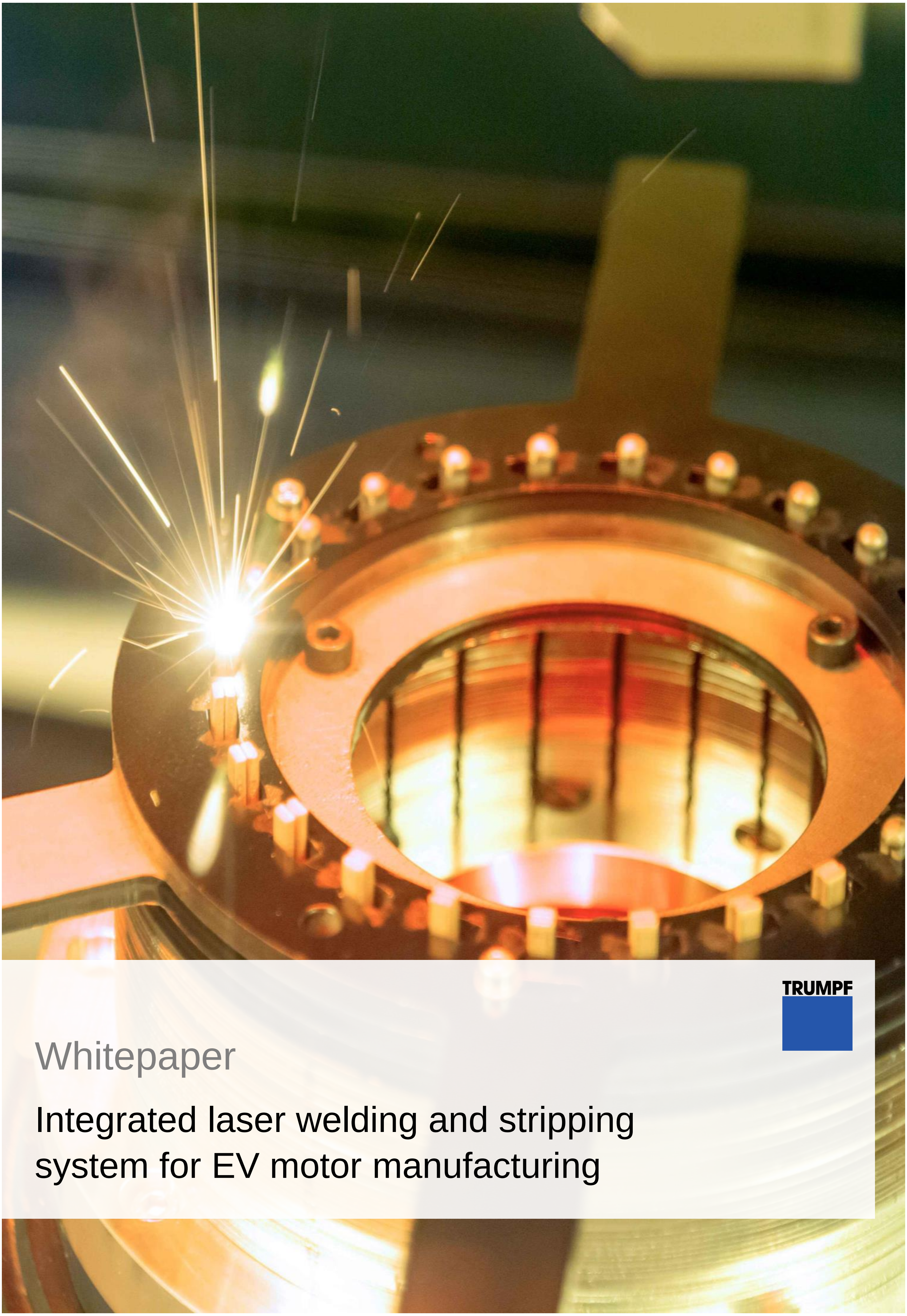

TRUMPF

Whitepaper

Integrated laser welding and stripping system for EV motor manufacturing

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Abstract

Among many technological developments in EV motor design and manufacturing, hairpin winding is a trend that is being adopted by more and more EV motor manufactures in either pure battery EV or Hybrid EV. It is also known as bar wound winding. This is a method which uses rectangular shaped copper wire instead of round wire inside the stator lamination. The advantage is increased slot filling ratio, which leads to high current density and thus allows a motor design with higher power density. Compared to conventional pull-in winding method, this process is relatively simple and full automation is already realized for mass production. Laser technology has shown itself to be a productive method with high-quality results for two production steps of the stator with hairpin design: stripping and welding of the hairpin ends. Stripping is performed with high power nano-second pulsed laser with multiple scanners for best quality and highest productivity, while hairpins welding is done with high brightness disk laser with beam oscillation and intelligent image processing for efficient and reliable welding results.

