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Influence of filler wires on weld seam properties of laser beam welded dissimilar copper connections

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Abstract

Due to its high thermal conductivity and corrosion resistance, copper and its alloys are often used for components of heat exchangers and pipe applications. These material properties results in a need of high energy densities for fusion welding which are provided by laser beam welding, for example. Here the small focal diameters lead to high energy densities and high thermal gradients. This offers the chance for a locally limited heat input and high welding velocities. However, a disadvantage of laser beam welding is the low gap bridging capability due to the small focal diameters.
A solution for this problem which is already applied for laser beam welding of aluminum and stainless steels is the use of filler wire. Thus this paper investigates the influence of copper filler wires on resulting weld seam properties of laser beam welded dissimilar copper alloy connections. At first the influence of welding velocities on weld seam properties for different gap sizes is investigated. Moreover the effect of different diameters of filler wires on weld seam geometries is determined. Here the resulting weld seam properties as geometrical shape and surface structure of the weld seams are analyzed. Besides this the mechanical and electrical properties of the welded connections are determined by means of tensile tests and four-point resistance measurements. According to the obtained results, the use of pure copper filler wire avoids seam and root collapse of the welded joints, decreases the electrical resistance of the welded components and improves the tensile strength and strain of the welded connections.

Keywords: Macro Processing; Joining; Welding

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1. Introduction

Copper is used in many technical applications due to its high thermal and electrical conductivity and corrosion resistance. Besides automotive industry, where pure copper is used in electronic drives, power electronics and wiring harness, the material is also used in heat exchangers and pipe applications in heating systems. If higher mechanical requirements have to be fulfilled, adding alloying elements such as tin or zinc is applied, in order to increase tensile strength, whereas electrical and thermal conductivity is reduced simultaneously. Wieland Werke 2015, Deutsches Kupferinstitut (DKI) 2015 When pure copper as well as copper alloys have to be joined by means of conventional welding processes some difficulties occur. Due to the high thermal conductivity of copper a high energy input per unit length is needed to melt the material and is often realized by low welding velocities. As a consequence of the high energy input, the width of the heat affected zone is enlarged and, in combination with the high thermal expansion coefficient of pure copper, severe welding distortion occurs. This distortion is accompanied by an increasing width of joining gaps due to the heating of the material prior to the welding process, which can be counteracted by the use of filler wires in conventional welding processes, e.g. tungsten arc welding or metal inert gas welding.

In contrast, laser beam welding offers high energy densities, resulting in small heat affected zones and low welding distortion. Consequently for welding copper higher welding velocities can be reached and welding cycle times are reduced. Up to now, laser beam welding of copper is carried out without the use of filler wire and thus the permissible width of joining gaps is limited to small values. Here filler wires can contribute to a higher gap bridgeablity in laser beam welding of copper. Furthermore filler wires are known to have an influence on weld seam geometry and mechanical properties of the joints in laser beam welding of dissimilar stainless steel connections and other metal combinations. Weigl 2014 Therefore this paper investigates the influence of filler wires on gap bridging ability and the resulting weld seam properties of laser beam welded dissimilar copper connections. In this context weld seam properties are characterized by the weld seam surfaces, the geometry of the cross-sections, the uniaxial tensile strength and the electrical resistance.

2. State of the art

2.1. Welding of pure copper

The absorption of copper for infrared wavelength at room temperature is low. Heider et al. 2011 Consequently, especially the initial phase of laser beam welding, when the material heats up to melting temperature, reflection is high and absorptions is low, is critical. Hence there are different approaches to increase absorption and stabilize the process during this initial phase. As the absorption of copper at room temperature is higher for wavelengths in the range around 500 nm Hess et al. 2011 shows an increase of absorption for infrared laser radiation, if a low-power second harmonic laser is used preliminary to the infrared beam. In this case the second harmonic beam is adjusted with a temporal or spatial offset in order to melt the material before the infrared beam reaches the work piece. Furthermore Heider et al. 2011 shows stable welding results for laser beam welding of pure copper, if intensity is increased by means of smaller focal diameters at constant laser power. This approach takes advantage of the high thermal gradients and higher velocities, reachable for welding with small focal diameters. Besides this there are approaches to increase absorption of copper at room temperature by oxidizing or roughening the surfaces, as multiple absorption of laser radiation is supported by oxide layers and rough surfaces. Bergström 2008, Glasmacher 1998 Corresponding results are published by Moalem et al. 2012 for pulsed laser beam welding and by Mann 2015 for continuous wave laser beam welding of copper.

