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# Influence of the feed rate and the lateral beam displacement on the joining quality of laser-welded copper-stainless steel connections

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**Abstract**

The present article deals with the laser-welding of copper and stainless steel connections for applications in power electronics. Here, the particular demand for such dissimilar connections is caused by the increasing implementation of electronics in areas with contact to corrosive fluids, which copper cannot resist. In this context the influence of a lateral displacement of the laser beam and the feed rate on the metallurgical properties of the dissimilar materials' connection is highlighted. The effects of these parameters are discussed on the base of metallographic specimen, micro-hardness measurements and element analysis.



*Keywords*: Copper; aluminium; dissimilar connection; beam displacement; feed rate; power electronics

## 1. Introduction

While components for power-electronics always need to offer appropriate electrical characteristics, applications in mobile systems also require a certain resistance against corrosive attack. This fact mostly originates from the trend towards putting the mounting location very close to the position of operation, where lubricants and acids contaminate the electronic assembly. In this context copper features an outstanding electrical conductivity, but only a limited chemical resistance [1]. That is why at points of installation with direct chemical attack copper is supposed to be replaced by stainless steels, which show an excellent corrosion resistance [2]. However, at points of installation apart from the direct corrosive attack copper persists in being the favorite material for electric usage. To implement the advantages of both materials into electronics it's necessary to join copper and stainless steel as a tailored-construction. Particularly the differences regarding the melting point, the thermal conductivity and the thermal expansion challenge the joining technology [3, 4]. Furthermore the absorption values for copper and stainless steel are very diverse considering the usually applied solid-state laser wavelength of 1064 nm. For these reasons a joining process by metal-continuity often leads to insufficient connection properties due to a thermal damage of the stainless steel and a minor joint cross-section on the copper side. In this context the influence of the

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feed rate and the lateral beam displacement on the quality of laser-welded connections of copper and stainless steel is analyzed.

## 2. Experimental results

### *2.1. Basics of the experiments*

For the experimental researches electrolytic copper and a common stainless steel are used, see table 1. Regarding the electrical and thermal conductivity, clear differences between the two materials can be observed. While copper features outstanding electrical and thermal conductivities, those of stainless steel are comparatively little. For this reason metal joints of copper and stainless steel are supposed to be used for electronic applications with high conductive cross-sections on the steel side. For example this could be ground connections of copper conductors to body structures made of stainless steel.

Table 1. Selected properties of copper and stainless steel [1, 2]

| **property** | **copper** | **stainless steel** |
|---|---|---|
| material number | 2.0060 | 1.4541 |
| crystal structure (ambient temp.) | fcc | fcc |
| denisty [g/cm$^3$] | 8,9 | 7,9 |
| electrical conductivity [10$^6$S/m] | 58 | 1,4 |
| thermal conductivity [W/(m*K)] | 401 | 15 |
| thermal expansion coefficient [10$^{-6}$/m] | 24 | 16 |
| melting point [°C] | 1084 | 1425 |
| boiling point [°C] | 2567 | 2750 |

The experiments are performed with a pulsed Nd:YAG laser source, which offers 70 J maximum pulse energy at a pulse duration of 100 msec. The laser radiation with a wavelength of 1064 nm is focused to a spot diameter of 400 µm at an operating distance of 100 mm.

With plates of copper and stainless steel an experimental setup according figure 1 is prepared. By a lateral beam displacement Δy towards one of the base materials, the welding process can be manipulated. The feed is carried out in x-direction, i. e. in direction of the contact surface of the plates, see figure 1.

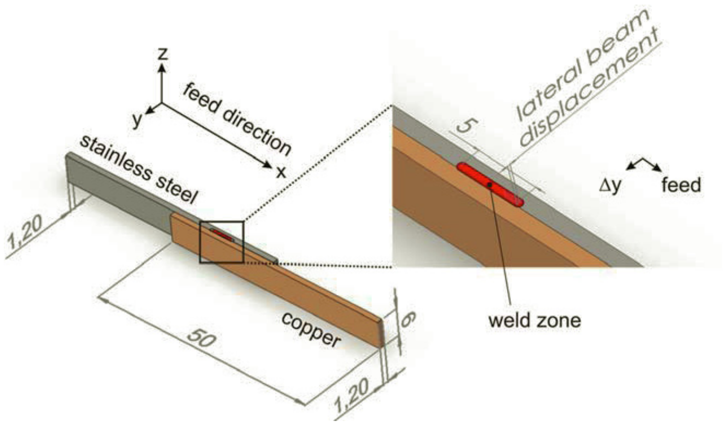


Fig. 1. Joint assembly including the definition of the lateral beam displacement Δy and the feed direction

