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Aircraft Propeller Hub Repair

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OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

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Aircraft Propeller Hub Repair

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Research sponsored by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Advanced Manufacturing Office, under contract DE-AC05-00OR22725 with UT-Battelle, LLC.

This project was conducted in partnership with Aaron Hollander and Paul Bolton of Piedmont Propulsion Systems, LLC. *This document does not disclose full details of all research and repair requirements. Repair of Aircraft components is subject to FAA approval. Please contact Piedmont Propulsion Systems, LLC for further information on any procedures mentioned in this document.*

ABSTRACT

The team performed a literature review, conducted residual stress measurements, performed failure analysis, and demonstrated a solid state additive manufacturing repair technique on samples removed from a scrapped propeller hub. The team evaluated multiple options for hub repair that included existing metal buildup technologies that the Federal Aviation Administration (FAA) has already embraced, such as cold spray, high velocity oxy-fuel deposition (HVOF), and plasma spray. In addition the team helped Piedmont Propulsion Systems, LLC (PPS) evaluate three potential solutions that could be deployed at different stages in the life cycle of aluminum alloy hubs, in addition to the conventional spray coating method for repair. For new hubs, a machining practice to prevent fretting with the steel drive shaft was recommended. For hubs that were refurbished with some material remaining above the minimal material condition (MMC), a silver interface applied by an electromagnetic pulse additive manufacturing method was recommended. For hubs that were at or below the MMC, a solid state additive manufacturing technique using ultrasonic welding (UW) of thin layers of 7075 aluminum to the hub interface was recommended. A cladding demonstration using the UW technique achieved mechanical bonding of the layers showing promise as a viable repair method.

1. AIRCRAFT PROPELLER HUB REPAIR

This phase one technical collaboration project (NFE-14-05024) was begun on February 7, 2014 and was completed on December 31, 2014. The collaboration partner Piedmont Propulsion Systems, LLC is a small business.

1.1 BACKGROUND

In the US alone turboprop hub repair / replacement is estimated to cost air carriers approximately $160 million per year. A significant portion of that cost is due to refurbishment of the contact face where the aluminum propeller hub is bolted to the steel output drive shaft. Piedmont Propulsion Systems' (PPS) is a repair depot that performs propeller hub refurbishment on turboprop aircraft for commercial carriers and is looking to implement repairs using additive manufacturing methods, which increase propeller hub life.

Propeller hubs are removed from the aircraft at prescribed intervals and reconditioned by machining to restore them to the original equipment manufacturers (OEM) specifications. Periodically, during the machining step, a die penetrant examination is used to discover discontinuities, prior to treatment with a corrosion inhibitor. Machining continues if discontinuities are detected up until the minimum material condition (MMC) is reached. If the MMC is reached and discontinuities remain, the hub is then scrapped.

The intent of this collaboration was to evaluate additive manufacturing methods to repair hubs that were at the MMC, by first removing the discontinuities below the MMC, then building back the base material to above the MMC. A second objective was to perform a failure analysis to determine if additive manufacturing could be used to modify the interface on new or reconditioned hubs extending the hub life indefinitely.

Interfaces between dissimilar materials in mechanized equipment and structures are common failure regions that result in unplanned disruption of operation. Degradation caused by fretting, corrosion, foreign particle embedment, differential thermal expansion, and differential load sharing are common challenges with steel parts mechanically connected to aluminum parts. Aluminum alloy propeller hub interfaces, steel-cored aluminum conductor transmission lines, aluminum connectors to steel drill pipe in the oil field; and high performance commuter train wheels are some common examples of these potential failure points that cover a diverse industrial infrastructure. An economical surface modification to aluminum at the steel interface has been a goal for decades to combat unplanned degradation of the interface.

PPS has been at the forefront of on-going investigations into alternative repair technologies to develop and test a process that allows the restoration of aluminum components affected by corrosion and wear that are beyond the original equipment manufacturer (OEM) Component Maintenance Manual (CMM) limits. This collaboration with ORNL focused on examining additive manufacturing techniques on aluminum alloy propeller hubs that had sustained damage in service at the interface of the steel output gear box drive shaft. The successful outcome was to identify causal factors in the premature failure of the hubs, and to identify a repair strategy that would not only provide the surety of service performance, but also be embraced by the Federal Aviation Administration (FAA) as an acceptable repair method. In addition the successful outcome would provide a value solution to other industries where aluminum, when mechanically joined to steel suffers degradation.