After passing the initial heating phase the material is molten and welding phase is reached. Especially in deep penetration welding of copper, when a capillary is formed by metal vapor, weld spatters and melt ejections are likely to occur. Severe melt ejections induce holes within the weld seam, can cause short circuits in electronic components and are classified as undesirable process instabilities. Heider et al. 2011 For this reason Heider et al. 2011 investigates the effect of laser power modulation on the occurrence of these process instabilities using a sinusoidal input signal generated by an external function generator and superimposed on laser power signal with the aim of maximizing the cross-section area. By means of this technology, a reduction of the number of process instabilities as well a constant welding depth is achieved. Further investigations of Heider et al. 2014 determine the effect of high laser power provided by infrared beam sources for laser beam welding of copper. In these investigation Heider et al. 2014 detects a process window for a stable welding process for pure copper without power modulation or the necessity for a second harmonic beam source. According to these investigations, a stable laser beam welding process with welding depths over 3 mm in pure copper is achieved, if laser power and welding velocities are set to high values (laser power ≥ 10 kW; welding velocity ≥ 9 m/min). Nevertheless there are still no investigations on using filler wires for laser beam welding of copper.

2.2. Welding of copper alloys

Depending on respective requirements, the material properties of copper have to be adjusted by the addition of different alloying elements such as tin or zinc for specific applications. Both alloying elements increase tensile strength and hardness of the materials in comparison to pure copper with increasing alloy content. Simultaneously the electrical and thermal conductivity as well as the reflection for infrared wavelengths at ambient temperature of the materials decreases. For this reason the weldability is improved especially for copper-tin alloys. Deutsches Kupferinstitut (DKI) 2015

As for pure copper, Hess et al. 2011 reduced the number of weld imperfection in CuSn6 bead on plate welds, by using a preliminary second-harmonic low power laser beam. In comparison to pure copper the relative reduction of the number of melt ejections per unit length was found to be higher for CuSn6 by applying this method. Moreover Heider et al. 2011 reduced the formation of pores at the root of CuSn6 bead on plate weld seams by applying a superimposed laser power modulation. Both authors confirm a better weldability and less weld imperfections in case of CuSn6 compared to pure copper.

In contrast the weldability of copper-zinc alloys is dependent on the amount of zinc. This is caused by the low evaporation temperature of zinc of about 1,180 K, whereas the melting temperature of copper is about 1,360 K. Consequently the evaporation pressure is already high, if the melting temperature of brass is reached. This situation is exacerbated by an increasing zinc-content. Due to the high evaporation pressure the length of the keyhole increases with increasing welding velocity and severe melt ejections as well as weld spatters occur during laser beam welding of brass. Hugger et al. 2014

Up to now there are no investigations in case of laser beam welding of dissimilar copper connections and the influence of pure copper filler wires on weldability of brass and bronze. Thus these issues are investigated within this paper.

