The availability of hi-tech engine parts repairs extends to all modules and structures for all major engine types. There are now many levels of high technology, and the costs of repairs are a fraction of new parts. Hi-tech repairs are thus able to save tens of thousands of dollars for each engine shop visit.

Hi-tech engine parts repairs: schemes & the economics

The repair of many engine components during shop visits involves high-technology (hi-tech) processes that restore the capability of engine components by utilising the latest welding and brazing techniques and coating technologies. Hi-tech repairs exist throughout the engine for all major engine types and their components, including the blades and vanes in every module, disc and shaft life limited parts (LLPs), casings, and combustion chambers. These repairs are now available for all modules and sections of each major engine type from several suppliers. The economic significance of hi-tech repairs is that they have the potential to save tens or hundreds of thousands of dollars in shop-visit costs. They have also contributed to preventing engine maintenance costs from increasing at a higher rate than has actually been experienced. More hi-tech repairs are constantly being developed and should contribute to further reductions in aircraft maintenance costs.

Types of repairs

Hi-tech repairs fall into two categories. The first category comprises repairs approved or licensed by the original equipment manufacturer (OEM). These repairs are referred to and listed in the engine's repair and shop-visit manual. Several repairs are often listed for each component, and primarily include those listed by the engine's OEM itself. Further repairs are provided by other repair agencies, which enjoy a stream of component repair work, but are also obliged to pay the OEM a royalty fee in respect of each component that they do repair. This royalty is built into the cost of the repair.

The second category covers non-licensed repairs that are often referred to as designated engineering representative (DER) repairs. These repairs are not listed in the engine shop manual, so they must be actively marketed by the repair agencies. No royalty fees have to be paid. DER repairs are approved by the European Aviation Safety Agency (EASA), the Federal Aviation Administration (FAA), the Civil Aviation Authority of China (CAAC) and other aviation authorities.

Because licensed repairs are listed in the engine shop-visit manual, DER repairs need to be of a similar quality to licensed repairs.

Some repair agencies offer both DER and licensed repairs. MTU Maintenance is a division of MTU Aero Engines, an engine OEM that is building part of the IAE V2500 engine and the Pratt & Whitney (PW) PW6000. MTU Maintenance therefore has licenses for component repairs on these two engines. "CFM International would not give us licenses for hi-tech repairs on the CFM56 family," says Adri van Ierland, vice president sales component repair services at MTU Maintenance. "MTU Maintenance has therefore developed a number of EASA-approved DER repairs for the CFM56-7B. Repairs that have been approved by the repair agency's aviation authority are then automatically approved by the FAA and other authorities."

Chromalloy is another provider of specialist repairs, and offers both OEM-approved and DER repairs. "We offer both types of repair for virtually every engine type," says Rob Church, regional sales director for the Americas at Chromalloy. Chromalloy has 33 facilities in 14 countries, and each one is a centre of excellence for a particular engine type or type of repair. Chromalloy provides repairs on high pressure turbine (HPT) airfoils and shrouds, compressor blades, seals, stators, cases and frames for most IAE, Rolls-Royce, General Electric (GE), CFMI and Pratt & Whitney (PW) engines.

Engine sections

The engine can be broken down into the turbomachinery modules, the accessories and quick engine change (QEC), engine casings, engine cowling and thrust reverser.

The turbomachinery can then be broken down into engine modules. These are the fan, low pressure compressor (LPC), HPC, combustor, HPT and low pressure turbine (LPT). There are now several hi-tech repairs for each component in each module.

Fan module

The main components of the fan module are the fan blades, fan struts and the fan case. Fan blades in older engine types were solid material. Later engines used honeycomb designs to save weight, while the most recent designs have used composite materials to achieve further weight reduction and provide more durable fan blades.

