Flexible laser system for high precision cutting, welding and drilling for aerospace applications.

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- Invited Paper -

Abstract

Laser machining processes i.e. cutting, welding and drilling are widely used in the manufacture of aero engine components. Laser drilling has been used for producing cooling air holes, whereas laser cutting has been used to fabricate a large variety of sheet-metal parts i.e. compressor vane segments. Laser welding, although very popular in the automotive industry, has remained a niche application in the aero engine industry, however slowly laser welding is finding few applications in aero engine manufacturing i.e. produce compressor stator cascades and join cover plates to the cast cores of high-pressure and low-pressure blades. Normally for each machining process a different laser source is required i.e. for laser drilling high peak power pulsed laser is needed to drilling cooling holes, whereas for welding a high average power continuous wave is need to weld thick sections. This also means different laser systems for each machining process, however this trend is slowly changing due new laser sources and new flexible 6-axis laser machining system suitable for 2 and 3D machining.

This paper describes cutting, welding and drilling results achieved with Laserdyne System 430 fitted with a high power QCW fiber lasers.

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laser cutting and welding are relative new, whereas the laser drilling is mature technique which has been used since early eighty.

1.1. Laser drilling

Holes are drilled into gas turbines; nozzle guide vanes and combustion rings primarily for cooling, figure 1. In the modern jet engine the temperature of the gases can be as high as 2000°C, Van Dijk et al. (1989). This temperature is higher than the melting point of the nickel alloy used in the combustion chamber and turbine blades. The way that the jet engines components are protected against these extreme temperatures is to use boundary layer cooling. The number of holes per component may vary from 25 to 40,000, Table 1. As the cooling air passes over the surface it forms a cooling film, which protects the surface of the component from the high temperature combustion gases.

Cooling holes can be produced either by EDM (electrical discharge machining) or by laser. EDM or spark machining consists of an electrode, which is held above the workpiece to produce a small gap between the two surfaces. An increasing voltage is applied between the electrode and the workpiece until the electric field becomes so intense that there is an electrical breakdown at the tip of the electrode. A spark will discharge across the gap. Due to the very small cross sectional area very high current densities can result, around 1000 A / mm². Typical temperatures in the region of the breakdown between electrode and workpiece are in the region of 5000 – 10 000 degree C re being achieved between electrode and workpiece. The EDM process uses discrete discharges to drill the hole. If a prolonged discharge is used then the ionisation channel will broaden resulting in reduced current density and damage to the tool and workpiece. This erosion can be intensified if a suitable liquid dielectric is used. It can also act as a coolant and a flushing medium, helping to remove EDM debris. These fluids are based on paraffin, kerosene and other petroleum distillations. More recently however deionised water has been used. When used at high pressure the drilling technique is referred to as high speed EDM. The electrodes are made from a variety of materials. Graphite, copper, and copper tungsten are used, but brass is used extensively for hole drilling. For deep hole drilling tubular brass is used.

<table>
<thead>
<tr>
<th>Component</th>
<th>Dia. (mm)</th>
<th>Wall Thickness (mm)</th>
<th>Angle (deg.)</th>
<th>No of holes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blade</td>
<td>0.3-0.5</td>
<td>1.0-3.0</td>
<td>15</td>
<td>25-200</td>
</tr>
<tr>
<td>Vane</td>
<td>0.3-1.0</td>
<td>1.0-3.0</td>
<td>15</td>
<td>25-200</td>
</tr>
<tr>
<td>Afterburner</td>
<td>0.4</td>
<td>2.0-2.5</td>
<td>90</td>
<td>40k</td>
</tr>
<tr>
<td>Baseplate</td>
<td>0.5-0.7</td>
<td>1.0</td>
<td>30-90</td>
<td>10k</td>
</tr>
<tr>
<td>Seal ring</td>
<td>0.95-1.05</td>
<td>1.5</td>
<td>50</td>
<td>180</td>
</tr>
<tr>
<td>Cooling ring</td>
<td>0.78-0.84</td>
<td>4.0</td>
<td>79</td>
<td>4200</td>
</tr>
<tr>
<td>Cooling ring</td>
<td>5.0</td>
<td>4.0</td>
<td>90</td>
<td>280</td>
</tr>
</tbody>
</table>

Although EDM is capable of producing good quality holes it is substantially slower than the laser and other disadvantages of this technique are:
- EDM is not suited to the production of holes at high or variable incidence angles where multi-wire heads cannot be used.
- EDM also requires reality complex consumables tooling and electrolyte fluids, both of which contribute adversely to cost of hole production.
- To increase temperature capability of the engine blades and vanes, a thin coat of a heat-insulating zirconia ceramics is applied on the surface of the blades as a thermal barrier coating, figure 2. EDM is not suitable for drilling through ceramic or ceramic coated materials.