3. Experimental setup

The laser source for the welding experiments was disk laser with a maximum output power of 4 kW, a beam parameter product of 8 mm x mrad, a diameter of the core fiber of 200 µm and a wavelength of 1,030 nm. For focusing and guiding the laser beam a Trumpf PFO 33 was used in combination with a focusing length of 255 mm and a resulting focal diameter of 340 µm. All experiments are performed in butt joint configuration, with the focal plane on the surface of the specimens, a constant laser power of 3,800 W, without shielding gas and under a lateral angle of incidence of 10°, in order to protect the optics from reflected laser radiation. The filler wires are drawn wires made of Cu-OF with diameters of 0.5 mm and 1.0 mm. During the experiments two different welding velocities (2.5 m/min or 3.5 m/min) and gap sizes (0.0 mm and 0.3 mm) are investigated. Three base materials, Cu-OF, CuSn6 and CuZn37, with a sheet thickness of 1 mm are shear-cut to quadratic specimens with an edge length of 50 mm and welded in as-rolled condition. Table 1 contains a selection of relevant material properties of the used materials.

Table 1. Selection of material properties of copper alloys Cu-OF, CuSn6 and CuZn37 at room temperature Wieland Werke 2015, Deutsches Kupferinstitut (DKI) 2015, Mann 2015

Material property and unit	Cu-OF (CW008A)	CuSn6 (CW452K)	CuZn37(CW508L)
Alloy components in %	Cu 99,95; rest ≤ 0,05	Cu 92,40 – 94,49	Cu 62,00 – 64,00
		Sn 5,50 – 7,00	Zn 36,00 – 38,00; rest ≤ 0,10
		P 0,01 – 0,40; rest ≤ 0,20	
Absorption in as rolled condition for 1064 nm	18.55 %	26.85 %	24,54 %
Lattice structure	cubic-face-centered	cubic-face-centered	cubic-face-centered
Melting temperature in K	1360	1193	1323
Heat conductivity in W x m^{-1} x K^{-1}	394	75	120
Thermal expansion coefficient in K^{-1}	17,7 x 10^{-6}	21,8 x 10^{-6}	24,0 x 10^{-6}

The dented edge of the specimens is positioned upwards and rolling direction was perpendicular to the welding direction. All weld seams are 45 mm long and the filler wire is positioned manually before the start of the welding process. Figure 1 shows the set up used for the welding experiments.

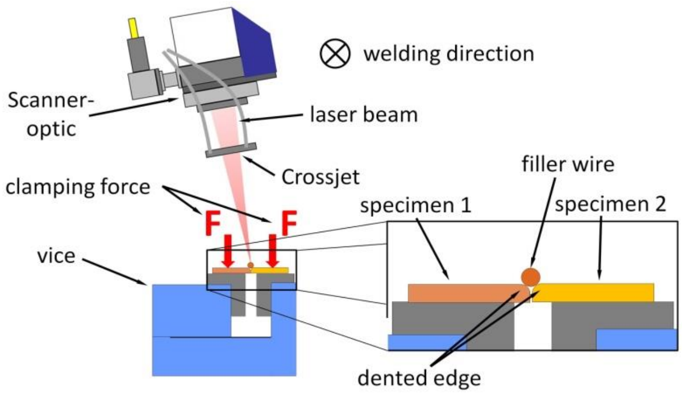

Figure 1. Set up used for the welding experiments

4. Results and Discussion

4.1. Weld seam geometry

The use of filler wire has a significant influence on the geometrical shape of the weld seams, which can be illustrated by means of three examples shown in Figure 2. The three samples in the upper row of Figure 2 are welded without filler wire, whereas the three samples in the lower row are welded with Cu-OF filler wire (Ø 1 mm).

