

Pulse Laser Beam Welding : In Seventh Heaven above Thailand

The work task was unmistakably defined: "To eliminate the difficulties encountered in the repair welding of aircraft turbine parts by using pulsed laser welding." It was triggered by the vision of an excellently trained aerospace engineer with inter-national professional experience, who recognized the decisive difference between this material-bonding joint technology and classic welding processes: Do not weld with electricity, but instead with pulsed light and its speed – resulting in unique advantages. The visionary's name was Barry Borji. In cooperation with DSI Laser Service (Thailand) Co., Ltd. he brought pulsed laser welded seams to above the clouds of Thailand, and far beyond. For the first time in 2018.

Thailand: Not only a paradise for holiday-makers, but also an MRO paradise

From a general tourist perspective, it is hard to imagine that Thailand is an important service hub for the aircraft industry. Internationally renowned companies are based there, inspecting, modifying and repairing components that are vital for take-off, flight and landing, such as landing gear, wings and turbines. In their technical language, this is called MRO

for short: Maintenance. Repair. Overhaul. The customer Barry was working for at that time, plays the main role in this story and is active in this industry: A Thailand-based U.S. MRO company, a service provider for customers flying high above the clouds. A global leader in the manufacture of aerospace structures, aircraft systems and components. An Original Equipment Manufacturer (OEM) for giants of the skies such as Boeing, Airbus, Lockheed Martin, Land Power Turbines and GE Aviation.

Before Barry's vision came to reality, damaged turbine parts were welded in the traditional way, using either tungsten inert gas (TIG) or metal inert gas (MIG) welding, but, for lack of a better technology, with quality compromises – keyword: pores and cracks – high above the clouds.

The cause of these and the generally poor weldability of the parts to be repaired lies in the current condition of the base material. In most cases, these are titani-



Pulse Laser Welding Note [19]



As humans, we have **only three choices**

about how to react at a specific situation :

1.) Ignorance 2.) Fighting 3.) Curiosity

Same about Pulse Laser Welding.

As professionals, we have only three choices :

Pretend, that PLW-Technology does not exists.

Protecting our (old) refurbishing method.

Open our mind for the revolutionary PLW-Technology
and **use it profitably.**

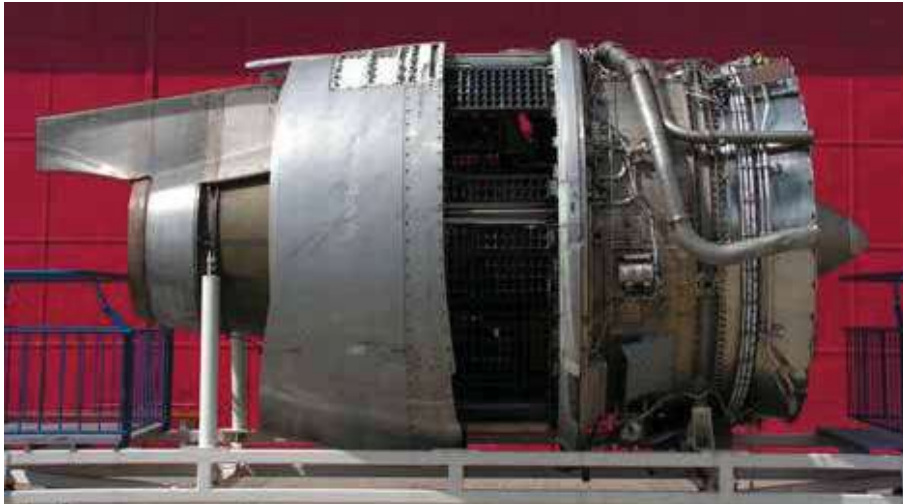


Fig. 1: A turbofan engine of the 1970s, type Rolls-Royce RB211 with the main components inlet, compression, combustion, exhaust gas (seen from right to left). (© Wikipedia)

