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LASER MATERIAL PROCESSING IN THE AERO ENGINE INDUSTRY. ESTABLISHED, CUTTING-EDGE AND EMERGING APPLICATIONS.

Paper 1005

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Abstract

Laser machining processes are widely used in the manufacture and repair of aero engine components. This paper provides examples of well-established, cutting-edge and emerging laser machining processes. A well-established process is laser metal deposition or laser cladding which is predominantly used to restore worn blade tips and seal fins. But the process also has the potential to restore complete airfoils of integral rotors, also known as bladed disks or blisks. In the FLEXILAS-project sponsored by the German Federal Ministry of Education and Research it was demonstrated that the quality of laser generated blisk blades is comparable to that of new ones.

1. Introduction

In the manufacture of aero engines, use is made—apart from fundamental processes like casting and forging—of predominantly machining processes like turning, drilling, milling, broaching and grinding. These processes form the by far largest content, approximately 85%, of the value chain in the production of aero engines.

Apart from these conventional manufacturing techniques, the manufacture of aero engines additionally involves numerous special processes. With these, once process parameters have proved optimal in process validation, they are frozen within close limits. The reason is that deviating process parameters will not necessarily reflect directly in impaired component properties. For quality assurance reasons, therefore, components or specimens manufactured with the aid of special processes need to be tested destructively at regular intervals. Special processes include all joining and coating practices, as well as all laser material processing techniques. While the value-added content of laser-based manufacturing processes remains relatively modest, these processes are indispensable in the cost-effective manufacture of aero engines. Manufacturing cost reduction indeed is the biggest driver behind the use of laser material processing technology, but it is not the only one. Some components could not, or not at reasonable cost, be manufactured without the aid of laser-based processes.

2. Aero Engine Materials

Modern aero engine compressors are increasingly implemented as blisk (bladed disk) constructions. This integral construction helps enhance compressor efficiency and reduce weight while providing high mechanical integrity. Used as compressor materials nowadays are titanium alloys because of their high specific strength. It is only in the rearmost stages of the high-pressure compressor that highly heat-resistant nickel materials like IN718 are needed to cope with the higher gas temperature prevailing there. In the combustor, use is made of nickel alloys like Hastelloy X, owing to their ready formability and excellent corrosion and oxidation resistance. To withstand the searing temperatures, combustors are in places additionally provided with thermal barrier coatings. High-pressure turbine blade materials are cast single-crystal nickel superalloys such as René N5, PW1484 or CMSX4. In the low-pressure turbine, nozzle vanes and rotor blades largely still are conventionally cast nickel superalloys like IN713 or MAR-M247. As a disk material in the high- or low-pressure turbine, the forged nickel superalloy IN718 is often used. Considered advanced aero engine materials owing to their high specific strength are polymer matrix and TiAl materials. Carbon fiber-reinforced plastic is already being used for the fan

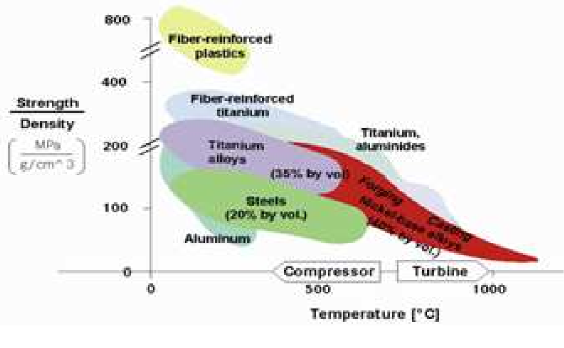

Figure 1 Specific strength of materials.

blades of the GE90 engines. Titanium aluminides are rapidly approaching use in low-pressure turbine blades. Fig. 1 provides a survey of the specific strength of the materials used in aero engines.

The laser material processing techniques used in engine manufacturing and repair are predominantly put to use on nickel materials and to a lesser extent on titanium materials.

3. Laser Material Processing Techniques in Manufacturing and Repair – State-of-the-art

Laser-based manufacturing techniques in the aero engine industry are used in both new parts manufacture and repair. While some of these techniques have been in use for only a few years, others have been applied for several decades already. Laser drilling, for instance, has been used for producing cooling air holes since the early eighties, whereas laser caving was adopted for generating shaped holes in high-pressure turbine blades just about a couple of years ago. Laser cutting has been used since the early nineties to fabricate a large variety of sheet-metal parts. Laser marking has been used to identify engine blades for about 20 years. Laser welding, although very popular in the automotive industry, has remained a niche application in the aero engine industry. Whereas laser cladding figures prominently in the repair of compressor and turbine blades. Among the group of surface finishing processes, the engine industry uses only laser peening. Other surface finishing techniques, such as laser hardening and laser remelting, have no relevance for the nickel and titanium materials mostly used in engine manufacturing. Presented below are some long-established and also some innovative applications of the laser material processing techniques.