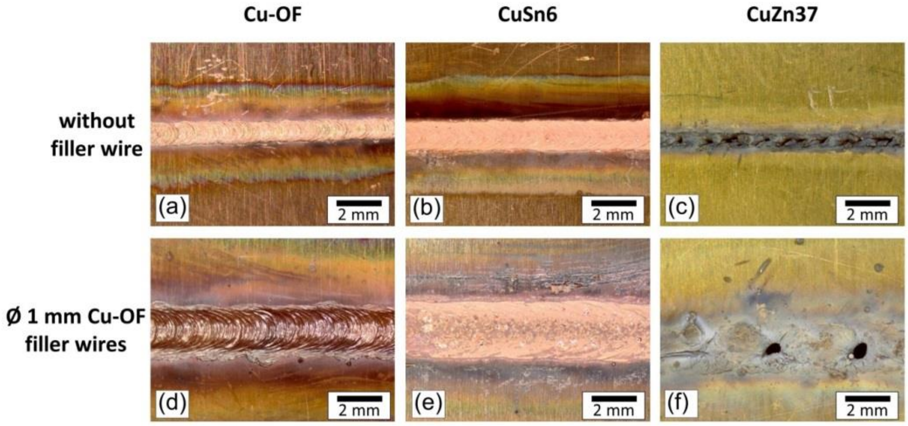

Figure 2. Top views of similar copper alloy weld seams in butt joint configuration: Upper row: welded without filler wire: (a) Cu-OF, (b) CuSn6, (c) CuZn37; bottom row: welded with filler wire (Ø 1 mm): (d) Cu-OF, (e) CuSn6, (f) CuZn37; all: lateral angle of incidence 10°, laser power 3,800 W, gap-width 0 mm, welding velocity 2.5 m/min

Due to the higher heat conductivity of Cu-OF, the temperature gradient alongside the weld seam in Figure 2 (a) is smaller compared to the gradient of CuSn6 in Figure 2 (b). This is accompanied by a smaller width of the heat-affected zone which can be estimated by analyzing the width of annealing colors. In contrast to Figure 2 (a) and (b) the weld joint in Figure 2 (c) is characterized by numerous holes, resulting from spatter due to high vapor pressure of evaporating zinc in case of welding CuZn37. The use of filler wire results in an increase of the weld seam width independent of the base material, as shown in Figure 2 (d) - (f). Additionally, the irregularity of the weld seam edge is increasing for Cu-OF (Figure 2 (d)), caused by the melt sloping over on the surface of the base materials during the welding process. A comparison of Figure 2 (c) and Figure 2 (f) shows an advantageous effect of Cu-OF filler wire on welding CuZn37: The number of holes is reduced significantly, although the size of holes increases. Nevertheless the connected length is more than six times higher in case of using filler wire. This effect can be explained by the lower zinc content of the melt caused by the use of pure copper filler wires.

In order to determine the influence of filler wire on the weld seam geometry for different base materials, the variation of the weld seam width on the upper surface of the base materials *Δw* is calculated using Equation (1). For this purpose the values w_{max} (maximal width of the weld seam) and w_{min} (minimal width of the weld seam) are determined as illustrated in Figure 3 (a).

$$\Delta w = \frac{2 \cdot (w_{\max} - w_{\min})}{w_{\max} + w_{\min}} \qquad (1)$$

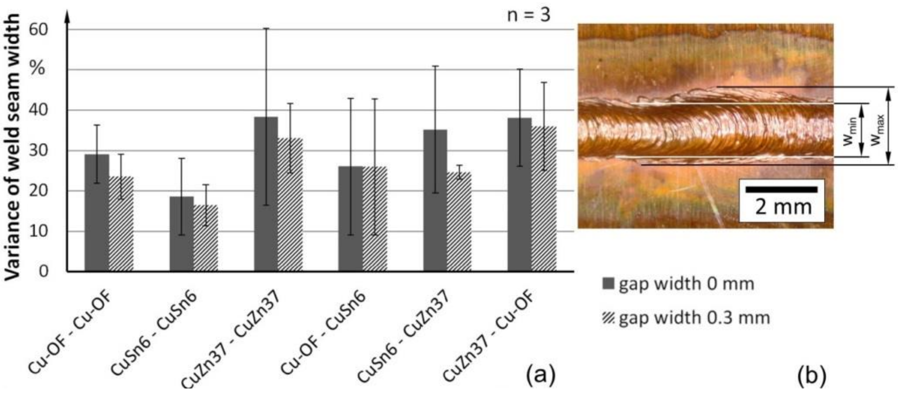

Figure 3. (a) Comparison of the variances of the weld seam width for similar and dissimilar copper joints, (b) principle of the determination of the minimal and maximal weld seam width all: welded with Cu-OF filler wire (Ø 1 mm), lateral angle of incidence 10°, laser power 3,800 W, welding velocity 2.5 m/min

