A Coherent White Paper

Improving fiber laser weld quality and yield with CleanWeld

While fiber lasers have been used in welding for over a decade, many end-users are still seeking to improve part quality, increase production throughput, and reduce process costs. Increasingly, manufacturers look to the laser or laser system supplier to lead this effort, often by providing a completely optimized solution that may even include a specific “process recipe” for the particular application.

Welding Application	Traditional Challenges	CleanWeld Results
Powertrain Components	Spatter	Low spatter Less porosity Can bridge 0.3 mm gaps without filler
Galvanized Steel	Requires spacers Inconsistent seam Produces voids	Zero gap welding Low spatter Applicable to curved parts
Motor Stator "Hairpins"	Weld defects Part deformation	Minimal defects No part distortion Low spatter Less porosity
Electric Car Battery Lids	Porosity Spatter	Deep penetration Consistent hermetic seal Low spatter
Aluminum Hang-on Parts	Hot cracking	No cracking Low spatter No filler required

Within Coherent (now including the former Rofin-Sinar industrial laser group), this is embodied in our CleanWeld™ initiative; an integrated approach to fiber laser welding that delivers up to 80% spatter reduction, as well as minimal cracking and porosity. In addition to improved process consistency, it allows some welding processes to be performed with 40% less laser power. The specific benefits of this methodology are summarized in the table.

CleanWeld delivers these improved results by combining Coherent's expertise in fiber lasers, delivery fibers, focusing optics, and process heads, together with our extensive welding process knowledge and in-house applications development capabilities. This gives Coherent a unique ability to manage precisely how laser power is applied in a given situation so as to maximize process control and stability, thus yielding consistently superior results.

All this is necessary because there are numerous factors besides just the laser that affect the welding process. The real goal is to control and maximize the stability of the energy/material coupling efficiency, keyhole and melt pool during the welding process – that's what produces superior results. But, actually accomplishing this can require a variety of techniques that range from changing the intensity distribution of the focused laser spot to introducing beam motion (wobble), to other factors like the precise dynamics of assist gas delivery or vapor evacuation. The CleanWeld integrated approach addresses all these areas.

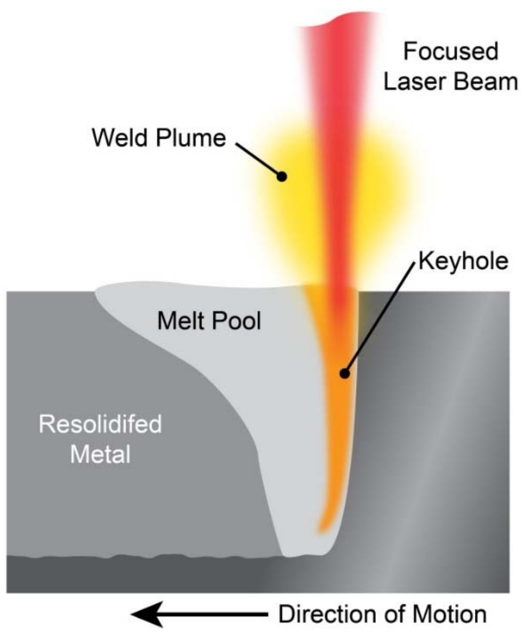

Figure 1: *Schematics of key hole and melt pool in laser welding.*

Technology Background

In keyhole, or deep penetration welding, the laser is focused to achieve a very high power density so that the metal actually vaporizes – this vaporized metal volume extends into the material creating a keyhole surrounded by the melt pool. Vapor pressure within the keyhole caused by laser beam absorption prevents closure of the melt pool. The focused laser beam and keyhole continuously move along the welding path.

The quality of a weld is determined by the stability of the keyhole during the welding process. The goal is to achieve a stable energy balance through the entire depth of the keyhole to ensure uniform absorption and non-perturbed molten flow around the keyhole. This in turn provides consistent weld depth and, more importantly, minimized spatter and porosity.

