Laser Welding of Copper using Multi Mode Fiber Lasers at near infrared Wavelength

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Abstract

Due to the increasing electrification of automotive drives and the expansion of decentralized renewable energy generation, the consumption of copper for the fabrication of electrical components such as electric motors or conducting paths increases. To join these components, laser welding is more frequently used since it represents a flexible and fully automatable joining process. Because of the high thermal conductivity, the low absorption coefficient for infrared wavelength of common laser beam sources and the resulting limited process efficiency, welding of copper alloys represents a major challenge for laser assisted processes. In this paper, experimental investigations are presented to identify arising process limits during laser welding of pure copper materials with multi-mode fiber lasers at near infrared wavelength depending on the applied laser power and welding velocity. In addition, a potential stabilization of the welding process by shielding gas support was examined. Further investigations were focused on the influence of shielding gas on the molten pool geometry.

Keywords: Copper; Laser material processing; Process limit; Shielding gas

1. Introduction

In modern material processing, copper materials are used in a wide variety of applications due to its unique physical properties such as its high thermal and electrical conductivity in combination with its good formability.

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Copper materials are mainly used in the electrical engineering and electronics industry. But, especially for the increasing trends towards electromobility and renewable energies, the physical properties of copper match the requirements concerning on the performance characteristics.

For the processing of copper, a wide range of joining technologies is state of the art, e.g. ultrasonic welding for battery production, hot crimping for electrical engine production and bonding for the electronics industry. Reflecting the trend of the modern industrial production, highly productive and automatable manufacturing processes are required. Fulfilling these requirements, laser welding has already been established in many other industrial applications due to its great flexibility, high degree of automation and the high power density of the laser beam. To apply this technology for joining copper materials, research on several challenges is necessary. In particular, the high thermal conductivity and the low absorption of near and far infrared laser radiation [1] prevent an effective and local defined material processing. At the moment, two different approaches can be observed to solve the above mentioned challenges. It is possible to either increase the absorption by using laser radiation in the green spectral range as well as to increase the laser intensity by using single mode lasers or pulsed lasers.

Nevertheless, the most widely used laser sources in industrial applications are near infrared laser sources with a wavelength of $\lambda_{IR} \approx 1 \mu m$. For this reason, there is a general need for enabling high quality laser material processing of copper by using near infrared laser sources. This paper presents an approach to improve the weld seam quality of copper processed by multi-mode laser radiation. This is achieved by increasing the process comprehension and deriving methods to minimize the appearance of melt ejections and weld spatters as well as explaining the influence of shielding gas on the welding process. In total, the process limits are extended to gain a stable welding process at a wider range of process parameters. Thereby, different welding results can be implemented to meet individual requirements [2].

2. State of the Art

2.1. Welding of copper materials

The main challenges during fusion welding of copper materials are the high thermal conductivity and the high specific heat capacity. A particular challenge for laser welding is the high wavelength dependency of the absorption coefficient of copper [1]. E.g. for a wavelength of $\lambda_{IR} \approx 1 \mu m$ only 5–15 % of the applied laser power is absorbed by the material depending on the temperature [3]. Due to these material properties only a small proportion of the total emitted laser power is available for the process. Therefore, pulsed lasers with high peak intensities are currently often used for welding of copper materials [4–6]. Using this pulsed radiation, fast melting with low heat dissipation is possible, which consequently increases the degree of absorption since the coefficient of absorption is dependent on the temperature. However, pulsed laser welds are limited in penetration depth and require long processing times. The development of high brilliance laser beam sources and lasers with shorter wavelengths offers new opportunities for an energy efficient laser welding of copper.