According to Figure 3 (a), a gap width of 0.3 mm reduces the average variance of the weld seam width as well as the standard deviation of the width of the weld seams. Comparing the variations of the weld seam width of similar joints for different copper alloys, the smallest values are determined for Cu-OF followed by CuSn6. The high variance of the weld seam width of CuZn37 can be explained by higher melt pool dynamics due to high evaporation of zinc which leads to an irregular melt flow to the side of the weld pool and a non-uniform edge of the weld seam. The analysis of the variance of the weld seam width of the dissimilar joints shows values lying in between the initial values of the similar joints for the corresponding copper alloys.

Figure 4 illustrates the influence of the welding process on the base materials and grain structure in case of Cu-OF. Here Figure 4 (a) shows the base material as a reference for the comparison of the weld seams. The comparison of the pictures of the cross-sections of the two joints welded with filler wires of different diameters indicates a higher weld seam width for filler wire with a diameter of 1 mm although the energy per unit length was held constant for all joints presented in Figure 4. This effect is caused by an increase of absorption and a reduced transmitted proportion of the laser radiation due to the use of filler wire and the higher material thickness, which has to be passed by the laser beam during the process. Besides this the use of filler wire induces notches on the root sides of the weld seam at the transitions from weld seam to heat affected zones, which will probably deteriorate the tolerable dynamic stress of the welded joint. Since no filler material is used in Figure 4 (b), root sagging and seam collapse can be identified at the bottom and the top of the joining partners, respectively. Using filler wire the cross-section area of the weld seams is enlarged and root collapse turn into weld reinforcement, which is small for filler wires with a diameter of 0.5 mm and large for a diameter of 1.0 mm while root sagging is nearly constant for all weld seams.
Consequently Figure 5 shows the effect of varying welding velocities on the height of the resulting weld reinforcement. Except for the similar connection of CuZn37, the heights of the weld reinforcements are increasing with increasing welding velocities due to the lower energy input per unit length. As seam collapse is considered as negative weld reinforcement, the columns of the joints including CuZn37 differ a lot and standard deviations are high which can be explained by the uneven surfaces resulting from high process dynamics. The lower heat conductivity of CuSn6 and CuZn37 and the changes in melt pool dynamics cause smaller weld reinforcement, since there is more time for the melt to cool down and, due to gravity, disperse uniformly over the weld seam width.

