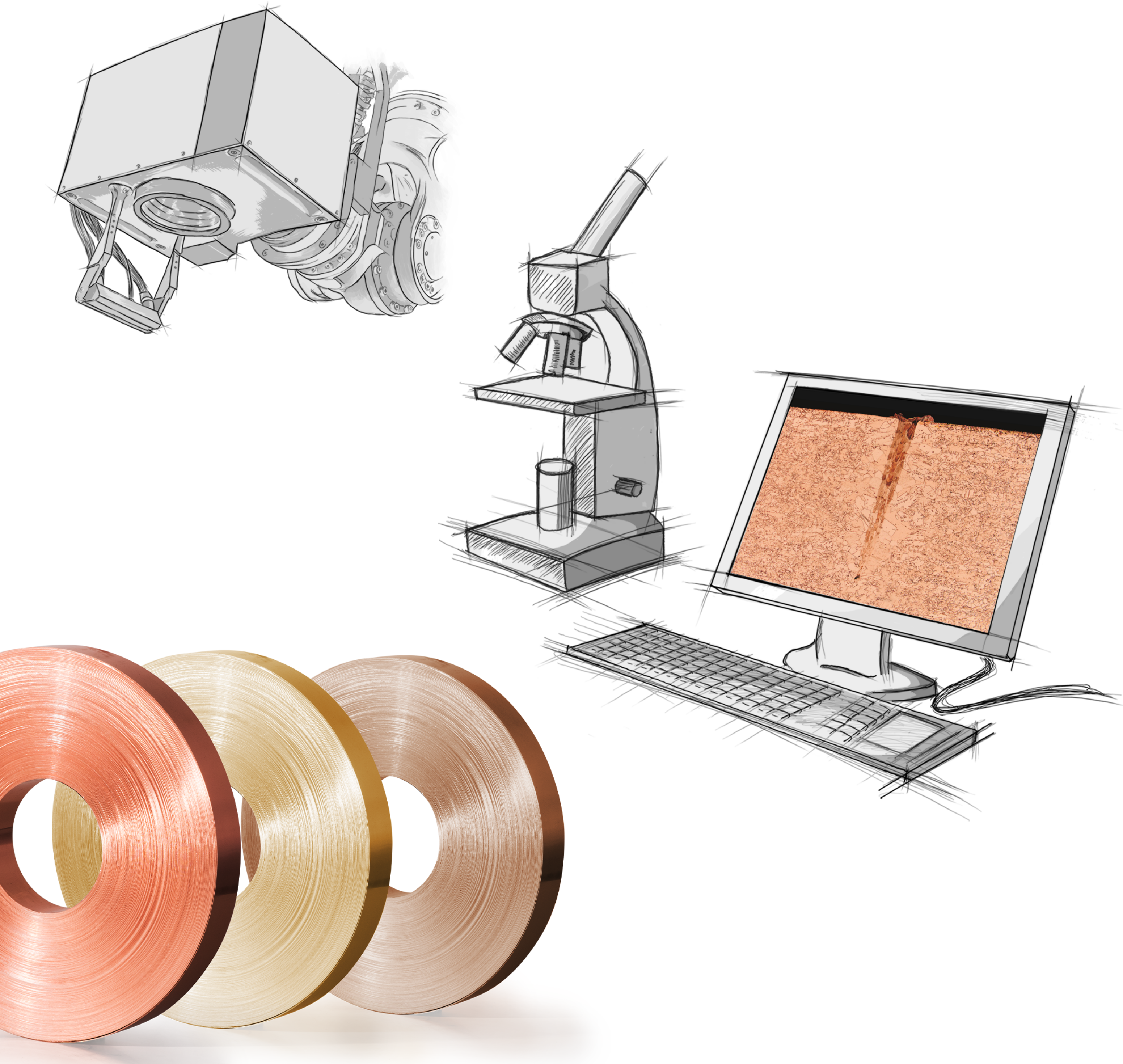
Welding of copper and copper alloy components



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1. Introduction

Welded joints on copper and copper alloys are characterized by their excellent reliability and reproducibility in terms of process technology, and by low transition resistance in terms of material properties. Welding is therefore one of the most frequently used joining technologies for copper and copper alloys, along with mechanical joining and soldering.

In the electrical engineering/electronics sector, components made of strip materials are mostly jointed by welding using the two well established processes, resistance welding or laser beam welding. Besides that, ultrasonic welding is becoming increasingly important. Electron beam welding and gas-shielded welding are also used for copper and copper alloys, although less frequently.

In principle, all pure copper grades and all copper alloys can be welded by any process. The decisive factor is the selection and setting of the parameters on the welding machines. The frequently heard statement that copper is poorly weldable or not suitable for welding is based on the different nature of copper materials compared to what welding personnel and engineers are used to from ferrous materials. As an example, copper dissipates welding heat much faster than steel does. Copper also has a much higher reflectivity to IR radiation, which makes it more difficult to couple laser radiation. It is therefore the task of copper processors to take these special properties into account when setting the welding parameters.

In recent decades, research and development in institutes and in the copper-processing industry have worked intensively on the task of generating welding knowledge about copper and making the various welding processes available for copper materials to users as an easy-to-handle industrial process.

This brochure provides information and a guideline how to weld Wieland strip made of copper and copper alloys, referring to the most common welding processes. It is intended as a supplement to the relevant technical literature.

2. Weldability – a complex subject

Welding represents a group of joining techniques, producing inseparable metallurgical bond connections of components by applying heat and/or pressure, with or without filler metals.

The weldability of a component is largely dependent on the three influencing factors which are material, design and manufacturing process. These parameters interact in complex ways. Thus, the material alone should not be the only factor to be evaluated when assessing welding issues. Instead, a holistic view of the complete welded construction is necessary, including its periphery, such as clamping devices and neighboring assemblies, as well as the component design.

According to Fig. 1, the term suitability for welding describes a pure material property.

It is given as soon as the chemical and physical properties of the material permit a welding that meets the requirements. In the case of fusion welded joints, the chemical composition of the material plays the central role. In the case of pressure welded joints (e.g. ultrasonic welding), mechanical-technological parameters such as hardness and roughness dominate. The suitability for welding can be assessed the better, the smaller the influence of the material properties is when determining the welding production processes for a specific construction.

A construction is considered "welding safe" if, with the material used, the component remains functional under the given operating conditions due to its design. Welding safety is thus determined, among other things, by the shape, geometry, number and arrangement of the welds, as well as the component geometry.

The welding possibility is given if the welds intended on a construction can be produced professionally under the selected manufacturing conditions. Joint type, component accessibility, and type and quantity of energy supply characterize this aspect of weldability.

Welding safety and welding possibility are the better, the more they are independent from other factors like weldability, construction, etc.

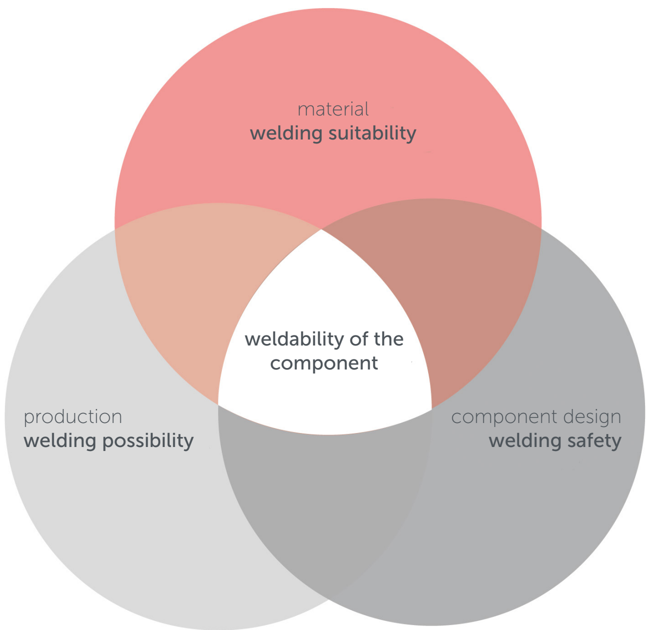


Figure 1 – Parameters influencing the weldability of components according to DIN 8528-1.

3. Welding processes for products made of copper and copper alloy strip

3.1. Resistance welding

Resistance welding, in addition to resistance brazing, has been used for decades on copper and copper alloys due to its high productivity and reproducible weld seam quality.

In this process, components pressed onto or against each other are welded, usually in an overlap joint, by means of resistance heating. Depending on the choice of welding parameters, component design and thermal conductivity of the material, a typical welding lens can form, but not always does. Usually In electrical engineering / electronics, the process is designed in such a way that the welding lens is avoided. This is achieved by producing the welding joint in the solid state. The components are heated to a maximum of 80 % of their melting temperature and the joint is realized via the electrode pressure. Finally, the joint is formed essentially by diffusion. This type of process control offers the advantage of low spatter formation.

In general, high currents must be used for resistance welding of copper and alloys with a high copper content, due to the high electrical conductivity. Furthermore, it is essential that the geometry and material of the electrodes, as well as the welding parameters (in particular current intensity and electrode pressure), are matched to the geometry and materials of the joining partners in such a way that the highest current density in the overall structure is present at the joint when current flows. In the simplest case, this is achieved by a relatively large electrode cross-section compared to the component cross-section. Projection welding is used to achieve particularly high reproducibility, whereby a hump of defined geometry is first embossed into one of the components to be joined. This is followed by welding with the joining partner, which can also have embossed humps.

