To verify the proposed repair solution, a curved blade to be repaired was used in the experiment and the blade tip model was reconstructed for the subsequent repairing process. Based on the model, the blade was built-up through a laser cladding process and then machined back to size through isoparametric machining strategy on a 5-axis Hermle machine tool. Finally, the experimental results are given and analysed.

Keywords Adaptive repair solution · Aerospace components · Defects · Geometry reconstruction · Blade machining

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1 Introduction

During the service life of any military or civil aero-engine, it is highly likely that at some stage ingestion of hard-body objects such as stones and nuts will occur. Due to the high airflow velocity through an engine, an object would not have to be very large to cause serious damage to the blades and vanes. On the other hand, due to the harsh environment of high rotational speeds, high pressure and high temperature, aerospace components suffer severe wear, distortion, and crack [1]. The consequences of such an event can be catastrophic and the financial costs to customers can often be high. The repair of worn parts is of great interest for aerospace industries to extend the life cycle of aerospace parts.

A turbine blade is an aerodynamic body having special geometry characterized mainly by an airfoil cross-section; blade design relies heavily on aerodynamic/thermodynamic theory to achieve a design with maximum efficiency [2]. For blade repair process, it is important to maintain the original blade shape and to achieve maximum efficiency for the restored blades, such as chord and thickness dimensions to match with the selected airfoil section. However, due to the various blade defects such as distortion and worn-out, an nominal CAD model from blade design stage is generally different from its corresponding worn blade model and therefore cannot be directly used for tool path generation for repair process. Currently, most of the repair processes for the repair of engine components are carried out manually [3]. The manual repair approach is to manually apply extra material to the worn-out area using a welding process, and then the weld bead is machined back to the correct size. In many cases, however, manual operations are not satisfactory from the points of view of cost and reliability [3]. Another common problem is that the components, such as curved blade and blisk(a disk with blades welded on permanently), are too complex for efficient manual treatment.

An automated repair method is, therefore, a key factor to compensate for part-to-part variations and to keep the tolerances for the actual parts to a minimum [3]. Several studies have been performed on specific aspects of blade repair, mainly classified into automated repair methods through measuring techniques [4–7], build-up process for welding worn blades [8–12] and adaptive machining solutions for welded blades [4, 13, 14]. Walton [4] presented a typical adaptive machining solution, which can digitise, compute and precisely restore the profile of a tip-welded compressor blade under two minutes. Dix [7] used 3D scanning points to construct blade airfoil profile and generated machining codes from the selected blade in a database. Huffman [11] has developed a laser powder fusion welding machine which integrates with a 2D vision system for blade repair. The vision system locates the part, adjusts for differences and generates a CNC program through AutoClad software for the welding process. Once the image is captured by the vision system, the software can rapidly provide the geometry profile in the x and y coordinates, generate tool paths and welding parameters for the laser welding process. However, due to the limitation of the 2D vision system, it is difficult for the Huffman Machine to be used for complex geometric components, such as curved blade and blade interlock repair. Bremer [13] introduced an adaptive machining solution for welded blades, which is reported to be able to compensate for both part-to-part variation and inaccurate clamping positions of complex components. In the straight blade repair system, two blade cross-sections below the welded bead are digitised through a tactile probe and the nominal geometry of the final domains is calculated based on the two profile data. Huang [14] proposed an industrial robots assisted turbine blades repair system.

Although the above research has been carried out on performing blade repairing through the approaches of digitising, laser cladding and adaptive machining, they are mainly focused on straight blade repair and haven't been focused on the repair of curved blades. Since the geometry of a curved blade cannot be created simply by one or two probed profiles, the nominal model necessary for repair process will be difficult to reconstruct, which therefore becomes a barrier for refurbishing a curved blade. Bremer [13] adopted a master blade surface model to best fit to the actual curved blade geometry to perform accurate repair process. Due to the variations of blade geometry, it is difficult to create such a master blade, and the author didn't give an effective method on how to create such a master geometry. The geometrical adaptation of the tool paths to the actual geometry needs to be performed for the repair of the complex components.

In this paper, the authors focus on the development of an adaptive solution to reconstructing the nominal geometry of the complex aerospace components. Based on the nominal geometry recreated for each part, an adaptive repair solution integrated with additive process and machining process can be achieved. In this study, a reverse engineering (RE) system based reconstructing approach has been proposed and developed for the nominal geometry reconstruction of a worn blade. As we know, RE is mainly used to re-engineer a component to get its CAD model for rapid prototype (RP) or rapid manufacturing (RM) and the majority of RE applications has been focused on surface modelling to suit CAD/CAM systems for the purpose of product design, replica, manufacture or inspection [15–21]. However, RE in this study is used for re-creating the defect area geometry where the original geometry has been damaged. Since the scanning data of the worn-out area is not suitable for nominal geometry creation, a reconstruction approach must be developed based on the data of non-defect area to recreate the geometry of defect area. This paper proposes a useful approach to reconstruct the nominal geometry for use of consequent repair processes including additive process and machining process. Based on the nominal geometry created, tool paths generated for welding and machining process can be geometrically adaptive to individual blade and achieve precise repair of curved blades. Through the machining experiments carried out on a 5-axis CNC machine tool for the repair of welded thin-curved-blades, the isoparametric tool paths were generated and used for validation of blade machining process.