For the generation of quasi-continuous weld seams with the pulsed laser system long-term laser pulses are used. Hereby the particular pulse duration is set in such a way, that the total length of the weld seam has an extension of 5 mm, see figure 1. In order to compensate the mass inertia of the linear axis, the acceleration phase up to the relevant speed is carried out ahead of the welding zone (welding on the fly). On the analogy, the deceleration of the linear axis system is done after the welding process.

The protection the molten zone against atmospheric interaction is realized by an inert shielding gas (argon), which is applied with a flow rate of 8 l/min.

### 2.1. Influence of the feed rate

By changing the feed rate of the laser welding process, the temperature sequence, the microstructure and the geometry of the weld seam can be influenced. At a fixed laser power higher feed rates reduce the time interval in which the base materials are molten and result in a comparatively high cooling-down ratio. For the experimental researches feed rates between 0 m/min and 30 m/min are used in combination with a fixed laser power of 3.000 W. With these parameters short weld seam with a length of 5 mm are produced. For the weld spot the pulse duration is set to 3 msec. With this pulse duration a weld depth and width comparable to feed rates of 15 m/min to 30 m/min can be reached. Figure 2 contrasts weld spots with weld seams generated at 15 m/min and 30 m/min.

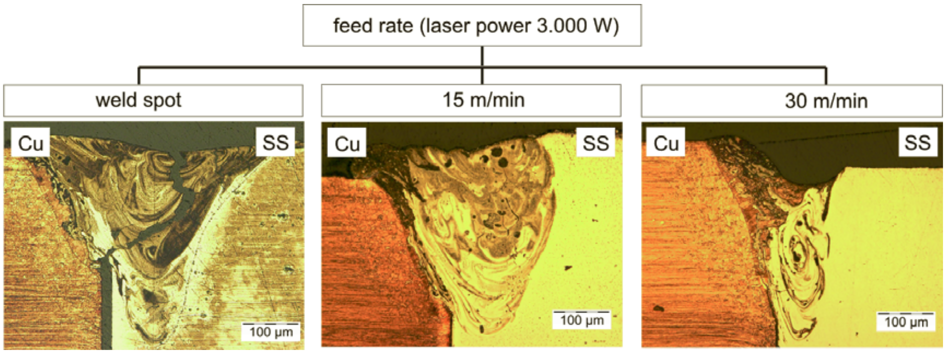


Fig. 2. Metallographic specimen of copper (Cu) and stainless steel (SS) connections at different feed rates; laser power 3.000 W; 3 msec pulse duration for weld spot; centered irradiation

In contrast to welds with a lower feed rate, the lower energy input per unit length at a feed rate of 30 m/min leads to a marginal reduction of the weld depth, whereas the weld width decreases significantly. This effect is caused by a superposition of approximately constant thermal conductivity values of both base materials and a higher process speed, so that the time for heat conduction within the materials reduces. Further more at a feed rate of 30 m/min material ejections out of the weld zone occur, especially at the copper side of the connection. On the analogy to humping-effects at similar material connections that high feed rates result in irregular weld seams with undercuts at the surface, see figure 2. Besides this degradation of the connection’s quality, the joint area of both basic materials also reduces.

In particular, it is important to know, that laser spot welds with no feed rate, which would generally lead to identical geometrical proportions as corresponding weld seams, often cause a crack formation. According to figure 2 these cracks usually range from the middle of the weld spot at the surface to the region where the joint area at the interface of the two dissimilar materials starts. Thereby, the path of crack does not follow any exclusive phase within the weld spot, but crosses the different phases stochastically. For this reason it is probable that these cracks do not derive from hardness increases within the microstructure and accordingly a brittle behavior. To clarify this assumption, micro-hardness evaluations of copper-stainless steel welds are carried out, see figure 3. The hardness traverse within the weld area is almost independent from the applied feed rate. As the stainless steel obviously does not perform any essential phase transformation to a martensitic structure, the hardness values in the weld stay below the level of the stainless steel basic material. Overall no direct relation between the feed rate and the hardness values can be detected. Therefore it is assumed that the reasons for the formation of cracks can mainly be found in the different thermal expansion coefficients of copper and stainless steel, see table 1.

