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Beam Shaping BrightLine Weld – Latest Application Results

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Abstract

This paper presents latest results on welding of steel, aluminum and highly reflective materials such as copper using the new TRUMPF beam shaping technology BrightLine Weld.
The technology is based on applying a TruDisk thin-disk solid-state laser with a so called 2in1 fiber. In combination with a novel system of variable laser power coupling into the inner as well as the outer fiber core, an application-tailored laser power distribution is created. This enables a new degree of freedom through beam shaping for laser keyhole welding.
The process benefits are significantly higher achievable feed rates, minimal spatter formation and highest weld seam qualities. For full penetration welding, it is even possible to reduce spatter formation on both sides of the weld seam. Endurance strength tests performed show that the weld seam characteristics of the high-speed welds fulfill state of the art requirements.

Keywords: laser welding; disk laser; powertrain; beam shaping

1. Introduction

Over the last years solid state lasers became a standard tool in materials processing since they offer numerous benefits as e.g. high energy efficiency, ability of easy fiber guidance and less demands of assist gas for welding. However compared to CO2-lasers, solid state lasers lead to a higher degree of spatter formation for deep penetration welding, especially at high feed rates. This results in a limitation of achievable welding speeds – or in other words - the full performance of solid state lasers with wavelength 1 µm could not be exploited up to now.

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By using beam shaping technologies it is now possible to overcome this limitation for solid state lasers. Just last year TRUMPF introduced its patented beam shaping technology BrightLine Weld which is based on applying a TruDisk thin-disk solid-state laser with a 2in1 fiber. In combination with a novel system of variable laser power coupling into the inner as well as the outer fiber core, as shown in Fig. 1, an application-tailored laser power distribution is created.

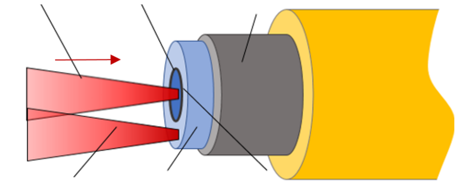


Fig. 1. Functional principle of BrightLine Weld showing how the laser light of a TruDisk laser is coupled into a 2in1 fiber. The core fiber and the ring fiber are used at the same time and the laser power can be distributed flexibly between both cores.

Fig. 2 thereby shows an example of the beam shape in the focal plane for different power distributions. Due to the power density distribution as new degree of freedom, there is no significant dependence between feed rate and spatter occurrence in various laser keyhole welding applications any more. In the following chapters we present latest industrial relevant laser application results for which we could achieve convincing benefits using BrightLine Weld.

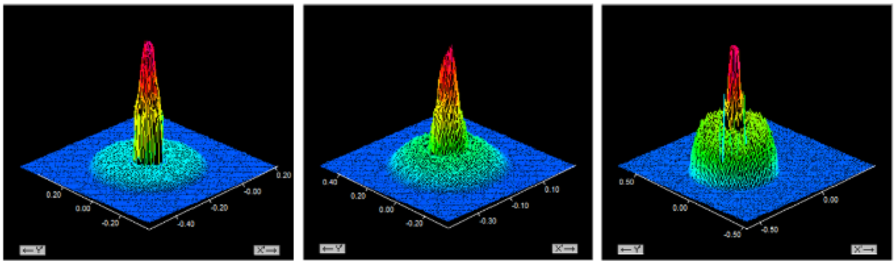


Fig. 2. BrightLine Weld beam shape in the focal plane of the laser beam. Left to right figure: Increasing laser power in the coaxial outer fiber core.