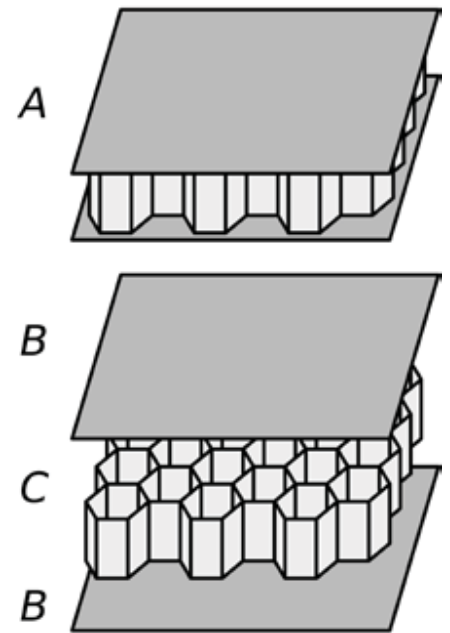


Fig. 2: Sandwich panel (A) with load-bearing face skins (B) and support core in honeycomb form (C). (© Wikipedia)

um alloys or “Inconel” that, at the time of their repair welding, are already many hundreds or even thousands of flight hours old, during which they have been exposed to high thermal-dynamic stresses. Mechanical deformations caused by a constantly changing operating temperature range of several hundred degrees Celsius: takeoff, landing, takeoff, landing ... hot, cold, hot, cold ... stretch, shrink, stretch, shrink ...

Compounding the general weldability, fast weld repairs, and desired seam quality are the ubiquitous topics of the aerospace industry: Weight Savings, Repair Down Time and Turn Around time (TAT), Aircraft on Ground (AOG). The equation is simple: less weight = more lightness = less fuel = greater efficiency. Every tenth of a millimeter and every gram saved counts. Accordingly, the sheets to be welded are extremely thin, which accelerates their thermal aging and the reduction of their service life, thus making them more difficult to weld. As already mentioned: pores and cracks.

This is how Barry, an engineer for stress and structural design, explained it during the first conversation with DSI Laser Service Thailand with a worry furrowed brow, which, however, smoothed out reflexively when he – rather unusual for an aircraft engineer aware of his great responsibility – almost euphorically talked about pulsed laser welding. This was closely followed by the concrete proposal of an extremely critical expert who, when

it comes down to it, wanted to see the theoretically advertised advantages of a technology in question proven by extensive practical tests: in a case study called “Aircraft engine exhaust-nozzle skin repair” – a simulated repair weld on the conically shaped exhaust of an aircraft turbine, which operates with a gas temperature of more than 600 °C (Fig. 1).

As can be easily imagined, this is designed differently from the exhaust-gas-diverting pipes under an automobile: thin, but not single-walled. Instead, it is a three-layer composite structure in honeycomb technology, known in aviation jargon as a “honeycomb structure” (Figs. 2 and 3): consisting of a honeycomb support core with

cover skins covering the honeycombs on both sides, thus supporting the composite – light as a feather and dimensionally stable. It is a classic example of structural bionics, in which a structure provided by biology (in this case the honeycomb) was successfully adopted in technology, colloquially known by the English portmanteau word “bionic”. This was created by the US military service neurologist Jack E. Steele (1924-2009) from the Greek word “bios” (life) and the suffix “-onics” meaning “study of” and was publicly in-



Fig. 3: Conical honeycomb exhaust jacket made of “Inconel 625”. (© DSI Laser Service (Thailand))

roduced in 1960 during a symposium with the theme “Living Prototypes – The Key to New Technology”. The Chinese National Stadium in Beijing, the world’s most famous “bird’s nest”, is also an example of successful bionics.

Back to the aircraft exhaust: The hexagonal shape of the honeycomb ensures perfect use of space, because there are no gaps. It is joined by ultra-thin cover plates of typically 0.54 to 1.5 mm on both sides, which guarantee a considerable reduction in weight – while at the same time providing enormously high stability thanks to the honeycomb structure.

The long journey: training, qualifications, sample welds and evaluations

The effort involved is justified when it is considered that, in the final analysis, human life depends on the implementation of a new technology. For this reason, an aircraft turbine is considered an “A-class component” in MRO jargon, the classification for major components of the aircraft fuselage and static engine components. On these, Barry’s vision envisaged, welding would soon be carried out using pulsed lasers. In addition, there would also be welding on load-bearing structural elements or PSE parts (Principal Structural Elements). These contribute, quite literally, to absorbing the flight, ground and pressure loads, which in turn reveals the fatal definition of an A-class component: Their failure will, in all likelihood,

lead to a catastrophic failure of the aircraft – with a crash out of the seventh heaven.