![Fig. 1. Laser drilled component.](image1)

![Fig. 2. Thermal barrier coated blade.](image2)

![Fig. 3. Ablation + EDM drilling of coated material; 3mm thick nickel based alloy with 0.65mm thick coating; ablation cycle time 7secs; EDM cycle time 28secs; 45 degrees from the surface.](image3)

When drilling TBC coated materials with EDM, the coating is normally ablated first with a Q-switched pulsed Nd: YAG laser (short pulses and high peak powers) followed by drilling with EDM. An example of this dual process is highlighted in figure 3, Naeem. M (2010).

1.2. Laser cutting

The laser cutting process is a very flexible with a number of advantages including attractive processing speed, high productivity, low running cost, and ability to manufacture parts with complex shapes, excellent cut quality, non-contact operation, and ease of automation. Hence, interest in the laser cutting process has greatly increased in the, aerospace industry. The laser cutting of 2D and 3D sheet metal is state-of-the-art and often outsourced to subcontractors. Laser cutting is fusion process and employs nitrogen assist gas for nickel based alloys i.e. Inconel 718 and argon assist gas for titanium based alloys i.e. Ti-6Al-4V. Laser cutting is a multiparameter process and with optimization of the parameters i.e. laser power, beam quality, spot size, gas pressure, focus position of the laser beam with respect to the workpiece, it is possible to produce crack and dross free cuts in a range of nickel and titanium based alloys. Figure 4 shows a laser cut shroud in IN718 material.
1.3. Laser welding

Continuous advances in the aircraft and aerospace technology impose ever-increasing demands on the materials used in the components and structures. To satisfy the requirements of the component design and manufacturing engineers these materials must be capable of being welded in a satisfactory manner.

Titanium, aluminum, and nickel alloys are used for various applications in the aerospace industry. Titanium alloys, such as Ti6Al4V (6% Al, 4% V), Ti6242 (6% Al, 2% Sn, 4% Zr, 2% Mo) and TiCu2 (2% Cu) are widely used in aeronautic and aerospace structures e.g. blades and casings of compressor stages in turbojets. Nickel based super alloys (Inconel 718, Incoloy 909 and Single crystal 2000) are used in the jet engines where the temperatures are very high (1400 degree C). Aluminium and its alloys (2000 series, 6000 series etc.) are most suited for structural members, especially fuselage and wing structures in airplanes. In airframe sections, attaching stringers that run along the length gives additional stiffness to the complete section. Figure 5 highlights different type of materials which are used.
Laser welding involves few manufacturing stages, edge preparation, and joint fixturing being the most time-consuming auxiliary operations.

The high beam power density creates a narrow, deeply penetrating weld pool, allowing through thickness welds to be made rapidly and accurately in a single pass without the presence of vacuum.

The low heat input creates a narrow heat affected zone (HAZ) with limited distortion and residual stresses, which reduces the need for reworking.

The process is easily automated for high volume production.

Filler materials especially with aluminum and its alloys can be used to achieve desired weld metallurgy and properties.

Filler material is also used to compensate for the poor fit-up and mismatch for butt joint welding. Filler may also be used to improve the weld geometry.

1.4. Laser sources

Several types of lasers are currently being used be for materials processing (cutting, welding, and drilling) in the aerospace industry though the most common lasers are CO₂ (gas lasers) for cutting and welding applications and high peak power Nd: YAG lasers (solid state lasers) for drilling applications. The last decade has seen the rise of high power diode pumped fiber lasers. These new continuous wave (CW) and Quasi continuous wave (QCW) lasers have been demonstrated to be a serious alternative to Nd: YAG solid state lasers (SSL) and CO₂ gas lasers for different materials processing applications in the aerospace industry.

The key advantages of fiber laser technology is its high beam and stable energy and power with time. The high beam quality of the fiber laser enables the beam to be focused to a small spot with a correspondingly high energy density. This enables very fast and efficient processing, yielding welds and drilled holes with a high aspect ratio.

The fiber lasers also offer the potential to reduced total cost of ownership. With its 1µm wavelength, the fiber laser has an absorption rate in metals at room temperature that is seven times higher than for the 10.6µm wavelength of a CO₂ laser. It is well known that the use of laser processing requires relatively high capital investment costs. However, it is important to note that the operating costs of a laser system will also play an important role in determining the production costs.