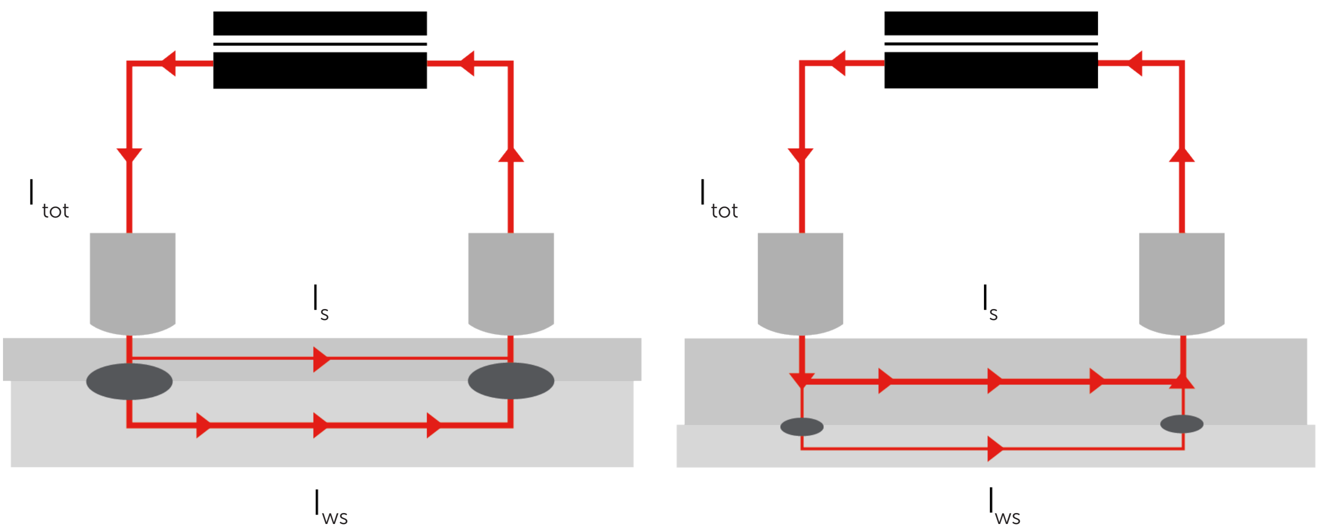


Figure 2 – Shunting effect due to incorrect component arrangement

If the current does not take the intended path through the components but is partially or completely conducted through the joining partners themselves or neighboring weld seams or current-carrying components, an unwanted shunting effect occurs. This results in welds that are too small or insufficiently strong. The causes of this defect are incorrectly designed electrode or component geometries, incorrect component arrangement, welding spots too close together or unfavorably materials for a given component design; examples, see Figures 2 to 4.

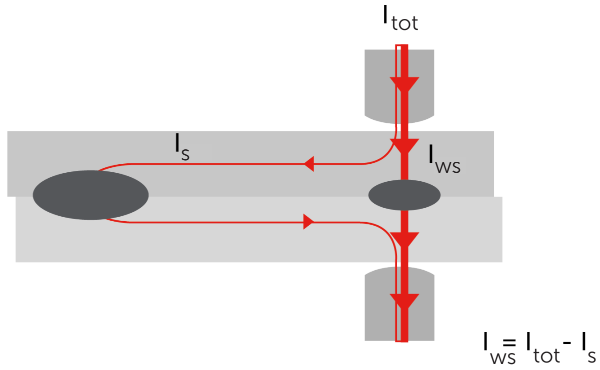


Figure 3 – Shunting effect due to weld spots located too close together

The correct selection of electrode materials represents the first important step in achieving reproducible weld joints. For joining partners made of highly conductive materials such as pure copper and low-alloy copper alloys (high copper alloys), the use of molybdenum or molybdenum alloyed with small amounts of titanium, zirconium and carbon (TZM), tungsten or tungsten lanthanum oxide, especially WL10/WL20, or tungsten copper (WCu) as electrode material is recommended.

These electrode materials are characterized by a high melting point and good thermal conductivity. TZM is characterized by increased high-temperature strength and lower thermal expansion compared to pure molybdenum. WL10 exhibits lower electron work function, increased creep resistance and better machinability compared to pure tungsten. Instead of the pure refractory metals, electrodes made of CuCrZr materials with brazed inserts of molybdenum, TZM and tungsten can also be used.

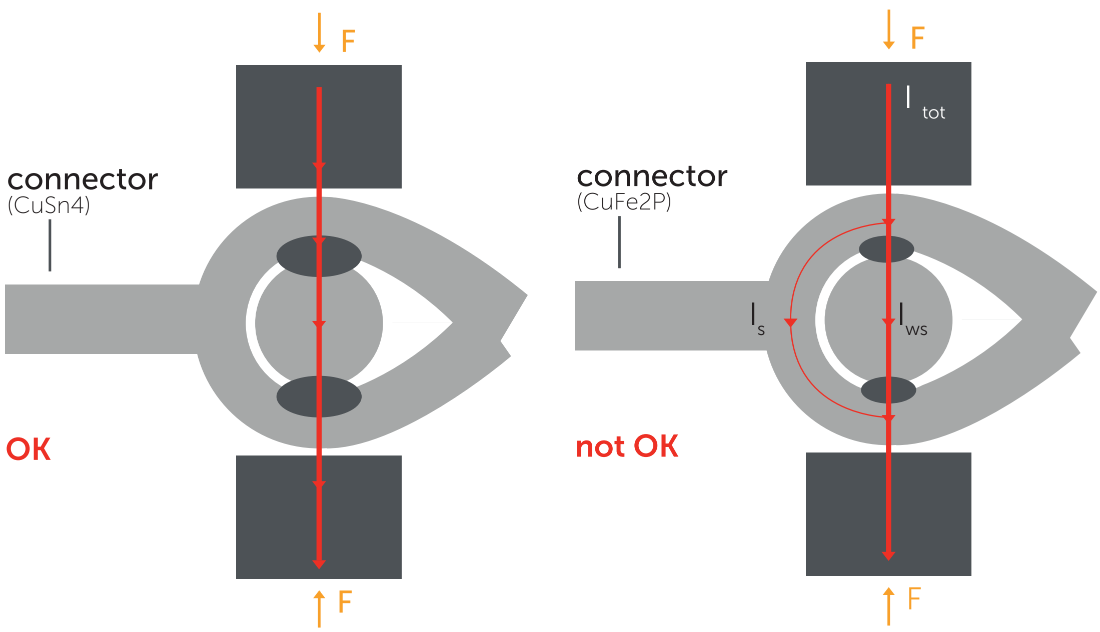


Figure 4 – Shunting effect due to component geometry not being adapted to the applied component material (right) – in the component geometry shown, the weld can be realized with a connector made of Wieland-B14 (CuSn4), but not with a connector made of Wieland-K65 (CuFe2P), as this copper alloy has a higher electrical conductivity and thus a bypass of the welding current occurs. Consequently, welding parameters, component material and component design are insufficiently matched to each other in the picture on the right.

For component materials with relatively low electrical conductivity, especially CuSn and CuZn alloys, we recommend electrode caps made of CuCr1Zr (Elmedur X) and CuZr (Elmedur Z). Both materials are low-alloyed, precipitation hardened copper alloys with high strength and hardness.

Figure 5 – Wieland Duro products

CuCr1Zr meets all the requirements for electrode materials, such as high hardness, wear resistance, thermal stability and a low adhesion tendency to a high degree.

CuZr has the advantage of approx. 10 % higher conductivity and thus offers the possibility of welding with lower currents and generating less heat at the electrode/sheet interface. This increases the service life of the electrode caps and further reduces the tendency for adhesions. A disadvantage is the lower hardness and wear resistance due to the absence of the alloying element Cr.

Further information on the electrode materials of the Wieland Group is available on the Wieland Duro website (wieland-duro.com)

As a result of buildup (adhesions), electrodes often have to be reworked or replaced because the current heating required for welding is no longer reproducible. in order to reduce such buildup and increase electrode lifetime, it is advisable to use joining partners that are provided with a coating. Tin coatings with a thickness of 1–3 µm are particularly suitable for this purpose. The tin coating has a low hardness, thus establishing excellent electrical contact with the electrode and protecting the electrodes from adhesion. Due to its low melting point (232 °C), tin melts early during resistance welding between the joining partners and is pressed out of the joining zone by the repositioning movement of the electrodes. Alloying of the weld zone with tin occurs only rarely. Another advantage of the tin layer is the increase in the real contact area in the electrode-sheet and sheet-sheet planes. This reduces the risk of local hot spots and weld spatters.

It should be considered that due to the very low melting point of tin and depending on the electrode/component design as well as the current intensity, the coating may be destroyed or the thickness of the coating may be reduced locally at the electrode/sheet interface.

Resistance roll seam welding is a process variation of resistance welding. In this process, the electrodes are designed in the shape of a roller, rotatably mounted and guided over the components to be joined under the effect of contact pressure. In this way, tight and closed seams can be produced by creating several overlapping weld spots directly behind each other. The shunting effect is not relevant in practice, as the temperature and the electrical resistance in the just welded area are still very high.

CONCLUSIONS:
Copper materials are suitable for resistance welding. Particular attention should be paid to

– the correct selection of electrode materials
– the use of a coating to increase the electrode lifetime
– a fine-tuning between welding parameters, component design and material of the joining partners

3.2. Laser beam welding

Laser beam welding is characterized by low energy input, low dimensional distortion of the component, high welding speed and slim seam geometries. Furthermore, it is possible to position the laser beam locally flexible by programmable focusing optics (PFO) and thus to generate wide seam geometries.

For laser welding of copper and copper alloys solid-state lasers of high brilliance with output wavelengths around 1 μm (IR range) are frequently used. Laser sources that emit laser light in the visible range of light (especially in the green and blue range) are constantly gaining new fields of application on the market.

During laser beam welding, the laser beam hitting the joining partners is partly reflected by the material, the other part is absorbed. The absorbed part of the laser radiation is converted into heat, which is used to melt the material. The degree of absorption depends essentially on the wavelength of the laser radiation used, its angle of incidence, as well as the type of base material and its surface properties (roughness, oxide layers, organic impurities).

The main challenge in laser beam welding is to handle the low degree of absorption of the solid copper when using the infrared laser radiation. Only about 4 % of the incident laser radiation is absorbed by the solid copper with a bright and shiny surface. A very high energy density is thus required to generate a weld pool. The weld pool subsequently absorbs about 10 % of the incident IR radiation. Thus, an absorption leap occurs during the phase change. This causes rapid heating of the molten copper and the formation of local hot spots in the molten bath, and frequently leads to weld defects such as spatter, ejections and pores. This problem is further intensified by the low viscosity of the molten copper and the high thermal conductivity of the solid base material surrounding the melt. Thus the welding heat dissipates very quickly from the seam area. Consequently, as the volume of the component increases, it is necessary to work with ever higher energy input, which unfortunately increases the probability of spatters and ejections.

