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Reduction of spatters and pores in laser welding of copper hairpins using two superimposed laser beams

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Abstract

Hairpin technology is a new degree of freedom in the manufacturing of eDrives for the automotive section of eMobility to increase the efficiency of the powertrain. Experimental investigations in laser welding of copper hairpins show that the specific beam profile of two superimposed laser beams, using a so called “2in1-fiber” (BrightLine Weld), stabilizes the keyhole and therefore reduces spatters and pores. High-speed videos of the process were used to quantify spatters. The generation of pores during the welding was investigated via online xRay-imaging. The observation shows that the opening of the keyhole is widened, if two superimposed laser beams are used. As a result, the shape of the keyhole is stabilized over time. In addition, the shape of the keyhole enables unrestrained degassing of vaporized material. The latter restricts bulging of the keyhole and therefore reduces the formation of spatters and pores during the hairpin welding process close to zero.

Keywords: laser welding; copper; hairpins; electric motor; eMobility; eDrive; powertrain; spatters; pores; xRay

1. Introduction

The electrification of the automotive powertrain requires new solutions for welding of copper-based material. A future trend in the manufacturing of electric motors is clearly based on wires with rectangular profile, so-called hairpins, Fleischer et al., 2017. These hairpins enable a closer arrangement of the wires in the stator in comparison to conventional coil winding technology, where usually wires with a circular profile are used. High efficiency of the drive is the result. In addition, the manufacturing of hairpin-based motors has a high potential for automation. The challenge of the fully automated manufacturing of the new type of electric motors, however, is the joining of the front end of each pair of hairpins, which is a new process step that has not been necessary in the conventional winding technology so far, Glaessel et al., 2017. Due to its flexibility, high degree of automation and productivity the laser is just the right tool to face this challenge.

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In Fig.1 and Fig.2 samples of welded pairs of hairpins are shown. The front sides are joined by generating a molten pearl of copper which results in a high width of connection. The geometry of the molten pearl achieves high electrical conductivity. In addition, the shape of the molten pearl can be used for quality assurance via camera-based sensors, Mayr et al., 2018.

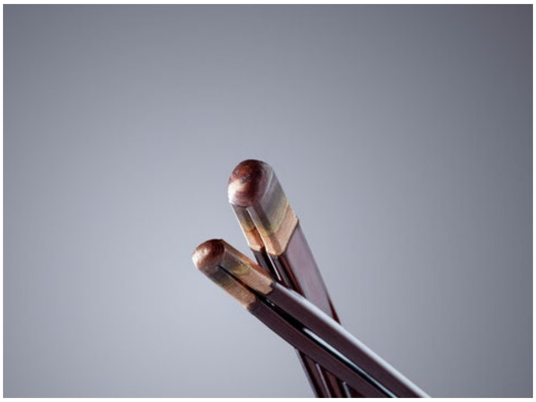

Fig. 1. Samples of different types of hairpins. The front ends are laser welded [TRUMPF].

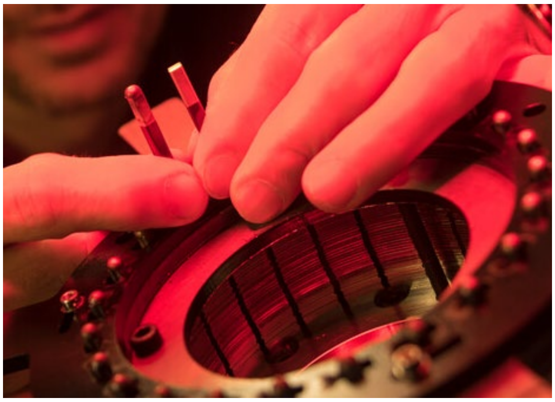

Fig. 2. Samples of hairpins from a stator. One pair of hairpins is not welded, the other is. Both samples show an unstripped area of which the coating has been removed via laser [TRUMPF].