The reduced cost of ownership of the fiber lasers is due to the high efficiency of the pump source and of extraction from the gain medium that leads to a wall plug efficiency for the laser, typically around 25-30%, Norman. S et al (2004) compared to less than 12% for a CO₂ laser and a few percent for a flashlamp pumped Nd: YAG laser. This leads to reduced electrical supply requirements and lower electrical energy consumption which is the major cost factor in any laser high power laser system. The higher efficiency also contributes to a more compact laser head. Compared to other solid state lasers fewer mechanical components are needed in the laser construction. This leads to significantly lower cost base than equivalent power SSL. Indications are that as the pump laser diode prices continue to decrease with increasing manufacturing volumes fiber laser prices will continue to decrease.

The high power single or multi-mode fiber lasers are ideal for cutting and welding applications, however not suited for laser drilling which is the biggest application in the aerospace industry. The introduction of QCW fiber laser with its high peak power up to 20kW and CW operation has changed all this. Now it is possible to use single laser source for drilling, cutting and welding. This paper heights cutting, welding and drilling data achieved with IPG 20kW QCW fiber fitted to Laserdyne 6axis laser machining system.
2. Experimental details

The processing trials were carried out on Laserdyne 430 5-6 axis machining center, figure 6. The new laser system is designed for cutting, welding and drilling of 2D and 3D component parts requiring exact precision suitable for a range of industrial market sector including aerospace. The system 430 is fitted with third generation BeamDirector®, figure 7, capable of drilling at angles as low as 10° from the surface. Other features include Automatic Focus Control™ for capacitive part sensing, patented Optical Focus Control (OFC) for sensing of thermal barrier coated surfaces, ShapeSoft™ software for programming shaped holes, BreakThrough Detection™ for drilling clean, consistent holes with the minimum number of pulses, and mapping.

The system 430 was fitted with an IPG 20kW QCW laser, figure 8. The beam from the laser was transmitted in a 100µm diameter fiber optic, which terminated in 140mm collimated output housing.
Fig. 8. IPG 20kW QCW fiber laser; 20kW peak power; 2kW average power; 200J pulse energy.

Laser and processing parameters used for drilling, cutting and welding are highlighted in table 2. Figure 9 shows processing heads used during the tests.

Fig. 9. Processing heads used for drilling, cutting and welding.
Table 2. Parameters for drilling, cutting and welding.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Drilling</th>
<th>Cutting</th>
<th>Welding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spot size</td>
<td>140µm</td>
<td>140µm</td>
<td>140-571µm</td>
</tr>
<tr>
<td>Processing gas</td>
<td>Oxygen</td>
<td>Nitrogen</td>
<td>Nitrogen, argon</td>
</tr>
</tbody>
</table>

3. Results

3.1. Laser Drilling

3.1.1. Uncoated material

Of primary concern to the component designer is achieving adequate airflow through the holes so that the appropriate cooling is provided. Airflow is governed principally by the size and shape of the hole and hence the need for tight control of size, roundness and taper. There are other factors also to consider; holes are often very closely positioned to one another on a component and any deviation in size may adversely encroach on other holes or even weaken the component locally. Excessive bell-mouthing or barreling is therefore undesirable in addition to recast layer and heat-affected zone.

The issue of hole quality is very important but is a subjective one. The qualities of a hole produced by laser drilling are judged on a number of different characteristics. The geometric factors are hole roundness, hole taper and variation in hole entrance diameter. The metallurgical factors are oxidation and recast layer. The recast layer, melted material that was not ejected from the hole by vapour pressure generated by the laser pulse, coats the wall of the hole leaving a thin layer of solidified metal. This layer can generate micro-cracks, which can propagate into the parent material.

Drilling results show that it was possible to produce very good quality holes in a range of aerospace alloys. This high beam quality laser produced holes with minimum taper (<5%) and recast layer very similar to EDM drilled hole quality. The cross sections of some of the holes drilled at various angles to surface are highlighted in figure 10. The hole sizes were varied by adjusting the laser and processing parameters i.e. peak power, pulse energy, pulse width, trepan speed etc.

Combination of Laserdyne system with its very accurate motion control and high beam quality ($M^2 < 10$), and top hat beam profile of the QCW fiber laser, it was possible to produce consistent holes in terms of roundness and metallurgy in a range of thicknesses.

