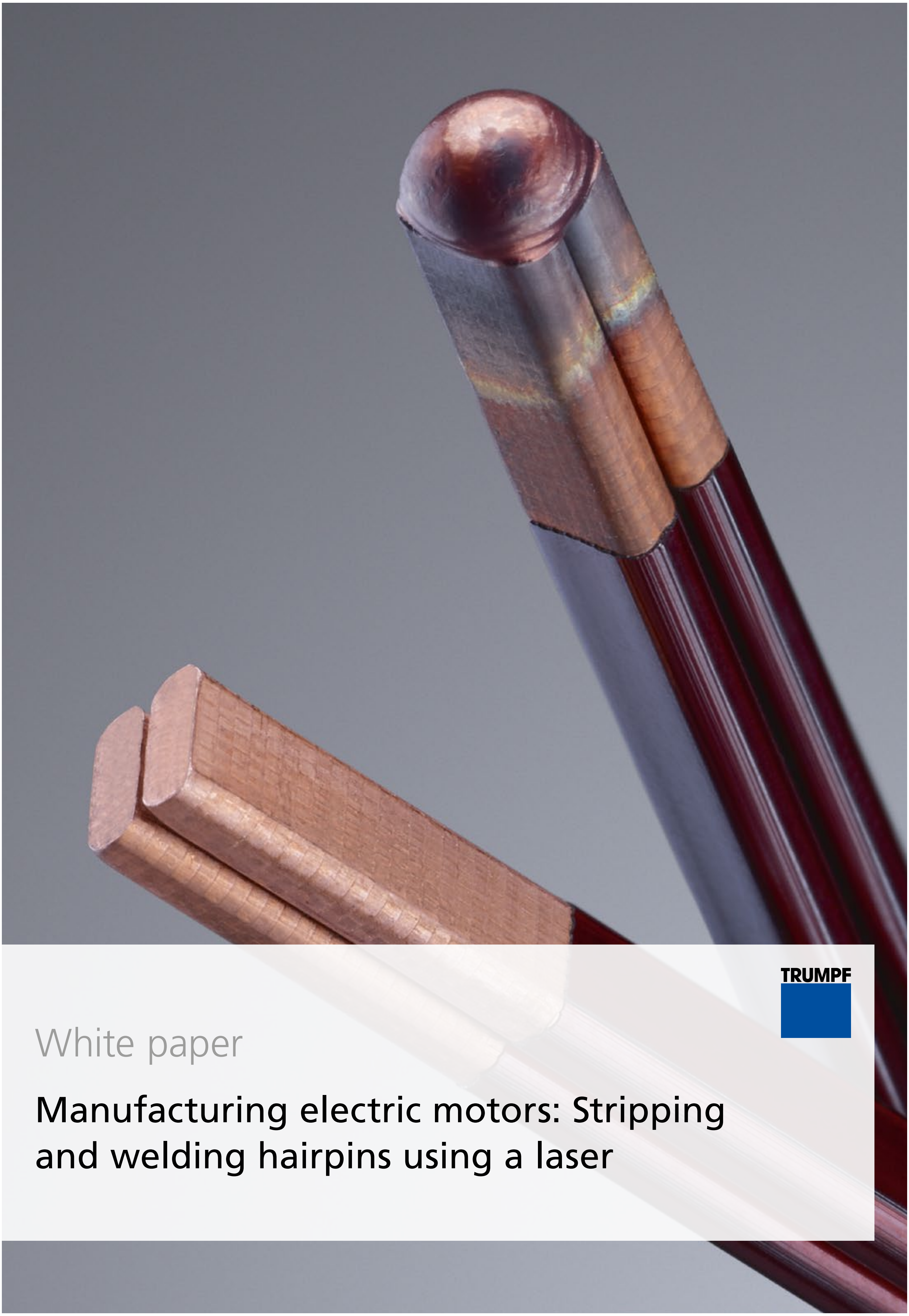

White paper

Manufacturing electric motors: Stripping and welding hairpins using a laser

Contents

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Summary

For powerful electric motors – above all for cars and other forms of electric mobility – the production of stators with copper wires with a rectangular cross section, so-called hairpins, has become prevalent. Laser technology has shown itself to be a productive method with high-quality results for two production steps of the stator: stripping and welding of the hairpin ends. Stripping is performed using pulsed processing, which removes all common insulation materials. When joining the hairpins, scanner-guided and camera-based welding with beam oscillation using a laser has proven itself to be a highly efficient method when it comes to speed and use of installation space.

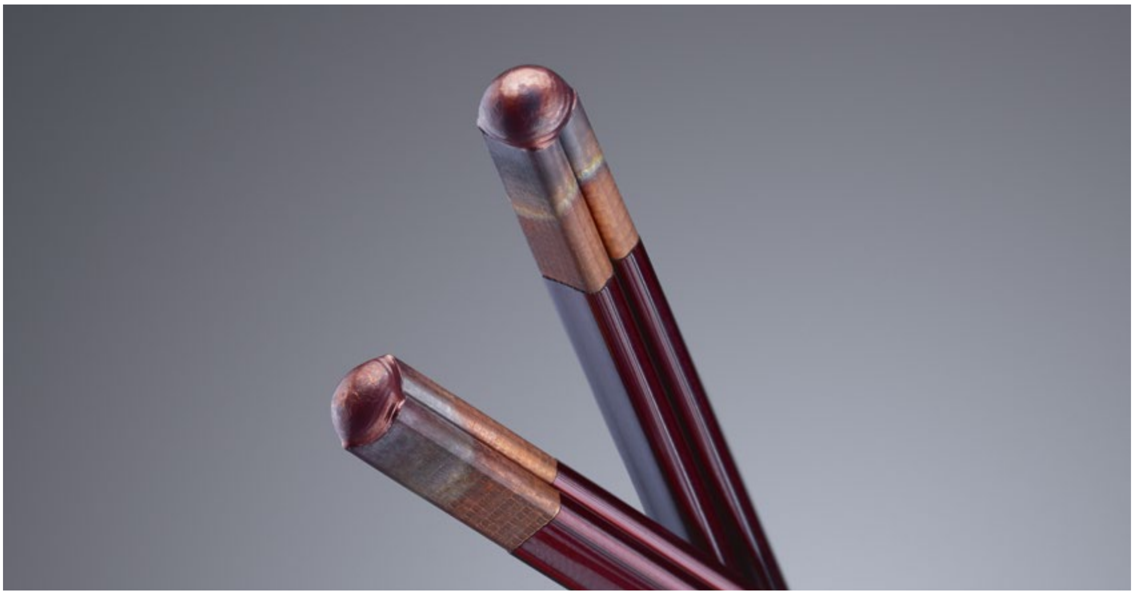

Figure 1: Hairpins that have been stripped and welded using the laser.

Situation

Due to the increasing demand for electric vehicles, manufacturers of electric motors are looking for more productive processes for high quantities, with the same high quality requirements when it comes to the welding result. An important impetus here is achieving a higher degree of automation to be able to produce higher quantities. One method in the construction of stators has therefore largely prevailed: Instead of winding copper wire around the individual stator grooves – as was often the case before – manufacturers have started embedding rectangular copper rods (called "hairpins" due to their shape) into the entire groove using compressed air. The typical edge lengths of the rectangular cross section of the hairpins is between 2 and 4 mm. The process achieves higher process speeds and can easily be automated. As the hairpins are stiffer than round wires, their alignment in the motor can be better controlled. The larger fill factor also results in a higher thermal load capacity, and higher motor power.

The copper rods are coated with an insulating layer which requires ablation at both ends locally (hairpin stripping) to enable contacting. Pulsed laser processing is suitable here to strip the hairpins. Compared to mechanical processes, such as planing and milling, laser processing is up to 80% more productive.