3.1. Laser Marking

Laser marking is an expedient, long-established practice. It is nevertheless presented here to complete the list and recognize its popularity in the aero engine industry. Today, diode pumped Nd:YAG laser systems of powers around 100 W are commercially available that produce more than 1,000 characters a second.

In aero engine manufacturing, 2D matrix marking was introduced several years ago. The advantage the laser has over alternative methods is that these 2D matrices can be produced very rapidly and that they are readily machine-readable. Marking is used mainly for the identification of compressor and turbine blades, owing to the relatively large quantities involved. Fig. 2 shows a low-pressure turbine blade marked in alphanumeric and 2D matrix codes. The marking depth is typically 10–40 µm. Laser marking is generally allowable on noncritical areas of nickel-base materials. On titanium components, proof must be furnished that laser marking will not negatively affect component properties.

Figure 2 Laser marked low-pressure turbine blade.

3.2. Laser Drilling

In the aero engine industry, laser drilling is a long-established and the most widely used among laser-based manufacturing processes. The high processing speed of laser drilling has relegated competing processes like EC drilling and electric discharge machining to secondary roles. They are used only when the aspect ratio of a hole, i.e. the quotient of the depth of the drilled hole divided by its diameter, is so large that laser drilling will not produce the quality level desired. Laser drilling has two major applications. These involve the incorporation of cooling air holes in combustors and in high-pressure turbine blading. The latter application is used on stator vanes as well as rotor blades. It constitutes the by far most significant application, considering that in aero engine manufacturing, blades are the only components manufactured in relatively large quantities. As a rule, the turbine vane or blade, clamped in a fixture, is moved along 5 axes, with the laser beam being fixed. Used as beam sources are pulsed Nd:YAG lasers with an average output power of up to 1 kW and pulse peak output powers of up to 50 kW.

Process variants used are trepanning as well as percussion drilling. The latter process, because of it much higher processing speed, finds preferred use. Given a relatively large drilling diameter and relatively shallow drilling depth, the former process is used also for making shaped holes, imparting a wobble movement to the laser beam.

Damage to the complex inner cavity by the incident laser beam must at all events be prevented. That is why the turbine blades are internally lined with wax prior to the laser drilling process. Non-evaporated wax needs to be removed by melting after the drilling process.

The cooling air holes in a turbine blade, sometimes numbering 500 and more, possess diameters of 0.3 mm to nearly 1 mm and are inclined at various angles with the airfoil (see Fig. 3).

The geometry of laser-drilled holes is substantially more irregular than that of electrochemically drilled holes. However, this will not negatively impact the integrity of the component as long as the thickness of recast layer, the crack length and the number of cracks per unit of length remain within given tolerances. Additionally, each cooling air hole should have a minimum diameter. For that reason, all cooling air holes of each laser-drilled turbine blade are checked for compliance with this criterion. In the case of non-compliance, individual holes can be reworked. Yet a turbine blade's proper cooling function is not ruled by the air flow through one particular hole but by the integral air flow through all of the holes. Accordingly, the shape and diameter of a single laser-drilled hole is less relevant as long as it is ensured that the integral air flow complies with given tolerances and that the diameter of the hole is larger than the specified minimum. The integral air flow, therefore, is also checked blade by blade.

Figure 3 Laser drilled turbine blade (the pins show the various hole directions)

3.3. Laser Caving

The laser can be used for both the surface removal (stripping, cleaning) and the three-dimensional removal (laser caving) of stock. Laser caving is a highly advanced method for producing shaped holes in turbine blades and vanes. Laser caved holes improve cooling efficiency, permitting turbine entry temperatures to be raised, and turbine efficiency boosted with it. To produce a shaped hole, a first step is to generate a cylindrical through-hole by means of percussion drilling. Subsequently, the flared portion of the hole is generated by laser caving. To improve accuracy and minimize processing time, it is necessary to integrate both the drilling laser and the ablation laser in one processing unit,

