Joining plastics and metal

Heat conduction joining with the multispot focusing lens

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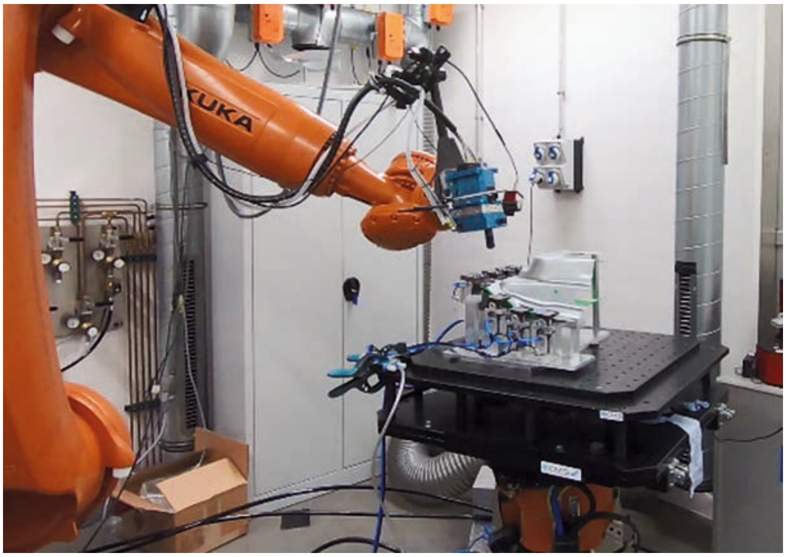


Multispot welding head during operation

A special optical system has been developed for laser material processing that delivers a homogeneous intensity distribution – both in straight lines and in tight curves. The intensity distribution of a wide hat profile can be changed locally and over time by nine parallel beams. The welding head is installed on a robotic arm that travels along the weld, and a temperature homogeneity of more than 90 % can be achieved within the weld spot.

Based on Einstein's principle of stimulated emission, in 1958, Charles Hard Townes succeeded in developing the maser which emitted microwaves, the forerunner of today's laser. Just two years later, Theodore Maiman produced the first laser for which no applications were known at that time. In 1962, the semiconductor laser was invented and found its way into the mass market in the following years due to its small size. The applications of the laser now became more and more diverse and favored its rapid development [1].

Today, industry is dependent on modern lasers. Extremely powerful, ultrashort-pulsed lasers with pulse durations of only a few femtoseconds are used in medical and measurement technology as well as in manufacturing technology and many other industries. However, all lasers have one problem in common, especially with joining techniques such as laser welding: the Gaussian intensity distribution.

A top-hat profile would be more suitable with the temperature distribution within the seam being as constant as possible [2]. In order to solve this problem, diffractive optical elements are often used to shape the spot. They provide an adequate intensity distribution in a straight line, but the problem arises again in narrow curves.

A radius problem

Especially with wide weld seams, there is a large difference in the feed rate on the outside (v_1) and inside (v_2) of a curve with a narrow radius (**Fig. 1**). Since the residence time on the inside is much longer, there is an increased energy input there, which degenerates the thermoplastic within the weld. Conversely, the energy input on the outside is too low, so that the material is not completely melted. As a result, the weld seam becomes unstable on the inside and outside and may only be loaded in the center. For materials that are easy to join, the weld is made as narrow as possible so that the difference in speed is minimal and the stable core area covers most of the width.

A large joining area is indispensable for stability when joining very different materials such as plastics and metals. Homogeneous temperature distribution is therefore very important for the resulting large seam width and the necessarily large spot diameter, even in curves.

Joins with wide weld seams

In the automotive industry, metal body parts often have to be joined with plastic interior components. The properties of the two materials are extremely different making it difficult to weld them. Since most plastics burn at temperatures far below the melting point of metals, uniform melting of the two elements is nearly impossible. The technique of heat conduction joining is an option in such cases whereby the metal part is structured by another laser process beforehand. The thermoplastic item and the metal part are then compressed and the metal is warmed up by the joining laser. Heat conduction leads to a rising temperature of the melting plastic. The liquid thermoplastic part is now able to fill the structure of the metal part, which provides the connection. It is possible to adjust the temperature of the thermoplastic part by changing the pressure between the two elements being joined (**Fig. 1**) [3].