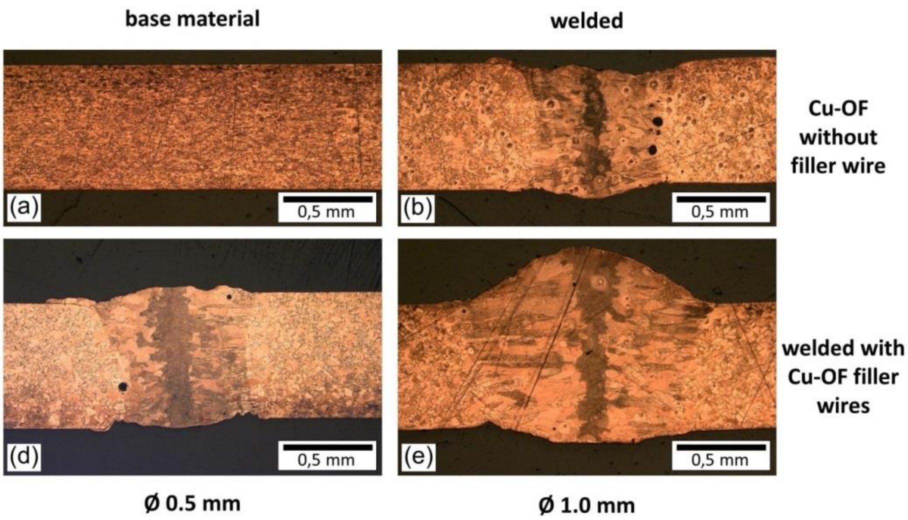

Figure 4. Cross-sections of similar copper weld seams in butt joint configuration: Top row: Cu-OF without filler wire: (a) base material, (b) welded; bottom row: Cu-OF welded with filler wire (c) Ø 0.5 mm, (d) Ø 1.0 mm; all: lateral angle of incidence 10°, laser power 3,800 W, gap-width 0 mm, welding velocity 2.5 m/min

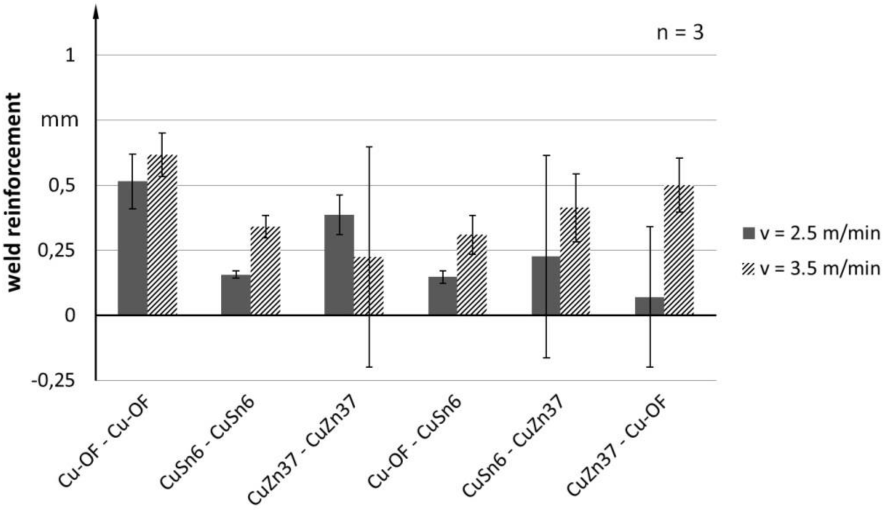

Figure 5. Comparison of weld reinforcements for similar and dissimilar copper joints at different welding velocities; welded with Cu-OF filler wire (Ø 1 mm), lateral angle of incidence 10°, laser power 3,800 W, gap-width 0 mm

4.2. Electrical resistance

In addition to the geometrical shape of the welded joints, copper joints are often evaluated with regard to the electrical resistance, especially for electronic applications, e.g. high power electronics. For this reason the electrical resistance of base material as well as welded joints is measured and presented in Figure 6 for a distance of the measuring points of 46 mm. As standard deviation is less than 0.2 x 10^{-5} Ω for all measurements it was omitted in Figure 6. Here the lowest electrical resistance is determined for Cu-OF, followed by CuZn37 and CuSn6. In case of Cu-OF electrical resistance is similar for base materials and welded connections, whereas the higher electrical conductivity of the Cu-OF filler wires is indicated by a decrease of the electrical resistance for CuSn6. Meanwhile for CuZn37 the influence of holes and melt ejections detected in the top views in Figure 2 is low compared to the influence of zinc as alloying element which results in a variation of the electrical resistance of the weld seams without a significant trend.