1.2 TECHNICAL RESULTS

To better understand damage conditions a literature review was conducted on propeller hub observations and a review of National Transportation Safety Bureau (NTSB) records was performed. Residual stress measurements were taken on the hub face of interest. Failure analysis was performed on some hubs that were below MMC.

The team then evaluated multiple options for hub repair that included existing metal buildup technologies that the Federal Aviation Administration (FAA) has already embraced, such as cold spray, high velocity oxy-fuel deposition (HVOF), and plasma spray. The team recognized that metallurgical bonding was thought to be necessary for propeller hub repair, and that these spray technologies did not produce metallurgical bonding, so other additive manufacturing methods for repair were then investigated.

The ORNL team helped PPS evaluate three potential solutions that could be deployed at different stages in the life cycle of aluminum alloy hubs, in addition to the conventional spray coating method for repair. For new hubs, a machining practice to prevent fretting with the steel drive shaft was recommended. For hubs that were refurbished with some material remaining above the MMC, a silver interface applied by an electromagnetic pulse additive manufacturing method was recommended. For hubs that were at or below the MMC, a solid state additive manufacturing technique using ultrasonic welding (UW) of thin layers of 7075 aluminum to the hub interface was recommended. A cladding demonstration using the UW technique achieved mechanical bonding of the layers showing promise as a viable repair method.

Fig. 1 shows the location of a propeller hub on a turboprop aircraft, with an image showing the typical area of anomalous indications causal for rejection of the hub for flight service. Five propeller hubs were provided to ORNL; one was a refurbished unit that was acceptable for return to service, one was as-removed from an aircraft just prior to performing maintenance refurbishment and the three others were at the minimum material condition (MMC) having just completed maintenance refurbishment, but had deleterious die penetrant indications precluding return to service. A summary of the hub conditions and actions performed by ORNL are in Table 1.

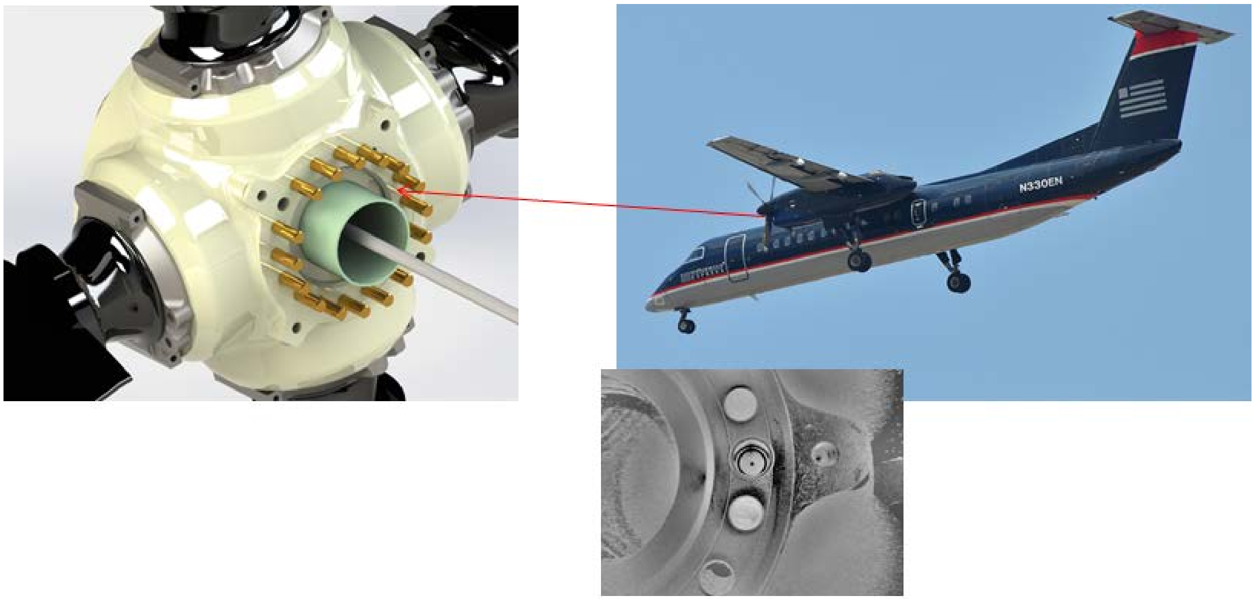

Fig. 1. Depiction of a propeller hub from a turbo-prop aircraft.