Hairpin insulating layer

The copper hairpins are coated with an insulating layer which requires ablation at both ends locally (hairpin stripping) to enable contacting. Common insulating layers for copper hairpins are:

- Polyamide-imides (PAI)
- Polyether ether ketone (PEEK)
- Polyamide-imides with polyimide foil (PAI+FEP)

PEEK behaves as a volume absorber for laser light anyway; for PAI and PAI+FEP, it is recommended that the first run over is used to carbonize the material to increase the absorption rate.

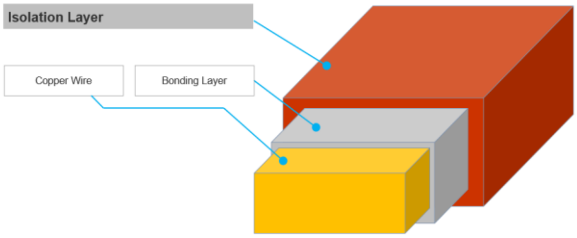


Figure 1: Illustration of hairpin isolation layer

Hairpin laser stripping parameters

For the ablation process, we used the TruMicro 7070 and TruMicro 7060 short-pulse lasers. The following process parameters were found to be ideal:

- Frequency: > 20 kHz
- Pulse overlap: > 40%
- Line overlap: > 40%
- Pulse energy: > 40 mJ

Depending on the insulation properties, stripping of PAI-coated hairpins achieves a removal rate of up to 13 cm^2/s (on average 7 cm^2/s) using the TruMicro laser. Stripping of PEEK-coated hairpins achieves a removal rate of 4 cm^2/s using the TruMark laser systems. The laser processes are therefore between 40 and 80% faster than mechanical processes.

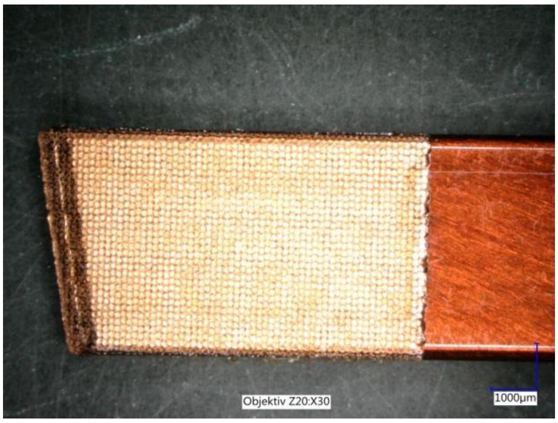


Figure 2: Laser stripping of PAI insulating layer

Hairpin stripping laser processing strategies

For system setup, the latest TruMicro7070 laser has 2kW average power, 100mJ max pulse energy and support up to 4 outputs with 4 scanners. One laser source can support 4 outputs in a 2+2 energy & time sharing mode to ablate four sides of the hairpins for highest productivity. Depending on the wire size and cycle time requirement, laser stripping strategy can be tailored.

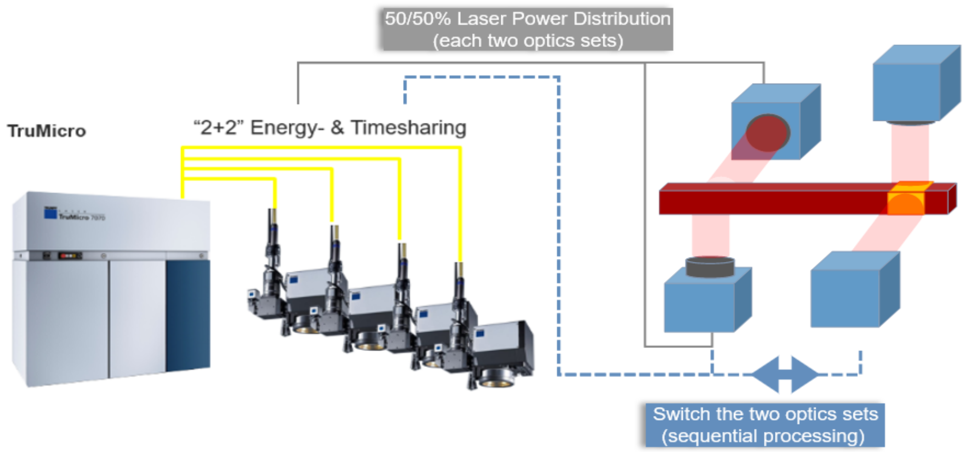


Figure 3: TruMicro 7070 with four outputs for hairpin stripping

Processing from four sides at an angle of 90°

This strategy is used mostly for hairpins with large cross section and short cycle time requirement. This alignment is possible with one TruMicro 7070 lase source. Here, an arrangement of four PFOs with a focal length of f = 160 mm and optical laser cable SQ 460 × 460 µm is used. Each set of two PFOs operates in a 50:50 division of energy. The TruMicro is therefore equipped with four outputs and two power splitting modules. Outputs 1 and 2 switch to outputs 3 and 4, when the first two opposite sides of the copper wire have been stripped.