A special welding device was developed to enable a homogeneous temperature even at different feed rates within a narrow curve. The device consists of a three-by-three matrix of small lenses. Every individual focusing lens receives its own input beam from an optical fiber and its own laser diode. The laser power from the different optical fibers can be adjusted individually so that the power at the nine different focal points can be changed. There are now nine spots arranged in a grid in the focal plane (**Fig. 2a**).

However, if a slight lateral offset is used, the Gaussian profiles of the individual spots become wider and overlap at the edges. This results in a square, extended top-hat profile which is quite homogeneous in itself (**Fig. 2b**). Straight welds are no problem any longer even if all lenses receive the same input power due to the resulting wide top-hat profile. In a curve, the track speed of the inner rays is smaller than of the outer rays. The energy difference due to the speed difference can be compensated by the adjusted power control of the individual channels [4].

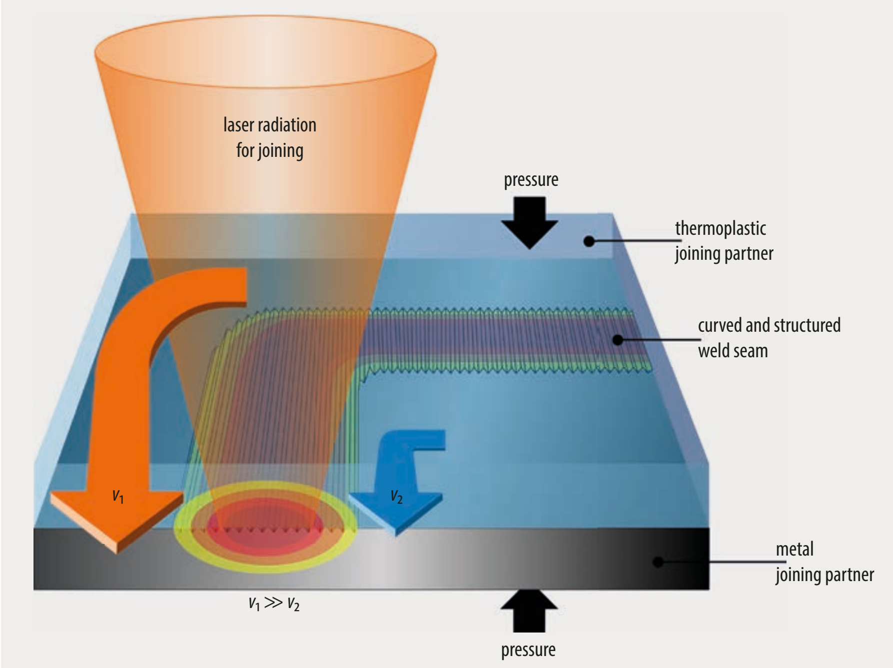


Fig. 1 Heat conduction joining in a curve allows plastic and metal to be melted together.

A diode laser with nine separately controllable laser diodes enables the intensity of the top-hat profile to be adjusted in the working plane. Optical fibers connect the laser and the lenses. The laser beams are focused by the small, adjacent lenses. An exchangeable protective window in front of the lenses keeps dust and dirt particles away and prevents the damage of the lens.

There are nine spots arranged in a grid at the focal plane. If the working plane is moved backwards about 100 mm along the *z*-axis, the laser beams overlap and form a uniform top-hat profile. The entire equipment is installed on a robotic arm that traverses the weld seam. Therefore, no scanner is necessary, which highly simplifies the optics. A clean top-hat profile only needs to be achieved at one point in the working plane rather than at a flat scan field because the input beams are not deviated. There is no need to worry about any scanner mirrors with external back reflections. Lenses to collimate the input beams are not necessary. The fiber end is focused directly through the individual lenses. Because of the offset between the working and the focal plane, diffraction-limited imaging is not necessary since small focal points are not important here.