To date, acceptable – but far from ideal – levels of weld quality and reliability using fiber laser technology have been possible. This is because one of the defining factors for this laser is its simple circular beam profile, which is great for cutting but less than ideal for penetration welding.

There are several tools which can be employed to control keyhole dynamics, and therefore optimize a specific welding process, and this is the essence of the CleanWeld approach. Probably the most obvious of these are laser power and the focused laser spot size, as well as the spot's spatial intensity distribution. In fact, it's really only useful to consider these three factors together, since it is really the *power density* (and how it is distributed) at the workpiece, rather than the overall power, which affects welding results. Focus position (location of the minimum spot size) relative to the top material surface is also critical.

Controlling the precise laser intensity distribution (laterally, and in depth) determines how laser energy is absorbed in the keyhole (and the keyhole's subsequent shape and temporal stability) as vapor expansion characteristics are balanced with melt pool flow. This is because the laser intensity distribution directly determines the temperature gradient at the workpiece and in the keyhole.

Traditionally, fiber lasers have employed a single, round core fiber which essentially delivers either a single mode or multi-mode, circular spot. Today there are several approaches that deliver more complex intensity distributions. These methods range from square (or other shaped) cores to multi-core fibers (such as fibers which consist of two concentric cores. For the latter, Coherent's Adjustable Ring Mode (ARM) lasers provide a ring beam with the highest brightness in the market, which also enables its use with a scanner, unlike lower brightness competitive products.

Next, various process (focusing) optics can be used to further manipulate or change the focused spot size, shape and position. Beyond this, the effective power delivered at a given position on the workpiece surface, and the rate at which it is delivered, can be altered using power ramping, laser modulation and beam motion techniques, such as beam wobble.

In addition to focusing optics, laser welding process heads may also incorporate nozzles for delivering process gases, and for removing the expanding laser vapor. In particular, certain assist gasses can be used to stabilize the heating of specific materials and calm melt pool dynamics. Gas flow can also be used to clear the plume and protect optics from debris.

By optimizing all these factors in our applications laboratory, Coherent is able to supply customers with a complete CleanWeld solution that delivers a specific weld quality and throughput speed, rather than just a laser with a given output power.

Aluminum Battery Lid Welding

One key step in the production of the lithium ion batteries used in electric vehicles is welding battery cases. It's critical that this weld produces a hermetic seal which will last over the lifetime of the component. In particular, this seal must prevent moisture infiltration because water reacts strongly with lithium, creating gas and pressure which could destroy the device. Furthermore, the welding process itself must produce no spatter, since metal particles (as well as moisture) can create internal leakage currents which would short-circuit the battery. Finally, the weld must be mechanically strong enough to withstand rough treatment, or even the shock of a collision.

Sealing the aluminum battery case has traditionally been performed using laser conduction welding because the battery walls are thin (< 1 mm). However, using conduction welding, it's difficult to achieve sufficient penetration to produce a strong enough weld with sufficiently low porosity to prevent the intrusion of moisture. But, using higher laser powers to achieve a deeper penetration (keyhole) weld runs the risk of creating pores and having an unstable penetration depth, which may lead to low welding strength, and virtually always causes some spattering.

Extensive development work at Coherent has proven that one solution for high speed, spatter free, deep welding of metals is to use a beam profile consisting of a central spot, surrounded by another concentric ring of laser light. Achieving this unusual configuration in the focused fiber laser spot is accomplished using Coherent's Adjustable Ring Mode fiber laser, the

HighLight® FL-ARM. This laser's delivery fiber augments a conventional circular core by surrounding it with another, annular cross section fiber core.

Coherent provides FL-ARM lasers with output powers ranging from 2.5 kW to 10 kW. The power in the center and the ring can be independently adjusted on demand over a range of 1% to 100% of the nominal maximum output. The core and ring beams can even be independently modulated, at repetition rates of up to 5 kHz. The ability to ramp up or modulate the ring and center independently enhances the ability to control the weld geometry and keyhole dynamics.