Because the 100 % reliability of these components to be repaired using pulsed laser welding is directly related to human life, Barry explained, extensive upfront trial welding and testing, qualification and certification are essential – all according to guidelines from the American Welding Society (AWS). The laser welding process was carried out with respect to the two standards AWS C7.4 “Process Specification and Operator Qualification for Laser Beam Welding” and AWS D17.1 “Specification for Fusion Welding for Aerospace Applications”.

Extensive training course with a final knowledge test

As no one, neither at the customer nor at DSI, was familiar with the application of these standards, an extensive training course with a final knowledge test had to be held at the customer’s facility. It was conducted by a lecturer, Mr. Ali Khan, who had traveled by invitation of Barry from England to Thailand especially for this purpose. He had been sent by The Welding Institute (TWI), which was founded more than 100 years ago in London’s Holborn Restaurant by 20 men with the aim of bringing together acetylene and manual arc welders. Their mission: “Welding connects.”

Since 1946, The Welding Institute has been located in Great Abington, near Cambridge. Nowadays, TWI is a large research and technology institute that is professionally focused on welding and joining technology, comparable to the numerous DVS SLVs in Germany. In addition to its headquarters and other branches in the UK, TWI has a presence in the USA and China, in Southeast Asia, South America and the Middle East.

After plenty of theory and final Certificate of Attendant awards for all attendees, they approached the practice: familiarizing themselves with the base material Barry selected for the case study, corresponding to the original turbine exhaust, called “Inconel” – the brand name of a minimum 58% nickel-based superalloy developed in the 1960s by Special Metals Corporation, a company based out of West Virginia. Specifically, Barry chose the non-magnetic alloy type “Inconel 625”, material number 2.4856 (AMS 5599). This has the high tensile strength properties required for gas turbine applications (up to 910 MPa) and a wide operating temperature range, from cryogenic to 982 °C. In addition, “Inconel 625” provides protection against corrosion and oxidation and has a hardness of 26-30 Rockwell (HRC) in the untreated state.

Two different material thicknesses were selected: 0.54 and 1.53 mm, so that the test welds could cover the widest possible range of applications, considering the strict standard specifications. What was still missing for welding was the filler metal, which was matched to the base material, was of the same type and met the strictly quality-monitored aerospace guidelines. In the industry it is known under the racy-sounding brand name “Turballoy 625”, selected diameter: 0.51 mm. Both sheet and wire were supplied by the customer.

To ensure neutral monitoring and evaluation of the test welds, the standard prescribes the involvement of an external, independent inspection authority. On the one hand, the Faculty of Engineering and Welding Technology of the King Mongkut’s University of Technology Thonburi (KMUTT) in Bangkok was commissioned, represented by the Japan-trained welding engineer, Dr. Titinan Methong,

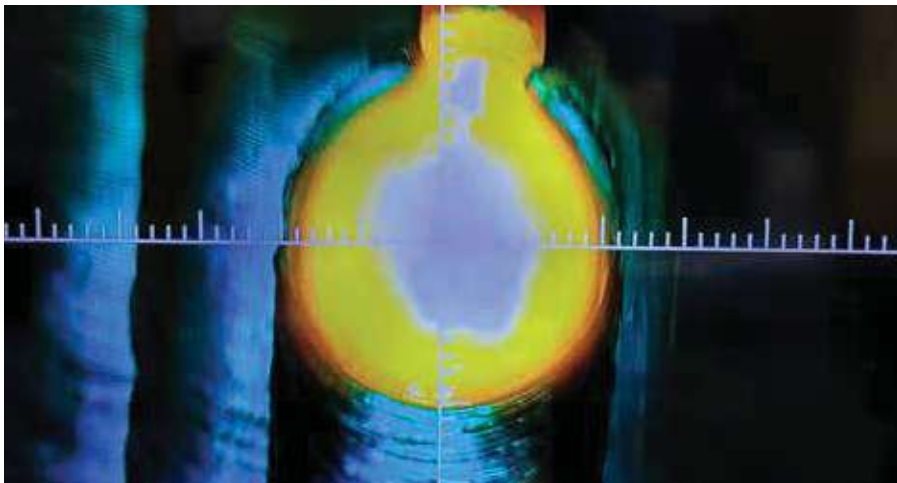


Fig. 4: Real-time monitoring of the pulsed laser deposition welding process, transmitted from the camera to the screen. Left: finished overlapping weld beads, centre: the “football-sized” melt pool into which the welder dips the “thick, goalpost-like” welding wire. (© DSI Laser Service (Thailand))