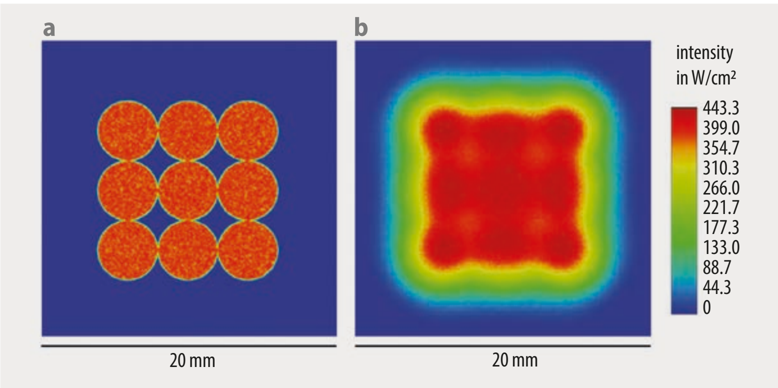


Fig. 2 Spot shape at the focal plane (a) and at the working plane (b), where the spots overlap.

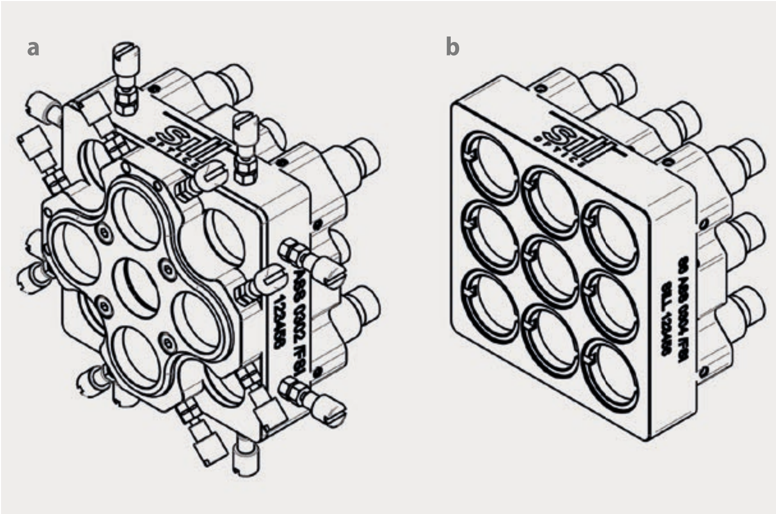


Fig. 3 A multispot lens is available with (a) and without (b) possible adjustment of the *x*-*y*-position.

Special features of the optics

During development, special attention was paid to thermal focus shift caused by the individual lens elements in an objective being heated by high laser power. This results in material expansion of the lenses proportional to the glass thickness at the corresponding position. For a biconvex lens for example, the material thickness at the center is significantly greater than at the edge, which reduces the lens radius with increasing temperature.

The focal plane of the entire lens shifts and the imaging quality decreases.

In addition, the refractive index of many simple optical glasses is strongly temperature dependent amplifying the thermal focus shift. The higher the input power, the more the individual lens elements are heated and the more intense the effect of the thermal focus shift.

If the nine lenses in the setup are exposed to different input powers, the thermal focus shift affects the lenses differently. So the individual focus positions shift and are no longer on a flat working plane. Therefore it is very important to minimize the thermal focus shift of all lenses.

Fused silica is a highly transmissive material whose refractive index has only a small temperature dependence. The material is ideal for avoiding thermal focus shift and was chosen for the lenses of the welding head. The lenses were also equipped with a high-quality coating that ensures very low loss of light at transfer from air into fused silica and from fused silica into air.

This reduces the reflection loss of about 4 % per area to values below 0.5 % per area at the corresponding wavelength. More importantly, the absorption in the coating is in the single-digit ppm range. The lower the reflected and absorbed amount of light, the lower the heating of the lenses. A cooled lens tube additionally ensures a homogeneous climate at the lenses and further reduces thermal focus shifting.

It is important to avoid any vignetting at the lens mount. Laser radiation is particularly well absorbed by the metal mount which would heat up the mount and thus the included lenses. This can be avoided using lenses whose free diameter is larger than the beam diameter at the lens. The proportion of the light reflected at the lens surfaces is minimized by the coating.

Due to this design, a minimum amount of the laser power remains in the lenses and keeps the lens temperature at a very low level. The cooled lens housing further reduces the lens temperature. The hardly noticeable radius changes and a temperature stable refractive index of the material result in a minimum thermal focus shift that affects neither the imaging quality nor the quality of the weld.

A ghost image is the back reflection from an optical surface that is focused by other lenses in front of or inside the lens. These back reflections should be avoided in optical design as they can cause heating and thermal focus shift or, in the worst case, damage. A ghost analysis was therefore performed on the multispot lens where the positions of all ghost images were checked and shifted to non-critical areas.