In this arrangement, there are virtually an unlimited number of possible combinations in terms of the power ratio of the inner to the outer beam. However, all these can be broadly grouped into the configurations shown in the drawing. These basic patterns can then be varied to deliver a wide range of processing characteristics to optimally service a diverse set of applications.

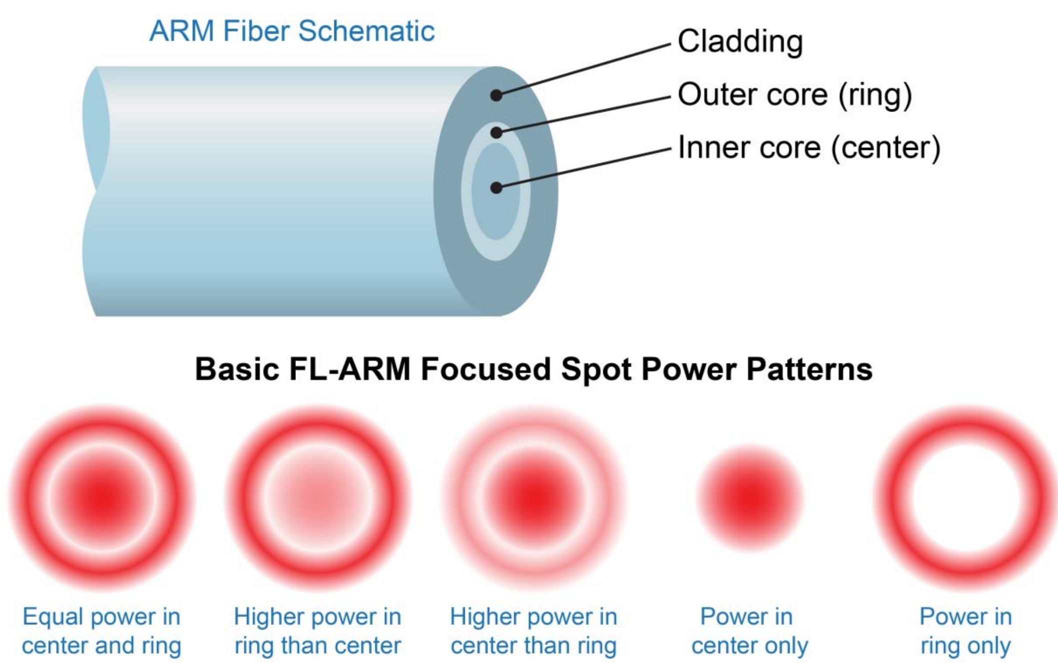

Figure 2: *Simplified ARM fiber schematic and the five basic power patterns possible in the focused laser spot.*

For fiber laser welding of aluminum, one challenge has been that the material has relatively low absorption in the near infrared. Small, unpredictable variations in absorption cause the penetration depth to vary, resulting in an uneven weld.

To address this, and to deliver the sufficiently fine control needed for keyhole welding of aluminum battery cases, the FL-ARM beam is configured with power in both the center and in the ring. Using this particular power configuration, the leading edge of the beam raises the aluminum temperature sufficiently to increase its absorption at the laser wavelength. Then, the center of the beam creates the keyhole, which is now very stable due to the pre-heating. The trailing edge of the ring beam keeps the melt pool open long enough to allow gas to escape. Because the keyhole is stable, and the material doesn't re-solidify as quickly, the entire process is more consistent, and the process window is larger. The ultimate result is uniform, consistent material penetration and higher quality, spatter- and porosity-free welds.

"Hairpin" Welding

An important step in the production of electric motors for automobiles is the welding of bar-wound copper pins into the stator of an electric motor. These stiff pins (called "hairpins" because of their "u" shape), replace the wire windings traditionally used in an electric motor. Because they are much more rigid than wire, their orientation in the motor can be controlled more precisely, ultimately resulting in the ability to handle greater thermal stress and higher motor efficiency.