who works for the university as a teacher and examiner. On the other hand, some of the test welds were analyzed at the Material Testing Center of the Chonburi-based Thai German Institute (TGI), managed and supervised by Arun Jeangsriaroen, a materials engineer trained in Germany at RWTH Aachen University.

All samples were welded in the presence of Barry as representative of the customer and Dr. Titinan as independent welding supervisor at the DSI Thailand Laser-Welding-Academy. Since 2020, the Academy has a technological cooperation with the DVS SLV-Hannover, which is why Prof. Dr.-Ing. Gerd Kuschner was also involved in the case study as material and technology expert. The study started with single- and multi-layer buildup welding, carried out with a 500 W powerful fibre laser machine manufactured by Alpha Laser Germany.

While the welder observed the molten pool through the microscope of the pulsed laser machine at $10 \times$ magnification and manually fed the wire, real-time monitoring of the welding process took place by all present. A camera installed between the microscope and the optics transmitted the ongoing process to a flat screen. The molten pool, with the size of a soccer ball, and the welding wire immersed in it, which appeared to be as thick and long as a goal post, could be observed (Fig. 4): A fascinating reality show from several points of view, which seemed to show a continuous welding process, but in fact consisted of individual pulses, each lasting 18 ms, whereby and during which the unique advantages of this welding process, which takes place with pulsed light and its speed, occurred.

It is extremely fascinating to hear the typical cracking pulse noise as background music while watching and to consider how the molten bath is not created. Not classically by electricity, but by shooting out of the optics of the resonator and – attention! – with 300,000 km/s onto the sheet metal. In lyrical terms: metal liquefied by tiny clouds of light. This process is extremely fascinating from several points of view, also due to the fact, that the melting bath diameter is not



Fig. 5: Macrosection of a successful position-counterposition joint weld with no significant heat-affected area of the base metal "Inconel 625", test piece thickness: 0.54 mm. (© DSI Laser Service (Thailand))