Once the hairpins have been embedded in the grooves, protruding ends on the top and bottom of the stator are twisted together using a fixture ("necking") or fixed in place, and then welded for contacting. The ends are not always ideally aligned to each other, however. If you use automated remote welding, a camera-based sensor system integrated in the laser optics helps achieve a reliable and reproducible result, and therefore the highest possible current flow.

Stripping of hairpins

Common insulating layers for copper hairpins are:

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

In the past, PAI coatings were almost exclusively prevalent in the industry, but we are now seeing a tendency towards a steady increase in PEEK and PAI+FEP. However, PAI coatings still have, and are likely to have in the future, the largest share by far.

Figure 2: Insulating layers on copper, from left to right: PAI, PEEK, and PAI+FEP.

Ablation process

All of these insulation coatings can be burnt away from the copper quickly and in a targeted manner using laser pulse processing. The laser light couples into the insulating layer, heats it up, and burns it off. 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 in order to increase the absorption.

The copper discolors due to the heat influence during laser ablation. This is not relevant for the further processing, however, as the structure of the copper is not changed. Burrs also form at the boundaries to the coated copper, which, in unfavorable circumstances, could lead to the burr becoming stuck on a surrounding component or fixture. The formation of burrs and edges can be optimized, however, through reworking using another femtosecond-pulsed laser.

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

Tests with the marking laser systems of the TruMark Series 7000 and 5000 also demonstrate very good results with ablation. To achieve a high ablation rate, the lens should have a focal length of 160 mm; depending on the production concept (see below) even higher. Depending on the process parameters, the copper surface has a slight structure following ablation with marking laser systems. This effect can be minimized by increasing the frequency or by defocussing. As the process is carried out in two steps – first the stripping, then cleaning – two different sets of laser parameters are used. Example of TruMark 7050: A frequency of 55 kHz during stripping. The first run over should be completed with a high speed of around 1 m/s, and then three runs over at 600 mm/s. For cleaning, a run over with 255 kHz and a speed of 3,000 mm/s is recommended. In the event of inhomogeneous coating thicknesses, it is important to align the process parameters to the thicker side. Depending on the hairpin type, you can achieve a processing speed of 0.3 to 3 cm^2/s.

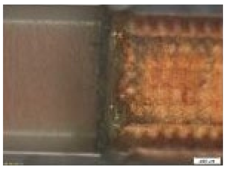

Figure 3:
Ablation process for PEEK: Carbonization at the boundary of the process window can be seen. Reworking with femtosecond lasers can improve the quality.

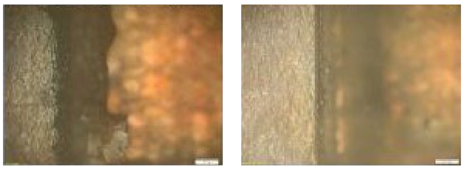

Figure 4:
Left: Edge quality after the stripping of PEEK.
Right: Following reworking with the femtosecond laser.

Figure 5:
Discoloration on the copper due to the high level of process heat.

Figure 6:
Ablation using a TruMark 7050 machine on a hairpin coated with PEEK. Carbonization effects are visible on the edge.

Processing strategies

Using lasers, hairpins can be stripped individually, as well as on the continuous coil before being separated, i.e. continuously and with an endless feed – the most widespread application in the production of hairpins. Depending on the feed rate of the separation machine, the programmable focusing optics (PFOs) must be arranged differently to enable stripping in the work area of the PFOs. Three different processing strategies are possible:

- Processing from four sides at an angle of 90°. This alignment is only possible with TruMicro 7060. 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. The maximum ablation length here is 56 mm.

- Processing from three sides at an angle of 120°. 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 7060 (not in parallel, however). The focal length of the lens should be 160 mm. With TruMark marking lasers, a scanner is supplied by its own beam source in each case; with a TruMicro machine, one beam source is enough for all three PFOs. With the TruMark, the maximum ablation length is 110 mm; with the TruMicro 50 mm.