Currently, to increase the degree of absorption for laser welding of copper, two different determining factors are mainly considered: The laser intensity and the coefficient of absorption. These factors and the methods to improve the energy absorption are summarized in Tab. 1.

| Variable                  | Method                                                                 |
|---------------------------|------------------------------------------------------------------------|
| Intensity $I_L$ (Laser power per unit area) | • Increasing the laser power of infrared multi mode laser radiation  |
|                           | • Increasing the peak intensity (pulsed lasers)                        |
|                           | • Increasing the peak intensity by using single mode laser radiation  |
| Coefficient of absorption $\alpha$ | Increasing the absorption by using laser radiation with green wavelength ($\lambda_{green} \approx 0.5 \mu m$) |

In several scientific publications, various approaches have been investigated regarding these variables. The broadest knowledge base is available for the use of laser radiation in the multi-kW range at infrared wavelength
(λ_{\text{IR}} \approx 1 \text{ μm}). By using high laser powers of $P = 10 \text{ kW}$ penetration depths of up to 10 mm could be realized \cite{7, 8}. A stable welding process depending on the feed rate and the laser power is constrained by two limits. On the one hand, it is limited by the deep penetration threshold, since at this limit heat conduction welding occurs. On the other hand, there is a limitation due to the occurrence of weld seam defects, such as pores and melt ejections. The laser power $P$, the feed rate $v$ and the spot diameter $d$ are considered as the major factors of influence on the process stability \cite{9}.

The formation of melt ejections was examined by \cite{10} using high-speed X-ray images. At the beginning of the welding process a narrow and straight keyhole is observed. During welding with a certain feed rate the tip of the keyhole begins to bend against the welding direction and a vapor bubble is formed. The formation of the bubble was explained by an increased absorption and vaporization caused by the bending of the keyhole. This bubble pushes against the liquid material in direction of the sample surface, which leads to a swelling of the weld seam surface, until the pressure created by the bubble is higher than the surface tension of the melt pool. After passing this critical point, almost the whole molten material is ejected.

A stabilization of the keyhole and therefore a reduction of melt ejections was achieved by a modulation of the laser power during welding \cite{11}. Additionally, the quality of the weld seam surface was improved due to the influence on the weld pool dynamics, but at the same time an increased number of pores in the weld seam were caused.

High peak intensities were addressed by the use of pulsed laser systems \cite{5, 6}. Another method to achieve high peak intensities is the use of single mode fiber lasers with maximum intensities of up to $10^{12} \text{ W/cm}^2$ \cite{12, 13}. In scanner-based remote laser welding, high-frequency beam oscillations are often used to adjust a specific weld geometry \cite{14, 15}.

A current development is the use of laser radiation with green wavelength ($\lambda_{\text{green}} \approx 0.5 \text{ μm}$). An increase in absorption comes with shorter wavelengths, as the coefficient of absorption increases. However, currently available continuous wave laser sources are limited to a laser power of less than $P = 300 \text{ W}$. In \cite{2} a comparison between green and infrared laser radiation is reported. To achieve the same penetration depth, only 30–50% of pure infrared laser power was required when using green radiation. Therefore, often a hybrid approach is pursued to reduce the required laser power compared to the application of pure infrared laser radiation \cite{13, 16, 17}. \cite{18} also suggests a hybrid approach during micro welding with pulsed lasers. The potential of green laser beam sources could be demonstrated, but available systems do not yet have the necessary performance level for a broad industrial application. Hybrid systems already improve the efficiency, but require an additional effort in systems engineering.

### 2.2. Manipulation of the weld pool geometry

\cite{19} shows that the geometry of the molten pool depends on the heat transfer in the material. Besides heat conduction especially heat convection in the liquid phase has to be considered. The flow of the liquid material could increase the width of the molten pool, if there is a flow on the surface directed outwards from the keyhole. By reducing this drift, the geometry of the pool becomes deeper and narrower \cite{20}. In addition to the fluid flow around the keyhole and the flow driven by the pressure of the vapor in the keyhole there are other effects which have an influence on the flow of the liquid copper. For example, there is also an influence of the gradient of the surface tension on the convection in the liquid phase on the upper surface of the welding pool. By the use of process gas the surface tension and therefore the weld pool geometry could be modified \cite{20}. For copper materials \cite{21} reported a decline of the surface tension if no shielding gas is used. He stated copper oxidation as the reason.