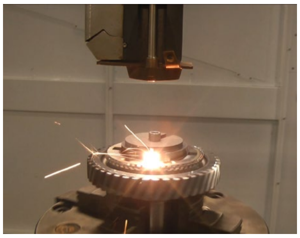
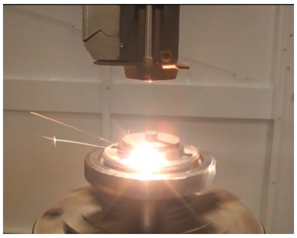
2. Fatigue strength tests and metallurgical investigation of welded powertrain parts

2.1. Fatigue strength tests

Welding of gear wheel parts has been one of the first key applications for laser welding with beam shaping. Typical requirements for these kind of applications are high welding speeds and clean welds. However high feed rates usually result in narrow weld seams. With that the importance of weld preparation increases and the components to be joined should be press fit to avoid welding imperfections caused by a possible gap. If the criteria for the weld preparation are confirmed, BrightLine Weld can be used very flexibly with a wide range of parameters. Either for optimizing energy efficiency or for optimizing machine productivity, as discussed in [1].

State of the art laser welding of a test gear wheel, i.e. welding without beam shaping, requires a laser power of 3.4 kW and a feed rate of 5 m/min can be reached. Spatters produced during welding need to be exhausted in order to reduce contaminations on part and machine, see Table 1 on the left. If BrightLine Weld is used to optimize energy efficiency, as shown in the central column of Table 1, the part can be welded at the same feed rate of v = 5 m/min with a lower laser power of P = 2 kW at a comparable weld depth. The spatter formation is low, so even no exhaust is required. On the other hand, it is possible to improve the productivity by increasing the feed rate combined with using higher laser power. This case is shown in the right column of Table 1. The same high-quality weld seam with low spatter behavior and equal penetration depth can be achieved with three times the weld speed at v = 15 m/min and P = 5 kW.

Table 1. Laser welding of a gear wheel. (Left) State of the art welding without beam shaping. (Center) Welding with BrightLine Weld for optimizing energy efficiency. (Right) Welding with BrightLine Weld for optimizing productivity.

State of the art	BrightLine Weld	
	Efficiency optimized	Productivity optimized
P = 3.4 kW	P = 2 kW	P = 5 kW
v = 5 m/min	v = 5 m/min	v = 15 m/min
		

Increasing the feed rate leads to a higher cooling rate of the molten material. To avoid possible mechanical limitations due to this fact, torque fatigue tests have been made. For the test, state of the art weld seams with v = 5 m/min are compared with BrightLine Weld seams with v = 15 m/min. The tests were carried out on disk-shaft test parts with an axial seam, which is illustrated in Fig. 3. As material combination the steels 20MnCr5 for the shaft and 16MnCr5 for the 5 mm thick disk were chosen. To avoid a falsification of the result due to the unwanted influence of a notch effect, the root of the weld seam is later turned off to a thickness of 3 mm and thus only the weld seam is tested.

State of the art	BrightLine Weld
TruDisk 3002	TruDisk 6001
fiber Ø 200 µm	fiber Ø 100/400 µm
m = 1.5:1	m = 1.1:1
v = 5 m/min	**v = 15 m/min**

Fig. 3. (Left) Powertrain test part consisting of shaft and disk connected with an axial weld. (Right) Weld parameters with m being the image ratio of the focusing optics and v being the weld speed.

For measuring the fatigue strength of the weld seams a torsion-axial test system was used. All measurements were done as pure torsion tests with symmetrical torsional load in both directions of rotation. The torsional moment is controlled in sinusoidal force progression at a frequency of 20 Hz. The fracture criterion is reached if the rotation angle increases by 1% compared to the rotation angle of a non-cracked test specimen. The selected maximal number of cycles for the trials is 2 x 10^6. Tests without reaching the fracture criterion were counted as "run" / no crack.

The tests are carried out as stair-step tests to measure the fatigue strength in form of a 50% survival probability. Subsequently the load tests are carried out on several samples and, depending on the test result of an expired test (no crack / crack), the loading amplitude of the following test is increased or decreased. The so-called "logarithmic increments" according to DIN 50100-2016 were chosen as steps. The results of the stair-step tests are shown in Fig. 4.