Repairs for earlier fan blades were limited to straightening blade edges and restoring blade curvatures. Further repairs were developed for nicks and dents in fan blade leading edges. Restoring blade curvature is intended to regain the blade's optimum airfoil shape,

Repairs for the latest generation of fan blades, which use composites and carbon fibre, involve the use of a polymer fibre matrix.

which results in fuel burn savings.

PAS Technologies not only provides fan blade forming processes, but also welding to repair fan blade leading edges.

A small number of new generation engines have composite and carbon fibre fan blades. Fan blades developed by General Electric (GE) for the GE90 and GEnx engines use an organic polymer fibre material to form a polymer matrix composite. "The repairs are based on coatings and flowpath repairs made only to blade surfaces," explains Tim Rasch, advanced repair team leader at GE Engine Services. "The leading edge on the GE90's and GEnx's fan blades is a titanium sheath that has to be removed before the exposed polymer matrix composite material can be repaired. While we have developed the repair with the polymer fibre matrix, we are now looking at ways to repair the actual load-carrying and structural elements of the parts. This will require completely new technology."

There are various issues with fan blades. "There is often erosion of the leading edge and shape of fan blades," says Norbert Arendt, manager repair development engine parts repair at Lufthansa Technik. "Fan blade chord length is also important. A shipset of blades can be changed on-wing, allowing hi-tech repairs to be made. Snecma recently developed leading edge patch repairs for CFM56 fan blades. Lufthansa Technik provides a welding repair. Fan blade repair processes depend on whether the blade is shrouded or wide chord. Shrouded blades are used on the CF6-80C2 and CFM56-3/-5 series. Processes start by removing blade coatings with a chemical strip or a blasting process. The surface is then shot peened to straighten the airfoil. The coating is re-applied using thermal techniques on the shrouds and dovetails, and the blade surfaces are then polished.

"More advanced repairs involve recontouring using hot forming to restore the blades' shape," continues Arendt. "Chord lengths have to be re-established following erosion of the leading edge and blade material. This repair of the leading edges is achieved by adding material with a welding process. We are developing these repairs for CFM56 engines. Demand for such repairs is increasing with higher fuel prices. The cost of these repairs has to be considered against new blades, which cost $20,000 each for older engines and up to $50,000 for wide chord blades used in younger engines."

Apart from the OEMs, there are few other fan blade overhaul and repair shops. PAS Technologies offers licensed repairs for fan blades that include forming processes to attain optimum airfoil shape, as well as welding, coating and tip repairs to fan blades.

MTU Maintenance has capability to repair the wide chord fan blades used in the V2500. Van Ierland gives an example of the economics of repair versus replacement: the average repair cost for each blade is $1,100 versus a list price of $38,000 per blade.

Other examples of fan blades are: the RB211-535E4, with a list price of $50,000 each; the CFM56-3, with a list price of $19,000 each; and the PW4000-94 fan blade, with a list price of $26,000 each. In contrast, the repairs of these blades are $2,000-3,000 for the RB211-535E4, $250 for the CFM56-3, and $600 for the PW4000-94.

LPC & HPC airfoils

The majority of repairs for LPC and HPC blades and stators are to restore leading edge airfoil profile, blade chord width and blade length. The importance of these is not only that shop visit costs can be reduced, but the aerodynamic efficiency of these blades also affects fuel burn performance.

Blades in the earlier stages of the LPC and HPC are typically made from titanium, while blades in later stages are often manufactured using nickel superalloys. Traditional engines use basic two-dimensional (2-D) blades, while later engines, such as the CFM56-7B, GE90 and GEnx, utilise 3-D blades. "The use of 3-D blades allows engines to have blades with changing geometry progressing through the engine," explains Rasch. "2-D blades are manufactured using traditional fusion welding processes. These blades can be repaired by cutting sections away, then adding material by fusion welding, and then machining to restore the shape and dimension of the blades.