Table 1. Summary of hub conditions and ORNL actions

Hub	Condition	ORNL Actions	Disposition after action
A	as-removed from aircraft	visual observations / photo documentation	Returned to PPS
B	Refurbished suitable for flight service	Stress analysis	Returned to PPS
C	Machined to the MMC discontinuities evident after die penetrant inspection	Destructively examined at noted discontinuities, Optical microscopy, SEM	Retained at ORNL
D	Machined to the MMC discontinuities evident after die penetrant inspection	Destructively examined at noted discontinuities, Optical microscopy, SEM, compositional analysis, coupons cut for ultrasonic welding	Retained at ORNL
E	Machined to the MMC discontinuities evident after die penetrant inspection	visual observations / photo documentation	Retained at ORNL

A review of National Transportation Safety Board (NTSB) investigations of aircraft crashes where hubs were examined indicates that even though hubs were not causal in the crashes examined, steel to aluminum fretting was observed. This type of fretting is commonplace on turboprops.

In conjunction with the NTSB information, and the examination of hub A where smearing was observed, fretting was deemed the likely source as a crack initiation event prior to propagation. The observation that the anomalies / cracks were all located adjacent to the dowel pin holes, lead the team to categorize the observations on the five hubs examined as a progression of fretting damage with eventual crack propagation.

The remnant cracks in hubs C, D, and E could not specifically identify fretting due to machining away of the contact face prior to examination; however fretting was considered the likely crack initiator, based on the similarities with hub A. It is hypothesized that fretting damage lead to stress concentration and that stress concentration in the zone adjacent to the dowel pin holes, where expected misalignment occurred, resulted in higher structural loads. The crack initiation was followed by propagation during the load cycles in service. The crack propagation in the case of hubs C, D, and E was sufficient to be present after refurbishment machining to MMC.

X-ray stress analysis at the flange face of the flight worthy refurbished unit, hub B, indicated compressive residual stresses commensurate with machined aluminum.   Similarly, X–ray stress analysis on hub D at MMC showed residual compressive stresses. In machined aluminum, compressive residual stresses are expected due to the imposition of the cutting tool on the base metal. The stress analysis was inconclusive.

Two of the hubs with die penetrant indications at MMC were sectioned for examination. Samples were prepared and observed under the optical and the scanning electron microscopes (SEM). The SEM analysis utilized the energy-dispersive x-ray spectroscopy module to identify elements at observed crack openings and discontinuities. The base microstructure was typical of AMS4141 aluminum. In areas where cracks and anomalies were observed, accretions high in chromium and oxygen were identified. Fig. 2 depicts a typical finding.   Chromium likely results from the chromate conversion treatment applied to inhibit corrosion of the hub in service.

