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High Power Fiber Laser Welding of Titanium and Nickel based alloys with and without the Filler Wire

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- Invited paper –

Abstract

Continuous advances in the aircraft and aerospace technology impose ever-increasing demands on the materials used in the components and structures and also impose ever increasing demands upon the engineers to develop new joining techniques.
Titanium and high temperature nickel and cobalt superalloys are used to manufacture and repair in- service damaged hot section components of aeroengine. These materials have excellent high temperature properties, however most of these alloys have poor weldability and suffer from porosity, weld zone and heat affected zone cracking.
Many methods can be used to weld these aerospace alloys. Tungsten Inert Gas (TIG) and Electron Beam (EB) are the most widespread techniques for welding these alloys. However, fiber lasers with its high beam quality and high average power can be a convenient alternative for welding even complex shaped components made of these alloys. The major drawback of the laser welding process is the stringent joint requirements. In the case of a typical butt joint the widest acceptable air gap for autogenous laser welding is usually 10% of the material thickness. This tolerances can be fulfilled when components are relatively small and manufactured with machining or laser cutting. Even in these cases for large components it is difficult to achieve the required accuracy when positioning them. The geometry of a joint, air gap and part mismatch varies from joint to joint and between products and production batches. Filler wire can be used to achieve to compensate for the poor fit-up and mismatch for butt joint welding, control weld geometry and achieve desired weld metallurgy.
Work has been carry out to develop laser and processing parameters to produce welds with nickel and titanium aerospace alloys to produce good quality autogenous welds as well welds made with the filler material that meet the stringent requirements of the aerospace industry.

Keywords: Laser welding, nickel based alloys, titanium based alloys, nickel based alloys, filler material, porosity and shield gases

1. Introduction

Continuous advances in the aircraft and aerospace technology impose ever-increasing demands on the materials used in the components and structures and also impose ever increasing demands upon the engineers to develop new joining techniques. Titanium and nickel based 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) [1]. Figure 1 highlights different type of materials which are currently used in the aero-engine.

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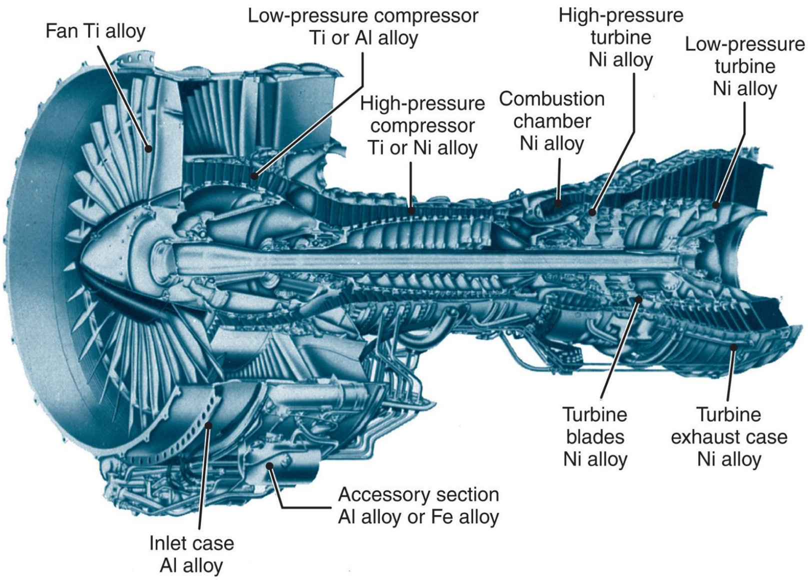


Fig. 1. Range of titanium and nickel based alloys currently being used in the construction of aeroengine

Many methods can be used to weld these aerospace alloys. Tungsten Inert Gas (TIG) and Electron Beam (EB) are the most widespread techniques for welding these alloys [2.3.4]. However, lasers with its high beam quality and high average power can be a convenient alternative for welding even complex shaped components made of these alloys [5.6.7]. High power laser welding can offer a number of advantages over other welding techniques i.e.

- 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 rework.
- The process is easily automated for high volume production.
- Laser light (fiber delivered) can be directed into inaccessible locations, providing the possibility for joints to be redesigned based on their function rather than the method of joining.

With regard to potential applications in the aerospace industry, these advantages could be translated into improvements in productivity and joint quality, as well as new opportunities for design, leading to an overall reduction in weight.