The remainder of the paper consists of the following. Section 2 describes the proposed repair system structure and repair solution. Section 3 analyses blade geometry, including straight and curved blades, and identifies the difference through comparison of cross-sections of a curved blade. Nominal geometry reconstructing method is presented in Sect. 4. Section 5 describes repair experimental setup and machining trials on blade tip repair. Finally, Sect. 6 summarises the conclusions of the paper and discusses our plans for future work.

2 Repair system description

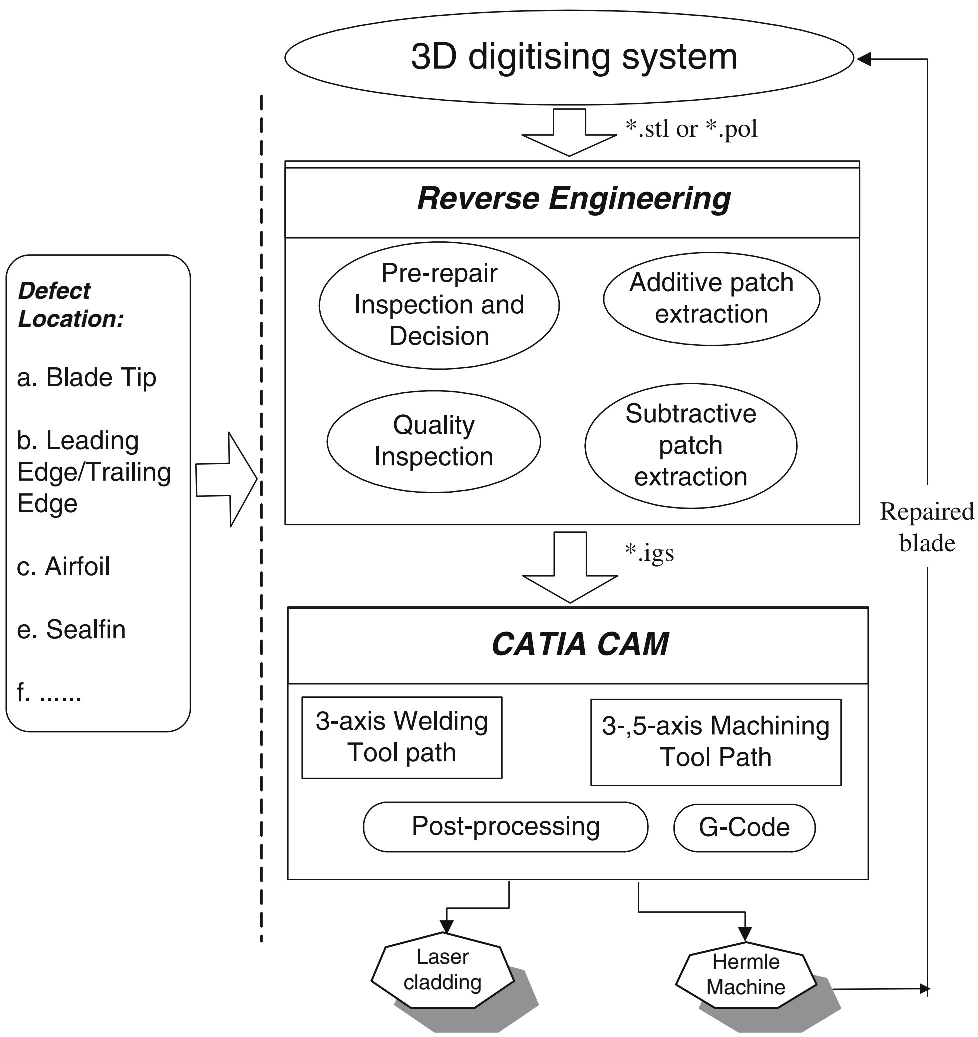
In the study, a repair system has been proposed to integrate a non-contact digitising system, a reverse engineering system and a CAD/CAM software for repair of complex geometry components. The system consists of three main modules. The first is a 3D digitisation system which is used to acquire a worn part's geometry and output the geometry model as a format of polygonal file. The second module is a reverse-engineering-system-based geometry reconstruction module. Its main functions contain pre-repair and post-repair inspection, repair patch extraction for additive repair, and worn-out patch regeneration for subtractive repair. The third module is a CAD/CAM system (such as a CATIA software), which is used to generate tool paths for welding and machining processes. For a complex component, three-axis tool paths for welding can be generated based on the additive patch created in RE module, and five-axis tool paths for machining can be generated based on the subtractive patch. Through post-processing to the tool path generated, numerical control code (such as G-code) can be produced to drive machine tools. The three modules of the system are inter-connected and are interfaced each other through file transfer. To keep the repair model consistent, a repair part only needs to clamp once on a fixture throughout the repair process. Figure 1 shows the general structure of the integrated repair system. The system can be used to repair various complex components(such as aerospace parts, die and mould parts and other sculptured surface) with a variety of defects of wear, crack, dent, distortion, erosion and undersizing.