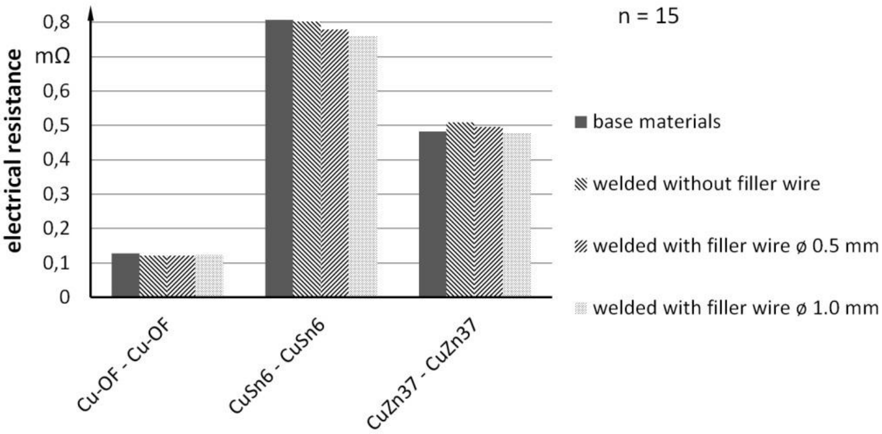

Figure 6. Electrical resistance of base materials and similar weld seams in butt joint configuration for different copper alloys; lateral angle of incidence 10°, laser power 3,800 W, gap-width 0 mm, welding velocity 2.5 m/min

4.3. Tensile tests

In order to determine the mechanical properties of the welded joint uniaxial tensile tests according to DIN EN ISO 6892-1 and DIN EN ISO 4136 are carried out. For this purpose flat tensile test specimens (DIN EN ISO 50125 form H 6.1 x 24.2) are prepared. The resulting stress-strain diagram for Cu-OF including base material as well as welded joints is presented in Figure 7. Since lattice structure of Cu-OF is cubic-face-centered cold formability of the material is high and elongations of nearly 30 % are reached. In contrast all welded joint show an elongation of less than 10 %, which is caused by several factors. First grain growth occurs within the heat affected zone of the welded joints due to the heating of the material. The resulting coarse grain structure decreases ductility of the material. Second the cross-sections of the welded joints are partly reduced by seam and root collapse forming a mechanical notch, appearing increasingly, if welding was carried out without filler wires. Thus the flat tensile test specimens are not elongated uniformly, and stress peaks appear at the mechanical notch, which lead to a premature failure of the specimen. For this reason mechanical properties of the welded joint, stress and strain, are increasing with the use of filler wire, which results in a higher cross-section area and is confirmed by the results shown in Figure 7. Here filler wires with diameters of 1 mm show a significant improvement of the mechanical properties in comparison to filler wires with a diameter of 0.5 mm.

While element composition of the weld seams stays constant for the similar connections shown in Figure 7, the copper content is changed when using Cu-OF filler wires, if CuSn6 or CuZn37 are welded in dissimilar configuration (Figure 8) to Cu-OF. Additionally, gap-size has an influence on weld seam geometry, according to the results presented exemplarily in Figure 3. Therefore Figure 8 shows the influence of different gap-sizes on stress-strain graphs, too. A comparison of the results of the similar Cu-OF joints in Figure 7 and

Figure 8 shows the influence of welding velocity on mechanical properties of the joints. Hence for similar Cu-OF joints welded with filler wire (ø 1 mm) a lower welding velocity improves the mechanical properties a lower welding velocity improves the mechanical properties significantly ($\Delta\sigma$ = + 50 N/mm², $\Delta\varepsilon$ = + 6.5 %). Additionally, in comparison to Cu-OF, the similar CuSn6 specimens show higher values for stress and strain due to the strengthening effect of the alloying element tin. Besides this for all materials investigated, bigger gap-sizes result in higher tensile strength and strains of the specimens. For the curves of the similar joints of Cu-OF and CuSn6 an abrupt failure can be seen in Figure 8 caused by geometrical notches or metallurgical notches respectively, which act as a starting point of a ductile facture. In contrast, better mechanical properties and no geometrical and metallurgical notches are determined for the dissimilar connection of CuSn6 and Cu-OF.