Especially with conventional welding processes, such as the tungsten inert gas welding (TIG), the use of shielding gas is an essential process variable. The inert gas is used not only for the protection of the component and the electrode tip from atmospheric gases, but is also applied to achieve different weld seam geometries and penetration depths \cite{22}. In this context, an important parameter is the heat conductivity of the shielding gas, which does not only affect the current density within the shielding gas during TIG, but also the resulting shape of the weld seam and the temperatures occurring in the work piece. As an inert gas with high heat conductivity, helium is often used as shielding gas because of its positive effect on the weld seam geometry \cite{23}.
3. Objectives and Approach

The broadest knowledge base is available for infrared lasers, since they have the widest distribution in the industry. As shown above, there is still a need to improve the process stability during laser welding of copper materials. Therefore, there is a high demand for further investigations on this process using lasers with infrared wavelength. In these investigations the process limit between the region without weld seam defects and the region of melt ejections is identified by welding experiments and an analysis of the weld seam surface. Furthermore, the course of the process limit is explained by the weld seam geometry.

By considering the advantages of the use of helium during TIG it will be clarified, whether helium could positively influence the process stability during laser welding of copper materials. Hence, experiments are conducted to investigate the effect of helium as shielding gas on the process limit and on the weld seam geometry.

4. Experimental Setup

As listed in Tab. 1, an increase of the laser power per unit area or the energy per unit length are possible approaches for welding copper materials. The experimental setup allows varying the laser power, the welding velocity and the focus diameter. In order to achieve the required high laser powers, a multi mode fiber laser of type YLR-8000 from IPG Laser GmbH with a maximum output power of 8 kW was used during the experiments. With these high laser powers and the resulting high intensities the coupling of laser radiation into copper materials as well as the formation of a keyhole for deep penetration welding was possible. For this application a fixed optics of type BIMO from the HIGHYAG Lasertechnologie GmbH with an aspect ratio of 1:1 was used. In combination with the laser fiber with a core diameter of \( d_c = 200 \, \mu m \) a focus diameter of \( d_f = 200 \, \mu m \) was attained. The optics was mounted on an industrial robot from KUKA AG. The welding motion was carried out by the movement of a linear axis, which supports welding velocities in a useful range for copper welding given by [9] and enables a fixed process region for simplified process monitoring. Fig. 1 shows the experimental setup as well as the important process parameters of the performed investigations.

![Fig. 1. Process parameters (left) and experimental setup (right).](image)

| Parameter          | Value | Unit |
|--------------------|-------|------|
| Max. laser power   | 8     | kW   |
| Wavelength         | 1070–1080 | nm   |
| Focus diameter     | 200   | \( \mu m \) |
| Intensity profile  | Top hat |      |
| Welding velocity   | 5–15  | m/min |

In addition to the parameters of the laser welding process, the properties of the copper material are essential for the experimental investigations. In order to have a comparability of the experiments, the oxygen-free copper material CW008A was chosen for all investigations. Tab. 2 summarizes the most relevant properties of this material. It is fundamental to ensure the use of bright specimen surfaces without oxidation, to guarantee a constant absorption coefficient. Segments with a width of 30 mm and a thickness of 5 mm were used as specimens. All experiments were performed as bead on plate welds with a weld seam length of 25 mm.
Table 2. Properties of CW008A.

| Property               | Symbol | Value | Unit    |
|------------------------|--------|-------|---------|
| Density                | $\rho$ | 8.94  | g/cm³   |
| Melting temperature    | $T_m$  | 1083  | °C      |
| Electrical conductivity| $\gamma$ | 58   | m/(Ω*mm²) |
| Thermal conductivity   | $\lambda$ | 394 | W/(m*K) |
| Specific heat capacity | $c_p$  | 385   | J/(kg*K) |

5. Results and Discussion

5.1. General Process Limits

In order to evaluate the weld seam quality for different experimental parameters the laser power as well as the welding speed were varied. Based on [9], the samples were analyzed and separated into two groups according to occurring melt ejections and ejection free weld seams. As displayed in Fig. 2, the parameter range can be separated into two areas, while the grey area represents the process limit. Left of the process limit the area of irregular melt ejections throughout the whole weld seam is indicated. The cross sections of these samples show holes which extend towards the entire weld seam depth. On the right side of the process limit, high quality weld seams can be produced without any defects visible in the cross sections and on the weld seam surface. Referring to the parameter combinations in the process limit region, no representative conclusion can be drawn, since it was not possible to obtain a reproducible weld seam quality. For laser powers between $P = 3$ kW and $P = 4$ kW the process limit is analogue to the results obtained by [9]. With an increasing laser power a higher welding speed is necessary to avoid melt ejections and weld spatters. In contrast, for laser powers between $P = 4$ kW and $P = 8$ kW a contrary trend was observed.