The crucial issue of the system is to reconstruct the nominal model of a worn part based on the 3D measurement model. Other issues to be solved contain near-net-shape welding process and adaptive machining processes for complex components. Further study on these activities is necessary and some special functions over a CAM system have to be developed. However, this paper will focus on the nominal model reconstruction, which plays an important role for the use of precise tool path generation.

3 Analysis of curved blade geometry

In a repair and overhaul industry, a common problem encountered is that the nominal CAD model from compo-

Fig. 1 Repair system structure



nent designers is different from its corresponding "in service" one and thus cannot be directly used for tool path generation for precise repair process. Therefore, a repair nominal model to individual worn blade needs to be created to fit the part-to-part variation. For aero-engine components, blade tip repair occupied the major repair volume of all parts [22]. Due to the severe wear happened in the engine cabin of an airplane, these compressor blades, straight or curved, are generally undersize due to wear on the tip and need to be restored back to the original size.

In this section, geometry analysis of worn blades is presented to show the geometrical difference between a curved blade and a straight blade and the cross-section difference of a curved blade at different height. The analysis result shows that the method used for straight blade repair is not appropriate for repair of curved blades. Nominal repair models should be reconstructed for the precise refurbishment of curved blades.

3.1 Straight blades

For the tip repair of a straight blade, the easy way to create the blade tip surface model is to use a good cross-section (CS) curve (without defects), offset the curve to the nominal height along z-axis, then blend or stretch the curve in CATIA software. The surface model created in this way below the weld bead can be used for machining through a 3-axis machine tool. Figure 2 shows the procedure of a straight blade tip reconstruction.

3.2 Curved blades

Different from a straight blade, a curved blade faces two problems: 1) The CAD model of a curved blade is different from its used blade geometry due to the defects of distortion and worn, as shown in Fig. 3. So the blade CAD model is not suitable for tool path generation for the repair process. 2) A curved blade has different cross-section geometry at different height of the blade. So the blending method through two CS profiles used in reconstructing tip geometry model of the straight blade is not applicable for repair of a curved blade.

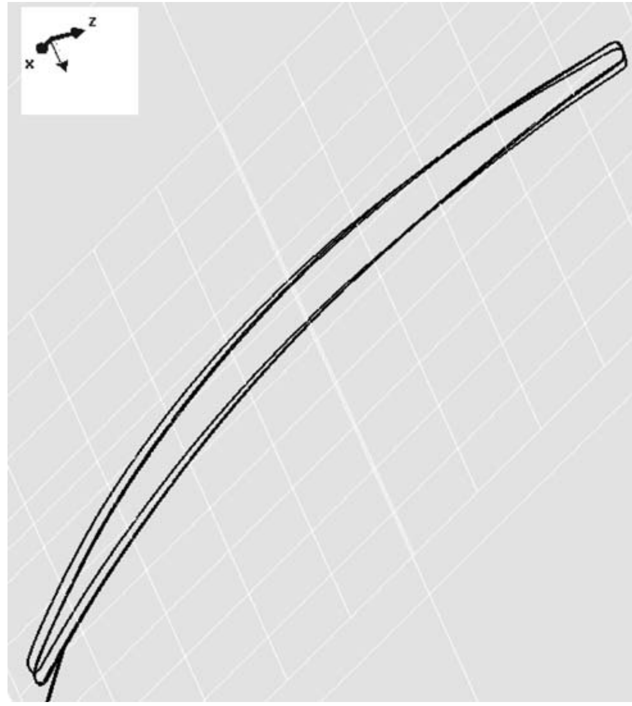


Fig. 3 Two cross-sections on a blade nominal CAD model and its worn blade scan model

The CS difference at different height is shown in Fig. 4. In Fig. 4(a), the cross-section1 (cs_1) and cross-sections2 (cs_2) are created on plane1 (P1) and plane2 (P2), respectively. The cross-section cs_2' is created by offsetting the cs_1 up to plane P2 along Z-axis. The two cross-sections of cs_2 and cs_2' are thus located on the same plane, Fig. 4(b) shows the difference of the two cross-sections. If the cross-section below the weld bead is offset up and used as the top curve for creating blade tip geometry, then the tool path generated upon it will cause incorrect tool paths for the subsequent machining process. Therefore, a nominal model adaptive to the worn component geometry needs to be created precisely