3.2.1. cw laser welding

When welding with continuously emitted laser radiation („continuous wave" – cw), a distinction is made in principle between two process management variants – heat conduction welding and deep penetration welding. At a power density of approx. 10^6-10^8 W/cm^2 and above, the heat conduction welding process changes to the deep penetration welding process. However, the differences between the two processes can also be illustrated using the more practical characteristic value of line energy (quotient of laser power and feed rate) (Fig. 7).

In heat conduction welding, low line energy is used, which only melts the material to be welded. The process stability of this technique is high, but the welding depth is low. Seams produced in this way are flat and suitable for joining thin components only.

Deep penetration welding (Figs. 6 and 7) is used to achieve larger welding depths. For this purpose, increased line energy is used. The laser light is absorbed so strongly by the melt that its temperature rises above the vaporization temperature. The pressure of the outflowing vapor displaces the melt – a vapor capillary (keyhole) is created. As the laser beam moves through the component, the melt flows around the vapor capillary, solidifying on its backside and leaving a slim, deep weld. If the line energy is too high, this process is susceptible to weld defects such as ejections, spatter, pores and shot-throughs.

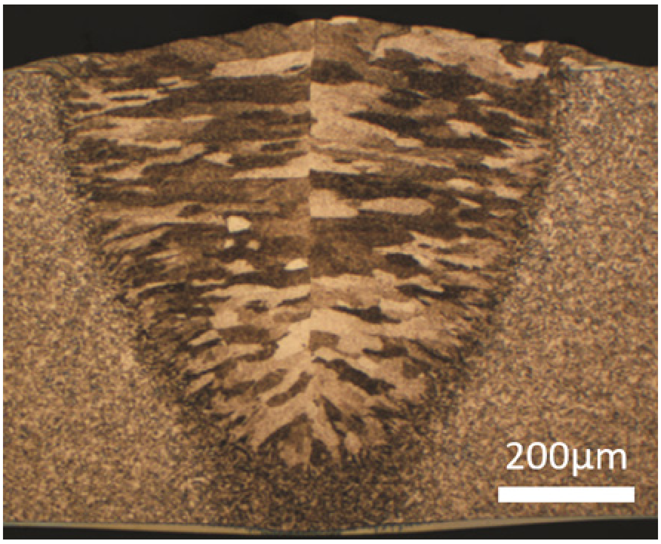


Figure 6 – Deep penetration weld in Wieland-B16

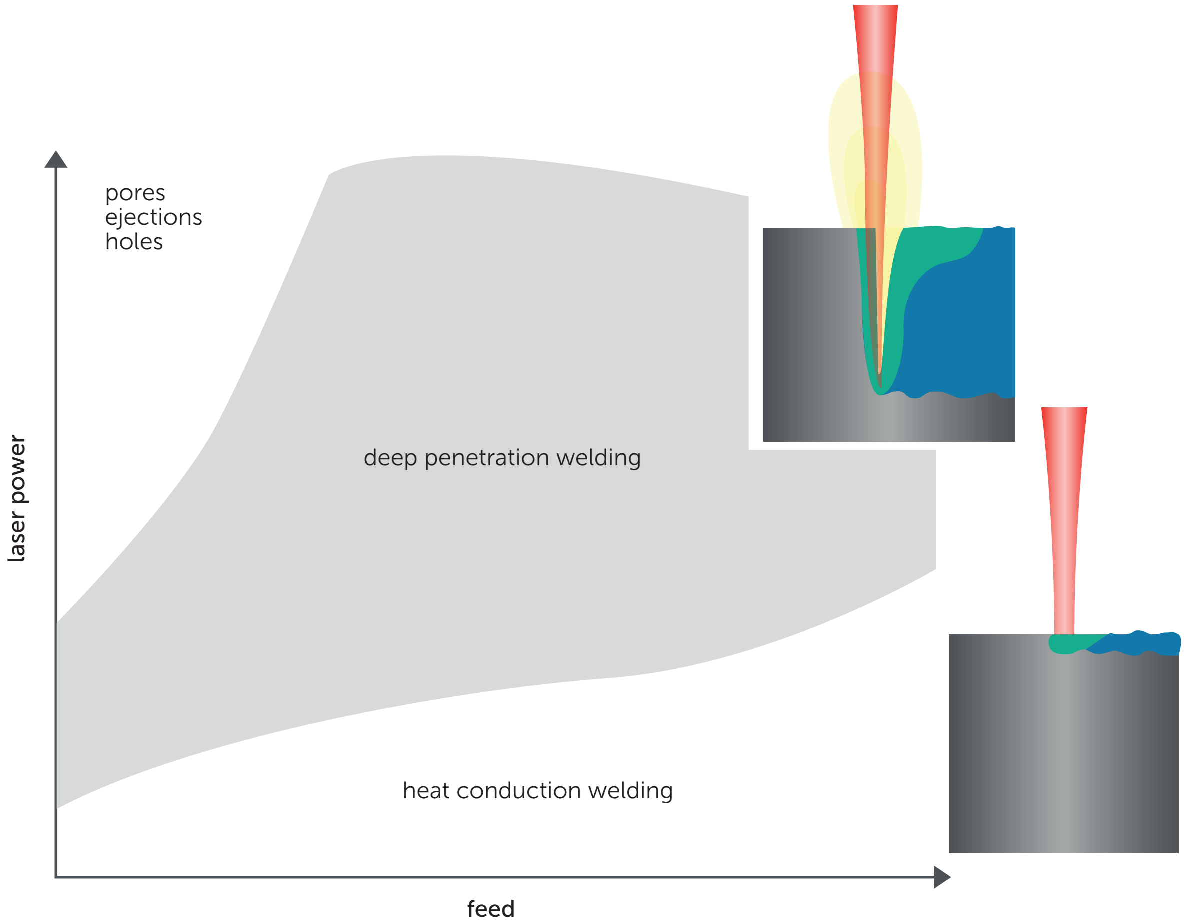


Figure 7 – Process window for cw laser beam welding

In order to stabilize the laser welding process and thus expand the process window for deep penetration welding, the following welding strategies have become the most established:

Power modulation

The laser power is not kept constant over the length of the weld seam but is modulated at a frequency in the range 100–1000 Hz, usually sinusoidally. This results in regular heating and cooling of the weld pool, which reduces the formation of hot spots and thus of weld defects.

Beam oscillation

The point of impact of the laser beam is deflected with defined frequency and amplitude perpendicular and/or parallel to the welding direction. If the deflection is purely perpendicular to the welding direction, this results in a sinusoidal path of the spot. If perpendicular and parallel oscillation are superimposed, the result is a helical path. This variant is known as „wobbling". By oscillating the beam, the process heat is distributed more evenly in the seam and the weld pool dynamics are influenced in a positive manner. Furthermore, this also allows the seam shape to be adjusted in a targeted manner.

Use of laser radiation with wavelengths < 1 µm

Visible, green light with a wavelength of 515 nm is absorbed by the solid copper significantly better (approx. 37 %) than infrared light (Fig. 8). The higher absorption improves the melting behavior of the material.

Furthermore, when the phase changes to the liquid state, there is a negative absorption jump to approx. 26 %, an opposite effect to infrared laser welding. This effect prevents a sudden melt overheating and decreases seam defects such as spattering. The so-called „green lasers" are therefore being used in more and more areas of industrial production. Welding with laser radiation in the visible blue light range (460 nm) is also being increasingly researched and offered on the market. The low wavelength promises even greater process reliability.

Laser beam welding in vacuum

By using a reduced ambient pressure (approx. 10^{0} to 10^{-2} mbar), the boiling point of the metal is reduced. As a result, the metal vaporizes during deep penetration welding even at lower temperatures. The lower temperature gradient between the vapor capillary and the molten metal results in a lower melt volume. The entire deep penetration welding process is therefore cooler and more stable. The risk of pore and spatter formation is reduced in this way. Furthermore, larger welding depths can be achieved than with laser welding at normal pressure.