2. Failure modes of copper welding

Laser welding of copper material is a great challenge due to its specific physical properties, such as the high heat conductivity and low absorptance for near infrared laser sources at a wavelength of roughly 1 µm. Mainly two types of failures are described in Heider et al., 2011, that mainly contribute to low acceptance of laser welding of copper in electric industries: first, spatters and blowouts from the process zone contaminate surrounding components and might generate holes in the weld seam. Spatters during the hairpin welding process can be seen in Fig.3. Second, pores inside the solidified material increase the porosity of the material and decrease the mechanical strength of the weld seam. An example of pores inside a weld pearl of a hairpin sample is shown in the section in Fig. 4.

In Heider et al., 2013 it is demonstrated via xRay analysis that pores are generated in the laser welding process of sheet material of copper from keyhole dynamics. Thereby, vapor is separated from the keyhole mostly near the bottom side and stays as a pore in the solidified material. These kinds of pores are in the following called process pores. Process pores reach a size, roughly described by a spherical shape, with a diameter of up to 1 mm or even higher.

It is also shown in Heider et al., 2013, that the high dynamic of the keyhole fluctuations generates spatters, which are separated from the melt pool at the back end of the keyhole. If vapor from the inside of the keyhole cannot escape from the keyhole opening in a sufficient manner, the keyhole starts to bulge. If the bulging carries forward to the top side of the material, the molten surface is opened in sudden bursts of which spatters are blown away.

It could be shown in Heider et al., 2014, that the process can be stabilized with very high laser power up to P = 16 kW and very high welding speeds of v ≥ 4 m/min. However, this method requires high invest in the laser source and system technology. Therefore, it is mostly applied in the area of welding thick sheets of copper with a thickness of t > 5 mm, such as busbars for power electronics, where the high laser power is without alternative.

Another promising approach to reduce spatters and pores is welding copper with a green laser source. The green laser with a wavelength of λ = 515 nm has a high absorptance in copper of A = 35%-40%, which enables a controlled penetration in the material with very smooth surfaces and reduced spatters, Alter et al., 2018. It is well suited in the battery manufacturing and welding of electronic components. However, nowadays commercially available laser sources are limited to a (cw-) laser power of P = 1 kW. Future developments up to higher laser power in the multi-kW of green laser power and high brilliance will provide a tool with high potential for a wide range of copper application. Until then, welding of copper hairpins will be a preferred domain of high power NIR-laser with multiple kW due to the high volume of molten material and short process times required.

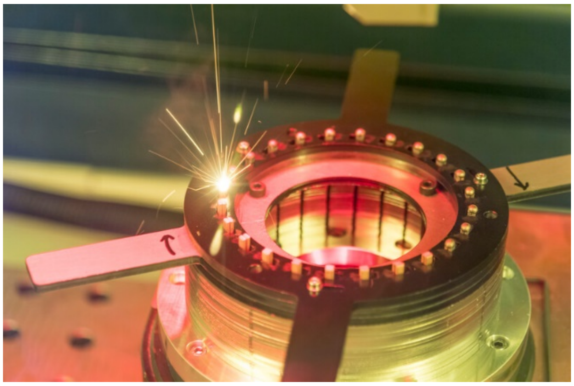

Fig. 3. Standard laser welding of hairpins with spatters from the process on a demonstrator of a stator [TRUMPF].

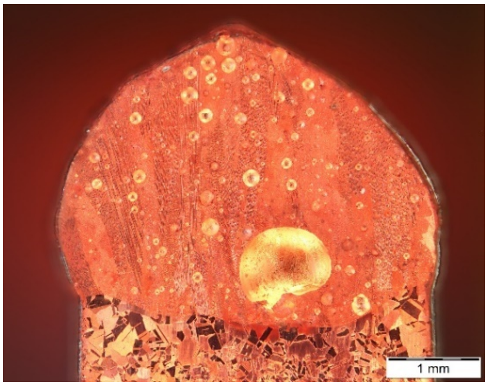

Fig. 4. Cross section of a welded pair of hairpins contains pores of different sizes.