Torsionssp. [MPa]	Versuchsnummer												
	1	2	3	4	5	6	7	8	9	10	11	12	13
129,03													
121,81		x		x						x		x	
115,00	o		o		x				o		o		x
108,56						x		o					
102,49							o						

Torsionssp. [MPa]	Versuchsnummer														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
129,03					x										
121,81		x		o		x				x					
115,00	o		o				x		o		x				o
108,56								o				x		o	
102,49													o		

Fig. 4. Results of the stair-step tests with [o] indicating a test part without crack and [x] indicating a cracked part. (Left) Results for state of the art test parts. (Right) Results for BrightLine Weld test parts.

The evaluation of the stair-step tests results in the following fatigue strength values for 50% survival probability (= 50% fracture probability):

State of the art: $\tau_{,50\%}$ = (114,5 ± 4,3) MPa

BrightLine Weld: $\tau_{,50\%}$ = (115,8 ± 5,7) MPa

The specified errors are calculated from the standard deviations and thus contain the statistical fluctuations. The torsional fatigue strengths of the state of the art welding method and BrightLine Weld are therefore the same. This means that there is no influence of the three times higher feed rate on the strength of the weld seam [2].

2.2. Metallurgical investigation

In Fig. 5 the etched cross section of one powertrain test parts welded with BrightLine Weld (right) is shown in comparison to state of the art laser welding (left). In both cases the seams form a slim V-shape. With BrightLine Weld both the weld seam and the heat-affected zone (HAZ) are narrower compared to state of the art. The average welding depth for the BrightLine Weld part is given by 3.6 mm. The structural changes in the HAZ are similar for the BrightLine Weld welding process on both sides of the seam: for the fine-grained material rather than the coarser-grained steel, essentially only the former pearlite grains are converted to martensite, the former ferrite grains are not converted or only near the grain boundaries. The higher welding speed of BrightLine Weld results in less time for carbon diffusion and less conversion of the ferrite.

The hardness curves in Fig. 6 are reflecting the information given by the cross section comparison. The hardened zones for the BrightLine Weld process are narrower compared to the state of the art weld without beam shaping. Regarding the actual hardness value of the weld seam, both methods are approximately equal. A hardness of about 450 to 470 HV0.1 is achieved in the welds. In the heat-affected zones, the measured hardness depends on whether the hardness impressions affect ferritic or martensitic grains. Hardening occurs in martensitic grains up to 650 HV0.1. On average, in the BrightLine Weld process, HAZ appears to contain a lower proportion of highly hardened sites, which is related to the higher proportion of residual ferrite grains [2].

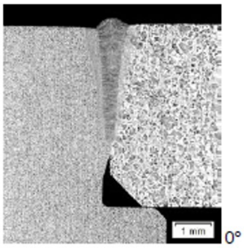


Fig. 5. Comparison of weld seam cross sections. (Left) State of the art test part. (Right) BrightLine Weld test part.

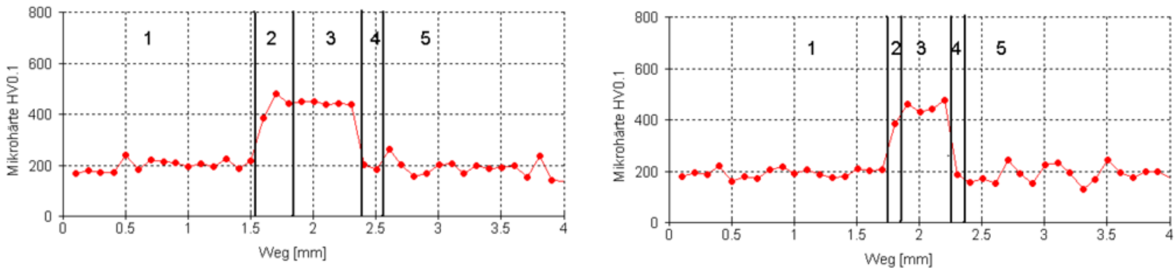


Fig. 6. Hardness curve through the weld seam for state of the art laser welding (left) and BrightLine Weld (right).