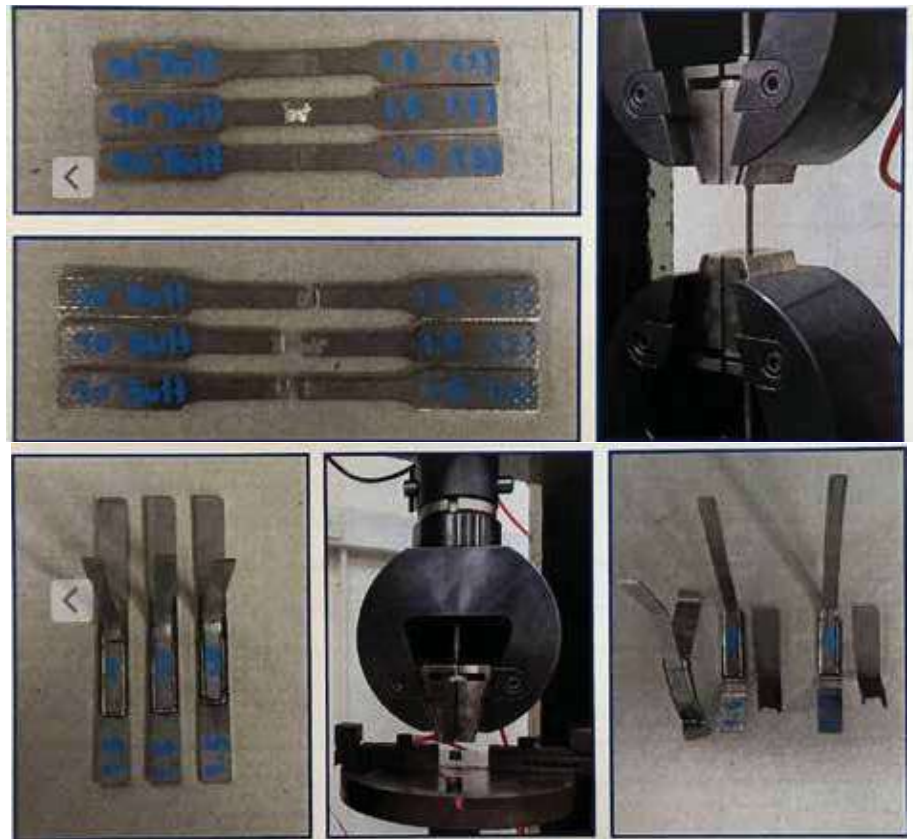


Fig. 6: Tensile test of 90-degree butt joints (top) and L-shaped doublers (bottom), made from "Inconel 625", test piece thickness 1.53 mm each, cracked in the base material, outside the heat-affected zone, at 932.26 MPa. (© DSI Laser Service (Thailand))

really the size of a soccer ball, but only 1.2 mm in diameter, into the centre of which the welder does not push a goal post, but rather dips his fingertip a 0.5 mm thin wire.

Dozens of test welds and just as many analyses

The aim of the first single- and multi-layer buildup welds was to check both the

metallic bonding between the base material and the filler metal and the bonding in the layer structure on the basis of the macro-sections made by them. This led to a gradual approximation, more and more completed from section to section, of the welding parameters adapted to the material and meeting the quality criteria laid down in the standard – an individual combination of pulse power (W), pulse duration (ms), pulse frequency (Hz) and pulse shaping (shape).



Fig. 7: Examples of areas in need of repair by pulsed laser: dented outer shell (left); inner shell previously repaired by TIG or MIG welding (rest). (© DSI Laser Service (Thailand))