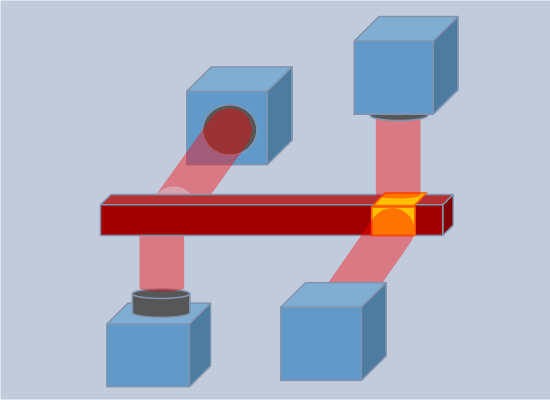


Figure 4: Laser stripping with 4 scanners

Processing from three sides at an angle of 120°

This strategy is used for hairpins with medium cross section and moderate cycle time requirement. This alignment is preferred for the TruMark Series 7000 for economical reasons and a larger process depth of focus. For certain hairpin types, it can also be realized with TruMicro 7070 with 160mm focal length.

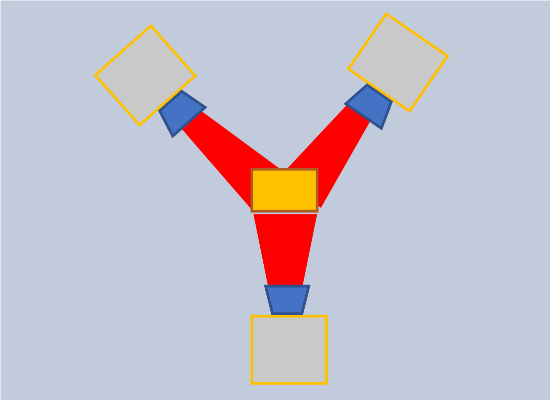


Figure 5: Laser stripping with 3 scanners

Processing from two sides at an angle of less than 60°

This alignment is only recommended for hairpins with small cross section and longer cycle time requirement. TruMicro 7070 with two scanners can be used. There is a high risk, however, that coating residues remain on the opposite sides to the scanner optics.

