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System design for reliable and robust laser-welding of copper in automotive series production

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Abstract

The evolution of mobility away from ICEs towards electric or electrified drives also created some new challenges for the series production of drive train components. With copper, a new material moves into focus in the drive train which needs to be welded. No matter if e-motors, e-boxes or batteries, copper needs to be welded and the laser fits best for the requests in most cases. The presentation will focus on what has to be considered for welding copper and to face these issues with an intelligent system-design to fit series production needs. Beside the design of the welding system with high-speed scanners and arrangement of the necessary components, the presentation will also focus on the matter of detecting the welding areas correctly to create a robust process that reduces costs and can cope with series production conditions.

Keywords: E-Mobility, laser welding of copper, pattern recognition, robust system design, process know-how;

1. Joining copper with near infrared laser

Since the “revolution in mobility” started and the numbers of electric vehicles (EVs) produced by the OEMs increased significantly, copper as new material moved into focus. As due to its electric characteristics the material is found in almost every part of the new drive train. The focus on lower prices retail, prices of the vehicles and increased production numbers causes the demand of reduced costs and raised efficiency in the production lines. This leads to the laser as joining tool - as well know from the body-shop in series production- it is fast and precise which reduces cycle times and costs and it can be used in highly automated production lines which is hitting the efficiency target. Therefore, the laser is the tool of choice of joining most of the copper in electric engines, electronics, batteries, etc.

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1.1. Characteristics of the material

Copper is unique material regarding laser welding. The characteristic of this material is significantly different compared to the characteristics of the usually used materials such as steel or aluminum.

The first difference is the absorption of infrared laser beam. It´s just around 5% by solid state copper.

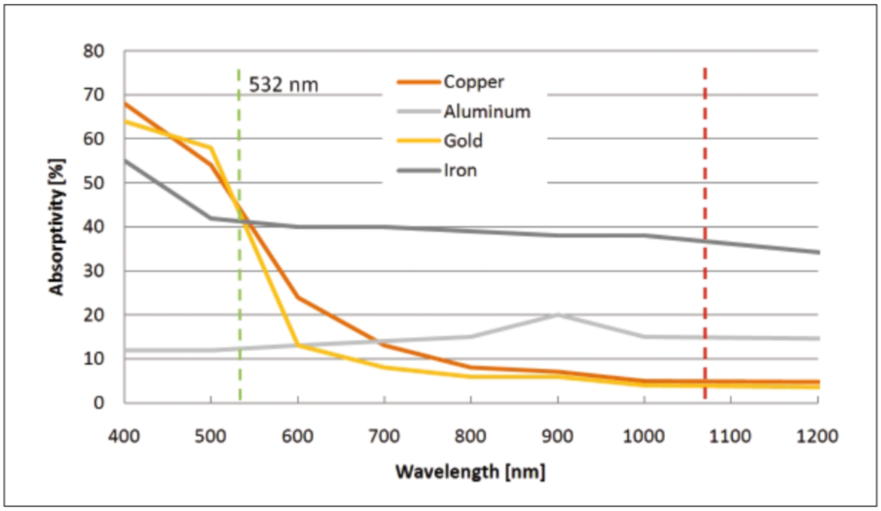

Fig. 1. Absorption of different light wavelength by copper (Source: Christoph Deininger, 2011. *“Copper machining with lasers”)*

But once the state of the material changes from solid to liquid and the keyhole is built up, the absorption of the laser beam increases immediately. Compared to steel there is no semi-solid, semi-liquid status during the welding process of this material, it exists only in either solid or liquid state. This leads to the next challenge regarding laser welding: the start of the deep welding process. The immediate switch from solid to liquid state of the material and the increasement of absorption causes a very turbulence melting pool with a very instable keyhole which causes a significant amount of spatter.

Additionally, the welding speed is a very important factor regarding smooth and spatter-free process of the cooper material. According to the research work of the IFSW of the University of Stuttgart in the DVS “HighSpeed” program welding speeds under 20m/min cause a turbulent melting pool and an instable keyhole which causes spatter and even blow-outs.