In the assembly process, the individual hairpins are first loaded into slots in the stator. Then, the ends of adjacent hairpins are welded together in order to connect them electrically; when the entire motor is finished, all the hairpins will act as a single, long, twisted conductor, just like the windings of a conventional electric motor.

Figure 3: *Unprocessed copper stator*

The two key imperatives of this process are that the weld maintain proper mechanical alignment of the pins, and also not produce any defects (inclusions). Hairpin alignment is important because the exact winding shape directly affects motor efficiency. Defects must be avoided because these increase the resistance of the final winding, thus reducing its electrical efficiency, and might also lower the mechanical strength of the assembly.

Coherent has developed a fiber laser based method for performing hairpin welding which achieves all these goals. The first key element of this process, which is based on a standard HighLight fiber laser, involves the use of so-called “beam wobble.” Specifically, in this case, the size of the focused beam on the work surface is deliberately made smaller than the total area to be welded. However, the position of the spot is rapidly scanned (wobbled) to cover that entire area.

Just as with the FL-ARM laser, the advantage of beam wobble is that it enables more precise control over the temperature dynamics of the melt pool. Specifically, moving the beam rapidly and iteratively over the part, and not allowing it to dwell on any one place, essentially preheats the part in a highly controlled way, rather than dumping all the power in at once, and makes the beam effectively larger without reducing the effective power. All this stabilizes the melt pool, reducing spatter, defects and weld porosity as compared to traditional laser welding methods.

Coherent also offers practical process related tools that improve results in laser hairpin welding in a production environment. For example, the company can supply a laser welding subsystem which includes a visual system to control the relative positioning of the focused laser beam and the pins.

Powertrain Component Welding

Welding of automobile powertrain coupling components has long presented a challenge for fiber lasers, specifically because these lasers typically produce some spatter. This type of contamination is particularly unacceptable on powertrain gears or bearing surfaces. Furthermore, spatter is often accompanied by weld porosity (since the spattered material may leave a void or an undercut), which can affect weld quality, strength and consistency.

Applications development work at Coherent employing the CleanWeld approach has proven that spatter can be largely eliminated even using a fiber laser. While the specifics involved optimization of multiple process factors, including laser power and gas delivery nozzles, probably the biggest improvement came from choosing the right delivery fiber. In particular, changing the focused beam profile away from a simple circular spot produced a substantial reduction in turbulence in the melt pool, which then reduces spatter. Sample welds confirm the quality of the optimized fiber laser welding process.

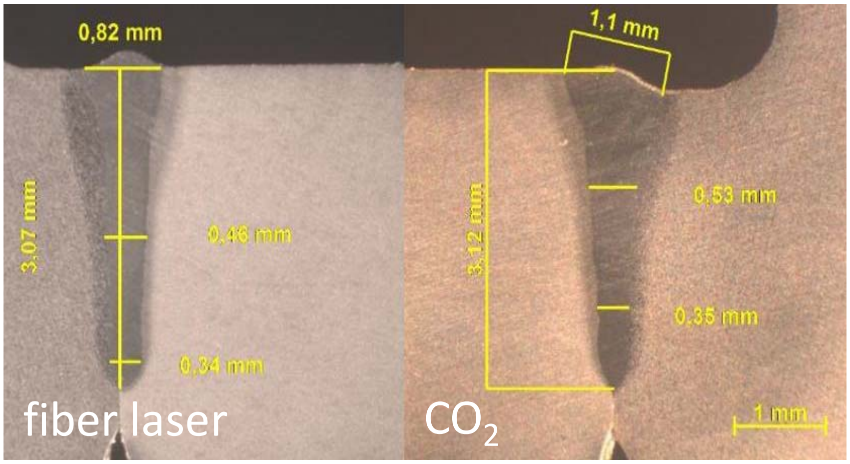

Figure 4: *Fiber laser and CO_2 laser welding of powertrain gears show essentially identical results, that is, a deep penetration weld with good aspect ratio and no spatter. Both welds were done at the same feedrate of 3 m/min.*

Figure 4 shows a narrow welding seam (width < 1 mm), which is useful when part dimensions are accurate (e.g. zero gap). This delivers minimal heat affected zone and distortion. The root width remains > 0.3 mm, similar to a CO_2 laser weld. However some powertrain welding applications have to bridge gaps, due to part inaccuracies. By smart adjustment of the optical setup, gaps of up to 0.3 mm can be bridged (without filler) by using a very calm weld with very little spatter and porosity (See figure 4).