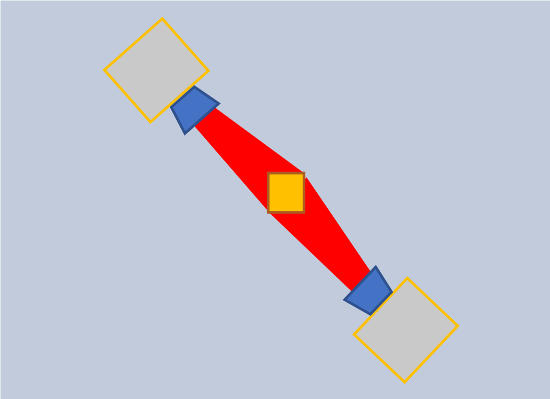


Figure 6: Laser stripping with 2 scanners

Hairpins laser welding challenges

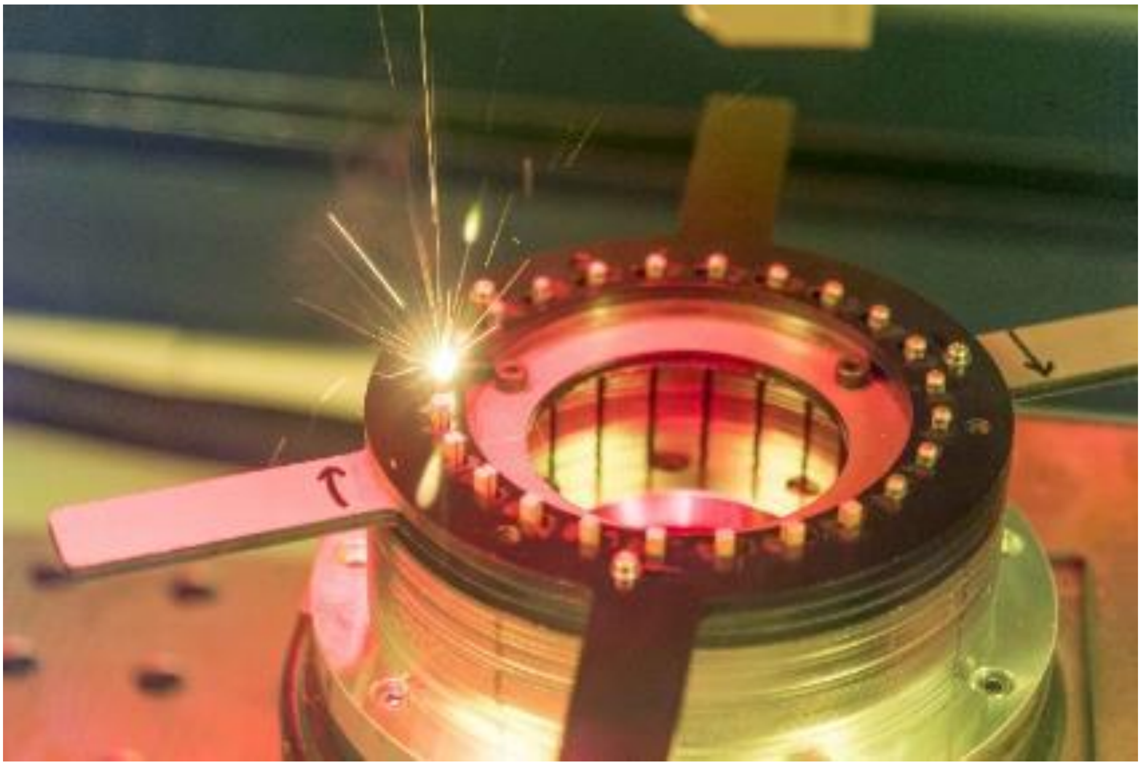


Figure 7: Hairpin welding in a stator

Depending on the number of grooves in the lamination and layers of windings, a typical stator design may require up to 120 welding operations. The copper wire material is normally EPT or oxygen free copper, the rectangular wire size can be from 2 by 1.5mm to 6 by 6mm. Each welding connection has to meet the electrical and mechanical requirement. A fatigue endurable connection is needed because it has to resist operation forces, vibrations, change in temperatures, and high current over the lifetime of the EV motor.

Firstly, copper is a highly reflective material with high thermal conductivity, which makes it difficult to be welded. Second, the winding heads are designed as small as possible, placed as close as possible, to achieve machine design with higher power density, so the welding has to take place in a very confined space, any spatter will potentially contaminate the stator and the components surrounding hairpins. Third, welding porosity that is left inside the welding will reduce connection area and create undesired high temperature inside the motor.

Another critical challenge is coming from hairpin assembly process. Two parallel and flexible pins are put through the lamination and clamped together, tolerances from height offsets and the width of gaps may negatively influence the welding process as it reduces cross connection, making it difficult to have repeatable results.

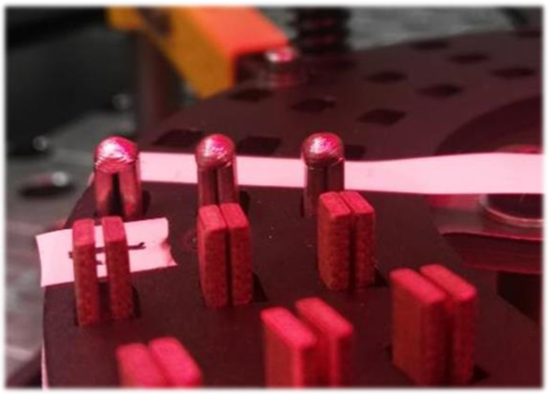


Figure 8: Hairpin arrangement with tolerance

Spatter and porosity suppression with BrightLine Weld

EV motor manufacturers typically specify hairpin welding quality on spatter, porosity, fusion area and weld bead shape, all of which are results of laser beam property and laser process parameters. Porosity, especially the large ones, or many small ones clustered, will create cooling problems and ultimately cause motor performance issue. Spatter control is important because large amount of spatter in a very confined area will damage the stator or create potential for shortcut.

Porosity and spatter formation depends on how laser energy react with copper material, thus they are direct result of laser beam property and laser process parameters. TRUMPF's patented Brightline weld technology is proven to be able effectively suppress porosity and spatter suppression.

BrightLine weld technology is a beam shaping methods it is realized through the patented 2-in-1 fiber, which is made of the inner core fiber and outer ring fiber. Laser power is able to be distributed freely between the inner core and outer ring, thus creating a superimposed two beams into one process zone.

The additional ring beam will create a larger keyhole opening to allow metal vapor to escape. This also helps to create a more stable keyhole to avoid keyhole collapse, thus avoiding large pore formation.