3. BrightLine Weld for laser remote fillet welding

For outside components of the car body as e.g. doors or clamps, Aluminum 6000 is the preferred material. It is of low weight and compared to Aluminum 5000 alloys it does not show flow textures. For further reducing the car body weight and with that the fuel consumption and the CO2 emission one is interested in using fillet welds with smaller flange size. However, the silicon components in 6000 alloys can lead to hot cracks, especially for fillet welds with a critical flange size between 2 mm and 6 mm due to thermomechanical stress. As one possible solution, partial penetration welding with beam oscillation can be applied to suppress centerline hot-cracks. But laser beam oscillation is currently limited to feed rates of approximately 4 m/min to 6 m/min [3].

In a new approach, the BrightLine Weld beam shaping technology has been explored for fillet welds of Al 6000 alloys by means of linear high speed welding. Fig. 7 shows the seam surface and the cross section of the linear BrightLine Weld fillet welds at a hot crack-critical flange position of b= 3 mm for three different sheet thicknesses. In all three cases hot crack free weld seams could be achieved. Due to the improved coupling into the material, spatters are reduced and the process can run at higher feed rates. The weld speeds were given by 10 m/min for the 1 mm sheet thickness, 8 m/min for 1.5 mm and 5 m/min for the 2 mm sheet thickness.

For the 1 mm sheet thickness the process window given by angular tolerance, focal position and gap bridging potential has been investigated in more detail. Successful gap bridging up to 0.3 mm has been proven for a high feed rate of 10 m/min. The laser beam needs to be placed with a precision of ±50 µm with respect to the edge and the angular tolerance of the weld tool is ±10°. This has been achieved without parameter adjustment at a power level of 6 kW using a TruDisk in combination with a TRUMPF PFO 3D. For higher speeds, an adaptation of the lateral position of the seam with respect to the fusion zone is required for sufficient gap bridging [4].

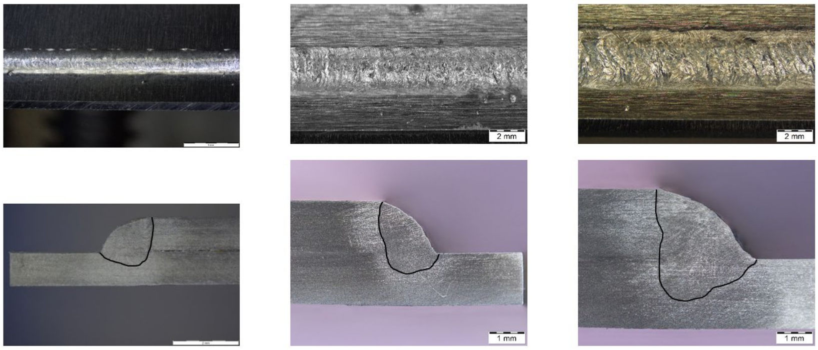


Fig. 7. Weld seam surfaces and cross sections of linear Al 6082 fillet welds made with BrightLine Weld. The flange position is given by b = 3 mm and the sheet thickness is given by 1 mm at v = 10 m/min (left), 1.5 mm at v = 8 m/min (center) and 2 mm at 5 m/min (right).

4. Producing highest weld depths in copper

Copper welding, in contrast to steel welding, typically shows the behavior that the welding process becomes more stable when increasing the feed rate and with that decreasing the weld depth. Reaching high weld depths at lower feed rates is the more demanding application.

In this chapter welding results in copper-ETP with high welding depth performed with BrightLine Weld are presented. Fig. 8 shows the cross section and the seam surface of the weld seam. The welding depth reaches up to 8.4 mm with a seam width of ≈ 1.7 mm at a welding speed of 3 m/min. The laser power was given by 16 kW. The high power density required for high welding depths can be assured by the core-fiber, which is obligatory for copper welding applications as the heat conduction losses are very high in copper. The ring-fiber stabilizes the keyhole and the spatter formation is reduced. Therefore, lower velocities can be achieved when using BrightLine Weld to gain higher welding depths with excellent quality. Compared to single spot technology the welding depth is increased by ≈ 40 %, as the lowest velocity for single spot is v = 6 m/min due to heavy blow out. The quality of the weld seam achieved with BrightLine Weld shows a more harmonic weld seam surface compared to single spot.