"In the case of new generation engines, fusion welding is used to re-establish the blade length. It is more challenging to restore the 3-D shape. One technique is numerically controlled (NC) machining," continues Rasch. "The first stage removes the old coating material, including some of the tip. New material is then added by fusion welding, and then the blade is NC machined into shape. It is very complex to restore the whole of the airfoil, and repairs that add material to the surfaces and the edges are being developed.

"LPC and HPC blade repairs are similar to those carried out for the fan blades," says Arendt. "We have developed an advanced recontouring process (ARP) for these blades, which

The biggest savings that can be realised from hi-tech engine parts repairs are to HPT blades. Full repairs, however, can only be made once, since the process has the effect of thinning the blade walls.

recontours the blades' leading edge profile and aerodynamic shape. The blade leading edges and chord width wear with engine operation, and the optimal leading edge contour and chord width is different for used blades compared to new airfoils."

Lufthansa Technik and MTU Maintenance have a joint venture in Malaysia called Airfoil Services which specialises in repairing HPC and LPC blades and vanes. "We tested HPC blades that were repaired using ARP techniques, and found that they have increased exhaust gas temperature (EGT) margin by about three degrees centigrade," says Arendt. "While this may not seem much, it does extend on-wing time by about one year in the case of the CF6-80C2 when used on a long-haul operation.

"We have also developed a super-polish technique to improve the aerodynamic efficiency of compressor blades," continues Arendt. "The problem is that the polish is removed a short time after the engine goes back into service, so we have recently developed a new coating of Chrome Nitride. This coating is only a few microns thick, and follows the exact contour of the blade. This new type of polish should last an entire engine run. We are currently comparing the EGT margin retentions of a treated and untreated engine on an A340. We are also performing borsecope inspections on the engines, and will monitor their fuel burn performance."

Other LPC and HPC blade repairs involve tip welding and grinding to re-establish blade length. "MTU Maintenance has developed an erosion-resistant (ER) coating, which is applied to HPC blades to prevent erosion of the leading edge and chord width. The ER coating is unique to MTU, and is a multi-layer metal-oxide-metal sandwich of these materials formed using nanotechnology," says van Ierland.

In addition to regular HPCs, a few engines have blisks, which are several stages of the HPC cast from a single piece of metal. "A blisk is cheaper to manufacture, and lower in weight, than several stages of a conventional HPC, but its drawback is that it is not possible to repair or replace a single airfoil," says Rasch. "We are in the process of developing such a repair."

Combustion chambers

The general evolution of engines has been to raise combustion temperatures to achieve leaner fuel burns. This has required more sophisticated cooling techniques. "Coatings are one technology being used," says Rasch. "Two new materials are Hastelloy X and HS188, both of which are traditional high-temperature strength alloys. These materials are highly weldable, which makes them easy to repair. They can then be re-coated.

"New generation engines like the GE90 have used cooling holes in combustors," continues Rasch. "These holes make repairs more complex to perform. New technology is now being used to re-establish the shapes of combustors. The material is burned away, so it has to be reapplied and the shape re-established."

Repair of combustion chambers is one DER repair offered by MTU Maintenance for the CFM56-7B. Although it is a DER repair, MTU Maintenance has developed a special thermal barrier coating that uses MTUPlus material for improved durability.

HPT repairs

Repairs to HPT blades and nozzle guide vanes (NGV) are among the most advanced performed throughout the engine.

The complexity of HPT blades and vanes is because they need cooling systems due to the high temperature environment they operate in. Blades and vanes have internal cooling channels and holes, drilled with lasers, to effect a flow of cooling air. They also use temperature-resistant materials and coatings to limit the erosion, oxidation and sulphidation of blades and vanes due to high temperatures.

"New coatings for blades have been developed as combustion temperatures have been pushed higher," says Rasch. "Blades and vanes have also acquired more highly engineered shapes as manufacturers have sought to improve the aerodynamic efficiency of HPT blades and vanes.