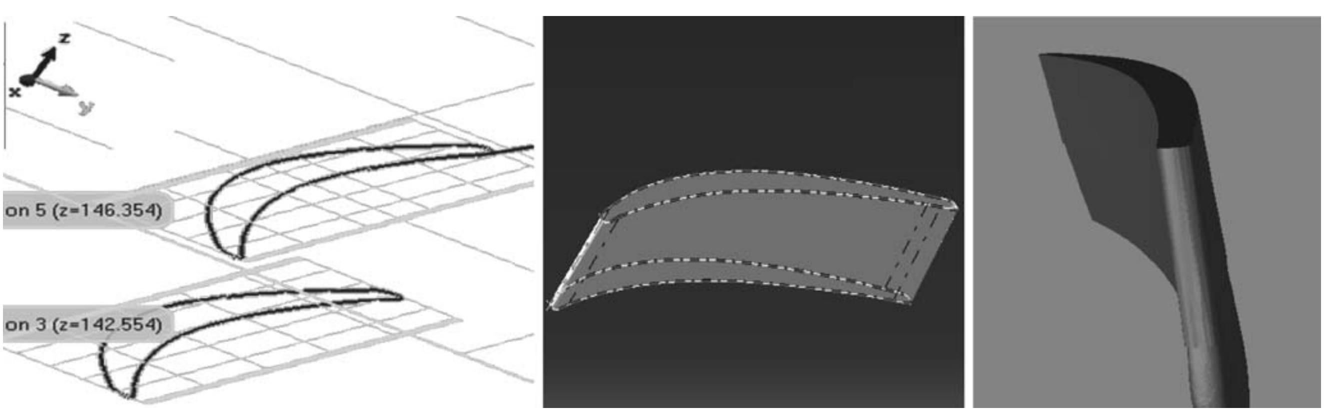
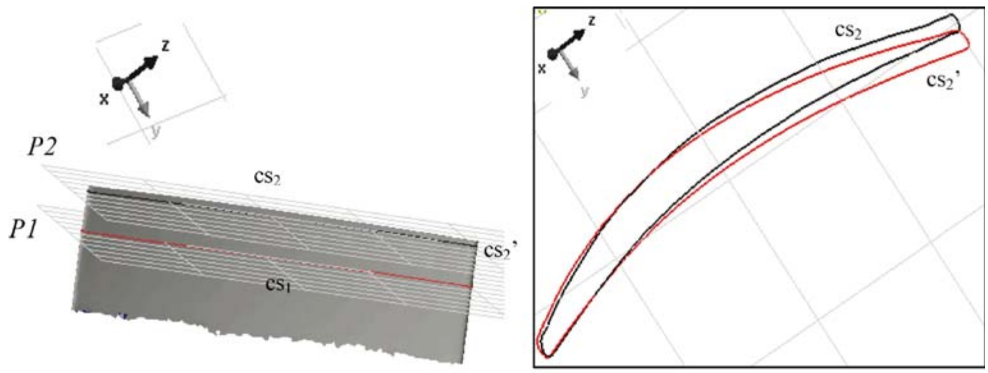


Fig. 2 The procedure of a straight blade generation through curve-offset- blend/stretch approach in CATIA system

Fig. 4 Cross-section comparison for a curved blade



(a) cs$_1$ and cs$_2$ on P1 and P2 plane, cs$_2$' created by offsetting cs$_1$ up to P2 plane

(b) Comparison of cs$_2$ and cs$_2$ on P2

and then it is appropriate for use of subsequent additive/subtractive repairing process.

4 Nominal geometry reconstruction

4.1 Curved blade tip

In this repair system, a reverse engineering (RE) tool was used to restore the worn part model and to extract repair geometries for tool path generation for a laser cladding and machining process. This section introduces the reconstructing procedure for worn area geometry. The reconstructed blade model is a defect-free polygonal model and can be used as a nominal geometry for further repair process.

Taking the blade tip geometry reconstruction as an example, we introduce the reconstructing procedure for repair of a curved blade tip defect. The blade was first digitised to get its polygonal 3D geometry. The scanned polygonal model is loaded into the Reverse Engineering software of Polyworks [23] for the tip reconstruction. Figure 5a shows the polygonal model of a blade with tip worn defect (short of size). The tip geometry will be recreated based on the scanned data. The reconstruction procedre is described in detail as follows:

Step 1: Create a plane (P_1) on the top of the scanned blade and create a second plane Ptop parallel to the plane P_1 with a distance of 2 mm along z-axis; offset the plane P_1 along z-axis by 0.05 mm, then slice the model by the plane P_1 and delete the triangles above $P_{1.}$

Step 2: Anchor a surface with several rows and columns around the tip area of the model and then best-fits the surface to the polygonal model.

Step 3: Extrapolate the surface rows *Ri* up by δmm (such as 0.5 mm), and then adjust the surface columns on the model.

Step 4: When reach the blade top plane (P_{top}), extrapolate the surface rows up by 0.3 mm, and adjust the surface columns to fit the model, then go to *Step 5*; when the *Ri* is below the P_{top}, go to *Step 3*.

Step 5: Resample the surface created as shown in Fig. 5b, and then fill in the gap between the resampled model with the original polygonal model.

Step 6: Slice the model by the P_{top} plane with the tip angle as the blade drawing required, and then create a wall on the top through the Triangles Edit in the polygonal modelling module.

Figure 6 shows a nominal blade tip model reconstructed through the RE-based surface extension approach. Based on the nominal geometry, a non-uniform rational B-spline (NURBS) surface model can thus be fitted in the RE system [23]. The model contains four NURBS patches, and it satisfies the continuity condition between these patches. Therefore, the model can be directly used in a CAM system for machining tool path generation.