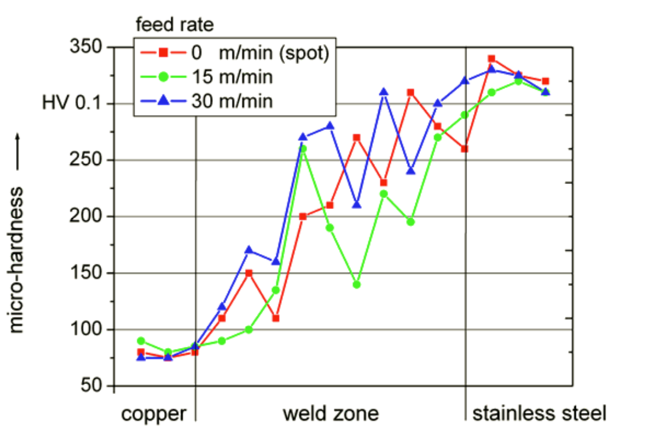


Fig. 3. Micro-hardness evaluations of copper (Cu) and stainless steel (SS) connections at different feed rates; laser power 3.000 W; 3 msec pulse duration for weld spot; centered irradiation; linear measurement at a welding depth of 0.1 mm relative to the surface; intersections (base material – weld zone) standardized

While weld seams feature a certain linear extension, the weld spot is limited to a comparatively little area. In combination with higher cooling-down rates at weld spots the thermal shrinkage produces extensive local strains. At weld seams a larger area is able to shrink and the maximum strains do not concentrate on such a little area as at a weld spot. Besides this fact, the temporal offset from the beginning to the end of a weld seam effectuates a non-simultaneous shrinkage of the molten area. Up to the moment when the last molten volume solidifies at the end of the weld seam the rest of the weld seam has already cooled down. In conjunction with reduced cooling-down rations caused by the higher energy input into the basic materials during seam welding the formation of cracks can be eliminated at feed rates higher than 0 m/min.

### *2.3. Influence of a lateral beam displacement*

In order to reach a maximum mechanical strength and a minimum electrical resistance, the joint area of copper and stainless steel is supposed to be as extensive as possible. However the energy input per unit length is limited to an upper range, as an excessive energy input leads to spilling and an insufficient connection quality. For the joining assembly according figure 1 and a material thickness of 1.2 mm in each case, the upper range of energy input per unit length is about 14 J/mm. Therefore the energy level for the subsequent welding experiments is set to 12 J/mm.

For a compensation of the differences in the melting and boiling points of stainless steel and copper, see table 1, a lateral beam displacement towards the stainless steel seems to be adequate. Though, the absorption of the laser radiation in the applied materials is very different, especially at the beginning of the welding process. At standard conditions and a wavelength of 1064 nm stainless steel absorbs about 35% of the energy input – on the contrary copper absorbs less than 5%. In addition the thermal conductivity of copper is more than 25 times higher than the one of stainless steel. That is why a considerable share of the laser energy is impetuously dissipated away from the welding zone into the base material. As a consequence, a laser beam displacement of 100 µm in the direction of stainless steel leads to a very asymmetric weld with a comparatively large melting range on the steel side, see figure 4. By applying no lateral beam displacement (centered irradiation) and accordingly 100 µm towards the copper base material, the weld zone becomes more and more symmetrical. This effect is caused by shifting the energy input towards the copper, which is the material with the minor absorption rate and the higher thermal conductivity. As a consequence, a higher share of copper is molten and takes part in the welding process. In order to get symmetrical proportions of copper and stainless steel and a maximum joint area, a lateral beam displacement of 100 µm towards the copper base material is recommended. Besides these geometrical aspects, a shifting of the energy input from one base material to the other also changes the element interaction of the weld zone. Depending on the element mixture in the molten state and the cooling-down rate, the hardness traverses in the area of welding changes.