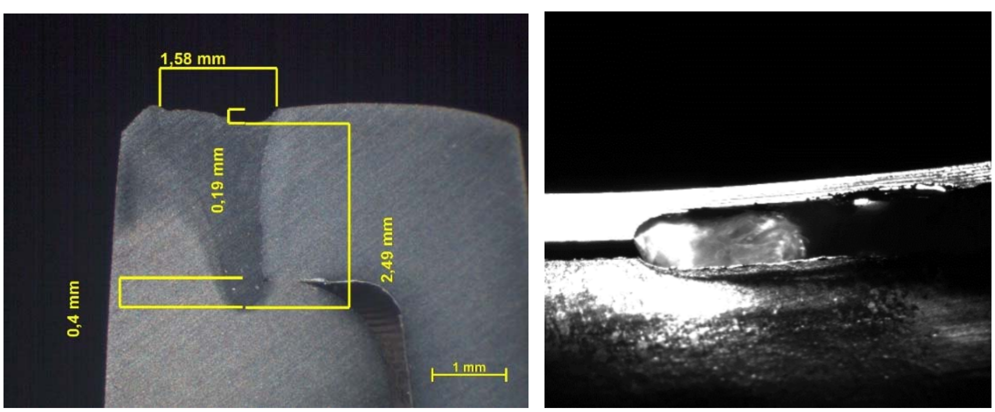

Figure 5: *CleanWeld setup to weld components with gaps of up to 0.3 mm without filler wire in a very calm welding process.*

In addition to eliminating spatter, the fiber laser welding parameters used in this case also enabled higher speed processing. In fact, one automotive supplier who has utilized this technique stated that their throughput had increased by 20% over their previous fiber laser process.

Automotive Hang-on Parts Welding

Automotive hang-on parts, which frequently incorporate aluminum, can present difficulties for laser welding. In particular, aluminum has a tendency to "hot crack" because of loss of its alloying elements during welding usually. This creates the need to add material into the melt pool, typically in the form of filler wire. Additionally, spatter is sometimes problematic for hang-on parts since it introduces contamination which can get trapped within an assembly (such as a door). For example, one manufacturer reported problems with spattered material subsequently migrating to and blocking door draining holes.

The CleanWeld solution for this again involved utilizing a dedicated intensity distribution in the focused laser spot. The optimized beam shape allows the part to be both pre- and post-heated, thus avoiding problems caused by rapid part cooling. It also eliminates spatter and the need to use filler wire. The results, and effectiveness of subtle changes in laser power distribution, are shown in the figure 5. Parts A and B show that, by adjusting the beam intensity profile, the depth of weld can be controlled while keeping the weld width constant.