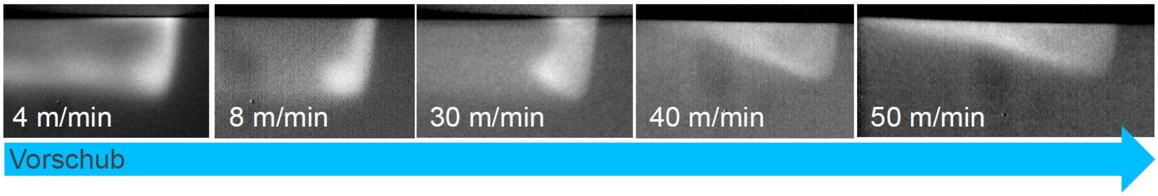

Fig. 2. Key-hole geometry in relation to the welding speed (Source: IFSW University of Stuttgart, DVS HighSpeed)

In addition to the behavior of copper during depth welding it also has to be considered that the viscosity of the melt compared to steel or aluminum is higher and therefore fast movements in the melting pool with the laser may churn it up which will cause spill over and spatter.

1.2. Current state of the art solutions

Currently the trend in the industry for copper joining are laser optics with scanners. The reason for using scanner optics is that a movement of the optic or the part will affect the cycle time negatively. Therefore, current state of the art is to use a scanning field which is as big as possible to avoid or at least reduce movements to a minimum. The common solution there is to use big objectives with an f-theta lens. This reduces the angle of irradiation of the laser beam at the part and makes a big scanning field possible.

Currently for depth welding applications the near infrared laser is still the technology of choice. But especially in micro-electronics applications or applications with a small welding depth as well as for heat conduction welding laser sources with green wavelength are more and more common. The advantage of the green wavelength is the better absorption of the laser light by solid state copper which results in a very stable and defined start of the weld.

To detect the welding point (like e.g. hair pin pairs) a pattern recognition is used. It´s based on a camera system and a software that interprets pictures and positions the scanners in the right way. Furthermore there are also concepts on the market which are using patented clamping devices, which – according to the manufacturers – are able to clamp the parts on a defined spot so that the scanner in the optic just has to do the welding strategy on defined coordinates.

2. Approach by Scansonic

The approach of Scansonic for a laser optic for welding copper differs from the current technologies on the market, but it also contains the technologies that are proven for welding copper. The optic named RLW-S (**R**emote **L**aser **W**elding – **S**hape recognition) is basically a scanner optic with a pattern recognition system. But the single elements as well as the software for the detection of the welding point was specifically designed for welding the different copper applications.

2.1. System hardware

First of all, the optic can be used with ever common disk or fiber laser source. Only an analog input at the laser source is need as it is controlled via the optic HMI.

The concept is a so-called post objective scanning optic which makes focus shifts and also the pattern recognition easier to handle and more predictable. As the camera for the pattern recognition looks over the same mirrors as the laser beam is directed the position detection in relationship to the TCP is completely drift free. As the sensor (e.g. for height detection) use the same way as the laser beam, the spot and the sensor point are in exact overlay.

The scanners itself are a construction done by Scansonic which was focused on high dynamic to match the high welding speeds copper requires. The possible scan-frequency of up to 1.000 Hz with a 46mm aperture make the used scanners the most dynamic on the market. This means contours which require a very high re-orientation speed can be done whit a constant energy input.

The system itself has a scanning field of 38x56mm which is smaller than the F-Theta solutions on the market, but big enough to see four slots at a stator of a common traction e-motor with three or for hairpin-pair rows. The smaller scanning-filed fits perfect in the Scansonic SCAPACS® kit which makes changes at the optic very easy as just single modules of the optic have to be changed. It uses a 2” protection glass which is secured by a small cross-jet.

For the illumination the choice was made to use a VCSEL-system with a total of up to eight benches with 3 VCSELs each. Also, the system was designed to be adjustable in illumination angle and position to be as good adaptable as the applications demands. A common LED-bench or an LED-ring are also available.

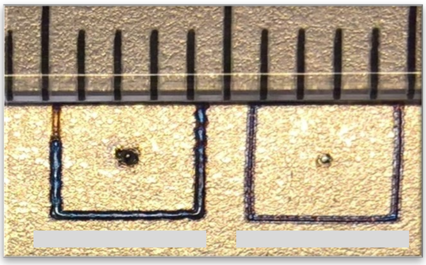

Fig. 3. Dynamics-test for used scanners

2.2. Pattern recognition

For the pattern recognition the camera uses a grey scale picture in full HD resolution. This means due to the small field of view of the camera and the high-resolution pictures the images taken for the pattern recognition are more detail and allow these fine adjustments.