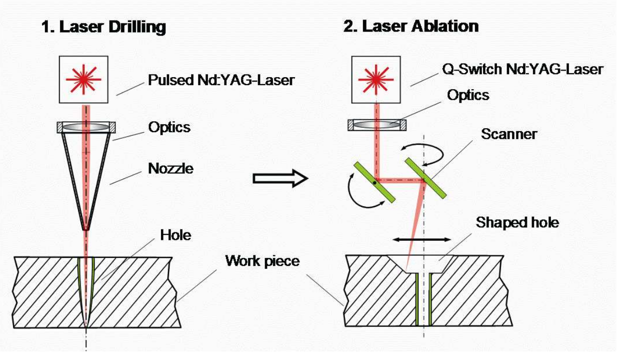

Figure 4 Production of shaped holes.

As a beam source for the ablation process, Q-switched Nd:YAG lasers with an output power of under 100 Watt are used. The laser beam, guided by a scanner system (see Fig. 4), removes material line by line. The thickness of an ablated layer would typically be 10 µm. Fig. 5 shows a high-pressure turbine rotor blade, illustrating the size of the shaped holes.

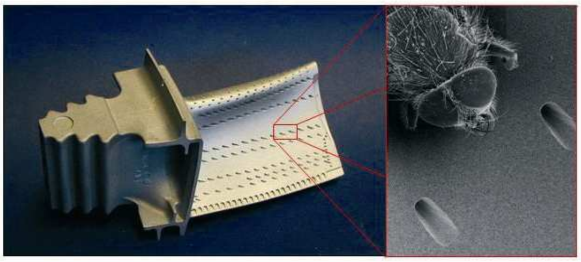

Figure 5 High-pressure turbine blade with shaped holes.

3.4. Laser Cutting

Laser cutting predominantly employs the fusion cutting method, using nitrogen as a cutting gas on nickel-base materials and argon on titanium alloys. An optimally conducted process leaves the cut edges in a metallic bright condition and produces only moderate surface roughness of a few µm, depending on the thickness of the stock. The laser cutting of 2D and 3D sheet metal is state-of-the-art and often outsourced to subcontractors. Fig. 6 illustrates a mixer under manufacture. This component is a fabricated sheet metal cone at the low-pressure turbine exit, serving to reduce noise. It is manufactured by first laser cutting two mixer petals from a deep-drawn tub-shaped part and then TIG welding them together to form the mixer.

Figure 6 Manufacture of a mixer by laser cutting.

Laser cutting is also used for the cost-efficient manufacture of compressor vane segments. For the purpose, up to 140 contoured openings each are cut from an inner and an outer shroud into which airfoils are subsequently joined by brazing. The resulting stator is then sectioned into vane segments. Owing to the brazing gap width requirements and the airfoil tolerance, the maximum allowable form tolerance of the openings is limited to 30 µm.

Figure 7 Laser cut shroud for the manufacture of compressor vane segments in IN718 material.

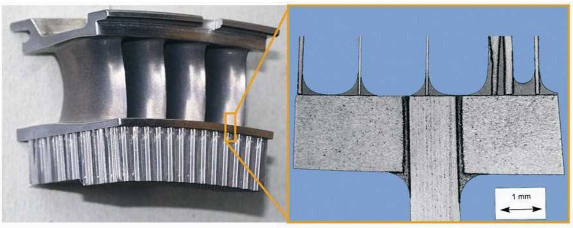

Figure 8 Vane segment with laser cut shrouds (left) and transverse section through the high-temperature brazed airfoil with honeycomb seal (right).

Fig. 7 shows a laser cut shroud in IN718 material. The radii of the contoured openings are a mere 0.15 mm at a material thickness of up to 3.5 mm. Fig. 8 shows a vane segment made from it, and a transverse microsection of a laser cut opening with a vane brazed in place.

3.5. Laser Welding

Unlike electron beam welding, laser welding is finding only few applications in aero engine manufacturing. The reason is that on the one hand, electron beam welding produces joints of a superior quality and on the other, less demanding applications—such as sheet metal joining—mostly rely on TIG welding. This inert gas welding technique provides cost advantages over laser welding and moreover, in some cases, is technologically advantageous, joint preparation being less critical.

In the manufacture of new parts, laser welding is used to produce compressor stator cascades and join cover plates to the cast cores of high-pressure and low-pressure blades. Both applications have been in use for well over ten years. In maintenance, laser welding is used primarily for automated repair procedures.