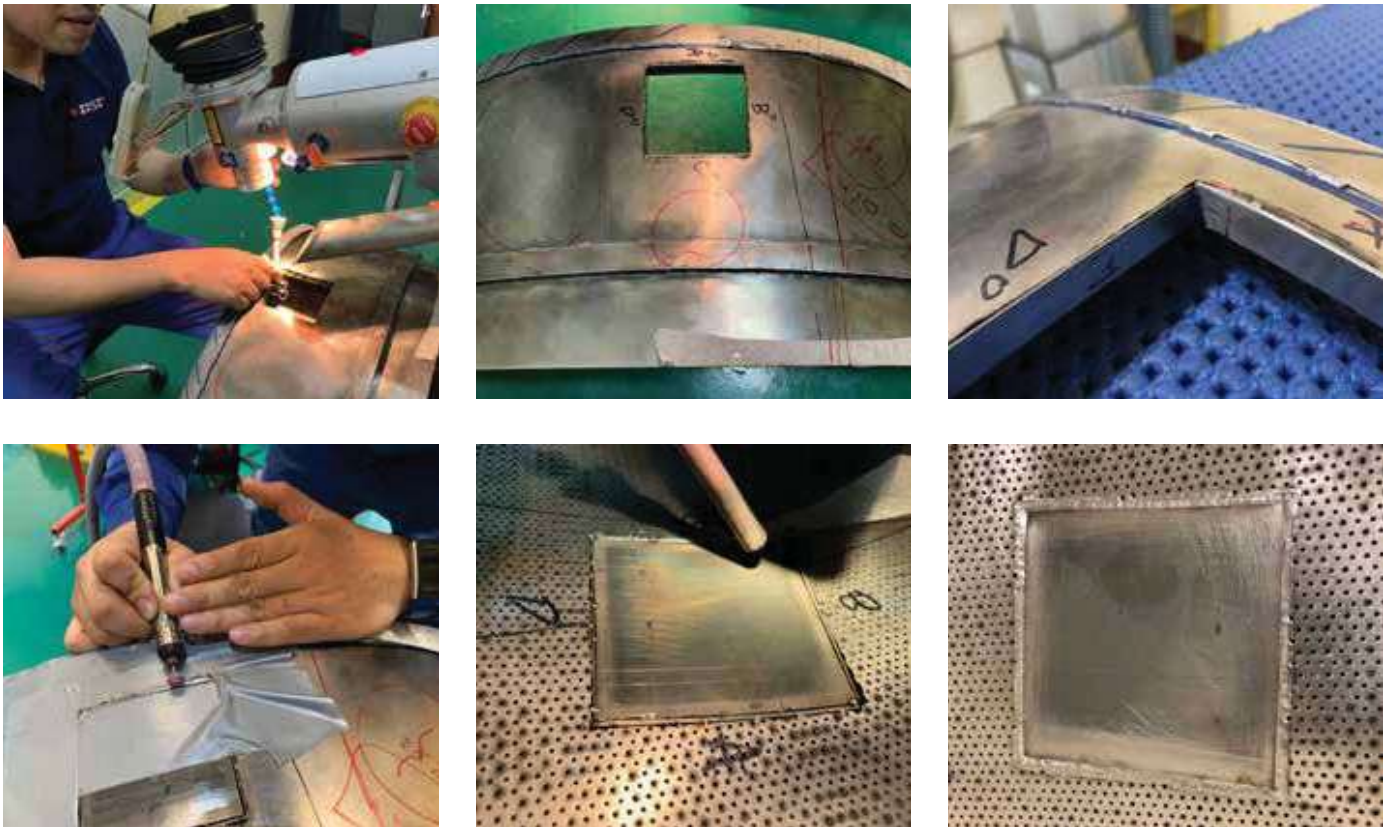


Fig. 8: Repair sequence (Standard Repair Procedure) honeycomb structure. (© DSI Laser Service (Thailand))

These were recorded, along with a dimensioned sketch of the test sheet, details of the welder, the welding sequence and other process-relevant data, in a preliminary Welding Procedure Specification, or pWPS. Later, after the required quality had been confirmed by tests on the test plate, the “p” was dropped: the preliminary instruction became the welding procedure specification. Its specifications must be strictly followed in the subsequent practical application to ensure the reproducibility of the tested and required quality. In parallel, a pWPQR (preliminary Welding Procedure Qualification Record) was created,

which, in addition to the WPS, contains the area of approval for the procedure.

The buildup welds were followed by different joint welds (Fig. 5): first in the classic butt joint and 90° fillet weld design, then with flat-face and L-shaped doubles, each welded all around. Finally, corner welds in 45°- and 90°-degree designs. In total, there were dozens of test welds and just as many evaluations.

The American Welding Society also prescribes the quality tests that the test welds have to undergo: Both non-de-

structive material tests (NDT) and destructive material tests (NDT), starting with visual testing (VT), followed by penetrant testing (PT).

To detect defects inside the weld, the standard prescribes radiographic testing (RT). In addition, because the welds are on a critical “A-class component”, ultrasonic testing is required, supplemented by a C-scan, a sophisticated method of displaying ultrasonic test data: Three-dimensional cross-sectional representations of the test object, and that although the specimen sheets were only 0.54 mm and 1.53 mm thick, respectively.

If an irregularity was detected in a weld sample, its length and width, its geometry and exact location were determined, then the result was compared with the allowances prescribed by the standard. This was followed by the verdict of the non-destructive tests: "Quality test passed" or "failed". Barry defined a failure as the worst-case scenario: the bursting of his vision, that is, with a full reversal thrust back to traditional welding methods. At this point, after so many test welds, the point of no return had long since passed from Barry's ever-optimistic point of view. A return to the starting point was no longer possible.

Destructive materials testing is about the eternal test of strength in welding technology: Who is the strongest? The base material or the filler metal, measured in megapascals (MPa)? The test of strength was performed and answered by the incorruptibly working tensile machine, which slowly but steadily first stretched and finally tore apart the weld specimens clamped between its claws one by one (Fig. 6). These tests, which also put Barry's nerves to the test, were used to characterize the strength and deformation behaviour under tensile stress. Taken with the high-speed camera, it was clearly observable how the plate gradually tapered off-centre and eventually cracked: In all weld cases exclusively in the base metal, far outside the heat-affected zone. The clear winner was: the welding technology of the pulsed laser.

At the end of all samples and their evaluation: A superior winner

When all test results were available, it came to the showdown: the direct quality comparison with those work samples that were carried out using classic repair welding processes, TIG and MIG. The comparison clearly showed the advantages of welding with pulsed light:

- 1) High weld strength
- 2) No significant HAZ, no heat-affected area of the base metal
- 3) No coarse grain formation weakening the microstructure
- 4) Clean welding process, no pores or cracks

- 5) No heat pre-treatment or post-treatment
- 6) Welding at room temperature.