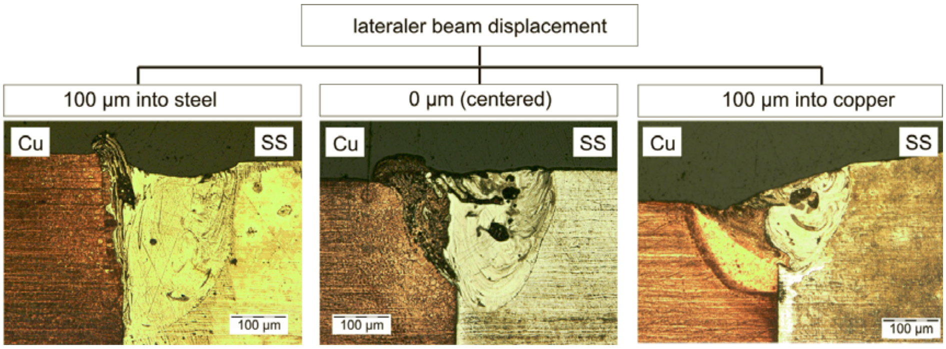


Fig 4. Metallographic specimen of copper (Cu) and stainless steel (SS) connections; energy input per unit 12 J/mm (feed 15 m/min, laser power 3.000 W)

In this context figure 5 shows the hardness values of copper- stainless steel connections with different lateral beam displacements at a welding depth of 0.1 mm relative to the surface in each case. According figure 5 the hardness values of the base materials are about 75 HV for copper and 320 HV for stainless steel. Beam displacements of 0 µm and 100 µm into the copper relocate the beginning of the hardness rising to the middle of the weld zone. In contrast to that, a lateral beam displacement of 100 µm into the stainless steel causes an increasing of the hardness at the fusion line of the copper. This behavior is corresponding to the proportions of mixed based materials, compare figure 4. The more stainless steel attends the welding process, the higher average hardness values in the weld zone appear. Consequently the lowest average hardness traverses can be reached with a lateral beam displacement of 100 µm into the copper. A hardness increase up to higher levels than the stainless steel can not be found. Therefore it can be assumed, that the austenitic stainless steel performs no significant phase transition into martensitic structure during the cooling-down sequence of the welding process. Furthermore, no formation of brittle intermetallic phases can be detected, which often can be found at dissimilar connections with copper [5, 6].

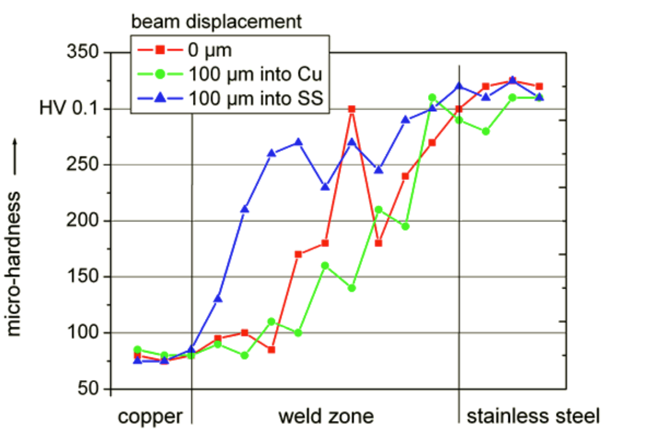


Fig. 5. Micro-hardness measurements of copper (Cu) and stainless steel (SS) connections; linear measurement at a welding depth of 0.1 mm relative to the surface; energy input per unit 12 J/mm (feed 15 m/min, laser power 3.000 W), intersections (base material – weld zone) standardized

The most distinctive fluctuations of the hardness traverse occur at a beam displacement of 0 µm. This effect derives from the most irregular intermixture of copper and stainless steel at a centered irradiation, whereas large coherent stainless steel fractions are randomly mixed with copper. In contrast to this irregular element intermixture at a centered irradiation, a lateral beam displacement of 100 µm into the copper base material causes a steady dispersion of the participating elements in the welding zone. Figure 6 highlights the chemical composition of the welding zone of a copper- stainless steel weld with a beam displacement of 100 µm into the copper base material at a weld depth of 0.1 mm. As the curve progressions for lateral displacements of 0 µm and 100 µm into the stainless steel are very similar, figure 6 only regards a lateral beam displacement of 100 µm into the copper.