![Fig. 2. Process limit for occurring melt ejections.](image)

For a further analysis of the mechanisms causing the observed melt ejections and weld spatters, the welding process is observed with a high speed camera. Using this method it was possible to capture a melt ejection in a sequence of pictures. In Fig. 3 this sequence is given. In the first picture, the welding process and the keyhole can be seen. In the next time frame, the keyhole is becoming unstable and a weld spatter is being formed, which can be seen in the third picture. In the fourth picture, the melt has already been ejected and a hole remains in the weld seam. After the ejection a new keyhole is formed, as displayed in the fifth picture. The last image is equivalent to the first
picture and thus it can be assumed that the weld spatters are created in a time span of approximately $t = 10$ ms. Additionally, this process explains the occurring holes in the welding seam.

![Melt pool with keyhole, Start of melt ejection, Melt ejection, Hole in the formed weld seam, Formation of a new keyhole, Melt pool with keyhole](image)

Fig. 3. High speed camera images show the formation of a melt ejection.

To explain the course of the process limit in Fig. 2, a full factorial experimental design was created. A linear regression is used to model the welding seam depth (model quality $R^2 = 0.99$) and the cross section area ($R^2 = 0.98$) as a function (2nd degree polynomial) of the welding speed and the laser power. In Fig. 4, the results are indicated by solid lines, which represent isolines of equal penetration depths (left) and seam cross sections (right), calculated for the corresponding laser power and welding velocity. For both diagrams a similar course can be observed. At faster welding velocities an increased laser power is necessary to obtain the same penetration depth and seam cross section.

![Penetration depth $t$ and Seam cross section $Q$](image)

Fig. 4. Penetration depth $t$ and seam cross section $Q$ estimated by regression models.
In Fig. 4, a contrary trend for the process limit can be seen between the laser powers $P < 4$ kW and $P > 4$ kW. An explanation can be derived from two publications. [8] explained the influence of the welding velocity on the formation of a vapor bubble, whereas [10] explains the rise of the melt ejection due to a vapor bubble. Based on these theories, melt ejections can only occur at a minimum welding depth. Otherwise not enough molten material is available to enclose the vapor bubble. With respect to the process presented in this paper, it can be assumed that for welding depths $t < 1.25$ mm the formed keyhole is not deep enough for melt ejections and weld spatters to occur. For laser powers $P_L > 4$ kW the process limit shifts towards slower welding speeds for increased laser powers. As calculated by the regression model, the welding seam depth and the area increase along the process limit. This causes an increasing volume of the molten material and of the ejected melt, respectively. An increased melt drop volume requires a higher energy and vapor pressure for an ejection. The observed shift in the process limit towards slower welding speeds can therefore be explained by the increasing penetration depth.

5.2. Influence of Shielding Gas on the Process Limits

To investigate the influence of helium on the occurrence of melt ejections, two series of experiments were carried out. In these experiments, the welding velocity was gradually decreased to the region of melt ejections. Fig. 5 displays the experimental parameters for these investigations at the laser powers $P = 6$ kW and $P = 8$ kW as well as images of the resulting weld seams.

![Fig. 5. Weld seams without melt ejections at $P = 8$ kW (left) and $P = 6$ kW (right) by the use of helium as shielding gas.](image)

Although the experimental parameters are clearly located in the area of melt ejections, it can be seen in the images that no weld defects occurred during all the referred experiments. Thus, a shift of the above described process limit in direction towards lower welding velocities is possible and consequently an increase of the region without melt ejections is achieved by the use of helium as shielding gas.