"The process of repairing HPT blades and NGVs first involves removing protective coatings," continues Rasch. "The damage to the actual metal of the blade and vane castings, and the cracks and burns, is then repaired. The problem is that the single-crystal material used to manufacture the original HPT blades cannot be re-grown. The only repair that can be carried out on the length of HPT blades involves adding material and then machining the blades to the correct dimensions, after which the cooling holes are re-drilled and the coatings are replaced."

One technique used by PW is repairing HPT blade tips with carbon boron nitride (CBN). "This gives the blade a strong and durable material that minimises blade tip wear and so maintains the clearance between the blade tip and the inner wall of the HPT case," says Hutton. "Cathartic arc coating is a technique used to target

One technology that has been developed to apply thermal barrier coatings to repaired airfoils in the engine's hot section is low pressure plasma spray (LPPS).

where on the blade tip the material will be deposited.

"Besides these licensed repairs for PW and V2500 engines, we have also developed a DER repair for the CFM56-3/-5/-7 HPT NGVs," continues Hutton. "These components experience a high replacement rate, but we can now repair a high percentage of these parts. The repair that we have developed provides HPT NGVs that are virtually zero-timed. The repair also provides more durability than a new OEM part. This new technique utilises a directionally-solidified nickel-based alloy, which comes from a group of superalloy materials."

MTU Maintenance has DER repairs for HPT blades and vanes for the V2500, CF6-80C2 and CFM56-7B. "Our DER HPT blade repairs are similar to the OEM's, and involve tip welding and extended tip welding," says van Ierland. "We also provide overlay coatings of a platinum aluminide (PtAl) material. We have also developed coatings for the underside of blade platforms and bases that protect them from the corrosion caused by heat, and from the build-up of oxidation and sulphidation. It should be noted that CFM does not have a platform coating for the HPT blades on the -7B series. We also apply a thermal barrier coating. The average repair cost per blade is about $1,000, which compares favourably with a list price of $9,000 for a new blade.

"MTU Maintenance has also developed repairs for HPT vanes that give the unit a full wrap coating, providing it with better thermal protection, whereas the OEM's repair only provides a half-wrap coating," continues van Ierland. "Again, the thermal coating material is used for protection on the airfoil, while a PtAl material is used on the underside of the base. NGVs also come as doublets, and we are able to split the assembly in half if one of the vanes is burned away. One vane is then re-casted, cooling holes are drilled and the protective coating is reapplied. The average cost for a split vane repair is $14,000, while the cost for a repair on a complete unit is $4,000. This compares to $29,000 for a new unit."