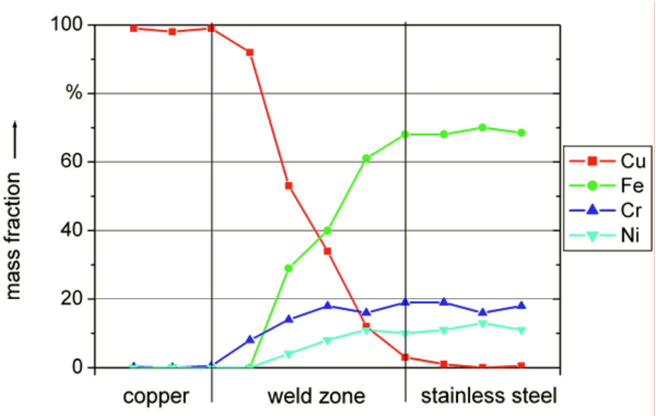


Fig. 6. Element analysis (EDX) of a copper (Cu) and stainless steel (SS) connection, welded with a beam displacement of 100 µm into the copper; linear measurement at a welding depth of 0.1 mm relative to the surface; energy input per unit 12 J/mm (feed 15 m/min, laser power 3.000 W)

While the copper used for the experimental investigations is technically pure, the stainless steel 1.4541 mainly consists of 18 wt-% chrome, 11 wt-% nickel and iron (rest). From the fusion line at the copper side to the one on the stainless steel side, a smooth dispersion transfer can be detected at welds with a beam displacement of 100 µm into the copper. This smooth element changeover from one to the other base material and the corresponding steady hardness traverse lead to copper and stainless steel connections, which reach higher tensile strengths than welds with a lateral beam displacement of 0 µm or 100 µm into the stainless steel.

## 3. Discussion

The quality of laser-welded copper-stainless steel connections can significantly be influenced by a lateral beam displacement and the feed rate. Considering the feed rate, the upper limit for the implied geometry and laser system can be found at 30 m/min. At this speed material ejections out of the molten zone occur and result in disadvantageous undercuts at the surface of the weld seam. On the other hand punctual weld spots with a feed rate of 0 m/min cause a formation of cracks over the whole weld, as such processes feature the maximum cooling-down rates combined with a concentration of the thermal shrinkage on a comparatively little volume. On basis of the experimental researches with the implied joining geometry and laser system, the copper-stainless steel connections of the highest grade of quality can be reached with a feed rate of 15 m/min. By using this feed rate no cracks due to a disadvantageous cooling-down ratio and a concentration of the thermal shrinkage to a minimum area occur. In comparison to faster process speeds a feed rate of 15 m/min does not lead to material ejections out of the melting zone combine with remaining undercuts. For a fixed laser power of 3.000 W the proportion of the weld depth and the weld width can be considered as ideal for the given work-piece geometry in order to get a maximum joint area.

In order to reach a maximum of joint surface and thereby also a maximum of tensile strength and conducting cross-section at a fixed energy input per unit length of 12 J/mm, joining geometry and laser system, a laser beam displacement of 100 µm in the direction of the copper base material can be recommended. In this way the energy input is shifted to the material with the lower absorption rate for the used laser wavelength of 1064 nm and the higher thermal conductivity. As a result symmetrical cross-sections of copper and stainless steel can be reached by a beam displacement into copper and a smooth transit of the element concentrations from one base material to the other follows. Further more the average micro-hardness of welds with a beam displacement into copper are lower than those of welds without a beam displacement and respectively a displacement into the stainless steel.

## 4. Summary and outlook

The present article deals with the influence of the feed rate and the lateral beam displacement on the quality of laser-welded copper-stainless steel connections. By means of metallographic specimen, micro-hardness measurements and element analysis, the generated weld joints are characterized. It is pointed out, that a feed rate of 15 m/min and a lateral beam displacement of 100 µm into the copper base material lead to the connections of the highest quality at a given joining geometry, laser system and energy input per unit. With these parameters no material ejections out of the molten pool occur, as well as no formation of cracks during the cooling-down phase can be detected. Altogether, the implied settings effectuate a symmetrical cross-section of copper and stainless steel and a maximum of joint area, which is important for the mechanical strength and the electrical conductivity of the dissimilar connections.

In the next time, the electrical characteristics of these dissimilar connections in dependency of the feed rate and the lateral beam displacement will be analyzed. In particular, the modification of the contact resistance of the welded connections shall be determined. Hereby measurements instantly after the welding process and after thermal and corrosive long-term strains are planned.

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