By using a normal objective instead of an f-theta lens all the problems by optically distortion especially in the outer areas of the scanning field don’t have to be considered. With the illumination changed from LED to VCSEL the target was to put as much light as possible in the right spot to be as efficient as possible. To keep the detection of the pins efficient and simple the choice was made to use a simple grey-scale pattern recognition. This means the software is just looking for the pixels in the exact greyscale as the trained pattern. On the one hand this makes it easier and faster to process the taken picture through the software on the other hand it makes the whole system much more flexible for other applications, as the software is not looking for specific contours. Additionally, the recognition algorithm can be extended by a correlation algorithm which is also having a look on the position of the pixels to each other. Furthermore, also a contour algorithm can be added. This software extension is looking for a specific drop of the greyscale in pixels beside each other to find e.g. edges.

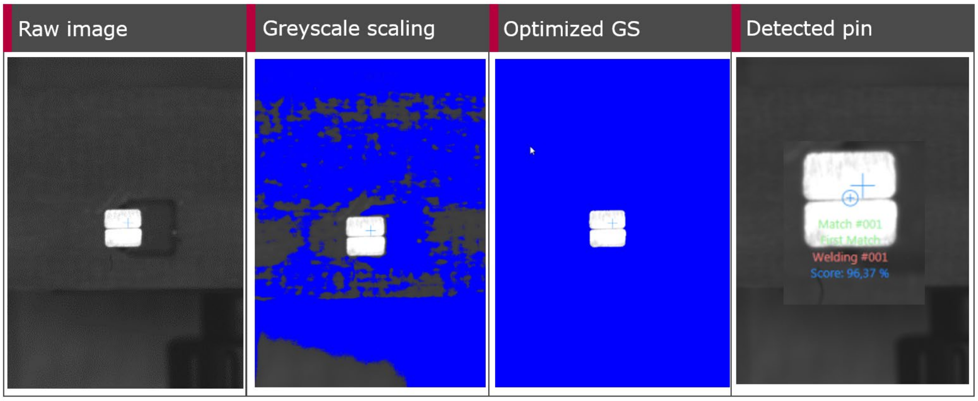

Fig. 4. Pattern recognition process

For sure the software and the used camera are important, but it always have to be kept in mind that the best camera-based pattern recognition is only as good as the illumination. So, a lot of effort was focused on making the illumination as flexible. The on the market common solution is to use a bench or ring mounted above the part and illuminate it directly – the so-called bright field illumination.

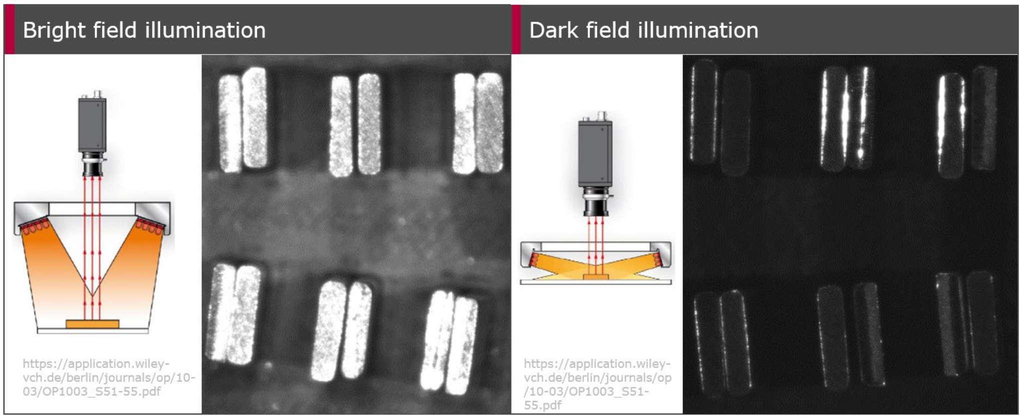

Fig. 5. Pattern recognition process

As seen in the right side of Fig. 5 the result at these hairpins looks quite good all pin pairs look very good illuminated and so very good detected. The pair in the top right spot looks a little bit different at the left edge which could be a slightly deformed pin. When the dark field illumination – light shining on the detection zone with a very flat angle- reflections in the “deformed” pins occur. This simple example shows that the pin preparation in consideration with the wear of the production tools in defines the illumination for a reliable pattern recognition in series production. So, it really matters if the pins are grinded, cut or just torn to define if the common bright light illumination is enough, if a dark field illumination is needed or if a combined solution is the right way.