4.2 Other defects repairing

Besides the blade tip defect, a number of other defects can also be repaired through the geometry reconstruction approach, such as leading or trailing edge defects (dents or cracks), blade seal fin worn, and airfoil surface defects. Table 1 shows some of the defects to be repaired. Table 1 also shows the corresponding repair features (profiles or patches) extracted and reconstructed for tool path generation for subsequent additive and subtractive process.

For example, for the repair of blade tip defect, the blade is normally short of size due to wear, the repair feature for welding or laser cladding is the tip profile, which is used to generate tool paths for welding. Once the blade was built up (material was added to the top of the blade), the machining process will be performed to remove the material and bring the blade back to size. This process will

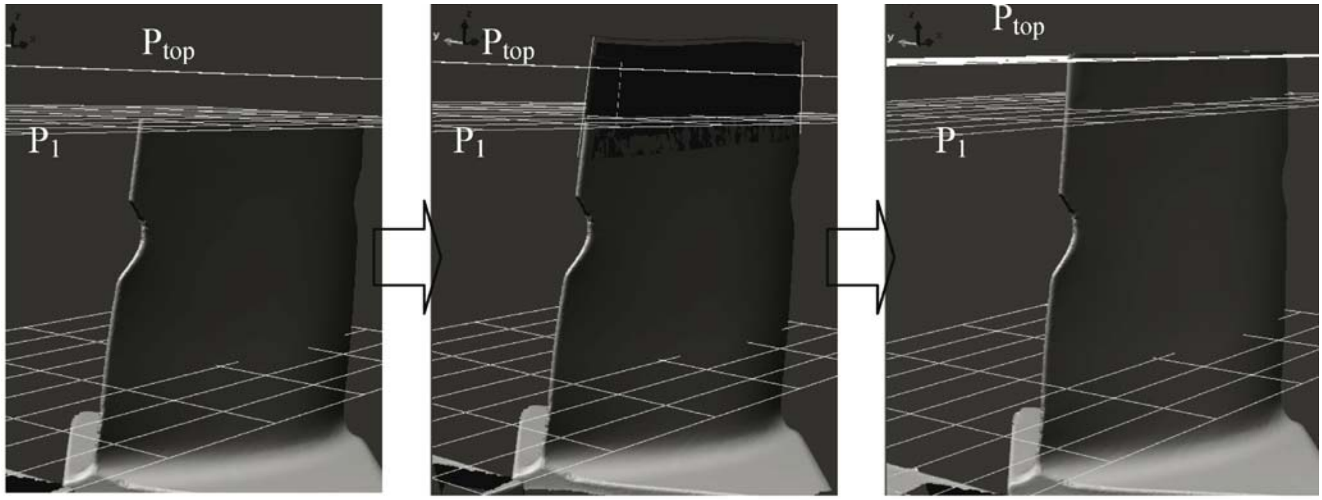


Fig. 5 Blade tip reconstruction procedure implemented in a RE environment

relay on the surface model reconstructed through RE-based approach, which is shown in the first row of Table 1. For the repair of blade edge defect, the welding profile feature and machining surface feature are created for tool path generation. Similarly, for the blade seal fin repair, the main defect is top worn, so it is necessary to add material onto the top of the seal fin area, and then machine off the extra material. To implement this process, the profile geometry used for welding tool path generation need to be extracted from the scan model, and the surface patch on the seal fin top need to be created for machining tool path generation. For repair of complex surface parts, such as airfoil surface and sculptured surface, the boundary profile of the repair area need to be extracted from the polygonal model, which can be used for welding tool path creation. For the machining process, a surface patch fit to the geometry of the repair part should be reconstructed through the approach introduced above to achieve accurate repair.

5 Blade repairing experiments

5.1 Experimental setup

In this study, the experimental work was carried out during the repairing of a curved blade tip. In the experiment, the blade tip to be repaired had been built-up through a laser