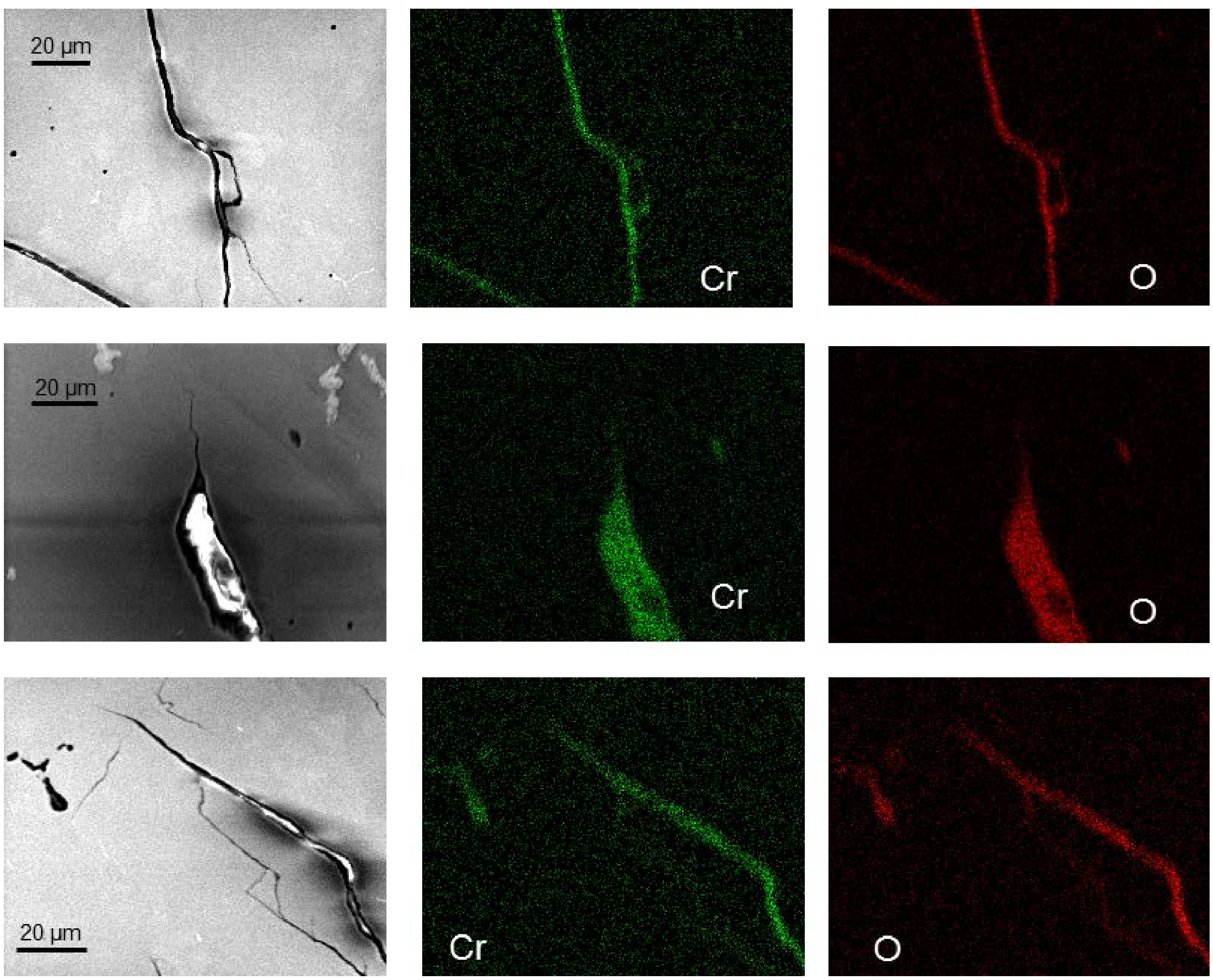

Fig. 2. Example of typical anomalies identified and associated with fretting in base metal adjacent to one of the dowel pins in one of the examined hubs. There is a noticeable concentration of chromium and oxygen in the crack opening likely associated with the chromate conversion process used to mitigate corrosion.

Because of the common proximity of the die penetrant indications to the dowel pin holes and the damage observed in the same location on the as-removed hub, solutions relating to repair were targeted at the area on the flange face adjacent to the dowel pins. For fretting prevention in new hubs, it was recommended that a recess in the mounting face be machined to simply prevent contact in the fretted area.

For repair of existing flanges, two approaches were recommended. Both methods require removal of all detectable damage, prior to attempting a repair. If damage removal left the hub above the MMC, then a silver cladding applied via electromagnetic pulse (EMP) technology was recommended. If damage removal left the hub below the MMC then a thin foil aluminum alloy patch, applied via ultrasonic welding was recommended to bring the flange face above the MMC.

The silver cladding method was vetted as being viable, but could not be attempted in this effort and is recommended as an approach for further research.

The ultrasonic welding method on the flange face was attempted at Fabrisonics in Columbus, OH, using samples removed from a scrapped hub. Mechanical bonding was observed upon sectioning of the weldment as depicted in fig. 3. The results indicate some promise toward achieving a metallurgical bond with further research.

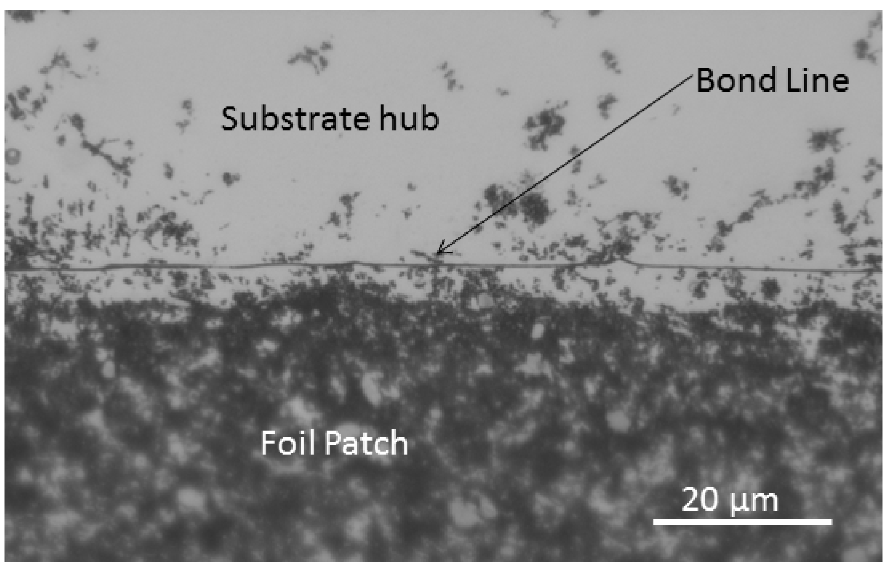

Fig. 3. Cross section of an aluminum alloy foil being attached via ultrasonic welding to a sample of a hub. The substrate hub is white, and the foil attachment is dark (bottom). The bond line is visible as a linear feature indicating mechanical bonding.