Features of the mechanics

The quite small individual lenses that have to be mounted in a small space to create a homogeneous top-hat profile in the working plane require complex mechanics. The diameter of the lenses constitutes only 13 mm. To compensate for manufacturing tolerances, the *x*-*y*-position of each focusing lens can be adjusted individually by moving it across the optical axis and fixing it with a set screw. The lengths of the mounts differ from each other in order to be able to reach each setting screw (**Fig. 3a**).

Although very good imaging quality can be achieved, this flexible design resulted in very high adjustment and manufacturing costs. Therefore, a successor model was designed in which all lenses are fixed (**Fig. 3b**). The imaging quality is still acceptable – with more than 90 % homogeneity in the top-hat profile. The successor model proves to be more suitable for industrial use due to the significantly lower adjustment work.

Furthermore, the lens must be stable against vibrations, since the mount is attached to a moving robot arm. A vibration test has shown that the imaging quality is not visibly affected by vibrations if the mechanics are simple and robustly designed.

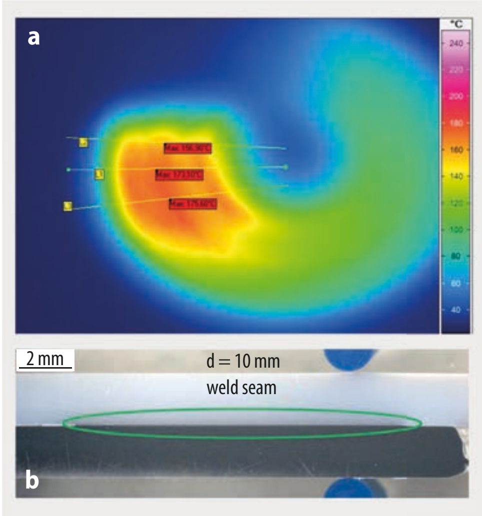
A series of test runs checked the welds and confirmed the functionality of the welding head. Firstly, the front and back of a servo oil reservoir were welded as an example of joints between plastics. Secondly, the interior fittings and the body of a car door were joined as an example of connections of plastic and metal (**Fig. 4a**). The weld seam is heated uniformly on both the inside and the outside. The temperature deviates within the spot less than 10 %. A cross-section checked the quality of the weld seam by heat conduction joining. The upper material is the transparent part while the lower material absorbs the laser radiation. No air-filled cavities or other effects are visible in the area of the weld (**Fig. 4b**), indicating a high weld quality [4].

Finally, a crushing test shows the high stress resistance of the weld. A shear tensile strength of more than 25 MPa was achieved for joints of plastic with plastic. The pleasing result for welds of plastic to metal was 15 MPa.

Conclusion

There is a need to be able to change beam characteristics during a welding process. The nLight company has developed its 'corona' fiber laser, which can change the beam characteristics during the process to change the spot shape [5]. However, the laser can only switch between a few different beam characteristics, which is certainly sufficient for many applications, whereas the welding device described in this article is continuously tunable. The wide top-hat profile, the high temperature homogeneity within the weld, the good imaging quality, and the adjustability of the intensity within the spot recommend the welding head for difficult laser joining tasks. Wide weld seams in heat conduction joining and tight curve radii are no longer challenging. Highly transmissive glasses and lens coatings ensure a stable process even for longer periods of operation. In addition, the lenses are resistant to vibration and can be installed on a moving system such as a robot arm. Various evaluations with non-destructive and destructive tests have proven the high quality of the weld seams.

Thanks to the multispot welding head, complicated weld seams are now feasible in heat conduction joining of plastics and metals. Such manufacturing techniques are of enormous importance to the automotive and aerospace industries and other markets. The prototype is very promising and will soon be ready for series production.



from [4]

Fig. 4 A thermal camera (a) proves the optimized energy input at a curve radius of 10 mm. The cross-section of the weld (b) shows its quality.

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[2] *B. O'Dea* et al., Proc. SPIE **11107**, Laser Beam Shaping XIX, 111070J
[3] *H. Potente* et al., Welding in the World **53**, R246 (2009)
[4] *V. Wippo* et al., Proc. of the 39th International Congress on Applications of Lasers and Electro-Optics ICALEO 2 (2020)
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