Fig. 6 Blade tip geometry reconstruction

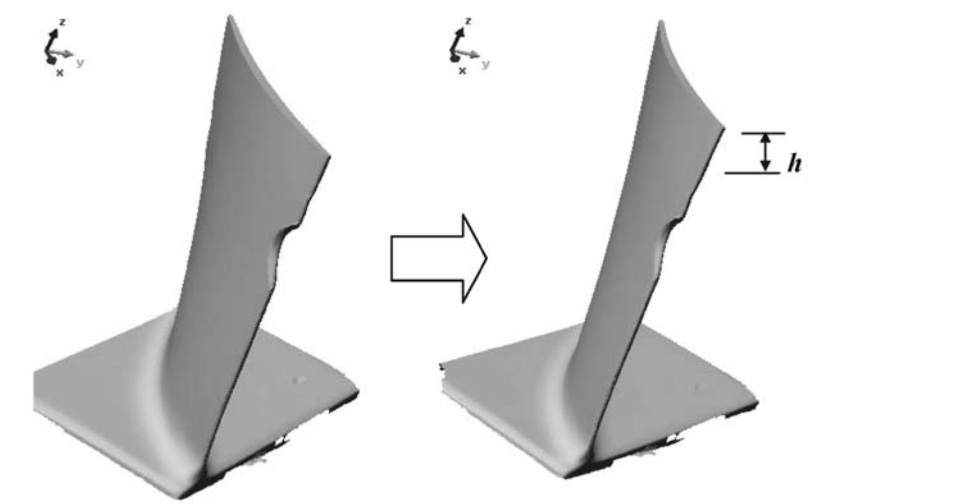
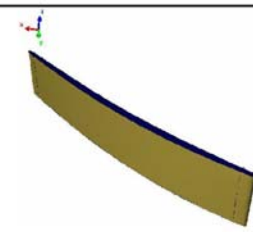
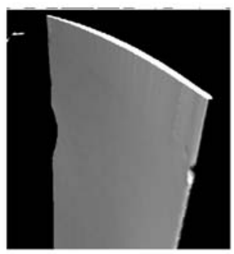
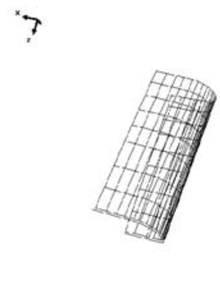
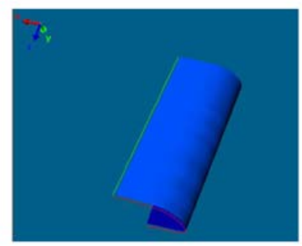
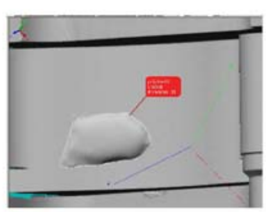
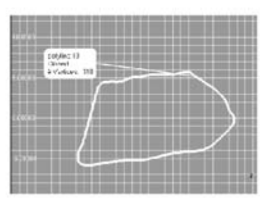
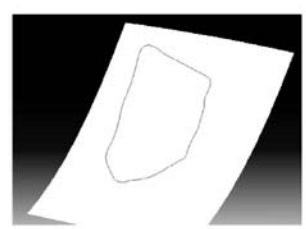


Table 1 Repair geometries reconstructed for laser cladding and machining tool path generation

Repair patches for subtractive process	*Nominal Geometry for Laser welding*	*Nominal Geometry for machining*
 **Blade tip repair**		
Blade edge repair 		
Blade sealfin repair 		
Sculptured surface components 		

cladding process. The welded blade was first clamped on its root on a pin-fixture to implement blade geometry digitisation. This process was performed through a GOM ATOSII topometric digitising system (shown in Fig. 7). This digitiser uses advanced projection technology and guarantees high data quality with a minimum of noise. The ATOS head is positioned freehand in front of the welded blade, and can be mounted on a tripod or a stand or held by a robot arm. An automated blade measuring process was performed through movement programming and a rotary table on which the blade was fixed with the pin-fixture. In the measuring process, measurement from different views is automatically transformed into a common object coordinate system and forms a complete 3D model. The 3D data set can then be exported as a standard file format for modelling purpose.

In the experiment, a special pin-fixture is designed and produced in order to maintain the blade pose in the process of digitising, build-up and machining. The fixture designed contains two clamping functions. One is to clamp blade root for blade digitisation, and the other is to

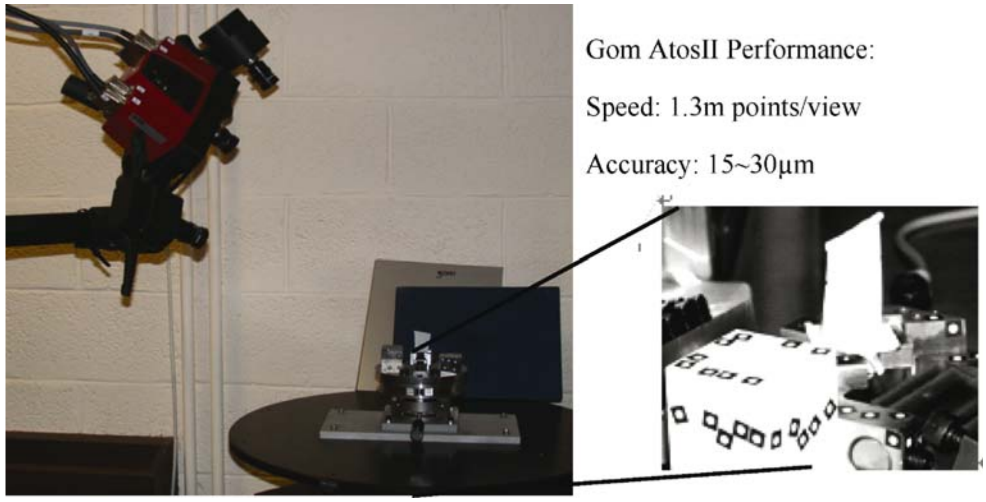


Fig. 7 Gom ATOS II optical scanner used for an automatic blade measurement

clamp on the airfoil surface through a number of screw pins, which is important to maintain the blade's position precisely during the welding process and machining process. This pin-fixture is adjustable to different surface shape and can thus be used for clamping different blades adaptive to their geometries to guarantee a high precision repair. It is, therefore, an appropriate tool for repair of a batch of blades.