Based on the observation that a wider weld bead could be noticed, it was assumed that helium affects the weld seam geometry. Therefore, experiments with ten different parameter settings spread over the region without weld seam defects were carried out. Thereby each parameter combination was welded with and without the use of helium. After the experiments, cross sections of the weld seams were prepared and the penetration depth $t$, the weld bead width $b$ and the cross section area $Q$ were measured. The results of these investigations are summarized in Fig. 6. To evaluate the experiments, the measured geometries of the weld seams generated by the use of helium are considered in relation to the measurements on weld seams welded without shielding gas. Fig. 6 shows the comparison of these measurement results for the penetration depth, the weld bead width and the cross section area. The result of each weld seam created with the use of helium was normalized by the corresponding result obtained
without shielding gas. In all three comparisons there is a significant difference in the geometry. The welding depth decreases on average by 15% by the use of helium. At the same time the weld bead width increases by 25%. Therefore it can be noted that helium as shielding gas causes a change in the weld seam geometry. These results confirm the observations of a wider weld bead.

Another effect shown by the evaluation is the decreasing cross section area, which decreases by an average of 20% by the use of helium. This leads to the conclusion, that through the use of helium a lower energy input is obtained or the high heat conductivity of the gas causes a greater energy dissipation.

Fig. 6. Comparison of the weld seam geometries welded with helium and without the use of a shielding gas.

**Explanation of the influence of the shielding gas on the weld seam geometry**

The surface tension of molten copper decreases with increasing temperature [21]. Hence, the surface tension of the liquid phase increases from the keyhole to the outer edge. This causes a force in the liquid in direction towards the outer edge of the melt pool, so that convection is established. Without the use of a shielding gas, the copper oxidizes caused by oxygen in the ambient air. This induces a drop of the surface [21], so that the moving force of the convection declines. Consequently, in absence of a shielding gas the liquid copper oxidizes, which reduces the driving force of the convection and therefore the pool geometry becomes narrower and deeper (Fig. 7 left). With the use of a shielding gas, the driving force of the convection is stronger, so that the molten pool becomes wider and flatter (Fig. 7 right).

Fig. 7. Cross sections of weld seams welded at \( P = 6.5 \) kW and \( v = 9 \) m/min without protection gas (left) and with the use of helium (right).

Fig. 6 shows also an influence of the shielding gas on the seam cross section. By the use of a shielding gas the seam cross section is reduced, which indicates that the deposited energy in the copper is lower. This could be
explained by the increased heat dissipation on the surface of the copper caused by a forced convection which is established by the use of a shielding gas that is blown onto the interaction zone. In the absence of a shielding gas there is only a free convection apart from ambient radiation. Hence, the dissipated energy in the copper is decreasing, if the moving shielding gas detracts more energy of the interaction zone than the ambient air.

Explanation of the influence of the shielding to the process boundary

The shift of the process boundary by the use of helium could be explained by two effects. Firstly, the helium influences the convection of the liquid phase, which results in a flatter and wider seam cross section. Therefore, the surface area of the welding pool increases. Consequently, the volume of the vapor bubble has to be bigger until the critical point is reached. Thus, the energy input has to increase, since more material has to vaporize. The second influence of helium is caused by the change of the surface tension. By the use of a shielding gas there is no oxidation of the copper material, which results in a higher surface tension. Therefore, the recoil pressure in the bubble has to be higher until the critical point is achieved. analogue to the bubble volume the energy input has to increase to enable a higher pressure.

6. Summary and Outlook

In conclusion, a certain process limit for welding of copper materials could be identified. It is shown that the process limit separates the investigated parameter range of laser power and welding velocity into two regions. While for smaller welding velocities melt ejections and melt spatters occur, higher welding velocities produce high quality weld seams without pores visible in the cross sections. It is shown, that the use of helium as shielding gas has an influence on the welding process. A shift of the above described process limit in direction towards lower welding velocities results in an increase of the region without melt ejections due to the use of helium as shielding gas. In addition, it is shown that helium has an influence on the weld seam geometry. With the use of helium, the penetration depth and the cross section decrease, whereas the seam width increases. An explanation is given for the rise of the melt ejections and the influence of helium on the welding process, which is derived by a change of the surface tension and the heat dissipation.

Further investigations will focus on the influence of other process variables, e.g. the focus position, on the process limit and the quality of the weld seam surface. As it could be shown that the use of helium has an influence on the welding process, it should be clarified whether the use of a shielding gas could improve the energy efficiency of welding copper materials by implementing considerations of efficiency.

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