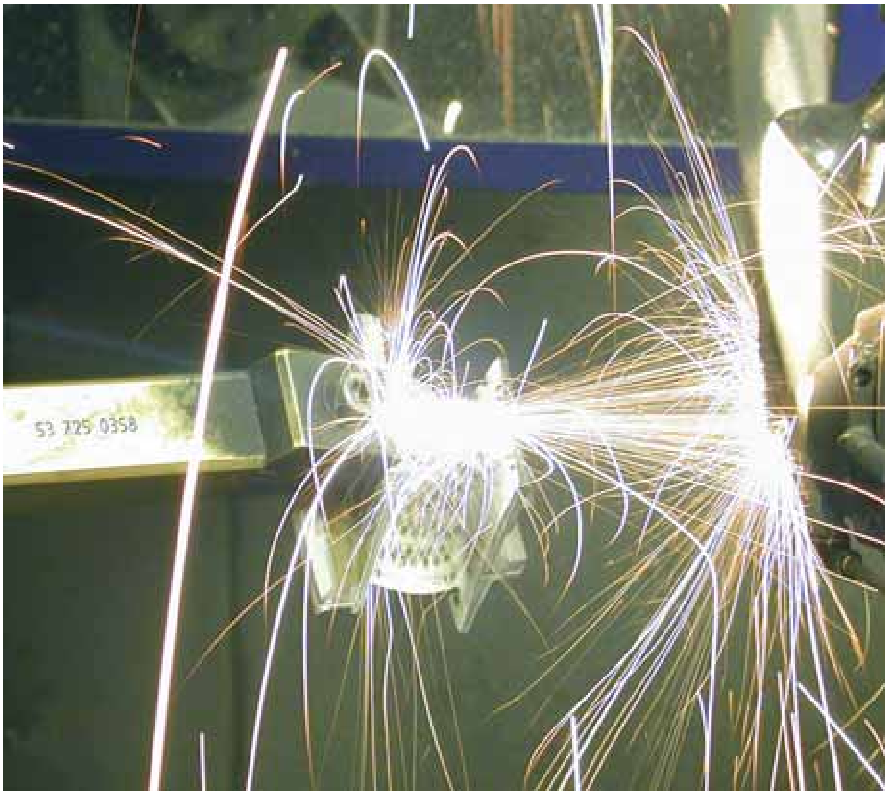
Chromalloy's HPT blade repairs are performed at its New York and Carson City, Nevada, facilities, where it has the tooling to carry out ceramic coatings. "Care is required when repairing HPT blades, since there is a limit to the number of times that a full repair of the blade can be carried out, because stripping the thermal barrier coating reduces the thickness of the blade wall," says Church. "A full repair can therefore only be done once, but lighter repairs can be made several times. A light repair involves blade inspection and repair of cracks. A full repair involves complete stripping of the thermal barrier coating from the blade and a recoating it with new protective material. Typically, a light or rejuvenation repair will be made at the first shop visit, while a full repair will be carried out at the second shop visit. Another rejuvenation repair will usually be made on the blades at the third shop visit, before the blades are scrapped at the fourth shop visit."

Chromalloy has a developed a proprietary blade tipping system for HPT blades using CBN technology for PW engine HPT blades. "For CF6 and CFMI HPT blades we have a repair that includes blazer technology. This is an automated digitised laser-welding system where the computer takes a picture of the blade tip, and then welds the tip using a laser," says Church. "The full repair starts with an eddy current inspection, after which the coating is removed. This is then followed by an ultrasonic inspection to check the blade wall thickness. The blade then has a pre-weld heat treatment, the tip is welded and recontoured to dimensions, and undergoes a post-weld heat treatment, followed by a non-destructive test. The thermal barrier coating is restored using Electron Beam Physical Vapour Deposition (EBPVD) technology. The blade is heat-treated, shot-peened and its cooling holes are then re-drilled using lasers."

"Repairs to NGVs are different. These use a technique that brazes an alloy that is compatible with the alloy of the NGV to fill the cracks," continues Church. "This alloy is applied like a paste, after which the blade is put in a vacuum furnace in order to solidify the repair".

Chromalloy has also developed a technique to apply an internal coating to HPT airfoils to protect them from corrosion. Airfoils can deteriorate from the inside outwards as a result of the high temperatures to which they are subjected. The repair cleans the internal cavity, and is then followed by an application of the internal coating.

As described, HPT airfoils typically have a light repair at the first shop visit. "About 94% can be repaired at this stage, while the rest are scrapped," says Church. "A full repair is performed on the blades at the second shop visit, where 10-20% of airfoils are scrapped and the remainder are repaired. About 20-40% of airfoils are then scrapped at the third shop visit when a second light repair is carried out. Taking the CF6-80C2 as an example, this has 80 blades in the first stage HPT. The average repair price per blade is about $1,000, compared to new



Laser drilling of cooling holes is one of the final stages in the repair of HPT NGV doublets. Along with HPT blades, repairs to these components derive some of the largest savings in engine maintenance.

PMA blades with a list price of about $6,000, and new OEM blades which have a list price of about $10,000. Considering that the blades can be repaired up to three times, it is obvious that substantial savings in material costs are achievable as a result of hi-tech repairs."