- Processing from two sides at an angle of less than 60°. This alignment is only recommended for TruMicro 7070; there is a high risk, however, that coating residues remain on the sides not facing the optics.

Depending on the insulation properties, stripping of PAI-coated hairpins achieves a removal rate of up to 13 cm²/s (on average 7 cm²/s) using the TruMicro laser. Stripping of PEEK-coated hairpins achieves a removal rate of 4 cm²/s using the TruMark laser systems. The laser processes are therefore between 40 and 80% faster than mechanical processes.

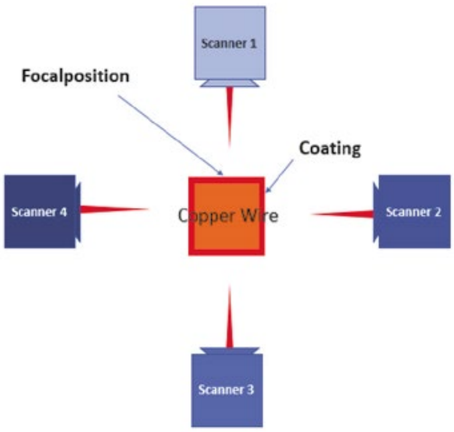

Figure 7: Processing from four sides with an angle of 90° to the copper surface.

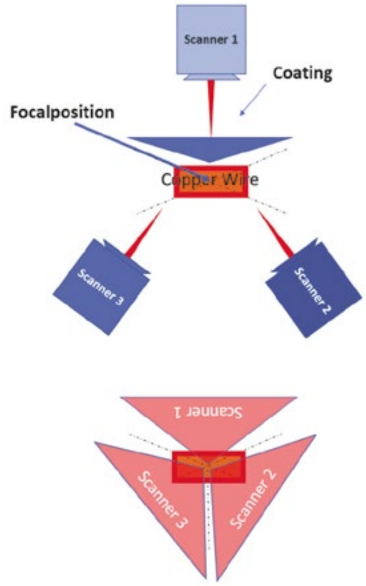

Figure 8: Processing from three sides with an angle of 120° to the copper surface.

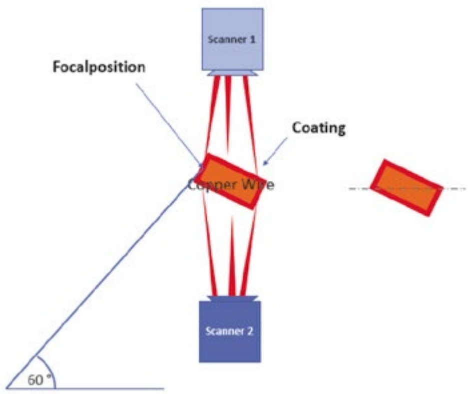

Figure 9: Processing from two sides with an angle of below 60°. This strategy is only possible with rectangular wires. The focal spot must be set to the center of the height of the pin.