3.1.2. TBC coated material

Thermal barrier coatings are being widely applied in many types of engines and in aircraft's gas turbines. To increase temperature capability of the engine blades and vanes, a thin coat of a heat-insulating zirconia ceramics is applied on the surface of the blades as a thermal barrier coating. The cooling of the components causes a pronounced reduction of the metal temperature, which leads to a prolongation of the mechanical component's lifetime. Alternatively, the use of thermal barrier coatings allows raising the process temperature, obtaining thus an increased efficiency. Thermal barrier coatings usually consist of two layers (duplex structure). The first layer, a metallic one, is the so-called bond coat, whose function is, on the one side to protect the basic material against oxidation and corrosion and, on the other side, to provide with a good adhesion to the thermal insulating ceramic layer. Such a ceramic coating is mostly made of yttria partially stabilised zirconia (YSZ), since this material has turned out particularly suitable during the last decades. At present, there are two principle methods to apply thermal barrier coatings, one is plasma spraying and the other is electron beam physical vapour deposition (EB-PVD). These methods have been studied excessively to avoid mechanical and adherence problems between coatings and substrate, Sivakumar, R et al (1989); Miller, R.A et al (1982); Tsui, Y.C et al (1986).
Laser and processing parameters were developed to drill through the TBC and then drill though the metal. With correct set of parameters it was possible to trepanned holes without any laser drilling induced damage in at the bond coat/ substrate interface. The results show that it was possible to drill holes without any cracking or delamination of the coating and typical cross sections of the drilled holes are shown in figure 11.

![Image](image1.png)

30 degrees; 0.56mm dia.; maximum recast layer 45µm; 0.97 second

20 degrees; 0.56mm dia.; maximum recast layer 83µm; 1.6 seconds

Fig. 10. Trepanned holes; uncoated 2.54 mm thick aerospace alloy; Oxygen assist; 140 µm spot size.

![Image](image2.png)

Fig.11. Trepanned holes; TBC coated; 2.54mm thick coated aerospace alloy; 0.56mm dia.; average recast layer 30µm; 1.17 seconds; 0.50mm thick coating; Oxygen assist; 140µm spot size.

3.2. Laser cutting

With the same set-up as for the drilling tests, cutting tests were performed on a range of nickel based alloys. The main requirement when cutting these alloys is to have oxide free cut edges without any dross or microcracking. With oxygen assist gas the cut is speed is fast compare to inert gas cutting but it leaves oxide layer at the surface so all the cutting tests were carried with oxygen free nitrogen assist gas.

Laser cutting is not all about having a very high beam quality/ high average power laser, it is also very important to understand the detailed melt flow conditions in a narrow kerf width produced by small spot diameters in order to provide an opportunity to optimise the gas- jet/melt interaction of high brightness fiber laser. The laser cutting is entirely gas assisted (oxygen or inert), variables related to the assist gas have a big influence on the cut quality. The material being cut generally
determines the type of assist gas used during cutting. The assist gas pressures, nozzle design and standoff also play a vital role in governing the gas dynamics and, thereby, significantly influence the cut quality.

With any material or thickness, the quality of laser cutting operation starts with a piercing process. During the cutting trials with a range of aerospace alloys, it was possible to produce very clean and spatter free pierce prior to cutting. This was achieved by combination of special set of laser parameters and Laserdyne machine software which allow to produce clean small pierce without any excessive burning or blow out. The control piercing prolongs the cutting nozzle tip and focusing optics life. Figure 12 shows example of clean pierce and cut edge quality of 5mm thick Inconel based alloy used for land turbine stator ring. The special features of the Laserdyne systems allows to cut very narrow profile slot with very accurate control over dimensions of the slots.

3.3. Laser welding

The main requirement when welding aero engine materials are:
- Clean top and bottom weld bead; i.e. no oxidization
- No porosity or cracking
- No undercut top and bottom weld bead
- Correct weld shape geometry

At Laserdyne extensive work was carried out to develop laser and processing parameters to weld a range of aero engine materials and results of this work will be reported at ICALEO 2014. Figure 13 example of laser weld which met all the above requirement.
Fig. 13. Inconel 625 alloy; 3mm butt joint with Inconel wire; nitrogen shield gas.

4. Summary

The processing tests (drilling, cutting and welding) carried out with the turnkey flexible laser system have shown that:

- Good quality holes have been achieved with both coated and uncoated materials. The trepanned hole quality (roundness, recast layer, tapper etc.) is due to very accurate motion control of 430 system and high beam quality ($M^2 < 10$), and top hat beam profile of the QCW fiber laser. Combination of both makes it possible to produce consistent holes at different angles of incidences.

- Small clean spatter free pierce and narrow profile slot with very accurate dimensions were produced in 5mm thick land base turbine stator ring. Again it was combination of both 430 system (special machine software) and QCW fiber laser (pulsed laser parameters) which produced very good cutting results in a range of aerospace alloys.

- Laser and processing parameters were developed to weld a range of aeroengine materials.

- Very little effort was required to change the set-up for the different process.

References