This study shows the newest results of hairpin welding trials with a new method to superimpose two laser beams of a multi-kW NIR-laser source to shape the intensity profile. The technology to achieve these superimposed beams is known as BrightLine Weld (BLW) and has already been published in Speker et al., 2018. The reduction of spatters and pores achieved with this method is presented in the following.

3. Experimental setup

The experimental setup for welding is shown in Fig.5. A so called 2in1-fiber is used that consists of an outer part, which has a ring profile, and an inner part, which consists of a single core fiber. If the term “superimposed laser beams” is used, the laser is directed in both, the ring and the core fiber. The term “single spot” in return describes the guiding of the laser only by the core fiber. The ratio of laser power of the ring and the core can be adapted by laser control of the TruDisk 6001 laser device that includes the technology BrightLine Weld. This technology consists among other features of the specific 2in1-fiber and the modified laser control unit.

The samples are some kind of a hairpin dummy, which consists of a copper workpiece cut from a copper sheet with a thickness of t = 4 mm. The profile area of the hairpin dummy is therefore 4mm x 4mm which is realistic copy of a real hairpin geometry. These dummies are used to guarantee equal experimental conditions in terms of gaps and surfaces, as well as the geometry of the edges.

The laser beam is oscillated with a scanner optics (TRUMPF PFO33-2) over the workpiece with the oscillation geometry of a circle described by a radius of r = 1 mm. The high-speed camera was positioned sideways with a tilt of 7° in order to record the process and to visualize spatters from the process. The xRay images of the process, as well as the xRay images after the welding have been taken perpendicular to the pin in x-direction.

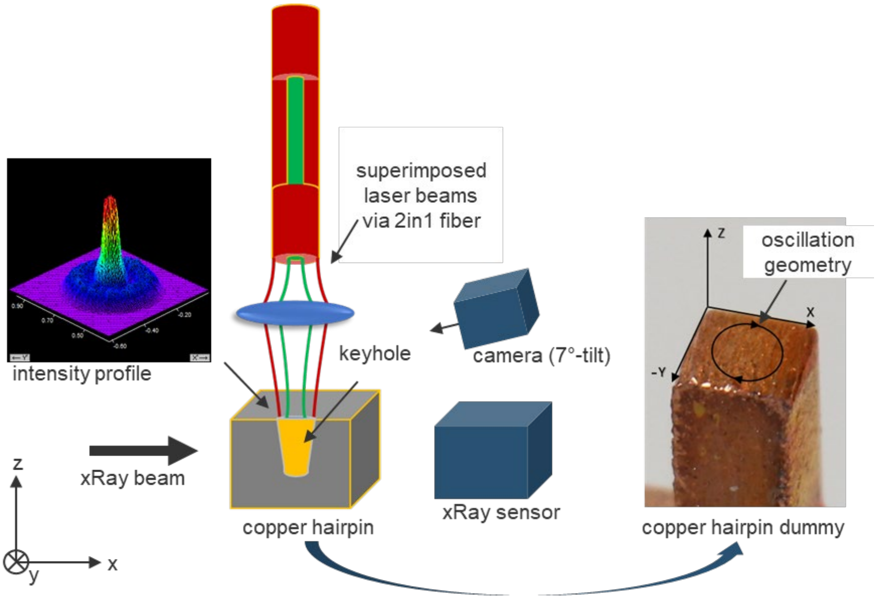

Fig. 5. Scheme of the experimental setup.

The process parameters can be found in Table 1. The laser power varies in dependency of the chosen ratio of the power between the core and the ring of the 2in1-fiber, while the process time of each hairpin has been kept constant.