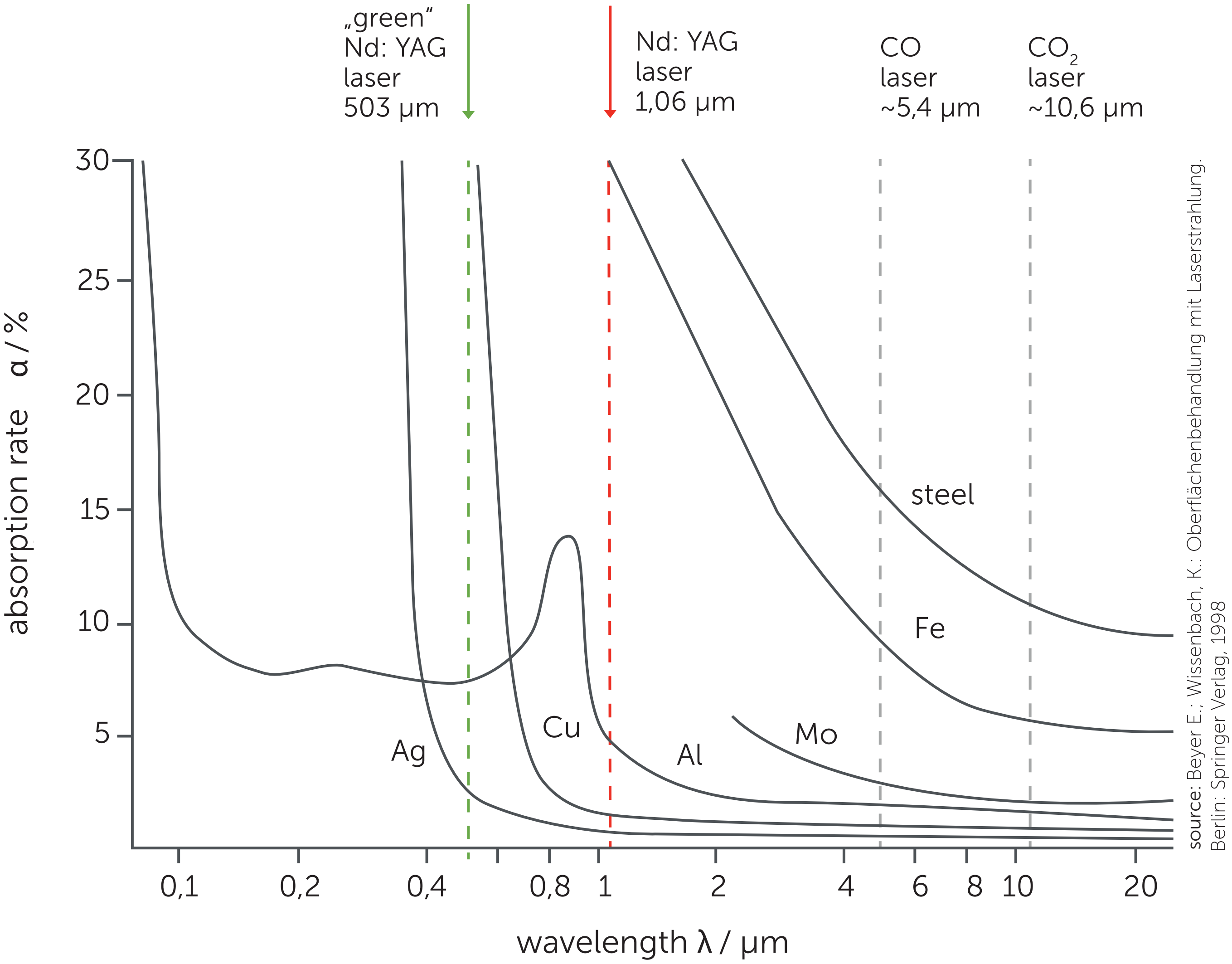


Figure 8 – Wavelength-dependent absorptivity of different materials

3.2.2. Laser spot welding

Laser spot welding is used for processing small, current-carrying contacts, especially those with low material thickness. No continuous line weld is produced, but only a spot weld by a laser pulse lasting a few milliseconds. Infrared laser radiation is frequently used. The amount of energy imposed on the material is lower (a few joules) and the welding duration is significantly shorter than with cw welding. The challenges described in 3.2. for welding copper materials and the characteristics of the solid surface of copper are even more severe. Local differences in the thickness of the copper oxide film and in the surface roughness determine the absorption properties of the material to be welded. In order to obtain reproducible welding results (spot depth and freedom from defects), the following techniques are essentially used.

Pulse shaping

In industrial practice, it has proven useful not to emit the laser pulse power constantly over time, but to vary the emitted power within the period of a pulse. The „pulse shape" is adapted to the specific material. For pure copper and bronze it is common to slowly ramp up the power at the beginning of the pulse, then abruptly raise it to a high-power plateau, and lower it again after a defined dwell time. With brass, there is a risk of zinc evaporation and so a continuous rise and fall of the laser power without dwell time is recommended.

Laser beam welding with wavelengths < 1 µm

As with cw welding, the use of lasers with a wavelength in the green and blue range of visible light can achieve advantages in process stability due to improved coupling. The green laser radiation reacts significantly less sensitive to different surface topographies and slight variations in oxide film thickness than IR radiation.

CONCLUSIONS:

Copper materials are suitable for laser welding. Particular attention should be paid to

– the strong reflectivity towards IR radiation in the solid state, combined with a clear absorption step at the phase change solid-liquid
– the particular suitability of laser radiation in the wavelength range < 1 µm
– the different melt behavior in heat conduction and deep penetration welding

3.3. Electron beam welding

In this process, the joining partners and the electron beam are located in a vacuum. When the bundled beam of highly accelerated electrons enters into the material of the joining partners, they are deflected and scattered by their atoms. In the process, part of their kinetic energy is converted into heat, which serves to melt the material. Typically, the electrons penetrate about 0.1 mm deep into the material. The exact penetration depth depends on the accelerating voltage of the beam and the density of the workpiece. If the energy density of the beam is sufficiently high, the heat generated causes the molten material to vaporize and a vapor capillary is formed. Similar to laser welding the deep welding effect occurs which makes it possible to produce deep and slim seams (Fig. 9).

The parameters power, feed rate and defocusing significantly determine the seam depth and width in this process. The techniques of power modulation and beam oscillation can be applied in the same way as in laser beam welding to vary the seam geometry.

Electron beam welding is similar to cw laser welding in many respects. The main advantage of the process compared to the laser is that the electrons are predominantly absorbed by the solid and liquid base material. Thus, very deep seams of up to 50 mm can be achieved in copper by electron beam welding. Furthermore, it is possible to influence the position and focus of the electron beam with low effort by means of magnetic fields. It is thus possible to produce several weld seams simultaneously („multi-bath technique"). This significantly reduces component distortion.

The disadvantage of the process is that it only works stably in a vacuum. The working chamber must be evacuated to about 10^{-4} mbar. Collisions with gas molecules would deflect the electrons and thus lead to undesirable defocusing of the beam. The larger the components to be welded, the larger the working chamber has to be. A large chamber increases the time required for evacuation and also the cost of pumping technology for vacuum generation. However, the vacuum also has a positive side effect: Oxidation of the seam surface is effectively prevented.

There are also welding systems which operate without vacuum, so-called non-vac electron beam welding systems. Due to the defocusing of the electron beam, only very flat and wide seams can be produced. To prevent oxidation of the weld seam, a shielding gas must be used (usually helium).

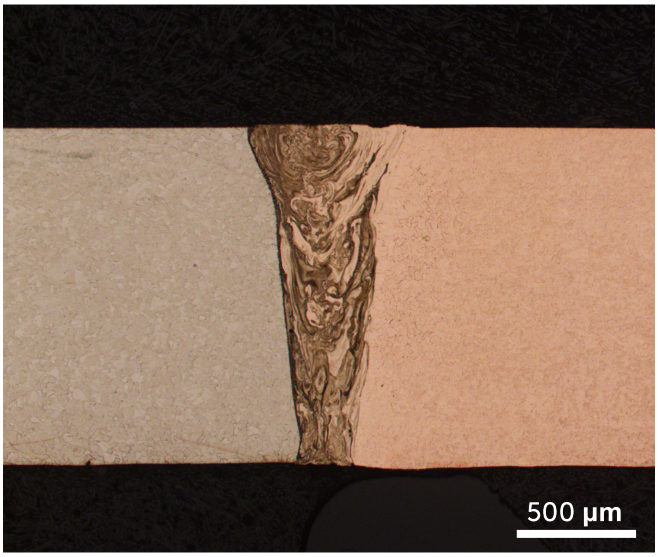


Figure 9 – Electron beam weld in butt joint between Wieland-F12 and Wieland-K14 – this process is mostly used in the manufacturing of strip consisting of two or more copper alloys.

CONCLUSIONS:
Copper materials are suitable for electron beam welding. Particular attention should be paid to

– the need for a constant vacuum to produce high-quality seams
– the different melt behavior for heat conduction and deep penetration welding – analogous to cw laser welding

3.4. Gas shielded arc welding

For copper and copper alloys, the two shielding gas welding processes TIG (Tungsten inert gas) and MIG (metal inert gas) welding are mainly used. Gas-shielded welding leads to high heat input into the components and thus to severe distortion. For this reason, they are only used for large-area components and large sheet thicknesses, especially in the handicraft sector. The large volume of the components, coupled with the high thermal conductivity of copper, causes rapid heat dissipation and makes preheating necessary in many applications.

TIG welding is used in particular for wall thicknesses < 10 mm. For higher wall thicknesses, high quantities of filler metal are required, which can no longer be applied sufficiently quick and economical by TIG welding, and MIG welding has to be applied.

The shielding gases used are argon, helium or their mixtures. In argon, due to its relatively low thermal conductivity, the arc ignites very easily and a soft arc with low energy density is formed, which is advantageous for thin-walled components.

The thermal conductivity of Helium is approx. 10 times higher and usable for thicker-walled components. Furthermore, helium allows an increased welding speed. Welding with helium allows deeper penetrations than with argon and welds with less pores. In practice, helium-argon mixtures have become established. This is also because argon offers a significant price advantage over helium. In some cases, argon-nitrogen mixtures are also used.

3.4.1. TIG welding

In TIG welding, the arc burns between a non-melting tungsten electrode and the joining partners. A filler metal usually is added, but not necessarily. Fig. 10 shows a TIG weld produced without filler metal.

Welding current sources with falling characteristics are usually used. Work is mainly carried out with direct current (for Al bronzes and Cu-Zn alloys with alternating current) and the electrode is connected as the negative pole. The electrode material almost always is thoriated tungsten. The tip of the electrode is pointed (slender arc) or rounded (broad arc) in order to form the optimal arc. Argon, helium and argon/helium mixtures with > 50 % Ar have become established in practice. Arc ignition takes place by means of a high-voltage pulse without contact or with contact at very low amperage (lift-arc technique). The use of the TIG pulsed arc is suitable for joining thin-walled components and components with different heat dissipation (strongly differing sheet thickness and/or thermal conductivity). With this technique, particularly few energy is applied to the material.

From sheet thicknesses ≥ 3 mm, the following applies: With increasing thermal conductivity of the material to be welded, preheating is recommended. For sheet thicknesses > 7 mm, very high preheating temperatures of > 300 °C are required. Additionally the use of fluxes is also recommended.

Figure 10 – TIG weld without filler material in Wieland-K65
TIG welds are mostly used as temporary welds to connect two strips before further processing and thus serve to reduce set-up times and increase the productivity during punching and coating. The transfer welds are removed after the stamping or coating processes. TIG weld seams are rarely/not used as joints in an electronic component itself.

3.4.2. MIG welding

In MIG welding, the arc burns between the joining partners and a melting electrode consisting of filler metal, which is automatically and continuously fed. Direct current is used with the electrode connected as the positive pole. Since additional heat is introduced into the joining zone by the melting filler material, preheating of the components is only necessary for very thick walls (> 10 mm). The use of fluxes is not necessary.

Impulse and spray arcs are commonly used for copper and copper alloys, as these types of arcs lead to a material transition in particularly fine droplets and spatter tendency is low. Ar, He, or argon-helium mixtures with > 50 % argon are used as shielding gases.

Spray arcs use argon-nitrogen mixtures with < 30 % nitrogen. The spray arc is used for filler and cover layers, as it allows smooth seam profiles to be produced.