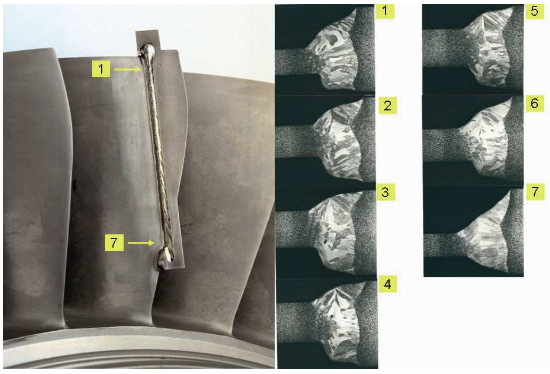

Figure 9 Laser welded low-pressure compressor blisk (left) and transverse microsections taken alongside the weld (right).

Fig. 9 shows a highly advanced laser welding application for repairing the leading edge of a low-pressure compressor blisk blade in a titanium material. Here, laser cutting along a standardized cutting contour is used to remove a damaged area. The welding contour is somewhat offset relative to the cutting contour toward the patch. As a result, the surplus material of the patch acts as a filler material, preventing notches from arising at the patch-to-airfoil transition. From the transverse microsections in Fig. 9 taken at various places alongside the laser weld it becomes apparent that the airfoil-to-patch transition is free from notching.

3.6. Laser Cladding

Laser cladding has since become an established practice. Its major application is in the repair of worn blade tips and labyrinth seals. Filler materials in powder form are mainly used for the purpose. Powder affords an advantage over wire in that it can be fed coaxially with the laser beam, so that also radiused tracks can be laser clad without having to follow up with the feed nozzle. As powder feed nozzles, use is made of annular as well as several symmetrically arranged individual nozzles.

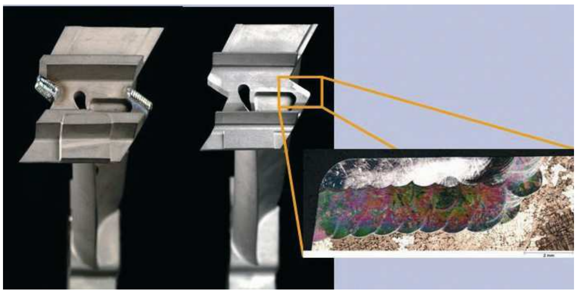

Figure 10 Stellite laser-clad low-pressure turbine blade after laser cladding (left) and in the finish-machined condition (right).

In the manufacture of new parts, laser cladding is used for the hardfacing of Z-shaped notches in low-pressure turbine rotor blades. Fig. 10 shows a low-pressure turbine blade after laser cladding and in the finish-machined condition. The longitudinal microsection shows that totally three layers were added by laser cladding.

Figure 11 Single-crystal high-pressure turbine blade laser clad with a cobalt material with a transverse micro-section through the transition area.

Single-crystal turbine blade materials, owing to their high Al content, are not amenable to fusion welding. When worn by rubbing, therefore, blade tips of single-crystal high-pressure turbine blades are restored using a dissimilar material. Use is often made of fusion weldable cobalt materials. Fig. 11 shows such a build-up-welded high-pressure turbine blade and an associated transverse microsection of the transition area.

3.7. Laser Peening

In aero engine manufacturing, shot peening is used for compacting component surfaces. It gives the surface a defined state, and tensile stresses set up during machining processes are eliminated. Accordingly, shot-peened components exhibit improved HCF and LCF properties. However, shot peening has a drawback in that it increases surface roughness. Also, the layer of residual compressive stress imparted on the surface is maximally about 1/10 mm deep. Laser peening is a highly advanced technique that eliminates the disadvantages associated with shot peening as described above. For the purpose, a thin coat of paint is deposited on the work piece and evaporated using a high-energy laser with an intensity of typically 10 GW/cm^2. A thin layer of water over the paint causes the resulting shock wave to travel only in the direction of the work piece, where it generates residual compressive stress up to 1 mm deep below the surface (see Fig. 12).