Table 1. Experimental setup and process parameters

Parameter	Value
Laser	TruDisk 6001
Optics	PFO33-2
Focal length	255 mm
2in1 fiber diameter core / ring	100 µm / 400 µm
Magnification	1.7: 1
Laser power P	2 kW - 6 kW
Focal position	On the surface of the hairpin
Welding speed	200 mm/s (= 12 m/min)
Welding time per hairpin	380 ms
Scanning geometry	Circle (r = 1 mm)
Profile of hairpin dummy	4 mm x 4 mm

4. Results

The reduction of spatters (4.1) while welding hairpins with single spot in comparison with two superimposed laser beams is detected with a high-speed camera and a record frequency of f = 10 kHz. The images of one video of the welding process of each hairpin has been superimposed. In order to localize the spatters over the whole welding process of the hairpin, the gray values of each pixel were compared over the video sequence and the maximum value was adopted for the given pixel.

The reduction of pores (4.2) while welding with superimposed laser beams have been detected with a xRay tool from the Institut für Strahlwerkzeuge (IFSW), of which a detailed description can be found in Boley et al., 2013. To achieve a higher resolution of the xRay images and to detect most pores, the welded hairpins have been x-rayed after the welding process a second time.

4.1. Reduction of spatters

In Fig.6-a)-I) a welding process with a single spot and 100 % of laser power in the core fiber is shown (all other parameters, see Table 1). Each of the white lines represent one spatter that is expelled from the welding process. The number of spatters is given below the images in Fig.6 and have been counted with the Image J – Fiji, 2019. The corresponding weld result is shown in Fig.6-a)-II). The spatters are count as spherical particles. Spatters with a diameter of d < 0.15 mm are called micro spatters, while spatters with d > 0.15 mm are called macro spatters.

In Fig.6-b)-I) it can clearly be seen that the welding process with two superimposed laser beams (BrightLine Weld) tends to less spatters and can even be reduced close to zero. Here, only 50 % of the laser power is directed into the core, while the rest of the laser power is provided by the ring fiber. However, more vapor is visible during the welding, of which no negative influence could be recorded. The weld result looks pretty much the same from the outside in comparison to single spot welding, as it is shown in Fig.6-b)-II).

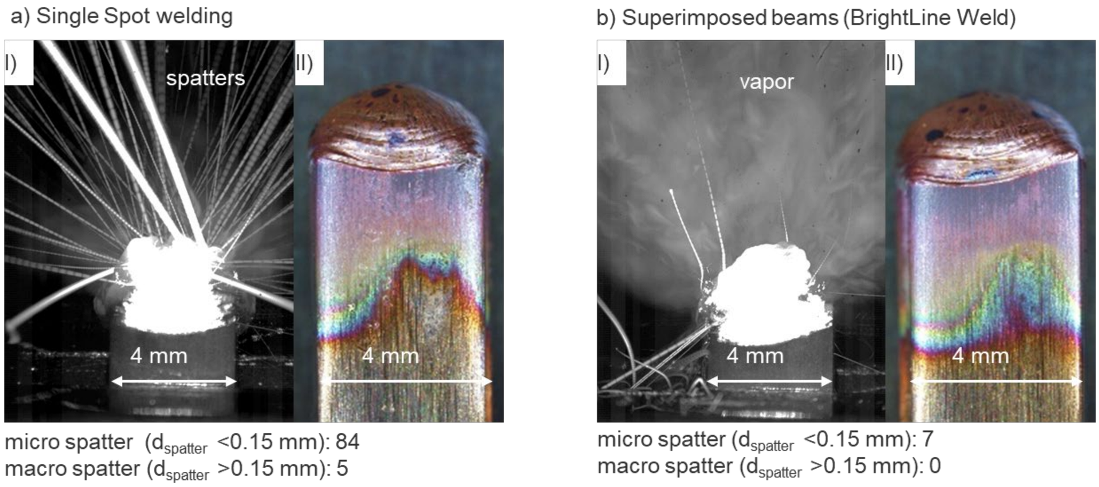

Fig. 6. Comparison of spatters from a hairpin welding process with a single spot, laser power P = 2 kW (a) and a welding process with two superimposed laser beams, laser power P = 4 kW (b). Beside both pictures of the process (I), the welding results are shown (II). All other parameters see Table 1.