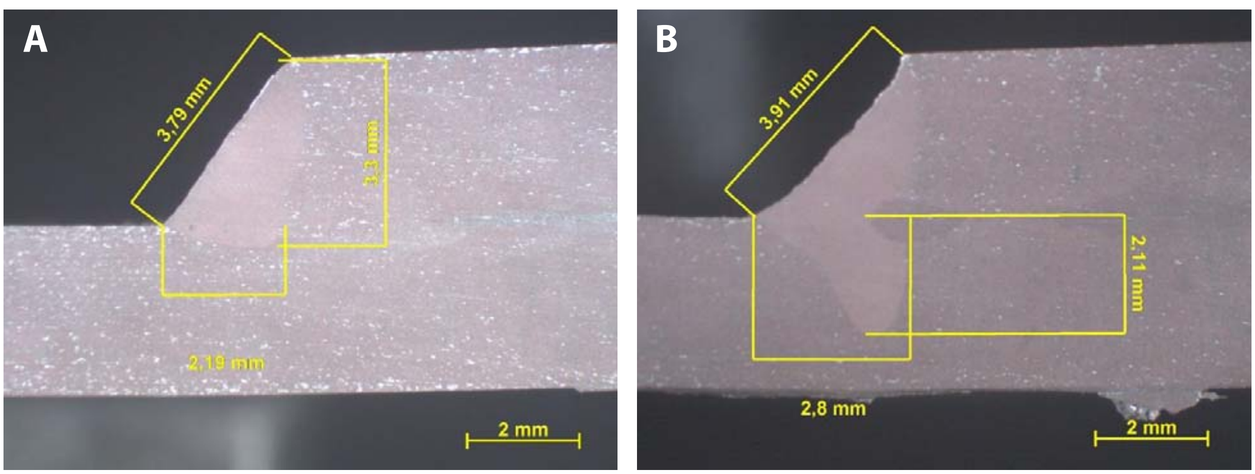

Figure 6: *These two fillet weld cross sections show the dramatic effect of changes in weld results with just minor adjustments in focused spot intensity distribution. In the first sample (A), the weld does not penetrate well into the bottom piece. A slight change in the intensity profile, which increased the pre- and post-heating effect, produced a weld (B) with excellent penetration, at the same feed rate of 5 m/min.*

Zero gap welding of zinc coated steel

Galvanized steel is another material widely used in automobile hang-on parts, as well as in bodies. Zero-gap lap welding of this material has presented a challenge for laser welding because the more volatile zinc evaporates first when the laser energy is applied to the material. This creates gas pressure which can blow out the molten steel, resulting in an inconsistent weld seam, as well as spatter that needs to be subsequently cleaned. This problem can be mitigated by either dimpling the material, or adding spacers between the metal sheets, so that there is sufficient space (~ 0.1 - 0.5 mm) for the vaporized zinc to vent in a controlled manner to the side, rather than the top, of the keyhole. But this approach has obvious drawbacks – any added steps increase manufacturing complexity and/or cost.

The CleanWeld approach has proven the ability to perform galvanized steel welding without the need for a gap between the parts. Once more, much of the laser power is distributed away from the beam center and into the edges. As with aluminum, this approach both pre- and post-heats the material, and also reduces the pressure at the center of the keyhole. This allows the zinc gas to vent out easily through the center without producing any spatter, even when the parts are clamped together with zero gap. However, it's worth noting that this power distribution is symmetric, so the orientation of the beam doesn't have to be changed to follow the direction of the weld seam, which might vary substantially on a contoured or shaped part. This greatly simplifies its implementation and can be done by using a scanner head.