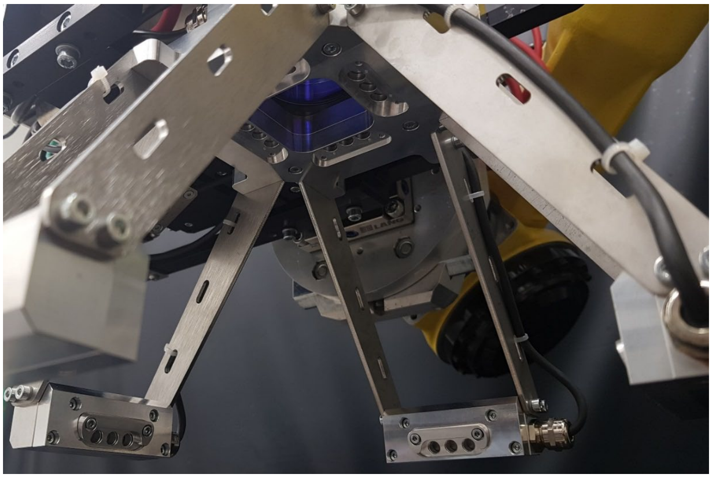

Fig. 6. Scansonic illumination concept

2.3. Reduced costs

Beside the reduced costs due to a lower scrap output due to a more reliable and robust detection of the welding situation in combination with robust process parameters, of course the running costs of a laser system have to be considered.

Here the Scansonic approach of small scanning field features two major advantages regarding TCO. First of all, the purchase costs for 2” protection glasses are significantly lower than for 5” protection glasses. Depending of the yearly purchased amount of protection glasses a 2” costs around 10€. A 5” protection glass comes for around 130€, this means it is factor 13 more expensive than a 2” even if it lasts longer due to the bigger distance between welding spot and optic an 13-times longer use-time is quite unrealistic.

To make the protection last as long as possible, a suitable cross-jet is needed to protect the protection glass from steam coming out of the welding pool and smaller spatter. For a cross-jet compressed air is used which is – state today – one of the most expensive production resources. One optic with a cross-jet for 2” protection glass consumes approx. 700-800 l/min, while a cross jet for a bigger 5” protection glass uses more than 2.200l/min and up to 4400 l/min. So, if we assume a company with working 220 days per year in three shifts per day with seven hours per shift with only four night shifts per week. The assumption in this example calculation that out of 130sec cycle-time the laser-on-time is 80sec which means only in 61% of the total time compressed air is consumed. The further assumptions are: 2” protection glass lasts on day while a 5” protection glass lasts five days and that the price for compressed air is 0,15€/m³.

Table 1. Costs per year

	Small scanning field (800l/min)	Big scanning field (2200l/min)
Costs protection glass	0,50€/h	1,29€/h
Costs compressed air	4,43€/h	16,62€/h
Total running costs	4,93€/h	17,91€/h
TCO per year	21.908,92€	79.592,04

It can be seen just by considering the consumption of protection glasses and compressed air the small scanning field has a cost advantage of more than 57.000€ for one laser optics.

3. Conclusion

The approach of Scansonic of welding copper can be summarized as follows. To achieve a 100% safe process the detection of component deviations in position is significant, this is secured by the adjustable bright and dark field illumination together with the intelligent and flexible pattern recognition algorithm.

To secure a constant and robust weld quality it is necessary that the optic is doing the same from the first to the millionth weld. Therefore the robust system design with high speed scanners with included target and actual position control, the post objective scanning with a drift-free position detection to the TCP, a completely rectified optical system in which all positions cartesian addressable as well as a low and constant focus shift is the way to secure constant welding results.

To reduce costs and increase efficiency the short cycle time due to very short shutter times of the camera, a fast detection in combination of welding multiple pin pairs in one go. The low TCO thanks to the small protective glass solution and the low compressed air consumption helps to improve the overall cost situation.

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