4.2. Reduction of pores

The welded hairpins have been analyzed after the welding with 2D-x-ray imaging. Fig.7-a), images 1) to 5) show the results with single spot welding and five repetitions (parameter, see Table 1). The images with repeated parameters show the fluctuation of pores in size and number between the different hairpins, although the experimental conditions have been kept constant over the number of samples.

In comparison to that, in Fig.7-b), images 1) to 5) show hairpins all welded with the same parameter setup and two superimposed laser beams (BrightLine Weld). It is clearly visible, that the qunatity and size of the pores are reduced significantly in comparison to single spot welding. However, the pores are not avoided completely.

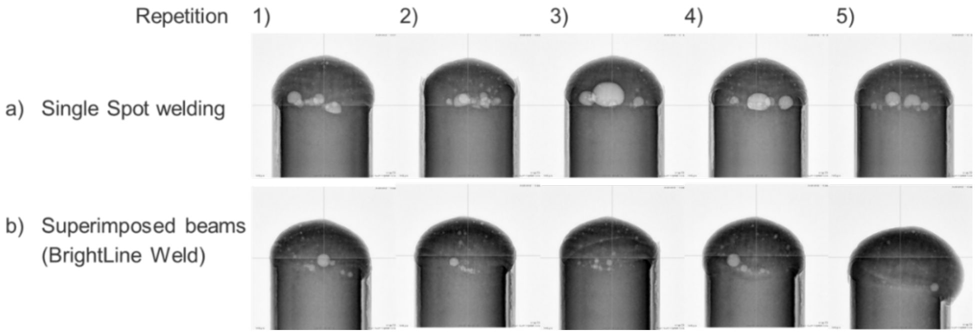

Fig. 7. xRay images of the welded hairpins to compare pores inside hairpins after a welding process with a single spot, laser power P = 2 kW (line a)1-5)) and after a welding process with two superimposed laser beams, laser power P = 4 kW (b)1)-5)). All other parameters see Table 1. From both welding setups five hairpins with repeated welding parameters each are shown.

4.3. Stabilization of the keyhole

In order to understand the mechanism behind the benefits of superimposed laser beams (BrightLine Weld) in terms of reduction of spatters and pores, the hairpins have additionally been x-rayed while welding. In Fig.8, a)-d) the keyhole can be seen after one out of twelve rotations of the beam oscillation. The red line shows roughly the shape of the keyhole. It can be seen, that for single spot welding (Fig.8, a)) and 100 % of the laser power in the core, the keyhole has penetrated the material deeply and in return is quite narrow. The width of the keyhole increases with less power in the core and more power in the ring, especially near the top side of the pin. Therefore, the keyhole opening on the top side increases, which is clearly visible in Fig.8, d).