The pulsed arc uses a pulse current which is superimposed on the base current. It is used in particular for welding in constrained positions and for buildup welding on steels.

3.4.3. Filler materials for gas shielded arc welding

Filler metals must be selected in accordance to the type of base material of the welding partners (Table 1). In DIN EN 14640, the filler materials for welding copper alloys by means of TIG welding (plate thicknesses > 1.5 mm) and MIG welding (all strip or plate thicknesses) are standardized. For plate thicknesses < 1.5 mm, the TIG process is used without filler metal.

Table 1 – Usable filler materials depending on the component material to be welded

Material of the joining partners	Filler material
Pure copper, CuFe2P, CuCrZr, CuNiSi	CuSn1, CuAg1
Tin bronzes (phosphor bronzes) CuSn4, CuSn5, CuSn6, CuSn8	CuSn6P, CuSn12P Use over-alloyed filler metal
Copper-nickel alloys	CuNi10, CuNi30
Zn-containing alloys (brass, nickel silver)	CuSn1, CuSn6P, CuSi3Mn1, CuAl8

CONCLUSIONS:
Copper materials are suitable for gas-shielded arc welding. Particular attention should be paid to

– the strong heat input and the associated component distortion, as well as the possible need for preheating, depending on the component volume and thermal conductivity of the material to be welded
– the effect of the different shielding gases
– the correct selection of filler materials

3.5. Ultrasonic welding

In contrast to the welding processes considered so far, ultrasonic welding does not form a melt to produce a material bond between the joining partners. The welding temperature is clearly below the melting temperature.

The connection is formed by bringing the component surfaces into such close contact that the freely moving electrons from the electron gas in the metallic components can exchange.

To realize this, bare metallic surfaces must be brought together to a distance of < 200 nm. For this purpose, the lower joining partner is firmly clamped, while the upper joining partner is gripped by a sonotrode, usually made of steel or titanium (Fig. 11). The sonotrode is pressed onto the upper component with a defined normal force, its ribbed surface structure usually leaving impressions in the component (Fig. 12 a).

This structure of the tool is necessary in order to ideally transfer the vibrations generated by an ultrasonic generator via the sonotrode to the upper component. In this way a relative movement between the two component surfaces is generated, which corresponds to the amplitude of the vibrations and is in the range of 50 to 500 µm.

The simultaneously acting normal force partially displaces thin contaminant films from the joining zone. Light oxide layers are broken up and also „rubbed out“ to a large extent. As a result, bare metal surfaces touch each other at certain points and form a material bond called „a-spots“. The entire process takes a few milliseconds up to 3 seconds maximum. The real bonding area via the a-spots is significantly smaller than the apparent contact area resulting from the component and joint geometry.

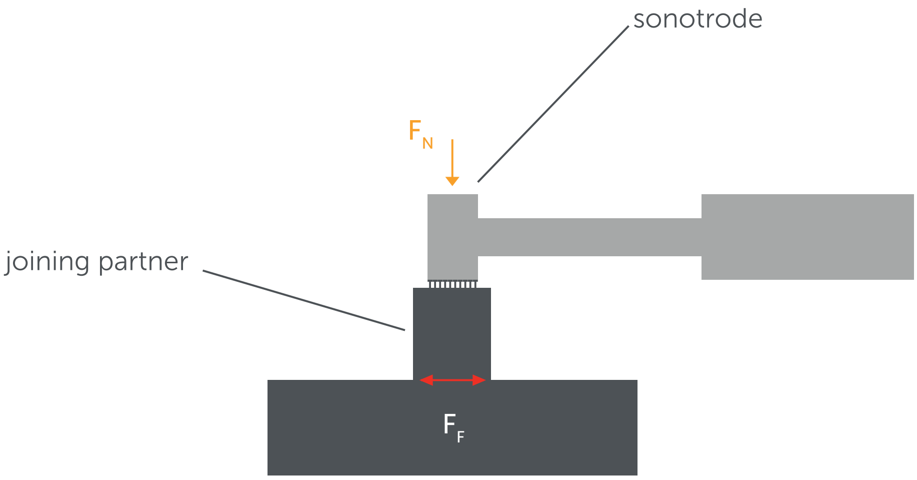


Figure 11 – Principle of ultrasonic welding

Ultrasonic roll seam welding is used to produce continuous, linear seams. In this process variant, the sonotrode is designed as a disc, rotatably mounted and oscillates in the axial direction.

The quality of the ultrasonic weld is usually characterized by the joint strength and is usually measured by means of a pull-off test. The welding result depends on the machine parameters, such as amplitude, welding energy, frequency, on anvil and sonotrode geometry, as well as on the properties of the parts to be joined. These are in particular the surface roughness, oxide layer coverage, impurities and component geometry.

Further quality relevant parameters are the sonotrode oscillation direction relative to the roll brush structure of the strip and the positioning of the joining partners to each other.

The complex relationships between the machine-side and material-side parameters influencing the ultrasonic welding result are not yet fully understood at the present state of the art and are subject of current research projects. In internal Wieland studies on the ultrasonic welding of copper and copper alloys, the following qualitative relationships were determined:

– The chemical composition of the uncoated base material has no effect on the ultrasonic welding result.
– The smaller the difference in hardness between the two joining partners is, the more successful the welding will be.
– Low roughness of the surfaces tends to have a favorable effect on joint formation.
– The alignment of the sonotrode oscillation direction parallel to the rolling or brush structure of the base material is also favorable.
– Visible tarnish layers, heavy contamination, soft surface coatings such as tin plating and a large difference in hardness between the joining partners are considered critical.

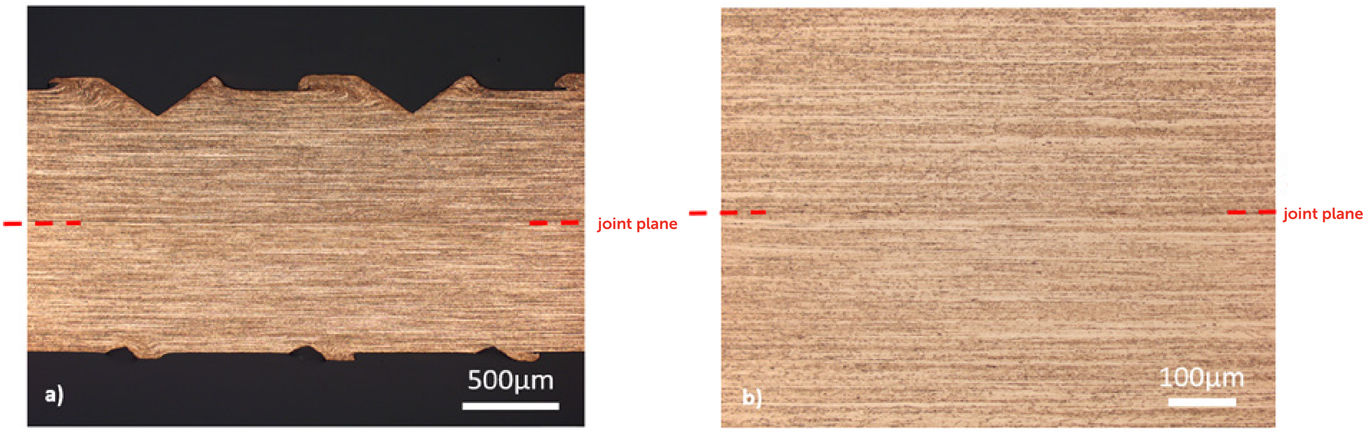


Figure 12 – Ultrasonic welded joint between two sheets of Wieland-K75, cross-sections in the optical microscope
a) 50x magnification, imprints of the sonotrode visible b) 200x magnification

CONCLUSIONS:
Copper materials are suitable for ultrasonic welding. Particular attention should be paid to

– clean and oxide-free component surfaces
– a low hardness gradient between the component surfaces to be joined
– a fine tuning between welding parameters, component geometry and surface properties of the components

4. Metallurgical aspects of fusion welding of copper and copper alloys

4.1. Pure copper

The main challenge in welding pure copper is its high thermal conductivity of 390 W/mK. Regardless of the type of fusion welding process, this leads to very rapid dissipation of the heat generated during welding away from the weld. This results in the formation of relatively small weld penetration depths and wide heat affected zones. In welding processes with low energy density (e.g. arc welding), preheating is therefore usually necessary. It is not necessary for welding processes with high energy density (laser, electron beam welding).

It is worth noting that the different phosphorus contents in the various pure copper grades reduce the electrical (and thus also the thermal) conductivity of the material, in some cases significantly (Table 2). This is accompanied by better melting behavior. The increasing phosphorus content slightly increases the susceptibility of the material to the formation of pores.

Oxygen containing copper (Cu-ETP) is not recommended for fusion welding applications, as there is a risk of the outbreak of hydrogen embrittlement due to oxygen which is bound as cuprous oxide and located at the grain boundaries. Hydrogen can easily diffuse into copper at temperatures > 500 °C and react with the oxygen, causing hydrogen embrittlement. The hydrogen from the atmosphere reacts with the cuprous oxide, forms water vapor which leads to a considerable volume expansion. Consequence is a characteristic bubble formation at the grain boundaries and finally cracking of the grain boundaries (Fig. 13). In order to check whether a weld contains cuprous oxide and is susceptible to hydrogen embrittlement, a metallographic section of the unetched weld can be viewed under dark-field illumination.

The cuprous oxide is clearly visible by its typical ruby-red color (Fig. 14). In principle, the risk of oxygen enrichment of the weld seam increases with the welding time and the size of the melt. In gas-shielded welding, therefore sufficient shielding gas coverage is essential.

The copper melt has a very low viscosity. Welding in constrained positions should therefore be avoided. Even in the flat position, the low melt viscosity leads to strong dynamics in the melt and thus frequently to spattering.

The typical microstructure of a fusion-welded copper seam is relatively coarse-grained and soft compared to the initial microstructure. Depending on the size of the weld pool as well as on the heat dissipation and the cooling rate, a stalked, epitaxially grown grain structure in the weld is formed. If cooling is extremely fast, so that homogeneous nucleation takes place and a very fine solidification structure is formed, softening is less pronounced and hardening may even occur, since the numerous grain boundaries and lattice defects hinder the mobility of dislocations. In the heat affected zone, the grain recrystallizes to a greater or lesser extent depending on the degree of deformation of the initial material. Higher degrees of deformation and thus higher defect densities in the crystal lattice lead to a higher recrystallization tendency, pronounced softening and wide heat affected zones.