The major drawback of the laser welding process is the stringent joint requirements. In the case of a typical butt joint the widest acceptable air gap for autogenous laser welding is usually 10% of the material thickness. This tolerances can be fulfilled when components are relatively small and manufactured with machining or laser cutting. Even in these cases for large components it is difficult to achieve the required accuracy when positioning them. The geometry of a joint, air gap and part mismatch varies from joint to joint and between products and production batches. Addition of filler material (i.e. wire) can be used to compensate for the poor fit-up and mismatch for butt joint joining as well as control the weld geometry and achieve the desired weld metallurgy [8].

Prima Power Laserdyne has undertaken a number of initiatives to develop laser and processing parameters which can produce good quality welds that meet the stringent requirements of aerospace, i.e.

- No or minimum porosity
- No cracking
- No top and under bead undercut
- Top bead seam width of certain size
- Waist (center of the weld) of certain size
- Weld interface width
- Bottom bead seam of certain size
- Oxidized free top and bottom bead

2. Welding data

2.1. Autogenous weld

Nickel alloy and titanium alloy (so called aero engine materials) can generally be easily laser welded [9]. The welds are usually neat in appearance and have low distortion when compared with their arc-welded counterparts. The fusion zone width and the grain growth can usually be controlled according to laser power at the work piece and the welding speed used. Although these alloys are readily, laser weldable special attention must be given to the joint cleanliness and the gas shielding. Both of these alloys are highly sensitive to oxidation during laser welding, especially titanium based alloys [10.11], therefore majority of the work of the development work was centered on experimenting with different gas shielding devices, i.e. coaxial, side jet, welding shoe etc. (Figure 2). The results show that best looking welds (bright and silvery) were produced with the weld shoe, coaxial shielding produced light contamination (light and dark straw colors) which is normally acceptable. The side jet produces welds with heavy contamination (dark blue/ powdery white) which is not acceptable (Figure 3). The most likely contaminants are oxygen and nitrogen, picked up from air entrained in the gas shield or from impure shield gas, and hydrogen from moisture or surface contamination. The oxides, nitrides and hydrides that form as a result of contamination increase the weld and HAZ hardness and lead to reduced fatigue life and toughness.

Coaxially gas shield arrangement mainly used

Coaxially gas shield arrangement mainly used for nickel based alloy

Gas shoe shield arrangement mainly used for welding titanium based alloy

Fig. 2. Diffèrent type of auxiliaires for the welding nozzle

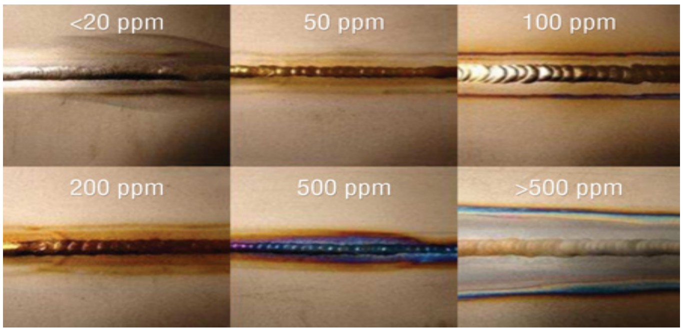
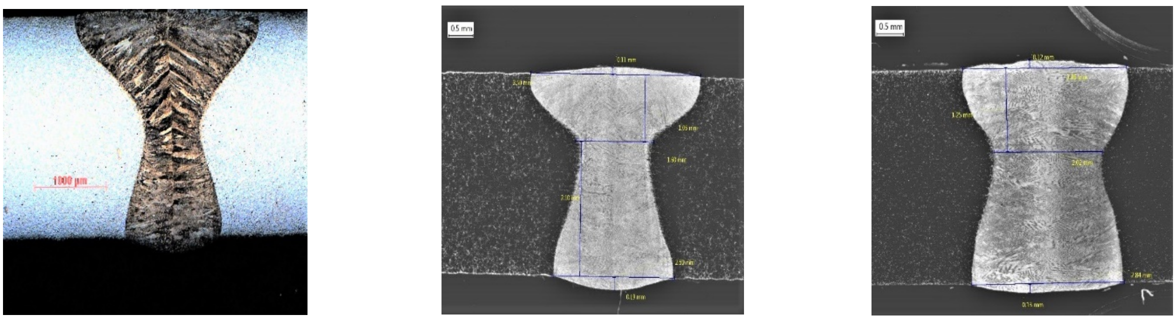


Fig. 3. Color of the weld metal and heat affected zone adjacent to the weld indicates the level of oxidation (ppm = parts per million) of the weld as well as quality and strength of the weld. Oxidation of less than 20 ppm produces a silvery, shiny

With optimum gas shielding arrangements as well as the laser and processing parameters it was possible to produce porosity and crack free welds in a range of nickel and titanium based alloys **(Figures 4-5)**.