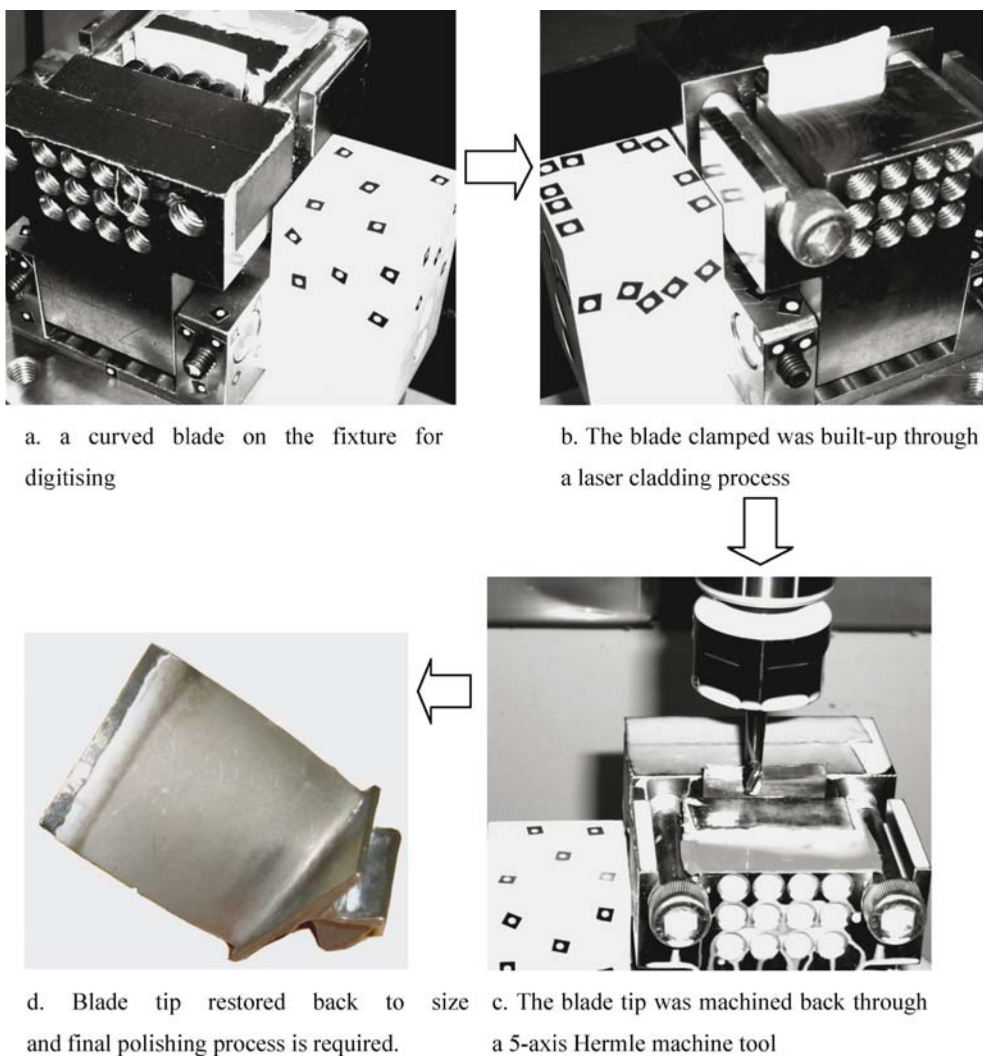


Fig. 8 Blade clamped on one pin-fixture throughout the repair process

Figure 8 presents the blade repair workflow used in the experiment. As shown in the figure, the repair process contains four stages: blade geometry acquisition through 3D digitisation, blade positioning through a pin-fixture, five-axis machining process performed on Hermle machine tool, and the machined blade to be polished for post-repair inspection. Based on the 3D geometrical data acquired by digitising process, a blade tip model through the proposed approach was reconstructed and transformed to a CAM system for tool path generation.

5.2 Tool paths for tip machining

Based on the blade tip model created, the tool paths adaptive to individual blade geometry can be generated. In this study, a CAM system, such as CATIA V5 system, was used for tool path generation. For the tip repair, four patches of NURBS surfaces of the blade tip are used for the generation of multi-axis tool paths. The coordinate reference system was defined by these white-black dots on the pin-fixture shown in Fig. 8. In the experiment, an isoparametric machining strategy was adopted, and a solid ball-end cutter and a solid radius end-mill cutter were selected for the tip machining. The machining tool paths generated are shown in Fig. 9, which were output as the ISO APT format and post-processed as G-code for machining operation performed on a Hermle CNC machine tool. When the blade machining process was finished, a certain mount of machining residual was left for final polishing.