Table 2 – Electrical conductivity of various pure copper grades in the soft-annealed condition

	Cu-OFE	Cu-OF	Cu-PHC	Cu-ETP (E-Cu)	Cu-HCP (SE-Cu)	Cu-DLP	Cu-DHP (SF-Cu)
Electrical conductivity (MS/m)	58.6	58.0	58.0	58.0	57.0	52	46
O content (ppm)				50–400			
P content (ppm)			30		30–40	50–120	150–400

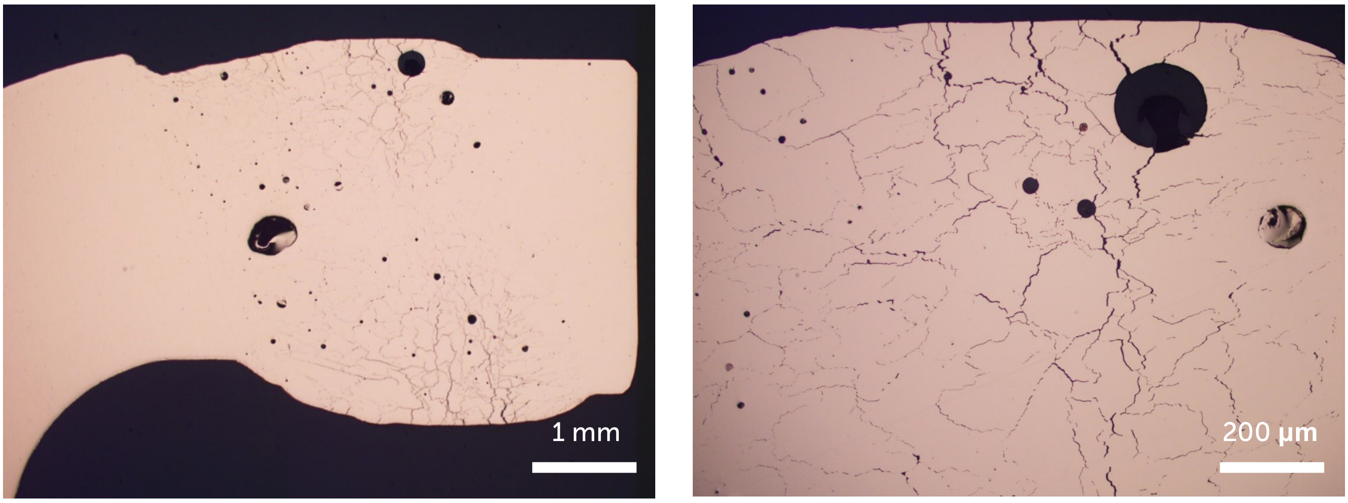


Figure 13 – Grain boundary cracks after breakout of hydrogen embrittlement

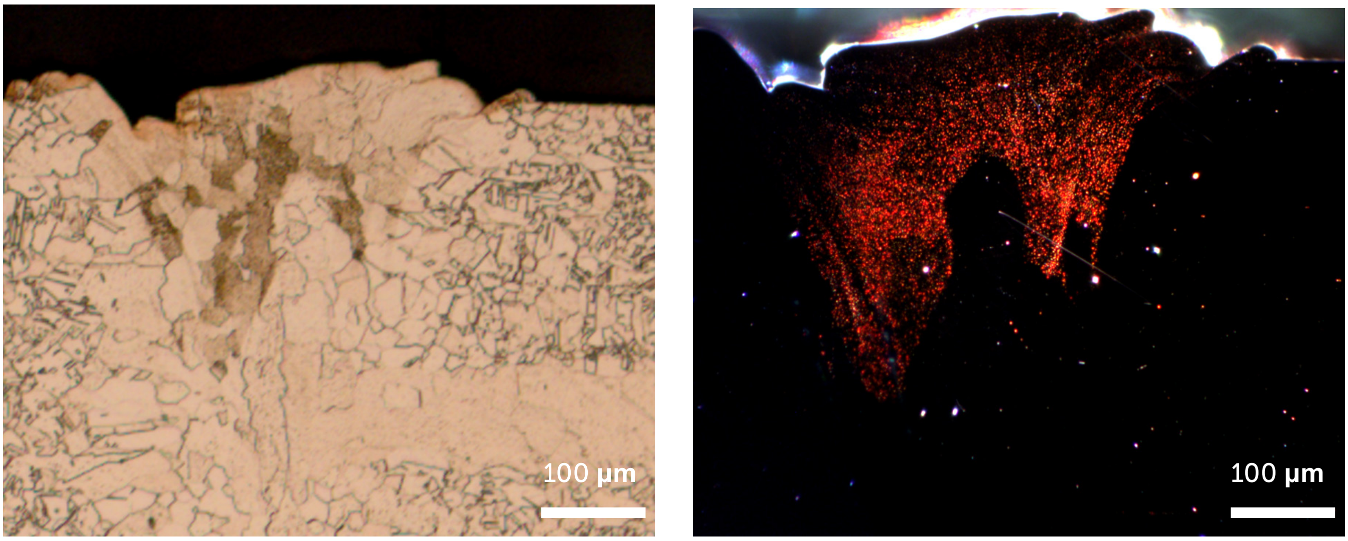


Figure 14 – Weld with cuprous oxide under brightfield illumination (left) and darkfield illumination (right)

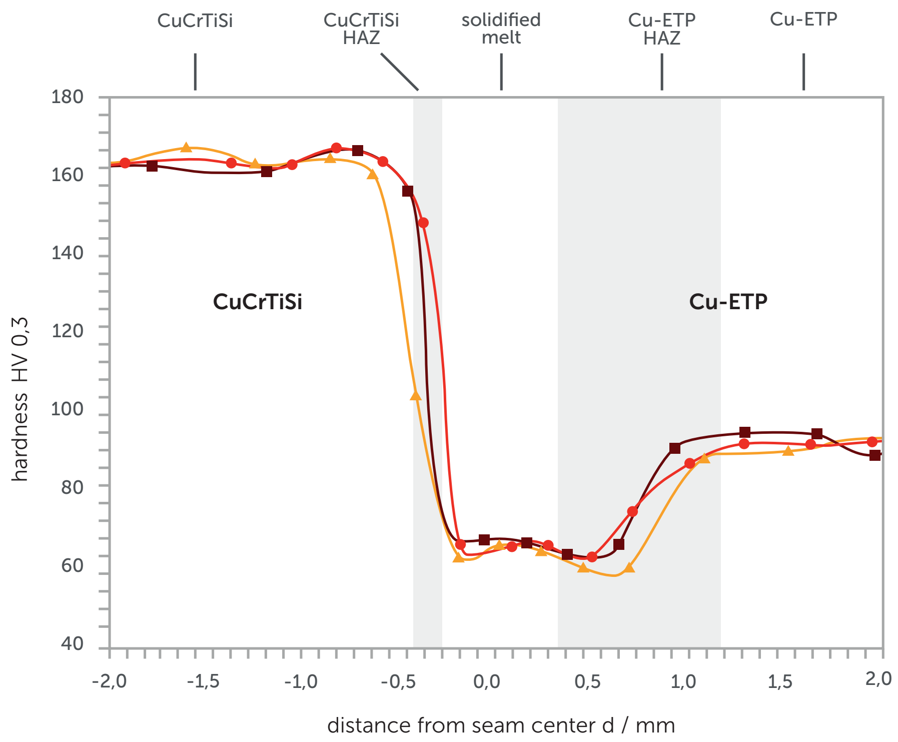
4.2. Precipitation hardening copper alloys

A technically important group of copper alloys are precipitation hardening high performance alloys. Those low-alloyed systems achieve their superior strength properties combined with good electrical conductivity through a defined hardening process and the formation of precipitations. These strength-forming precipitations are partially or completely dissolved by fusion welding processes in the area of the weld seam, resulting in very strong hardness reductions in this area (Fig. 15).

The microstructure of the weld seams in these alloys is characterized by coarse grains, just as in the case of fusion welded pure copper. On the one hand, this makes the seam microstructure easy to form, but on the other hand it is not as mechanically strong as the initial microstructure. When designing welded components made of precipitation-hardened copper alloys, special attention should therefore be paid to ensuring that the weld seams are located in areas with as little mechanical stress as possible.

The dissolution of precipitates can slightly increase the specific electrical resistance of the material locally. The heat affected zone is usually narrower than in pure copper welds, since the low-alloyed copper has a lower thermal conductivity and heat accumulation may occur. Furthermore, the recrystallization tendency is always related to the degree of cold work. Although this is higher compared to pure copper, the precipitates hinder grain boundary migration and thus reduce the recrystallization tendency of the microstructure. Precipitations in the heat-affected zone can coarsen and thus locally reduce strength.

In resistance welding, only tin coated material should be welded, since precipitates can adhere to the electrodes and thus reduce their lifetime significantly.



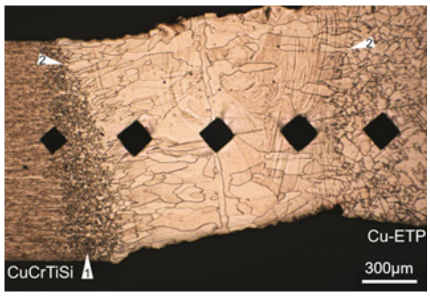


Figure 15 – Butt joint between Wieland-K75 and Wieland-K32 – the hardness profile shows a significant drop in hardness in the area of the weld and in the heat-affected zones which have different widths.

4.3. Tin bronze

Note 1: Tin bronzes are often described as „phosphor bronzes".

Note 2: This chapter includes the material CuSn0.15 (C14415, Wieland-K81), as this is a very low-alloyed tin bronze from a metallurgical point of view.

4.3.1 Weld formation

With increasing tin content in the copper lattice, the thermal conductivity of the tin bronze decreases significantly (Fig. 16). The fusibility of the material improves with decreasing conductivity and a stable melt can be generated without problems. Relatively large weld seams and narrow heat affected zones are therefore characteristic of welds in bronze in comparison to welds in pure copper.