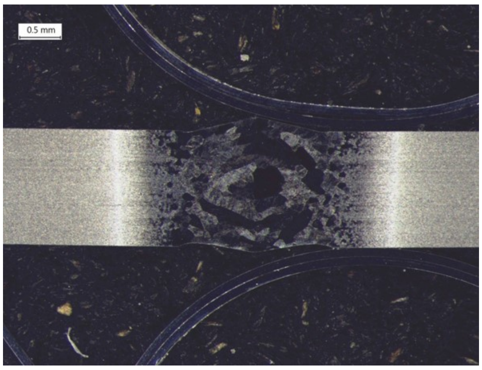


2.3mm thick Inconel 718; welding speed 2m/min

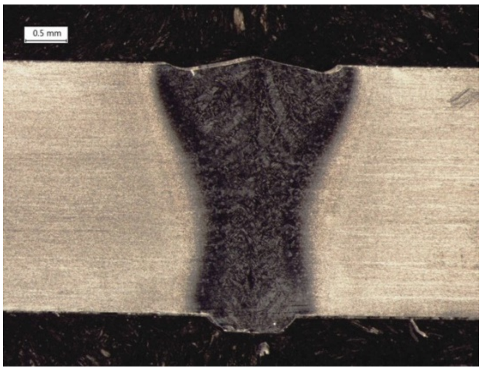
3.2mm thick Hastelloy-x; welding speed 1m/min

3.2mm thick Haynes 230; welding speed 1m/min

Fig. 4. Autogenous butt joints with zero gap; nickel based superalloys; nitrogen shield gas; average power 1.80kW



1.4mm thick Ti-6Al-4V alloy;
welding speed 2.3m/min



3.0mm thick Ti-6Al-4V alloy;
welding speed 1.7m/min

Fig. 5. Autogenous butt joints with zero gap; titanium based alloys; argon shield gas; average power 1,80kW

2.2. Welding with filler material

As demonstrated with autogenous welds, laser welding can be a convenient alternative for welding complex shaped components made of nickel and titanium alloys, however the major drawback of the laser welding process is the stringent joint requirements. In the case of a typical butt joint the widest acceptable air gap for autogenous laser welding is usually 10% of the material thickness. This tolerances can be fulfilled when components are relatively small and manufactured with machining or laser cutting. Even in these cases for the large components it is difficult to achieve the required accuracy when positioning them. The geometry of a joint, air gap and part mismatch varies from joint to joint and between products and production batches. Filler wire can be used to achieve to compensate for the poor fit-up and mismatch for butt joint welding, control weld geometry and achieve desired weld metallurgy.

A detailed study of laser welding with filler wire was carried out to develop laser and processing parameters, including welding and wire speeds for the production of full penetration welds with different amount of joint gaps. The development work led to production of real parts in aerospace industry which passed the stringent requirements of the aerospace industry i.e. weld geometry, metallurgy and the mechanical properties. One such example was laser welding of Pylon, which is the item that mounts the engine onto the wing. A total of nine welds with total length of over 1m long were made with the filler material to compensate for the poor fit up and mismatch of the parts.

Laser welding with the filler wire is a multiparameter process [12] and there are a number of laser and filler wire parameters which determine the quality of the resultant weld. Some of the important parameters are listed below.

Welding/filler wire speed

The wire feed rate for a given air gap and plate thickness is an important parameter and is dependent on welding speed, the cross sectional area of the gap between the joint face and cross sectional area of the filler wire. Addition of filler wire generally results in a 10% to 20% decrease in welding speed, for a given laser power, to compensate for the laser energy required to melt the wire [13].

If the filler wire speed is too low the amount of heat generated from the laser beam will affect the wire and the material being welded may be able to melt a bigger section of the wire end. This may result in formation of a liquid metal bridge formed, formation of a drop at the end of the wire, and momentary disturbance of the process stability [14]. Too high filler wire rate causes the energy supplied to the welding area to be insufficient for stable and permanent wire melting. The volume of liquid metal at the end of the wire and in the liquid metal bridge increases thus flooding the air gap. Additionally, non-melted wire enters the back area of the pool, pushing out the liquid metal, which, by solidifying, forms characteristic humps of the weld surface and porosity at the root of the weld. Excessive wire speed can also reduce the penetration depth, weld width and topbead height [14].