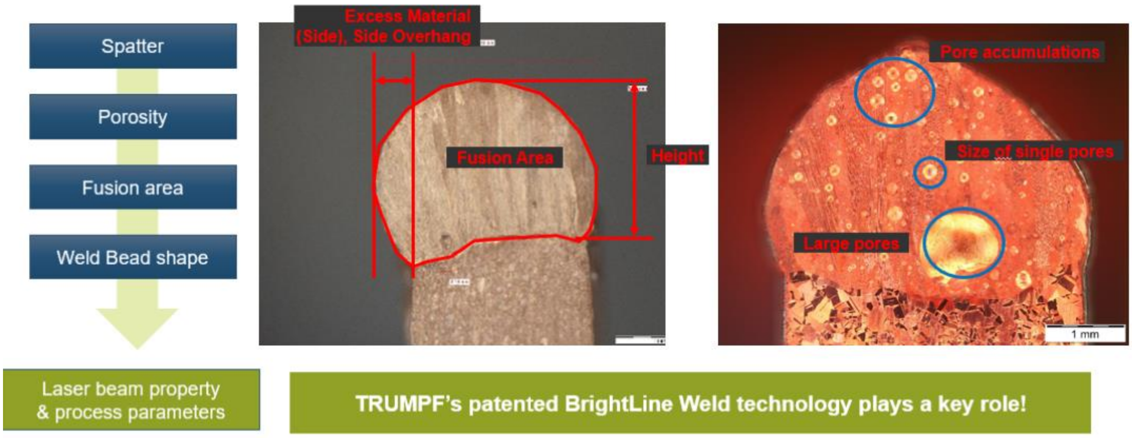


Figure 9: Typical hairpin weld imperfections

At the same time, the additional ring beam changes the dynamics of the melt pool too. The metal melt, which is accelerated to the surface direction, receives an opposing impulse through the ring beam and deflected to the side.

As a result, with the combined effect on keyhole and melt pool dynamics, by introducing a superimposed ring beam, it is shown in test that up to 90% of the spatter in copper welding can be reduced.

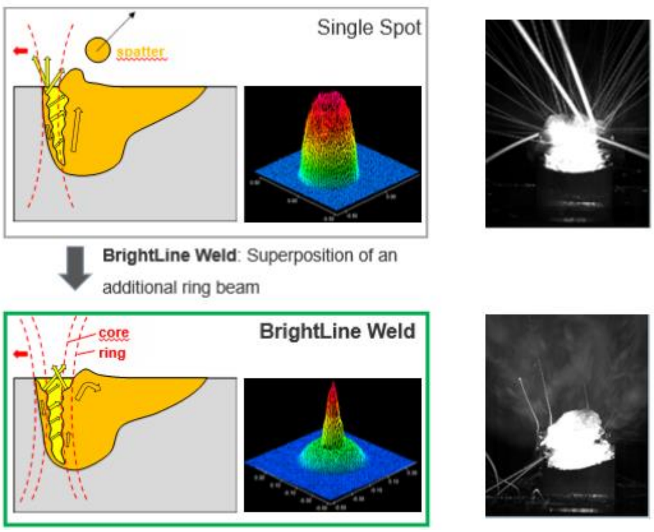


Figure 10: BrightLine Weld Technology for spatter reduction

Laser beam oscillation for gap bridging, optimized fuision area and weld beam shape

During the welding process, we use wobbling in order to be able to bridge larger gaps. The joint situation has a considerable influence on the oscillation geometry to be selected, in order to be able to melt the material between both materials optimally. Here, a linear oscillation geometry is to be recommended in particular if the hairpins are to be joined on their short sides; a circular or elliptical geometry is to be selected on the other hand if the pins are to be joined on their long side.

To ensure good mechanical and electrical connection, many EV manufactures specify the weld cross section area must be 100% or higher of single pin’s cross section area. At the same time, the overhang of the weld seam should be to allow grooves and hairpins can move closer to each other for a compact size. By using beam oscillation strategy, the operator has more freedom to optimize the process parameters to meet the requirements.

By combining BrightLine Weld with beam oscillation, we achieve a high processing speed with minimum spatter and formation of pores. The weld seam has a high tensile strength and is deep enough to achieve optimum conductivity. Furthermore, optimized fusion area and bead shape can be achieved by adjusting beam oscillation parameters.

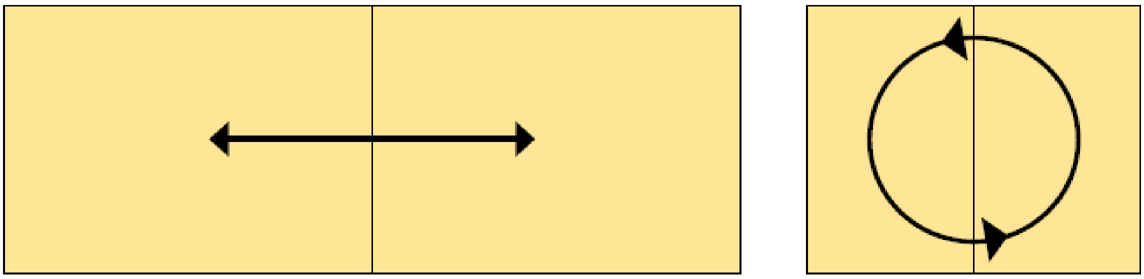


Figure 11: Linear oscillation geometry for a joint on the short side of both hairpins (left) and circular/elliptical oscillation geometry for a joint on the long side