1.3 IMPACTS

Due to increased fuel costs, airlines increasingly view turbo-prop engine aircraft as a viable alternative to turbo-jet powered aircraft in the regional aircraft market. For flights of less than 1,000 miles, the turbo-prop is approximately 25% more fuel efficient than the equivalent sized jet aircraft. The turbo-prop also has the advantage of a reduced maintenance, repair and overhaul interval.

$80 to $160 million dollars is spent each year replacing turboprop hubs for a variety of maintenance issues, hundreds of millions more are spent for similar wear and corrosion issues on other flight critical parts. With a successful repair strategy to the propeller hub / steel shaft interface PPS will look to increase the life cycle of the propeller assembly not only reducing the airplane carriers' direct operating costs but also reducing the environmental impact of manufacture and disposal of replacement components. More importantly, PPS believes that the development of repairs for forged aluminum components such as the specific example developed herein would have numerous potential applications throughout the aerospace industry that could result in potentially billions of dollars of savings.

With a successful repair strategy to the propeller hub / steel shaft interface PPS will look to increase the life cycle of the propeller assembly not only reducing the aircraft carriers' direct operating costs but also reducing the environmental impact of manufacture and disposal of replacement components. More importantly, PPS believes that the development of repairs for forged aluminum component such as the specific example proposed herein would have numerous potential applications throughout the aerospace industry that could result in potentially billions of dollars of savings.

Additive manufacturing methods for modification of aluminum at the contact face with steel in dissimilar mechanical joints has broad application in not only aviation, but rail, oil and gas, and electrical power transmission.

1.4 CONCLUSIONS

A literature review was conducted on propeller hub observations and a review of National Transportation Safety Bureau (NTSB) records was performed. Residual stress measurements were taken on the hub face of interest. Failure analysis was performed on some hubs that were below MMC. Fretting was the likely cause of crack initiation around the dowel pin locations and solutions to combat fretting were proposed.

The team evaluated multiple options for hub repair that included existing metal buildup technologies that the Federal Aviation Administration (FAA) has already embraced, such as cold spray, high velocity oxy-fuel deposition (HVOF), and plasma spray. The team recognized that metallurgical bonding was thought to be necessary for propeller hub repair, and that these spray technologies did not produce metallurgical bonding.

The ORNL team helped PPS evaluate three potential solutions that could be deployed at different stages in the life cycle of aluminum alloy hubs, in addition to the conventional spray coating method for repair. For new hubs, a machining practice to prevent fretting with the steel drive shaft was recommended. For hubs that were refurbished with some material remaining above the MMC, a silver interface applied by an electromagnetic pulse additive manufacturing method was recommended. For hubs that were at or below the MMC, a solid state additive manufacturing technique using ultrasonic welding (UW) of thin layers of 7075 aluminum to the hub interface was recommended. A cladding demonstration using the UW technique achieved mechanical bonding of the layers showing promise as a viable repair method.

2. PIEDMONT PROPULSION SYSTEMS BACKGROUND

About Piedmont Propulsion Systems (www.piedmontpropulsion.com)

Piedmont Propulsion Systems, a subsidiary of First Aviation Services Inc. offers extensive propeller maintenance and overhaul capabilities to the commercial, regional, military, corporate and general aviation industry at its headquarters facility in Winston-Salem, North Carolina. PPS has over 60 years of experience in propeller maintenance and is an FAA and EASA Part 145 Repair Station. PPS is a Hartzell and McCauley authorized services center and also has factory trained Dowty and Hamilton technicians. PPS is the world's leading propeller overhaul facility serving the Dash 8, ATR, EMB-120, Saab 340 and DHC-6 platforms.

About First Aviation Services Inc. (www.firstaviation.com)

First Aviation Services Inc. (FAvS), located in Westport, Connecticut, is a leading provider of repair and overhaul, rotables management and related engineering services to the aviation industry worldwide. FAvS' principal operating subsidiaries are Aerospace Turbine Rotables, Inc. (AeTR) in Wichita, Kansas, and Piedmont Propulsion Systems, LLC (PPS) in Winston-Salem, North Carolina. FAvS also owns a minority interest in Aerospace Products International, Inc., based in Memphis, Tennessee.

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