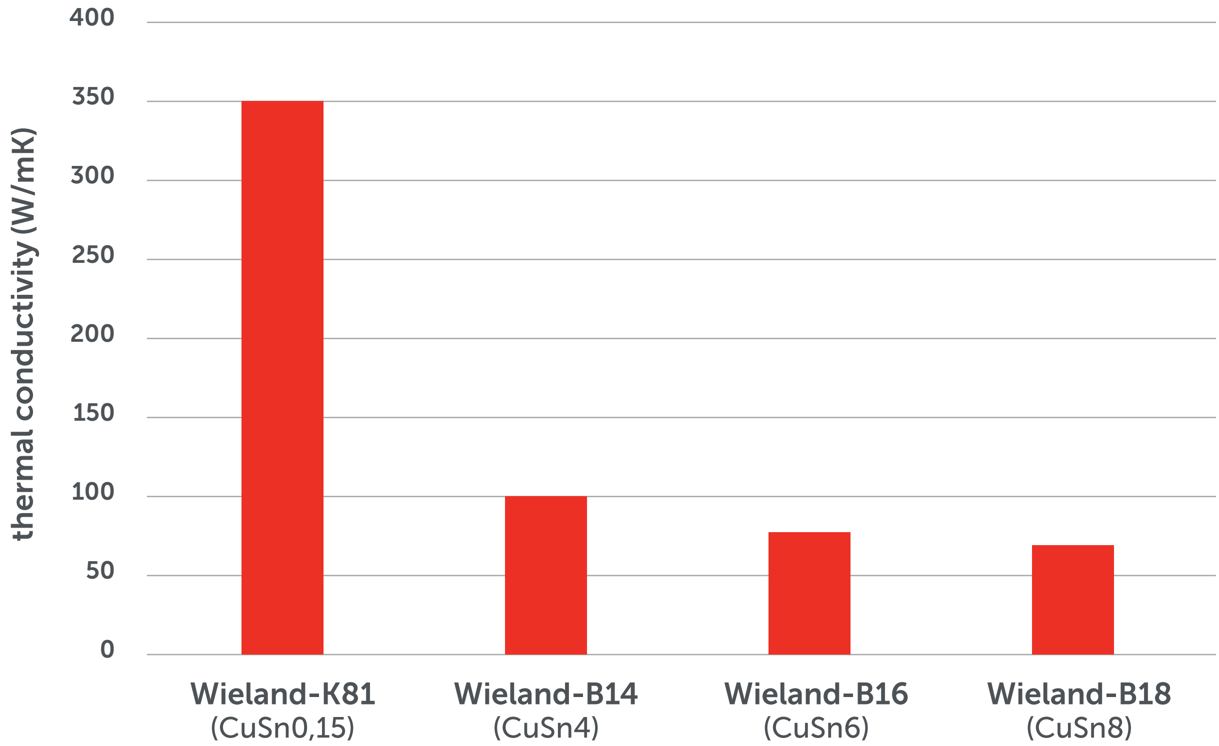


Figure 16 – Thermal conductivity of tin bronzes in dependence on tin content

4.3.2 Microstructural processes

The large solidification range in the binary system Cu-Sn (Fig. 17) is the reason for the formation of dendrites and the occurrence of micro segregations during welding.

At the beginning of solidification, a solid solution crystal with low tin content initially forms. As it grows, tin concentration in the residual melt also grows. Impurities and foreign elements stay in the solidification front and accumulate in the interdendritic space. Here tin content is sufficiently high for the formation of the intermetallic β-phase, which transforms into the δ-phase ($Cu_{31}Sn_8$) during cooling. Finally, the interdendritic space is clearly different frome the dendrite arms in terms of a deviating chemical composition, a relatively high content of impurities and foreign phases (if existing at all), the existence of the brittle δ-phase as well as an increased defect density of the crystal lattice. These effects, which increase the higher the tin content is, cause an increase in the hardness of the weld microstructure compared to the microstructure of the heat affected zone (HAZ), which is softened by recrystallization and recovery.

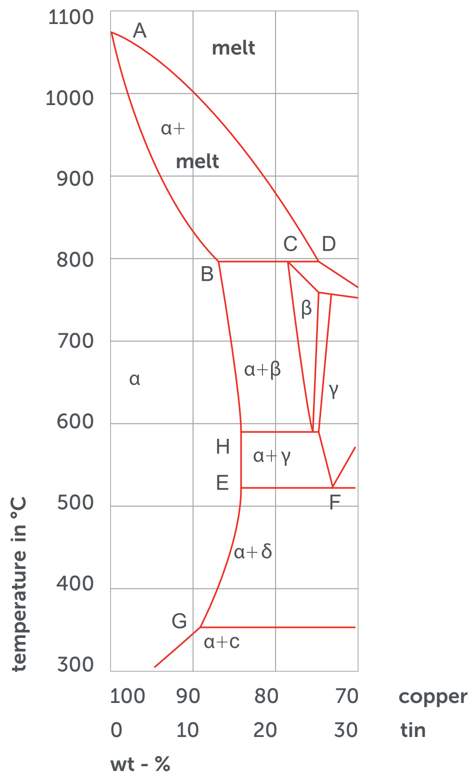


Figure 17 – phase diagram Cu-Sn, extract of Cu-rich area (acc. to G.V. Raynor, Ann. Equilibr. Diagrams No.2, London 1949).

4.3.3 Susceptibility to hot cracking

Furthermore, these effects influence the hot cracking susceptibility of the weld. The hot cracking risk initially increases with increasing tin content of the bronze, reaches a maximum at approx. 2 % tin and decreases again with further increasing tin content (Fig. 18). Due to the accumulation of low-melting tin as well as impurities in the interdendritic space, a liquid phase remains there for a relatively long time. This can be easily ruptured by stresses occurring during the solidification process – the typical hot cracking mechanism. From tin contents of significantly > 2 %, the tendency to hot cracking decreases, as the interdendritic space becomes increasingly solid. Simultaneously a second hard intermetallic phase forms.

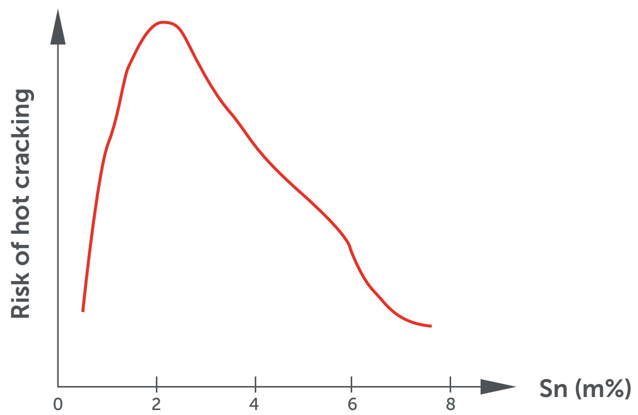


Figure 18 – Qualitative correlation between the tin content in a bronze and the risk of hot cracking during fusion welding

In cases that both welding partners consist of the same tin bronze, e. g. both are made of Wieland-K81 (CuSn0.15) or Wieland-B16 (CuSn6), there is no serious risk of hot cracking. However, in cases the material is different, e. g. one partner is made of Wieland-B16, the other of Wieland-K81 or of pure copper, a tin content close to the critical range can occur in the weld. Whether hot cracks do occur or do not, depends on the strip thickness and on the total energy input (weld volume) as well as on the cooling rate.

4.3.4 Influence of phosphorus content / casting technology

Bronzes cast by strip casting are produced with a higher phosphorus content, because this makes strip casting possible at all and reduces the melt viscosity. Bronzes cast by slab casting do not require this phosphorus content. By omitting the phosphorus in slab casting, bronze strips with higher conductivities can be produced.

The phosphorus content of tin bronze also affects its welding suitability.

Cu-Sn alloys produced by slab casting are more suitable for welding, because phosphorus increases the susceptibility to hot cracking during welding by forming low-melting phoshorus-containing phases at the grain boundaries.

4.4 Cu-Zn alloys

Cu-Zn alloys alloys tend to strong zinc evaporation during fusion welding because zinc has a low evaporation temperature of 907 °C. This effect is accompanied by increased porosity, strong spatter formation and sometimes explosive melt ejections. The weld seams of such alloys are often highly fissured (Fig. 19). Intensity and frequency of these weld irregularities are the more pronounced, the higher the zinc content in the alloy is. During fusion welding of Cu-Zn alloys, the heat input into the component should be kept as low as possible (e.g. by low amperage or low beam power and by high feed rate). Alternating current should be used for gas-shielded welding, as the heating-up of the melt is less in comparison to welding with direct current.

Laser and electron beam welding use very high energy density. Although the overall energy input into the component is low with these processes, the local amount of energy is very high, which leads to heavy melt ejections during deep penetration welding of brasses and special brasses. In order to smoothen the seam and increase the seam strength, the weld upset can be re-melted with a strongly defocused beam.

Due to the low melting point of lead (327 °C), lead-containing brasses additionally are susceptible to hot cracking. Fusion welding of these materials should be avoided.

When welding the zinc-containing manganese bronze Wieland-FX9 (CuMn15Zn15Al1), the deoxidizing effect of the element manganese has a positive effect on the melt flow in principle. However, the negative effects of zinc evaporation also dominate in this alloy.

In general, it can be stated that Cu-Zn alloys are less suitable for beam welding. In contrast, the use of resistance welding, pressure welding and brazing processes is more recommended.

The special brass Wieland-S12 (CuSn3Zn9) is an exception. Due to its relatively low zinc content of 9 % it is considered suitable for welding.