As presented in the repair trials, the proposed repair system provides an integrated solution for blade repair, which integrated the repair processes of digitisation, reconstruction, build-up and machining operation. In the system, once a blade was clamped on the pin-fixture for repairing, its position was fixed until the repair was finished. In the system, the 3D blade model acquired through an automated digitising process was the only geometry used for blade tip reconstruction, for tool path generation, and for the post-repair inspection. The integrated solution has the advantages of adaptive clamping for individual blade geometry, accurate positioning, adaptive geometry modelling, repair time saving for unnecessary re-clamp and transformation, one digitising process and data share. The problem with this solution is that clamp deformation for thin blade repair may cause inaccurate geometry model for tool path generation. For blade tip repair, this can be solved by digitising the blade while it has been clamped by the pin-fixture. Through the blade repair trials, we found that the procedure for blade tip model reconstruction is time consume and the nominal model created will directly affect the repair accuracy. Repair efficiency should be considered in future research work.

6 Conclusions

Due to the geometrical variation in individual worn complex component, it is a tough task for aerospace industries to refurbish these parts with an automated, accurate and fast repair solution. This paper analysed the geometrical difference of cross-sections of a curved blade at different position. Through the geometry comparison of a

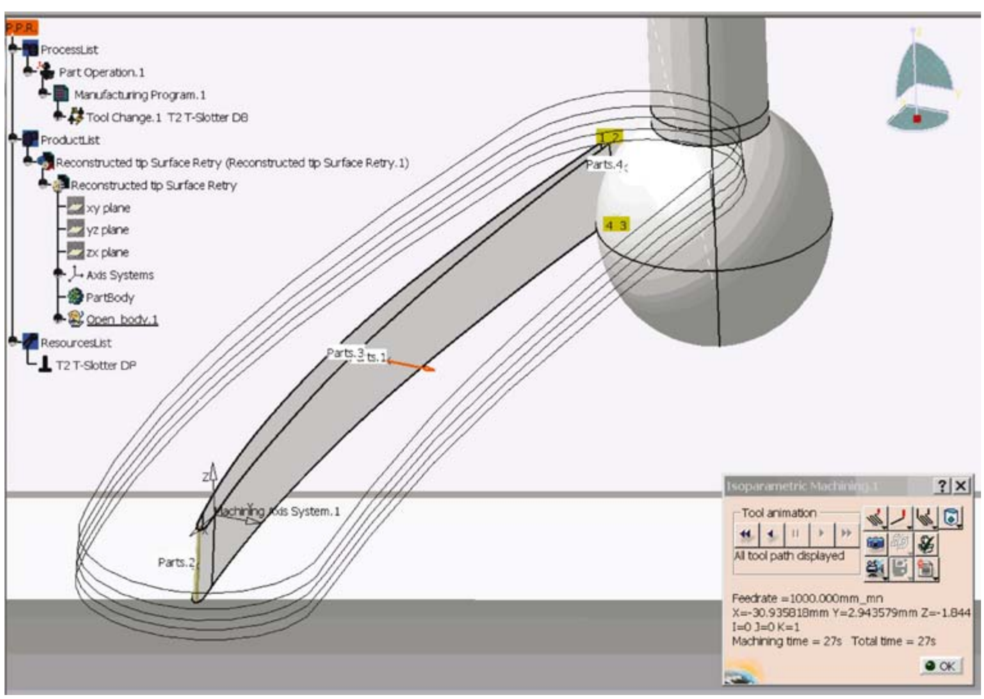


Fig. 9 Isoparametric tool paths generation in CATIA for blade tip machining

curved blade and a straight blade, it concludes that current repair methods used for straight blade repair are not appropriate for repair of a curved blade. To tackle the problem of geometry variation of individual worn component and the problem of original CAD model no long suitable for accurate repair of the worn parts, this paper proposed an integrated solution for refurbishing complex components. The kernel of the solution is to reconstruct the geometrical model adaptive to the worn part to be repaired based on the 3D measurement through an optical scanner. A RE-based surface extension approach was introduced to reconstruct the repair area (blade tip), and the reconstruction procedure for a curved blade was detailed in the paper. The model created can then be used in a CAM system to generate tool paths for the build-up and machining processes. Experimental trials on blade tip repair were performed to verify the solution. The experimental results show that the proposed approach is feasible for repair of a curved blade and can be used for repair of complex geometry components. It has the advantages of adaptive clamping for individual blade geometry, accurate positioning, adaptive geometry modelling, repair time saving for unnecessary re-clamp and transformation, one digitising process and data share. Due to the complex procedure and interactive operations in the process of reconstructing a nominal geometry of a worn part, the model reconstruction process is time consuming and the nominal model created will directly affect the repair accuracy. Therefore, future research work should be carried out on improving the efficiency and accuracy of the reconstructing method.

Acknowledgements The authors would like to acknowledge the support by the Natural Sciences Foundation of China (Grant No. 50675040), by the Natural Sciences Foundation of Guangdong Province (Grant No.04009491, P.R. China), and by the UK Engineering and Physical Sciences Research Council (EPSRC) under Nottingham's IMRC (Grant No.GR/R67019/01). Test parts support by Rolls-Royce Plc in Derby is gratefully acknowledged. The authors would like to thank the referees for their constructive and valuable comments that have contributed to a much improved paper.

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