The conclusion of the welding supervisors and test commission: Problem-free pulsed laser repair welding of the dynamically heavily preloaded superalloy "Inconel 625".

Immediately after the successful qualification at the end of 2018, DSI Laser Service Thailand performed the first repair welds on original turbine parts at the customer's plant. Each time, the pulsed laser welding system had to be used on the move because the turbine parts are not allowed to leave the factory during the entire repair process for reasons of quality assurance and flight safety. This was preceded, carried out by Barry, by elaborate structural calculations and simulations. A union of the high arts of engineering and those of welding technology. In this specific case, with regard to the areas to be repaired. Regarding their size, shape and location. Critically checking whether the overall component still meets the quality requirements of the original dynamic stress after repair.

In the future, primarily those areas are to be replaced that are either dented or in need of quality improvement: those areas that have been repair-welded by TIG or MIG in the past (Fig. 7).

In parallel with Barry's calculations, a working sample in the original format and material ("Inconel 625") was started as training of the honeycomb-structure repair sequence (Standard Repair Procedure) (Fig. 8):

- 1) Cutting out the damaged honeycomb structure
- 2) Grinding of interfaces without burrs and covering by frame sheets consisting of "Inconel 625", tacked by pulsed laser
- 3) Grind edges protruding from the frame flat
- 4) Staple prefabricated cover plates ("Inconel 625") corresponding to the original contour into the frame on both sides
- 5) Weld frame and plates on both sides to the original structure using pulsed laser

- 6) Quality control: In addition to the usual non-destructive tests mentioned earlier, geometry testing was added due to the curved, slightly conical shape of the component. That is, checking compliance with permissible distortions and form and positional tolerances.

Training on the work sample was followed by the first honeycomb repair on an original turbine part (Fig. 9), with which the first pulsed-laser-welded seams flew into the Seventh Heaven over Thailand a little later, and far beyond.

The technology of pulsed laser welding takes off

The success story that began with Barry's vision and materialized in an aircraft exhaust quickly continued, both with this and other customers within the MRO industry, where one knows another and word of the unique benefits of pulse laser welding spread like wildfire. Test welds on other "Inconel" alloys and materials followed: for example, on "Inconel 718" (AMS 5832) and "Inconel 713 LC" (AMS 5391), where LC stands for low carbon and guarantees a maximum carbon content of 0.03 -0.07%. In addition, test welds were made on the high-strength titanium alloy Ti 6-2-4-2 (Ti6Al2Sn4Zr2Mo).

All these materials, which are also capable of withstanding high thermodynamic temperatures and stresses, are used to make components for Auxiliary Power Units (APU), combustion chambers, exhaust nozzles, also jet engine exhaust tail cones. Soon, these were also being repair-welded using pulsed lasers. But that is another exciting story, told separately, about welding with pulsed light and its speed.

On the way to even higher spheres

Time leap to the year 2023: Once again, the view leads to the sky – and this time, too, driven by the vision of a customer also based in Thailand, originally from Singapore. This customer wants to send pulsed laser-welded seams into space.



Fig. 9: Repair welding by pulsed laser on a conical exhaust gas jacket made of "Inconel 625" and constructed using honeycomb technology. (© DSI Laser Service (Thailand))

Only this much can be revealed: These are to hold together the high-strength aluminium fuel tanks, operating under 60-bar overpressure, of a launch vehicle traveling at 4 km/s from Earth ... all the way to an orbit 400 km above.

It remains to be seen whether the technology of pulsed laser welding will be able to continue its success story, which once began on the safety of the workshop floor, far beyond the earth's atmosphere. One thing is certain: it remains exciting.

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Pulse Laser Welding Note [18]



The term „Point of no return“ is used in aviation.

From this point, it is no longer possible to return to origin.

Same with Pulse Laser Welding Technology.

It marks that magical moment, when its unique advantages reveal to the open mind. When previously thoughts about impossible applications suddenly become true.

The return to classical arc-welding methods is no longer possible.

More inspiration at DSI Thailand Laser-Welding-Academy