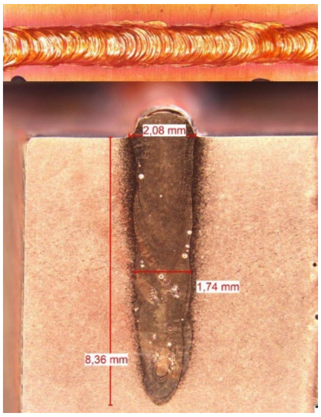


Fig. 8. Welding of copper-ETP at a power level of 16 kW using BrightLine Weld. Seam surface (top) and cross section (bottom) are shown. The welding depth in Cu-ETP reaches up to 8.4 mm with a seam width of ≈ 1.7 mm at a welding speed of 3 m/min.

5. Full penetration welding with BrightLine Weld

The applications shown in the previous chapters were dealing with partial penetration welding. Full penetration welding is an even more challenging application. For optimizing the process, not only the top side of the weld seam has to be investigated regarding weld seam quality and spatter formation but also the bottom side. With a new 2in1 fiber with larger diameters for BrightLine Weld we were now able to influence the keyhole in such way that we can realize a stable welding process on both sides of the weld seam at the same time.

5.1. Full penetration welding of tubes and profiles

Tubes and profiles are typically bent and welded from very long sheets (so-called continuous process) at high feed rates of e.g. 30 m/min. Up to now, the state of the art laser for this application is the CO2-laser. For solid state lasers the challenges to overcome are: full penetration welding at high feed rate with almost no spatters both on the top and the bottom side of the weld seam. Furthermore, welding at that high feed rates can result in notches and humping on the topside and also in undercut and dropping on the bottom side of the weld seam. For visible weld seams, as it is the case for tubes and profiles, this is not acceptable.

With BrightLine Weld we were now able to successfully perform full penetration welding of stainless sheets in a thickness range of 0.5 mm – 4 mm at a feed rate of up to 30 m/min for thin sheets. The process is almost free of spatters on both sides of the weld seam. In Fig. 9 an exemplary welding result of a 2 mm thick stainless steel sheet welded at a high feed rate of 12 m/min is shown. The top side of the weld seam is free of notches and humping while at the same time the bottom side is free of undercut and dropping. With that the weld seams are of highest quality fulfilling the optical requirements for visible weld seams.

Furthermore we were able to transfer these results onto real tube parts, which can be seen in Fig. 10. Here we show the cross section and the seam surface of a full penetration weld seam of a bended stainless steel tube with a thickness of 0.8 mm performed with BrightLine Weld. The weld seam is fulfilling the same quality criteria as the above shown sheet welding results [4].

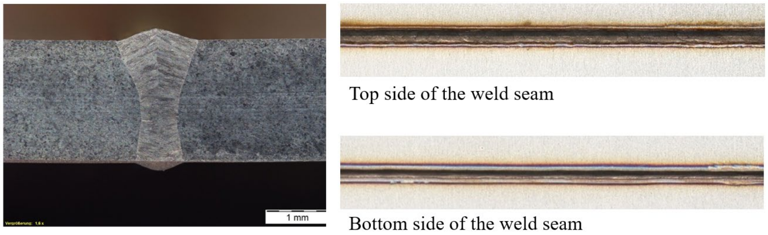


Fig. 9. Cross section (left), top side and bottom side (right) of a full penetration weld of a 2 mm stainless steel sheet performed with BrightLine Weld at a feed rate of 12 m/min.

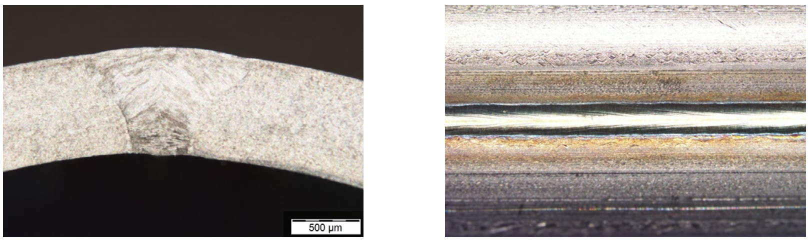


Fig. 10. Cross section (left) and seam surface (right) of a full penetration weld seam of a bended stainless steel tube with a thickness of 0.8 mm performed with BrightLine Weld at v = 10 m/min.