Other examples of the list prices of new HPT blades are the RB211-535E4 at about $7,000 each, the CFM56-3 at about $6,500 each, and the PW4000-94 at about $11,000 each. These prices compare with the cost of repairs that are about $900 for the RB211-535E4, $850 for the CFM56-3, and $1,100 for the PW4000-94.

HPT vane segments have higher OEM list prices by comparison, with the unit for the CFM56-3 costing about $25,000. Repairs by comparison average about $1,200.

Another important HPT component is the shrouds that provide a seal between the blade tip and HPT inner wall case to form a gas path seal. "The objective is to restore the rub-strip surface of the shroud that faces the blade tip. This surface uses the same alloy as the HPT blade," says Church. "This material is applied using either a low pressure plasma spray (LPPS) or high velocity oxygen fuel (HVOF) technique. The HPT shroud provides an abradable surface for blade tip rub mounted on a backing strip. This backing strip can be out of dimensions, and we have developed a repair for this that includes stripping, checking for cracks, and using LPPS/HVOF to apply new material. This is followed by heat treatment."

LPT repairs

Since the LPT experiences lower temperatures than the HPT, LPT blades and vanes have simpler coatings and do not have the cooling holes and channels that HPT airfoils have. Repairs to LPT airfoils are therefore simpler. Some technology used in the engine's hot section is still used in the HPT, however. While HPT blades tend to be repaired at every shop visit, LPT blades are usually repaired every second shop visit.

"Traditional engines used the same tip welding processes for HPC blades on LPT blades, but they also use plasma spray processes to apply metal material to the blades to build up thickness. The blades are then ground to dimensions," says Rasch. "The LPT only gets overhauled every second or third shop visit, and the airfoils have fewer environmental coatings compared to HPT blades."

Airfoil Services in Kuala Lumpur provides DER repairs LPT blades and vanes for: the GE CF34, CF6-50 and CF6-80; the CFM56 family; and V2500.

Seals

Seals are an important engine structure in relation to maintaining engine performance. Knife seals comprise two components: a series of rotating knife-edge discs with seal teeth; and a honeycomb rub in the inner wall of an engine casing. The design is intended to prevent longitudinal airflow. "During engine operation the seal teeth wear and deteriorate, allowing airflow to escape around the top of the teeth, and so flow longitudinally through the engine," says Rasch. "These seal teeth can be repaired by using laser welding, plasma welding and tig welding to apply blobs of metal to the seal teeth. The shape and dimension of the teeth is then restored by grinding, although laser welding provides a possibility to eliminate this."

Casings

Casings are high cost items, so repairs to these units provide an opportunity for large savings. The main casings are the fan case, LPC, HPC, combustion module, the HPT, the LPT module, and the turbine rearframe.

Examples of the list prices of engine cases are $440,000 for a CFM56 fan frame, $315,000 for a RB211-535E4 fan case, $553,000 for a PW4000-94 HPC front case set, $515,000 for a CFM56 combustor case, and $609,000 for a PW4000-94.

One example of a repair developed for casings is Lufthansa Technik's unique DER repair for the turbine rearframe on the CF6-80C2. "The part has a list price of about $0.5 million," says Arendt. "The turbine rearframe is at the end of the engine, has an attachment for the pylon, and has a housing for the bearing that supports the low pressure shaft. The unit also has struts between the housing and the outer shell. We have developed a patch repair for where these struts join the outer shell, and where cracking occurs. The repair starts by defining the size of the patch with optical scanning. A hole is cut in the outer shell in the area of the crack. A CAD model is made of the case with the hole made where the crack was. This allows a new patch to be designed. The CAD data is then transferred to the machine that makes the patch. The patch is then welded using an electron beam, and the final stage is recontouring with blending."

Cases are joined together by flanges, which get worn during engine operation. PW has developed a repair to replace the flanges on the static structures such as the HPC or LPT cases. "We use an electron beam to produce a new flange and do a large amount of material replacement," says Hutton. AC