Welding of hairpins

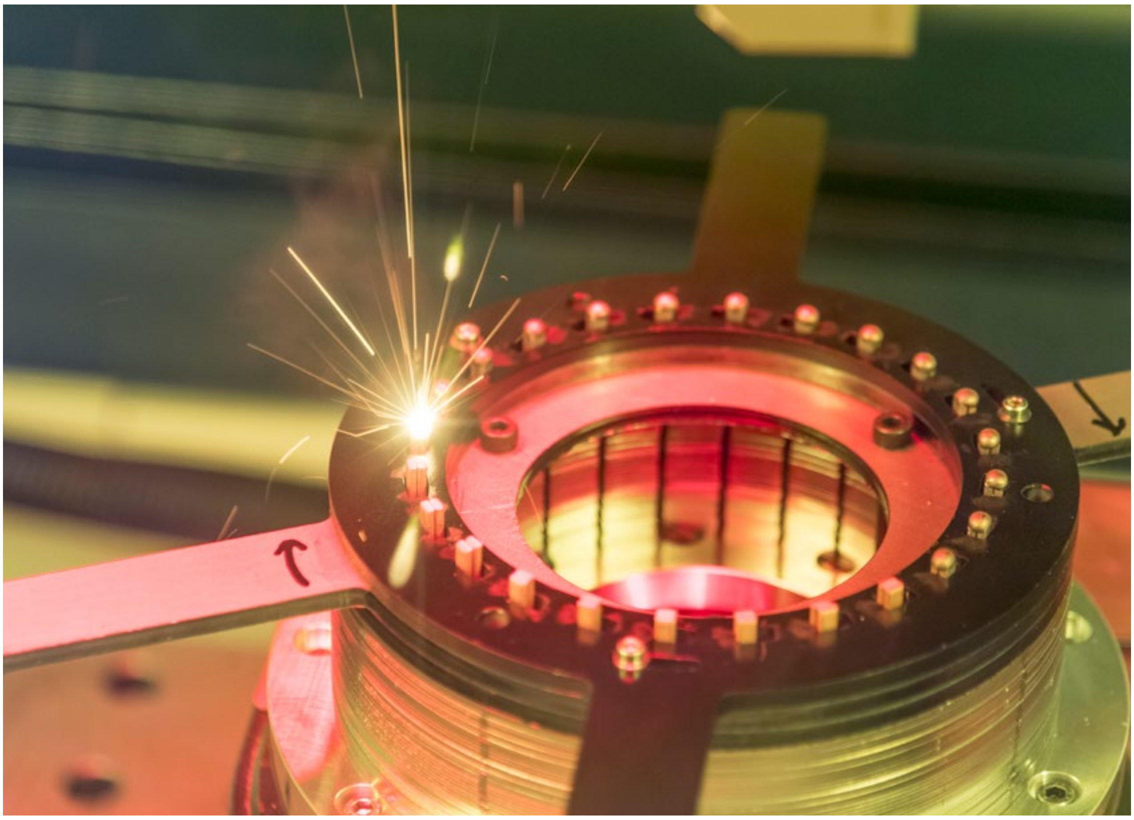

Figure 10:
Process situation for hairpin welding.

The protruding ends of the hairpins in the stator must be welded on a pair-by-pair basis following insertion in order to create the best possible electrical contact. For welding preparation, they are sheared off at the ends to create a smooth surface, and then twisted together or fixed in place. Here considerable positioning tolerances have to be accepted: The hairpins are not always optimally aligned with each other. Tolerances when it comes to height offsets and the width of gaps may negatively influence the welding process, as the connection is reduced through this. At the same time, the requirements for the weld seam tolerances are very tight. This challenge must be mastered during welding.

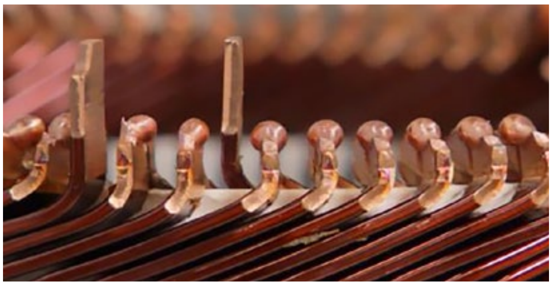

Figure 11:
Welded hairpins with a welding depth of 2 to 3 mm. The individual pairs have a different orientation and alignment, which makes the use of scanner optics with image recognition necessary.

The protruding ends of the hairpins in the stator must be welded on a pair-by-pair basis following insertion in order to create the best possible electrical contact. For welding preparation, they are sheared off at the ends to create a smooth surface, and then twisted together or fixed in place. Here considerable positioning tolerances have to be accepted: The hairpins are not always optimally aligned with each other. Tolerances when it comes to height offsets and the width of gaps may negatively influence the welding process, as the connection is reduced through this. At the same time, the requirements for the weld seam tolerances are very tight. This challenge must be mastered during welding.

