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A COMPREHENSIVE INVESTIGATION OF COPPER TUBE JOINTS MADE BY RESISTANCE SOLDERING

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Original scientific paper

The aim of the study was to assess the technological solderability of copper tubes by electric resistance. Soldering by electric resistance is an alternative to classical flame heating. The melting interval of experimental solders was determined by the use of DSC analysis. The most frequently occurring defects in soldered joints were identified and the factors affecting these defects were revealed. The Cu_3Sn and Cu_6Sn_5 phases were observed on the boundary of analysed joints. The average thickness of IMC (intermetallic compounds) on specimens fabricated by resistance soldering was 1,4 µm greater than in the case of flame soldering. The quality of soldered joints fabricated by electric resistance is affected by the factors of heat transfer between the carbon electrodes and soldered tubes.

Keywords: *copper pipes, resistance heating, soldering*

Sveobuhvatno istraživanje spojeva bakrenih cijevi izrađenih čvrstim lemljenjem

Izvorni znanstveni članak

Cilj je ovoga rada bio procijeniti tehnološku lemljivost bakrenih cijevi električnim otporom. Lemljenje električnim otporom je alternativa klasičnom zagrijavanju plamenom. Vrijeme taljenja eksperimentalnih lemila određeno je DSC analizom. Ustanovljene su najčešće greške zalemljenih spojeva i otkriveni faktori koji su ih uzrokovali. Primijećene su faze Cu_3Sn i Cu_6Sn_5 na rubovima analiziranih spojeva. Prosječna debljina IMC (intermetalnih spojeva) na uzorcima izrađenim čvrstim lemljenjem bila je 1,4 µm veća nego u slučaju lemljenja plamenom. Na kvalitetu spojeva dobivenih lemljenjem električnim otporom utječu faktori prijenosa topline između ugljičnih elektroda i zalemljenih cijevi.

Ključne riječ: *bakrene cijevi, zagrijavanje otporom, lemljenje*

1 Introduction

Copper tubes are applicable in almost all applications of technical equipment in buildings and they meet the most stringent requirements on quality, reliability and aesthetics. They are suitable for the assembly of classical heating, for the distribution of potable water, hot utility water, natural gas, propane-butane, oil and pressurised air, and in equipment for the utilisation of solar energy [1].

Flame brazing and soldering are currently used for the fabrication of joints in thin-walled copper tubes. Attempts are being made in present-day technical practice to replace this aged technology by the resistance soldering of copper tubes. The advantages of this process are mainly the higher heating rate of soldered joints and higher fire safety, since an open flame is not used. The application of alternative heating methods should also aim to reduce the financial demands of assembly and to increase the speed of the working procedure [1, 2].

Regarding the design, the socket overlapped joint is mostly used for the assembly of copper tubing which must be capillary soldered. Capillary clearance for the tubes with diameters from 6 mm up to 54 mm varies from 0,02 to 0,3 mm depending on the soldered tube diameter [2]. The overlap length is determined by the strength calculation. Similar calculations of joints are given for example in reference [3].

The effect of capillary clearance on overlap length in socket joints for softer tin solders is shown in Fig. 1 [1]. This dependence suggests that at smaller joint clearance a greater path of solder running-in is achieved [4].

The aim of our study was to assess the technological solderability of copper tubes by the use of electric resistance heating. The effect of the heating procedure on the size and distribution of intermetallic phases on the boundary of soldered joints was studied. Also, the thermal properties of experimental solders were investigated.

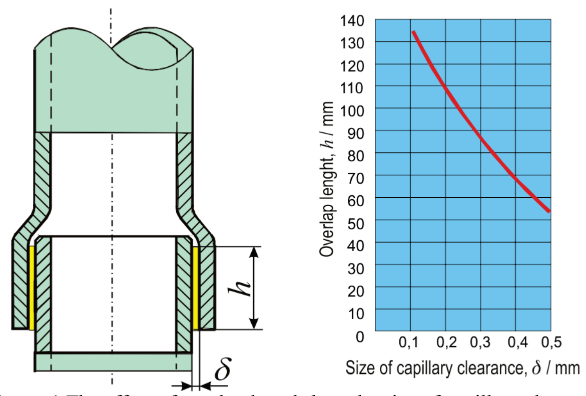

Figure 1 The effect of overlap length h on the size of capillary clearance δ [1]

2 Experimental research

Material of the soldered tubes was Cu-DHP grade with a minimum 99,9 % purity. The Cu-DHP grade means that the copper has to be de-oxidized with phosphorus and it must not contain oxygen on its surface. Semi-hard thin-walled copper tubes of 18 mm diameter and 1 mm wall thickness were used for the experiments, together with threaded fittings made of CC499K material, in accordance with standard EN 1982, with a Cu5Sn5Zn2Pb composition.