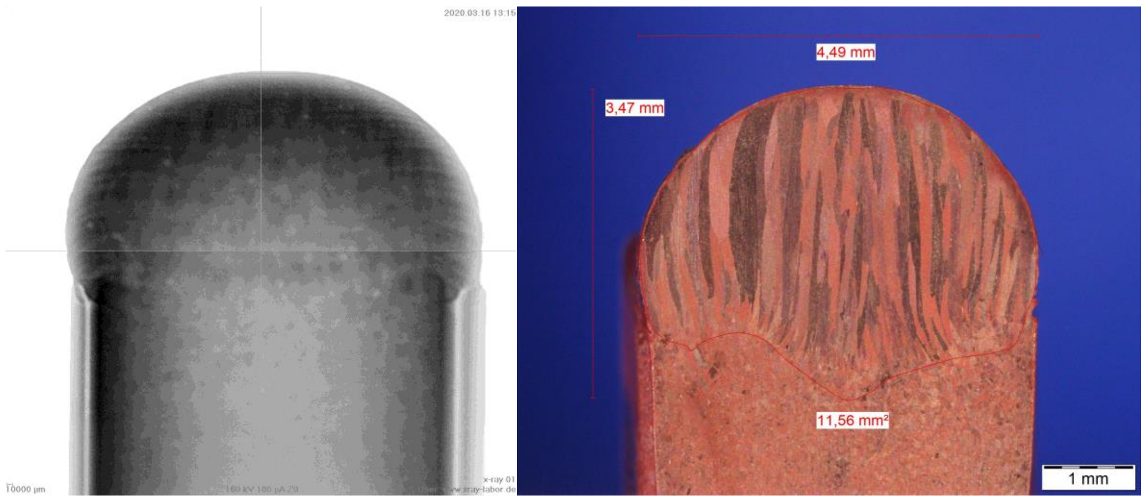


Figure 12: High quality hairpin welding shown in CT and cross section image

Higher beam quality brings higher productivity

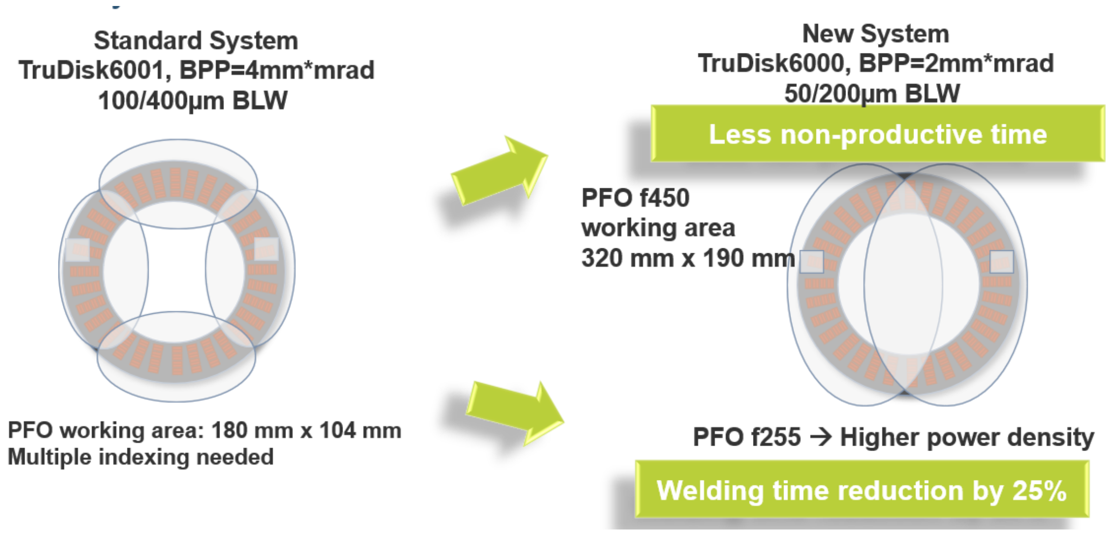


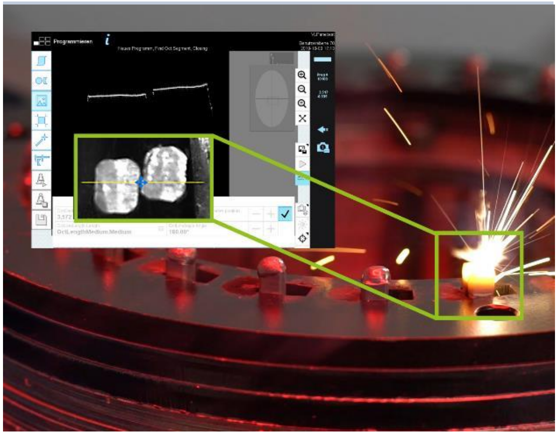
Figure 13: Higher beam quality brings higher productivity

A typical EV motor haa over one hundred hairpin contacting points, in a fully automated stator line for high volume production, laser welding sometimes is the bottleneck. Therefore, increasing productivity to match the rest of the assembly line is crucial.