Laser beam- filler wire interaction

An exposed length of wire that is too short prevents the wire from being melted at the initial area of the bead, resulting in the laser beam directly melting the material in the weld joint. Conversely, an exposed length of wire that is too long causes the extended wire end to be pressed against the plate surface, and as a result, at the initial stage, the laser beam melts the wire through, dividing it into two parts [15]. As a result, the point at which the process starts is covered with a wire end welded onto the surface and difficult to remove. In an extreme case, the welded-on wire end could cause a collision with the gas shielding nozzle, disturbing or even eliminating the gas shielding.

Wire feed delivery angle

Angles between 30 and 60 degrees from the vertical can be used with 45 degree being the norm, as it simplifies setting the required wire intersection position with laser beam centerline [16]. Angles greater than 60 degrees makes the latter difficult and angles less than 30 degrees causes the wire to intersect a large area of the laser beam, causing melting and vaporization of the wire without incorporating into the weld pool.

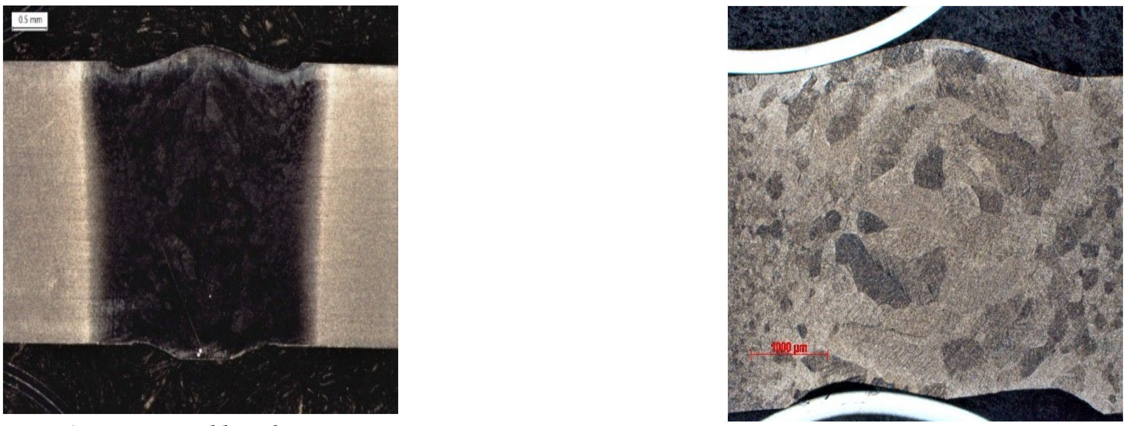
Focused spot size

The spot size should be close to the filler wire diameter. A laser spot size too small compared to the wire diameter lead to welds with porosity because the filler wire has not melted properly [17].

Figures 6-7 highlight the transverse sections of the laser welds with joint gap of 0.15mm for both3.2mm thick nickel and titanium based alloys butt joints respectively. The welds were fully penetrated without any cracking, porosity and no underfill/ undercut of the top bead. For aerospace alloys welding the underfill of the topbead is undesirable because it reduces the cross sectional thickness of the weld, which may lead to reduced tensile strength as well as fatigue strength of the weld during the service.

Autogenous weld, slight undercut at topbead *Weld made with filler material, no underfill/undercut*

Fig. 6. 3.2mm thick Inconel 625 superalloy; butt joint with 0.15mm gap; 1.2mm diameter Inconel 625 wire; average power 1.80kW; nitrogen shield gas



Autogenous weld; undercut and few pores *Weld made with filler material; no pores and undercut*

Fig. 7. 3.2mm thick Ti-6Al-4V titanium based alloy; butt joint with 0.20mm gap; 1.0mm diameter wire; average power 1.80kW; argon shield gas

3. Summary

In the aerospace industry where emphasis is on quality for the obvious reasons, until recently the general trend has been to remain with electron beam and TIG welding in favor of laser welding. However, more and more manufactures are looking in laser welding for joining aerospace alloys. Some of the nickel based alloys, especially, high strength, precipitation hardened materials presents much more of a problem, as these are prone to heat affected zone and strain age cracking that limits the manufacturing and repair weldability for these alloys. Consequently laser welding methods (with and without filler material) are being evaluated. The work carried out at Prima Power Laserdyne has heighted that:

- High power laser welding offers same features and results as electron beam welding
- Laser welding is capable of high welding speeds as opposed to a TIG or MIG method
- Very good parameters control once the proper parameters have been established
- Filler material can also be used to compensate for the poor fit-up and mismatch for butt joint configuration. Apart from improving the fit up, filler material improves the weld geometry, i.e. eliminates the top and bottom bead undercut

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