5.2. Full penetration welding of tailored welded blanks (TWB)

Compared to the laser welding process of tubes and profiles, the challenge for tailored welded blanks is the dissimilarity of the two joint partners. Typically, the welding situation is a butt joint with two different sheet thicknesses. Alternatively, the joint partners can have different material properties as e.g. different tensile strengths. Tailored welded blanks are made for car production in high quantities. Therefor high cycle times and high productivities are required. Another key aspect is the quality of the welded joint. The geometry of the weld seam has to fit into defined standard specifications given by parameters like seam width, seam reinforcement and root relapse. In addition notches and undercut should be avoided, the spatter occurrence must be minimized.

With the above mentioned new fiber for BrightLine Weld we were now able to realize these requirements. Important for the welding quality is the adjustment of the welding parameters. The intensity of the laser beam has to fit to the feed rate. In Fig. 11 the result for a feed rate of v = 8 m/min is shown. The sheets have a thickness of 2.6 mm and 1.7 mm. For a stable welding process which is tolerant to external influences a large spot diameter is recommended. The large spot size leads to the need of high laser power. So, it is necessary to use 8.5 kW to achieve the high quality at the feed rate of v = 8 m/min. Hereby, only 40% of the energy are used in the core of the 2in1 fiber to achieve the full penetration. The other 60% of the energy in the ring are necessary to stabilize the keyhole and avoid welding imperfections. Due to an adjusted core-to-ring power ratio a comparable absorption behavior can be achieved for different feed rates. So, operators have the choice to achieve high quality welds by using high laser power and a resulting high productivity or by saving laser power and reducing feed rate.

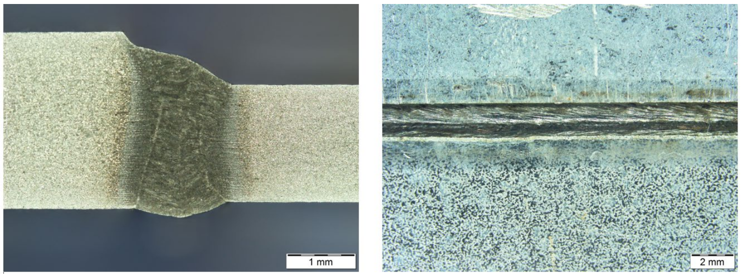


Fig. 11. Welding of TWB (ZStE340 steel with 70 µm Z140MB coating on both sides) with a thickness of 2.6 mm and 1.7 mm at a feed rate of v = 8 m/min. The power share into the inner fiber core was given by 40%. (Left) Cross section of the weld seam. (Right) Seam surface.

6. Summary and outlook

Latest application results on welding with the new TRUMPF beam shaping technology BrightLine Weld have been presented. For powertrain components BrightLine Weld has successfully been applied at high speeds. With respect to fatigue strength and hardness of the weld seam, tests performed show that the high speed welds are comparable to state of the art welds. In Al 6000 fillet welding BrightLine Weld enables linear welding at high speeds without hot cracks. For copper-ETP, it was possible to produce weld seams with highest penetration depth and low feed rate. By using BrightLine Weld for full penetration welding of tubes and profiles and also tailored welded blanks, solid state lasers are now catching up to CO2 lasers regarding spatter suppression and weld seam quality at high weld speeds.

The ability of BrightLine Weld to adjust the power distribution of the laser beam optimally to the specific welding task makes it a promising tool for many laser applications. For the operator however, an additional parameter can also make the setup of a new process more complex. For simplifying the use of BrightLine Weld, the new software BrightLine Weld Professional will be introduced. It contains welding curves for different optical setups and different materials and proposes in a user friendly software interface the optimal power distribution and focal position. With that operators can take advantage of the process benefits enabled by BrightLine Weld without an increased effort for searching process parameters.

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