The standard system is a 6kW laser with beam quality of 4mm*mrad, using a 100/400um BLW fiber, that is 100um inner core and 400um outer ring fiber. We have to use a PFO with 255mm focal length to have the appropriate spot size and power density. The PFO working area is 180mm by 104mm, so normally we have to index the stator a couple of times to cover all the pins to be welded.

The new generation hairpin welding system we use is a 6kW laser with beam quality of 2mm*mrad, it is incoupled into a 50/200um brightline weld fiber, that's 50um inner core and 200um at the outer ring. The beam diameter out of the fiber is reduce by half, which allows us to use a focal lens double of before. We can use a longer 450mm focal length that has a much larger working area. In this case, it is 320mm by 190mm, and allows us to cover the whole stator without indexing or fewer indexing times, so overall less non-productive time.

On the other side, if you continue to use 255mm focal lens, you can achieve a higher power density. While we don't always need the highest power density, in this case, we can achieve higher speed with less power, the total welding time per pin can be reduced by 25%.



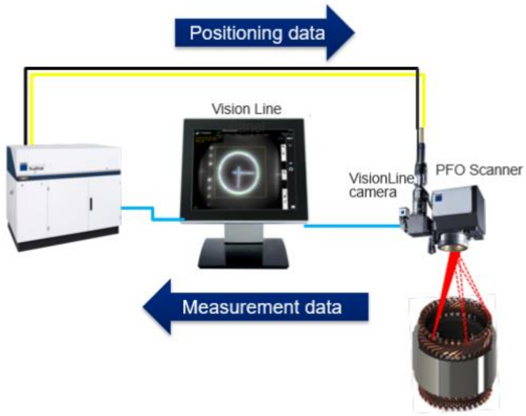


Figure 14–16:
Image processing system for hairpin welding (top left), typical hairpin positioning error (top right), and hairpin laser welding system setup (bottom left)

Intelligent image processing system

As the pairs to be welded have different orientations and are not always optimally aligned to each other, we use PFO scanner optics with integrated positioning using image processing (VisionLine). The camera-based sensor system detects the position and orientation of each individual pair, automatically aligns the optics in real time, thereby making the small gaps and positioning deviations in the hairpins tolerable. Figure 16 shows the system setup overview. A high definition co-axial camera is mounted on the PFO. Before welding takes place, measurement data on each pin will be sent back to the laser controller, the galvo mirror on the PFO will be repositioned to compensate the tolerance. VisionLine software allows the operator to freely define the algorithms and obtain measurement data. For hairpin welding, the three most important measurements are the angle, gap and offset between two pins. You can use the touch screen to easily program the camera to capture and measure these features, as well as define the threshold value for each as quality control steps. Based on gap, offset and angle measurement data, you can have the laser parameters adapted to each specific pin arrangement. For example, you may want to increase power or decrease speed, if a larger gap is detected. Another example would be to change laser beam path depending on the offset. Figure 17 shows weld quality improvement with adaptive laser parameters based on image processing measurement on hairpins with 0.5mm gap.

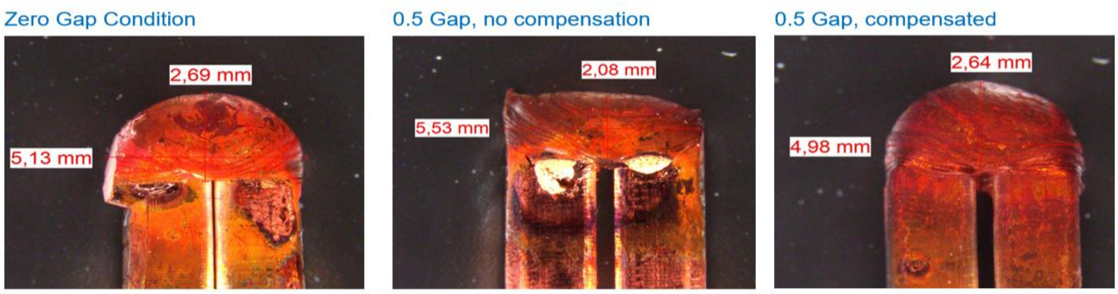


Figure 17:
Hairpin laser welding quality improvement with adaptive laser parameters based on image processing system

What is next? 3D feature detection with OCT sensor

One of the constrains that we have with the vision system is we can't detect the height difference between two pins. The camera won't be able to tell if one pin is higher than the other. For that, we used the OCT sensor in co-axial to the camera. OCT standards for Optical Coherent Topography, it is a 3D imaging technology using a low coherence interferometry that captures hairpins height difference in high resolution. Such information can be used for further optimizing laser welding parameters purpose.