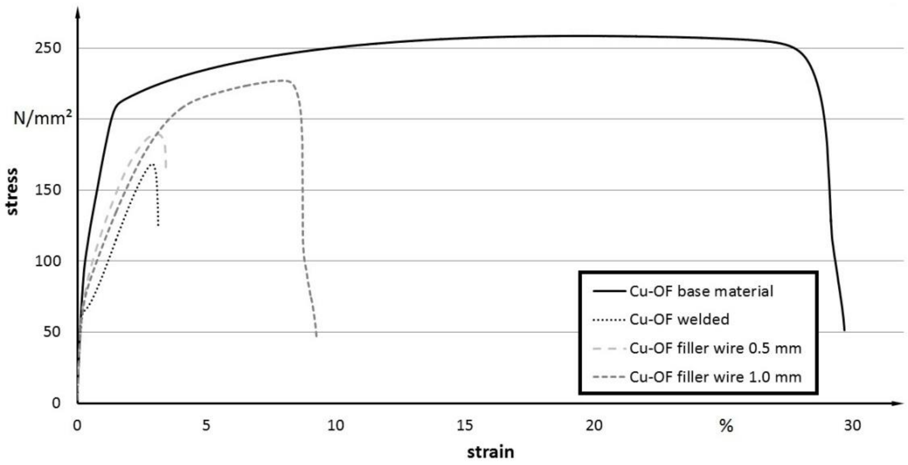

Figure 7. Stress-strain diagram of base materials and similar weld seams in butt joint configuration for Cu-OF; lateral angle of incidence 10°, laser power 3,800 W, gap-width 0 mm, welding velocity 2.5 m/min

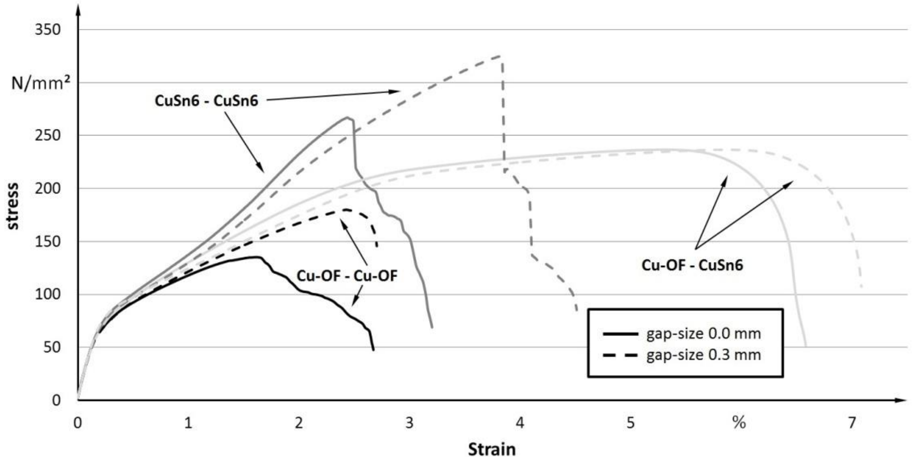

Figure 8. Stress-strain diagram of similar and dissimilar copper joints in butt joint configuration for different gap-widths; lateral angle of incidence 10°, laser power 3,800 W, welding velocity 3.5 m/min, Cu-OF filler wire (ø 1 mm)

5. Conclusion

This paper investigates the influence of filler wires together with joint gap-sizes and welding velocities on resulting weld seam properties of laser beam welded copper alloys. Accordingly filler wires increase weld seam width, weld reinforcement, as well as root sagging and decrease the number of weld seam imperfections in laser beam welding of brass. Furthermore the electrical resistance of the joints stays constant for Cu-OF and decreases for CuSn6 and CuZn37 in comparison to the base materials, if Cu-OF filler wires are used. The loss in tensile strength and strain due to the laser beam welding process is partly compensated by the use of filler wires, whereas the use filler wires with bigger diameters results in higher mechanical properties of the welded joints. Additionally a probable sensitivity for geometrical and metallurgical notches has to be considered at laser beam welding of copper alloys using filler wire.

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