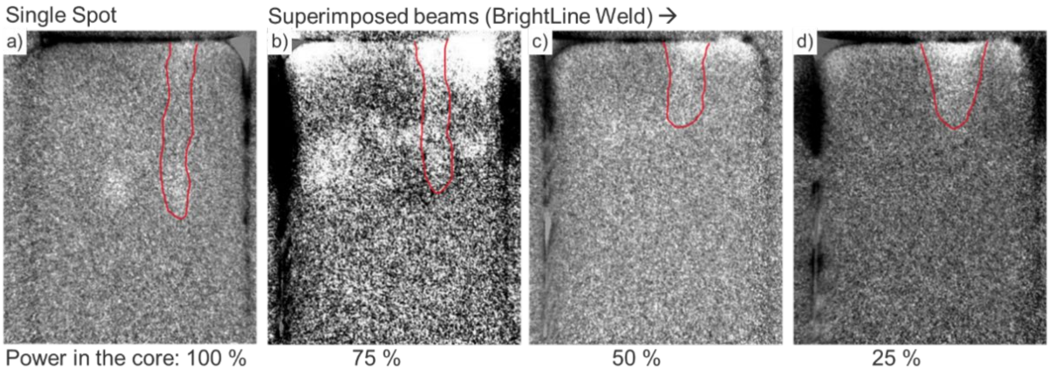

Fig. 8. Online xRay images of the hairpin welding process to visualize the geometry of the keyhole. The ratio of the laser power between the laser from the core and from the ring varies from 100 % in the core (Singel Spot) to 75 %, 50 % and 25 % (BrightLine Weld). All other parameters see Table 1.

It is shown that the superimposed beams generate a more conical keyhole shape. It is guessed, that this specific keyhole geometry stabilizes the degassing of vaporized material. In contrast, a longer and narrow keyhole at single spot welding tends to be bulging or collapsing and prohibits the vapor from flowing out of the keyhole. It is assumed, that the effective degassing of the conical keyhole, which was generated from superimposed beams, is responsible for the reduction of spatters and pores.

5. Conclusion

The presented experiments of hairpin welding show a significant reduction of spatters and pores while using two superimposed laser beams (BrightLine Weld) in comparison to single spot welding. X-ray images of the welding process suggest the keyhole to be opened with the use of superimposed beams and be therefore stabilized over time. The conical keyhole enables a better degassing and therefore prohibits bulging of the keyhole, which could be responsible for the reduction of pores. In addition, the spatters are reduced close to zero. However, the laser power has to be increased, if superimposed laser beams are used.

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References

Fleischer, J., Haag, S., Hofmann, J., 2017. Quo Vadis Winding Technology? A study on the state of the art and research on future trends in automotive engineering. Retrieved from https://www.wbk.kit.edu/downloads/2017_02_21_Studie_Wickeltechnik_final_EN.pdf

Glaessel, T., Seefried, J., Franke, J., 2017. Challenges in the manufacturing of hairpin windings and application opportunities of infrared lasers for the contacting process, 7th Int. Elect. Drives Prod. Conf. (EDPC), pp. 1-7

Mayr, A. et al., 2018. Evaluation of Machine Learning for Quality Monitoring of Laser Welding Using the Example of the Contacting of Hairpin Windings, 8 th Int. Electric Drives Prod. Conf. (EDPC) , pp. 1-7

Heider, A., Stritt, P., Hess, A., Weber, R., Graf, T., 2011. Process Stabilization at welding Copper by Laser Power Modulation. In Proceedings of Lasers in Manufacturing (LIM), Physics Procedia 12, 81–87

Heider, A., Sollinger, J., Abt, F., Boley, M., Weber, R., Graf, T., 2013. High-speed X-Ray analysis of spatter formation in laser welding of copper, Phys. Procedia 41, 112–118. https://doi.org/10.1016/j.phpro.2013.03.058

Heider, A., Stritt, P., Weber,R., Graf, T., 2014. High-power laser sources enable high-quality laser welding of copper. In: Proceedings of ICALEO, Paper 401

Alter, L., Heider, A., Bergmann, J.-P., 2018. Investigations on copper welding using a frequency-doubled disk laser and high welding speeds. Procedia CIRP 74, pages 12–16

Speker, N., Haug, P., Feuchtenbeiner, S., Hesse, T., Havrilla, D., 2018. BrightLine weld-spatter reduced high speed welding with disk lasers. Proc. SPIE 10525, 105250C

Boley, M, Abt, F., Weber, R., Graf, T., 2013. X-ray and optical videography for 3D measurement of capillary and melt pool geometry in laser welding. Phys Proc 41, pp. 481-488, 10.1016/j.phpro.2013.03.105

Image J – Fiji, 2019. TrackMate. Retrieved from https://imagej.net/TrackMate