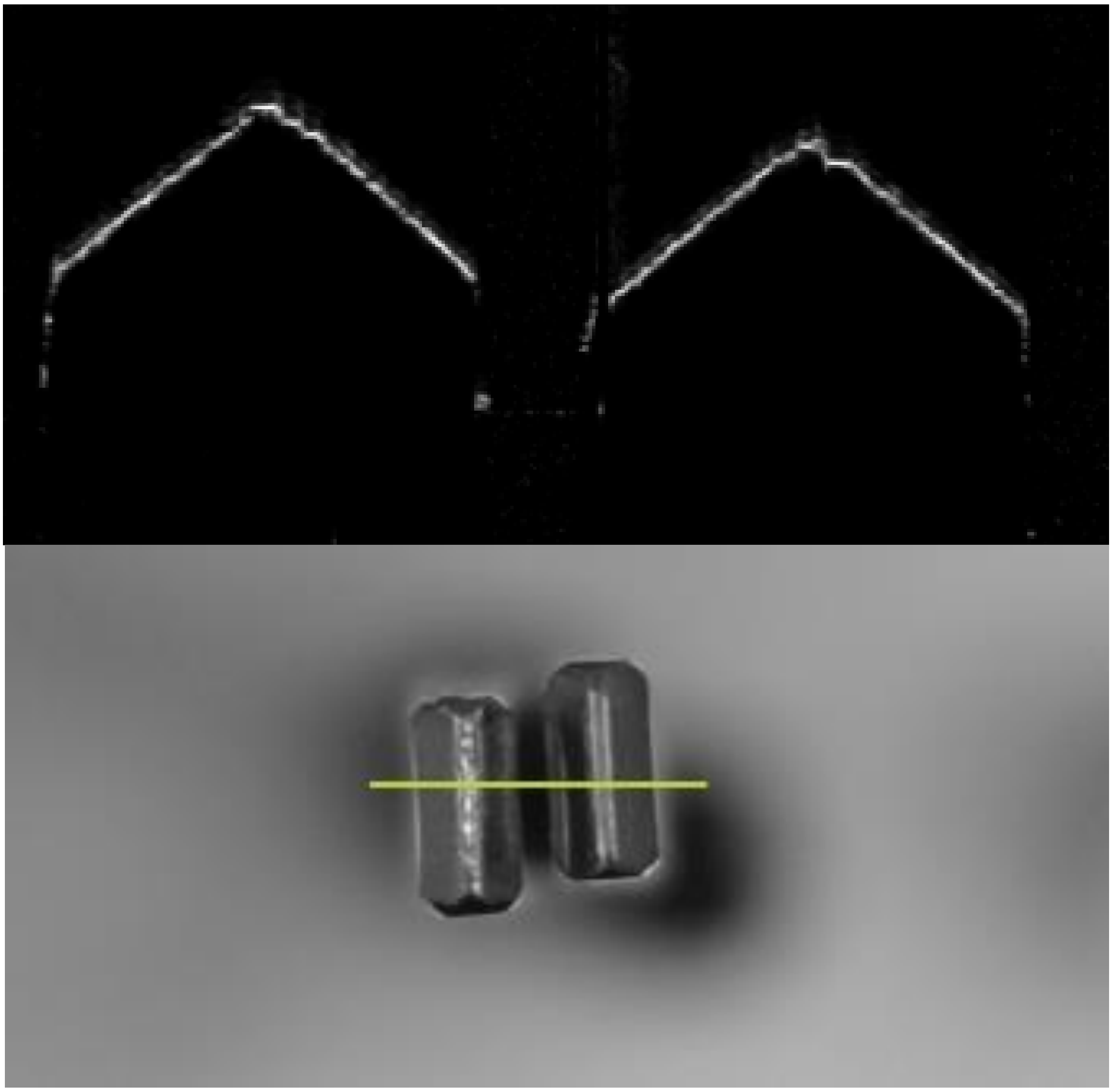


Figure 18: Hairpin 3D feature detection with OCT sensor

Conclusion

EV motor manufacturing with hairpin winding offers great advantages, but it also poses challenges for a reliable and efficient joining technology that was new to the stator manufacturing business. For hairpin welding system design, typical considerations are listed below.

TRUMPF has developed an innovative and integrated solution, including laser and optics for welding and stripping, as well as minimum spatter and porosity. This welding process is achieved by using the patent BrightLine weld technology. With a higher beam quality at 2mm*mrad and 50/200 BrightLine weld fiber, even higher productivity can be achieved.

To overcome the positioning tolerance and imperfect part preparation, an integrated Vision system is used to adapt welding parameters to the actual hairpins condition, this greatly improves the process control for EV motor mass production.

Figure 19: Hairpin welding system overall considerations

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