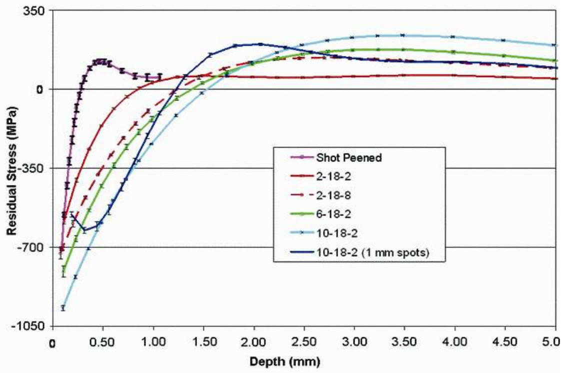

Figure 12 Comparison of the residual compressive stress distribution in a laser-peened and a shot-peened titanium material schematic (Courtesy of Metal Improvement Company).

4. Emerging Applications of Laser Material Processing in the Aero Engine Industry

As previously indicated in Chapter 3, the laser has already found varied uses as a tool in the aero engine industry. New developments in the areas of laser beam sources, system and process engineering promise to provide further potential applications for laser material processing in the aero engine industry. Two potential future applications are described below.

4.1. Selective Laser Melting (SLM)

Selective laser melting is a rapid prototyping technique that generates metallic components layer by layer from a powder bed. For the purpose, a scanner-guided laser beam fuses the powder and joins it to the previously fused layer. Subsequently, the process chamber is lowered and a wiper deposits the next powder layer. The process is repeated until the component is built up generatively. Fig. 13 illustrates a vane segment in a nickel-base alloy as generated by SLM (left) and in the finish-machined condition (right).

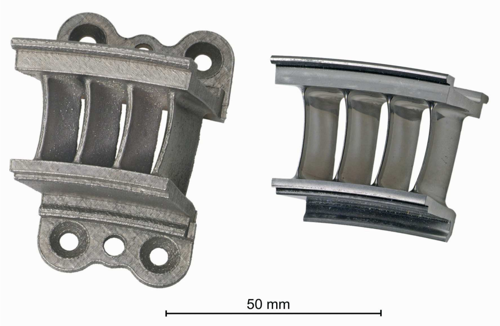

Figure 13 Vane segment in a nickel-base alloy as generated by SLM (left) and in the finish-machined condition (right).

4.2. Laser Generating to Replace Blisk Blades

In the laser cladding applications described in Chapter 3 the layers generated are just a few millimeters high. Yet the process will also generate substantially higher layers and will therefore be generally suitable for the generative build-up of components and accordingly for the replacement of blisk blades. In the FLEXILAS project the technique was transitioned to specimens having the original airfoil shape of a high-pressure compressor blisk blade in titanium material.

Fig. 14 on the left shows a generatively built-up compressor rotor blade in titanium material in the laser-clad condition. Since the blade stub and the mask enveloping it are forming a plane surface, an undercut-free transition between it and the laser-clad layer can be generated especially on the leading and trailing edges. After laser cladding, the specimens were heat-treated and subsequently the airfoils were milled to final contour (see Fig. 14, right). The generative layer build-up in the finish-machined condition amounts to 80% of blade span.

To verify properties, fatigue tests were conducted. For the purpose, the airfoils were clamped in a test rig by their root block and excited to vibrate in the fundamental bending mode (1F). Then when a preselected number of load cycles was reached, the amplitude was incremented until crack initiation. The crack could then be detected as a change in natural frequency. The airfoils ultimately failed at exactly the predicted area in the base material (see Fig. 15).

Fatigue tests have shown the fatigue behavior of generatively built-up airfoils is comparable to that of airfoils in base material.

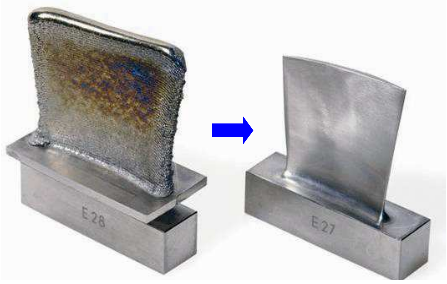

Figure 14 Generatively built-up airfoil in titanium material after laser cladding (left) and in the finish-machined condition (right).

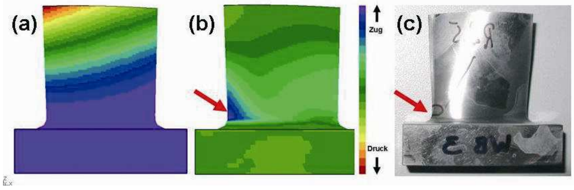

Figure 15 Calculated strain (a) and stress (b) in a compressor airfoil in titanium material excited in the 1F mode. In the fatigue test the airfoil (c) failed at exactly the predicted area in the base material (red arrow).

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