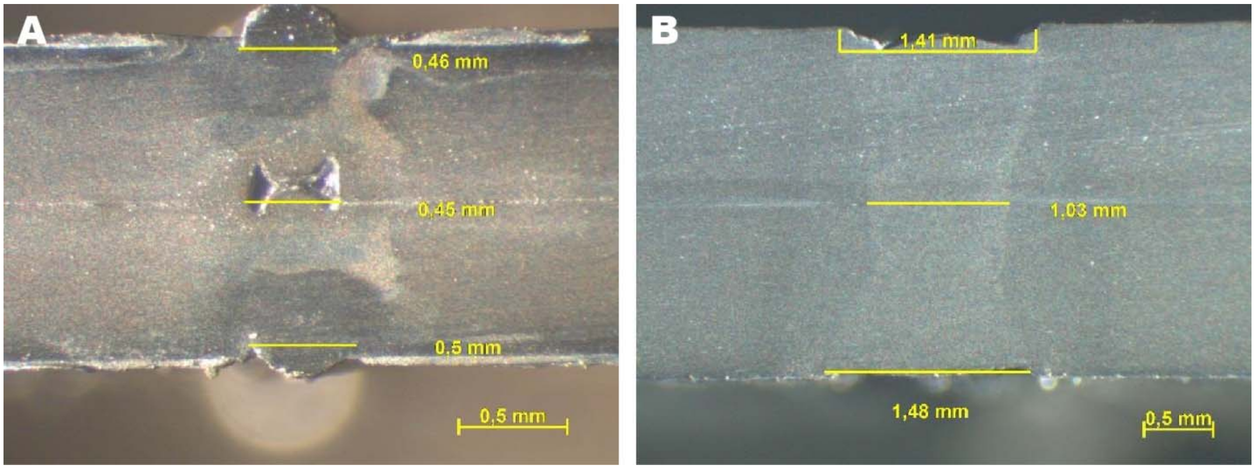

Figure 7: *Cross sections showing the weld seam for 1.25 mm thick zinc coated steel, processed using a fiber laser without a gap between the sheet and at a feed rate of 3.3 m/min. A) Conventional laser focusing creates a seam with voids, and B) the FL-ARM creates a weld seam with excellent uniformity and no porosity.*

Stainless Steel Profile Welding

Stainless steel tubes are produced by forming a flat strip so that its profile becomes cylindrical, and then welding the gap to create a closed tube. The precise shape, dimensional accuracy and material characteristics of the weld seam affect the ability to further form the part (e.g. produce bends and curves), thus placing very stringent demands on weld quality, particularly for automotive applications.

CO_2 lasers have long been used for profile welding, and still remain the standard. This is because they produce excellent weld seam quality and can deliver high feed rates. Fiber lasers haven’t been able to match these results at the necessary throughput, although manufacturers would like to switch to this technology to take advantage of its inherently better cost of ownership characteristics.

One problem with traditional fiber laser profile welding is spatter, which produces mass loss and side kerfs, lowering weld seam mechanical strength and reducing quality and seam consistency. The problem usually arises because stainless steel absorbs the near infrared fiber laser output more strongly than the longer CO_2 laser wavelength. This high absorption causes more rapid material heating, which is also confined to a smaller region, both of which lead to turbulent and chaotic dynamics in the melt pool.

Utilizing the Coherent FL-ARM to modify the standard fiber laser power distribution reduces turbulence in the melt pool. This makes the dynamics of the welding process similar to the stable conditions encountered in conduction welding, yet yields the high aspect ratio of a keyhole (deep penetration) weld. Most important, it enables the fiber laser to deliver these high quality results at market enabling throughput levels, typically in the 8 m/min to 24 - 30 m/min depending upon thickness and material.

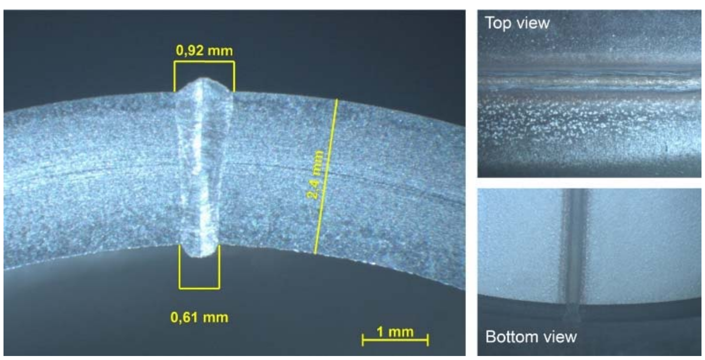

Figure 8: *Cross section, top view and bottom view of a profile weld in stainless steel.*

Conclusion

In conclusion, as fiber lasers become a mature technology, further improvements in fiber laser welding are most likely to come from a better understanding, and control, of the factors which influence exactly how laser energy is applied to the workpiece. The CleanWeld effort at Coherent has already proven that dramatic improvements in weld seam geometry, spatter, cracking, porosity and process stability can all be achieved by using a variety of technologies and techniques in a novel, cohesive fashion. This yields manufacturing processes with higher quality and ultimately, lower cost.

www.coherent.com | tech.sales@coherent.com | 800-527-3786 | 408-764-4983