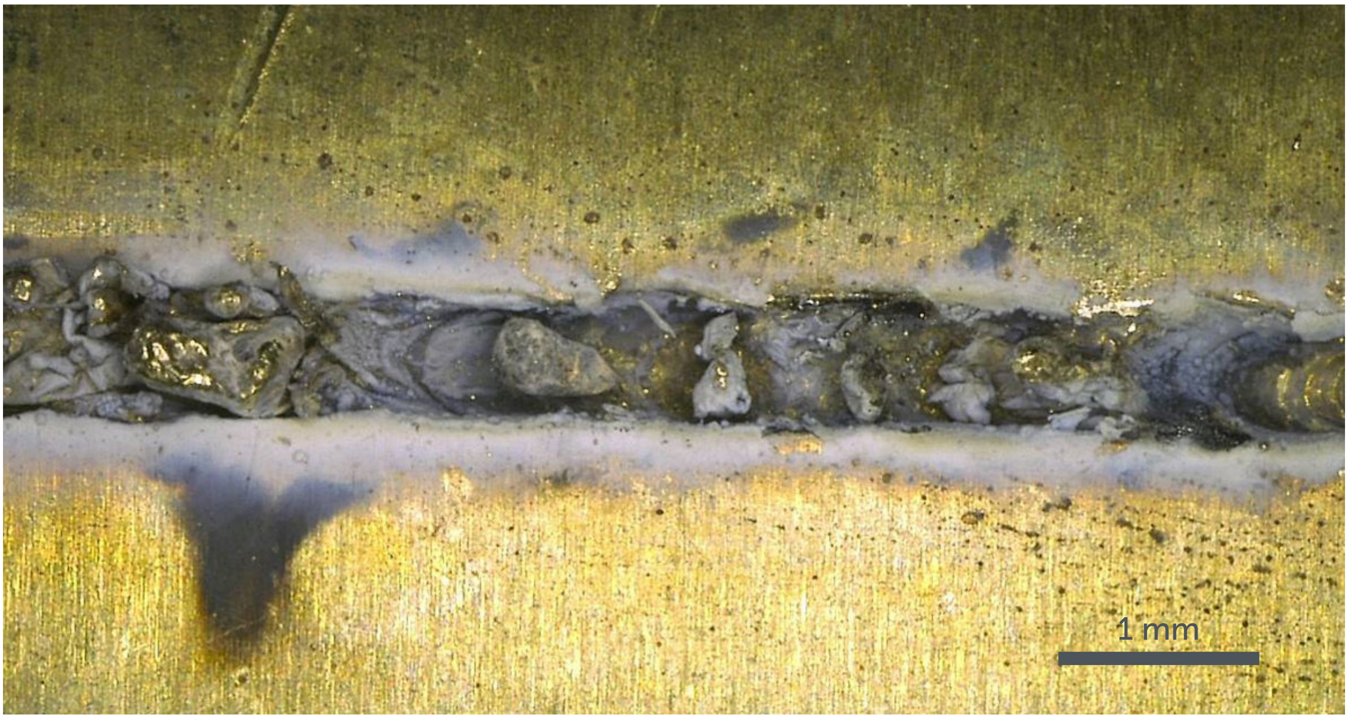


Figure 19 – Laser weld in CuZn37

4.5. Cu-Ni alloys and nickel silver

Copper and nickel form a continuous solid solution crystal without interfering intermetallic phases. Furthermore, the thermal conductivity of Cu-Ni alloys is significantly lower than that of pure copper, which results in good fusibility and a stable melt. The suitability for welding of Cu-Ni alloys without other alloying elements is classified as excellent.

With increasing nickel content, the solubility for hydrogen in the Cu-Ni melt increases, which leads to increased porosity. Therefore, care should be taken to ensure a high degree of component cleanliness. In gas-shielded welding, shielding gas coverage of the arc and the melt is particularly important. In addition, the oxide layer should be removed by grinding or etching prior to welding. Otherwise viscous slags of nickel oxides could form, which severely impair the welding process.

Copper-nickel alloys which also contain tin, such as Wieland-L49 (CuNi9Sn2), tend to form low-melting intermetallic phases and thus strongly tend to hot cracking.

Cu-Ni-Zn alloys (nickel silvers) suffer from the unwanted effects caused by zinc, which are observed when welding Cu-Zn alloys. Zinc evaporation is even more pronounced compared to brass, because the zinc atoms are less strongly bound in the Cu-Ni matrix than they are in a Cu matrix.

Further information on copper alloys is available in the Wieland brochure „Strip for connectors“.

5. Welding of components which are covered with metallic coatings or benzotriazole

Metallic coatings are applied to copper and copper alloy strip in order to improve their properties in various ways, e.g. contact properties for connectors, corrosion properties and more.

However, the coatings also influence the suitability of the joining partners for welding. The most important types of coatings and their influence on the welding processes are briefly described below.

5.1. Tin

The very soft tin coating, which has a low melting point,is the most commonly used type of metallic coating for copper and copper alloys in electrical engineering and is used in particular for connectors. The tin coating applied by hot-dip tinning forms an intermetallic phase (IMP) between free tin on the surface and the base material during the coating process already. The IMP is desired because it is an effective preventing measure against whisker formation (Wieland SnPUR®). This IMP can be intentionally further developed until all elentary tin is consumed by subsequent heat treatment. Then the tin layer consists of IMP only and is very hard (Wieland SnTEM®). Furthermore, silver as an alloying element can be added to the molten tin. Thus, a tin-silver layer is created which improves the temperature resistance of the coating (Wieland SnTOP®).

Further information on hot-dip tin coatings is available in the Wieland brochure "Hot-dip tinned copper and copper alloy strip".

Alternatively, tin can be applied by electroplating including downstream reflow treatment process which causes the formation of the IMP. Hot-dip tin and electroplated tin reflow coatings affect welding processes in the same way.

In laser, electron beam and arc welding of tinned copper materials, the melt mixes up with tin from the tin layer. This can take place in form of tin streaks in the weld zone (Fig. 20), resulting in a mechanical weak spot. At high line energies, alloying (formation of bronze) may occur locally.

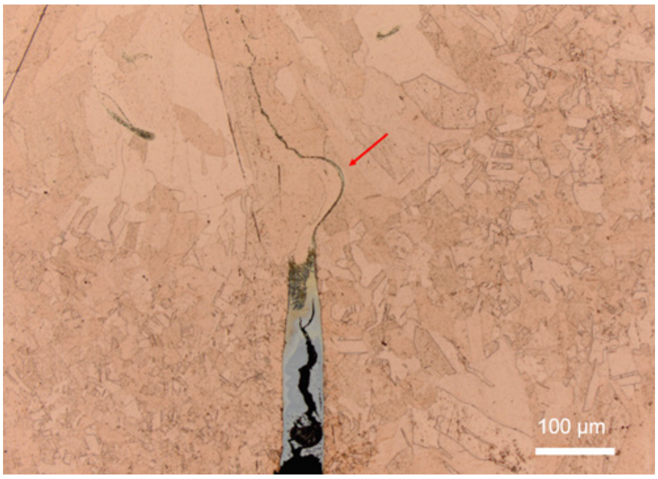


Figure 20 – Tin streaks in a seam root after welding of tin coated pure copper

The high absorption coefficient of solid tin of approx. 45 % with respect to IR radiation significantly improves the coupling of the laser beam.

In resistance welding, the tin layer offers advantages. Its low hardness leads to an increase in the real contact area in the electrode-sheet and sheet-sheet planes. As a result, the risk of local hotspot and spatter formation is reduced. Alloying of the weld seam is not to be expected, since the tin is pressed out of the joining zone during the process (see chapter 3.1).

It should be considered that, due to the very low melting point of tin (232 °C) and depending on the electrode/component design as well as the current intensity, the coating may be destroyed or the thickness of the coating may be reduced locally at the electrode/sheet contact point and in close vicinity.

During ultrasonic welding of tinned materials, a lubricating effect can occur, even with fully tempered tin coatings. This results in longer welding times and lower seam strengths.

5.2. Nickel

The most important nickel-based coatings are the electroplated pure nickel coating (melting temperature: 1453 °C) and the phosphorus-alloyed electroless nickel coating (melting temperature is approx. 900 °C at a P content of 11 %).

Due to the high melting temperature of nickel, mixing of the nickel layer with the molten copper occurs only rarely, but is possible in laser, electron beam and inert gas welding. Since copper and nickel form a continuous solid solution, a one-phased alloy mixing is uncritical under mechanically aspects. It must be noted that the electrical conductivity of the Cu-Ni-alloy material is locally reduced. The absorption coefficient of solid nickel for IR radiation, at approx. 26 %, is higher than for copper and thus improves the coupling of the beam during laser beam welding.

During resistance welding, electroplated nickel can cause problems. If the base material is already molten but the high-melting nickel coating not yet, it acts like a separating membrane and prevents joint formation between the joining partners. If the coating is destroyed by the repositioning movement of the electrodes while the base material is molten, melt is released abruptly, resulting in strong spatter formation. Unmolten nickel layers in resistance welds can also represent mechanical weak points in the joint. In the case of electroless nickel (which contains P), the problems described usually do not exist, since its melting point of approx. 900 °C is slightly below that of copper.

5.3. Silver

The melting point of silver, approx. 962 °C, is slightly below the melting point of copper (1084 °C). The copper-silver binary system is a system with limited solubility in the solid state. Dilutions of silver and copper in a fusion weld consequently lead to the formation of an eutectic weld structure and local solid solution regions with a high copper or silver concentration.

Such a seam structure exhibits good strength and toughness, on the other hand locally slightly increased electrical resistivity. The absorption coefficient of silver with respect to IR radiation is only approx. 4 % and is thus very similar to that of solid copper. Therefore, silver coating does not affect the coupling behavior of the IR laser beam during laser beam welding.

Resistance welding is just slightly affected by the silver coating due to its melting point, which is similar to that of copper. The coating is displaced from the joining zone to the side if the process is appropriately controlled. Furthermore, the coating remains largely intact at the electrode-sheet contact surface.

Experience shows that a thiol passivation which frequently is applied to silver coatings does not have any negative effect on the welding process.

5.4. Temporary corrosion inhibitor benzotriazole

Benzotriazole (BTA) is a standard temporary corrosion inhibitor for semi-finished products made of copper and copper alloys. It is applied to the strip surface in the form of an aqueous solution and is subsequently present in a chemisorbed monolayer. BTA protects the base metal from atmospheric oxidation for several months (time period depends on the alloy and storage conditions).

There are no documented effects, neither positive nor negative, of BTA monolayers on the welding behaviour of copper and copper alloys during resistance, laser, electron beam, shielding gas and ultrasonic welding.

Further information on this subject is available in the Wieland brochure „Strip shelf life – visual appearance and solderability“.

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