During preparation for welding, we recommend cleaning the hairpins of any residues using suction equipment. Some welding defects and spatter on the stator and the clamping fixture can even be avoided with this alone.

As the beam source for hairpin welding, we use a disk laser from the TruDisk Series 3001 to 8001 in a TruLaser Cell 3000. The laser works with a wavelength of 1,030 nm and a maximum power of 6 kW. This results in a welding process with a high process speed (processing time per seam t ≤ 0.4 s, depending on the size of hairpins).

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.

The entire system, comprised of laser, optics, and sensor system, is highly integrated, fundamentally works autonomously, and can be operated independently of the system if necessary. Externally, a standardized control system is sufficient.

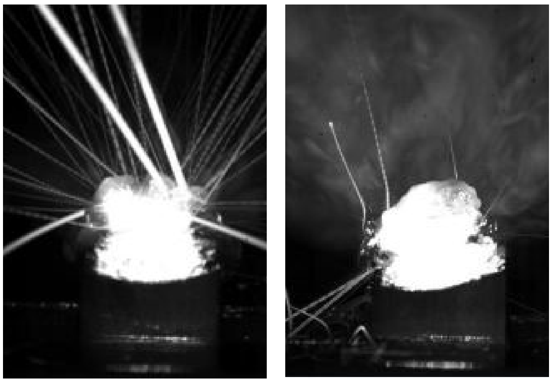

Figure 12:
Left: Weld with a lot of spatter.
Right: Considerably less spatter due to optimized beam guidance.

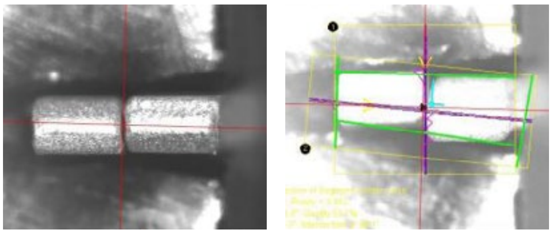

Figure 13:
Position detection with VisionLine Detect image processing integrated into the optics.

Figure 14:
The VisionLine camera-based image processing detects the position of the component, aligning the welding job correspondingly.

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. In this way, 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, as a result of the laser welding, the overhang of the weld seam is reduced to almost zero, meaning that grooves and hairpins can move closer to each other. This means more compact concepts are possible when it comes to the installation space of the motor.

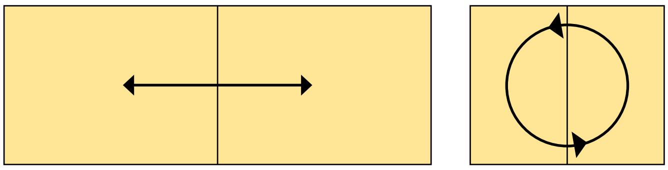

Figure 15:
Linear oscillation geometry for a joint on the short side of both hairpins (left) and circular/elliptical oscillation geometry for a joint on the long side of both hairpins (right).

Conclusion

During the stripping of hairpins, ablation using laser pulses is an extremely economical and reliable processing method. Due to the possibility of using different processing strategies, the process can be integrated with flexibility into the applicable industrial setting. Compared to mechanical processes, stripping is up to 80% faster. During welding for the contacting of hairpins, the TruDisk 6001 to 8001 or TruDisk 3000 to 5000 with scanner optics and image processing sensor system provide the fastest and cleanest results. The combination of disk laser, scanner optics, and image processing sensor system guarantees a highly productive joining concept for hairpins in the production of electric motors that meets high quality requirements (low levels of spatter and pores). Furthermore, the welding process provides the highest levels of flexibility when it comes to the component geometry and variety due the scanner optics.

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