Tin-based soldering pastes, containing about 60 % solder, in powder form, and around 40 % flux, were applied. Besides the pastes, solder in the form of a wire of identical composition was also added to the joint zone. The flux was based on inorganic salts with ammonium chloride, EN 29454-1standard designated as 3.1.1.C. The technical data of soldering pastes and solders are given in Tab. 1.

Table 1 Specifications of solder pastes and solders [5, 6]

Commercial name	Producer	Composition	wt. / %	Melting range / °C
Degufit 4000	BrazeTec	Sn3Ag	96,7 Sn 3,3 Ag	221 ÷ 230
BrazeTec 4				
Paste Cu 3	Rems	Sn3Cu	97 Sn 3 Cu	230 ÷ 250
Lot Cu 3				

2.1 Resistance soldering

Resistance soldering is a process whereby the necessary heat is obtained from the thermal effect of the electric current passing through the electrodes which are made of material with a high resistance and a high melting point. The soldering heat is generated in carbon electrodes and is transferred by conduction through the soldered parts to the joint zone. In order to enhance the heat transfer, the soldering electrodes are made in the form of prisms.

Resistance soldering equipment of the type Rems Contact 2000, designed for the soldering of copper tubes in the size range ∅6 ÷ 54 mm, was employed for the experiments. The basic principle of soldering equipment is shown in Fig. 2. The carbon electrodes of the soldering equipment are pressed onto the soldered copper tube. By switching on the contactor (S) the secondary current circuit with a low voltage of 7 V and a high current intensity is closed. The carbon electrodes exert relatively high electric resistance in the secondary current circuit of the transformer (cable, electrodes, heated tube). Therefore, they are very rapidly and intensively heated and in the case of larger tube diameters they achieve temperatures up to 900 °C. Electrodes have to provide as large a contact area as possible with the soldered material. Therefore, the prismatic form of the electrodes is advantageous.

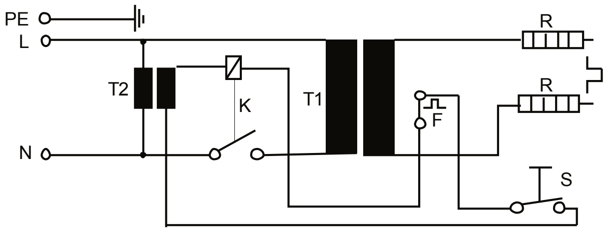

Figure 2 The wiring diagram of resistance equipment [6]

The main parameters of the soldering equipment and the technological process of resistance soldering are given in Tab. 2.

Table 2 Parameters of resistance soldering equipment type Rems Contact 2000

Input power	Nominal voltage	Nominal current	Secondary current
2000 V·A	230 V	8,7 A	250 A /AC

For comparison with the technological soldering process, flame soldering technology was also used with the application of combustible gas type MAPP. Soldering was performed with the Bernzomatic T 757 type torch with piezo-electric ignition. The torch provides the maximum primary flame temperature of up to 2010 °C. The parameters of the soldering equipment are given in Tab. 3.

Table 3 Parameters of flame soldering equipment [7]

Type of torch	Combustible gas	Heating value of the primary flame	Burner thermal output
Bernzomatic T 757 P	MAPP	2323 kJ/h	3432 W

2.2 Assessment methods for soldered joints

A DSC analysis of solders was performed by using the NETZSCH STA 409 C/CD equipment with the assessment software NETZSCH Proteus. Preliminary analysis was performed at the heating rate 10 K/min in the temperature range from 30 to 350 °C in shielding gas Ar with a 6N degree of purity. Measurements were taken in two heating cycles with a heating rate of 1 K/min in the temperature range from 200 to 250 °C. The Sn, Bi, In etalons with a 4N degree of purity were used for calibration and verification of the achieved values.

Specimens of soldered joints were processed by standard metallographic procedures. Grinding was performed with emery papers (SiC) with grain sizes 320, 680, 1200. Polishing was performed with diamond suspensions with grain sizes: 9 μm, 3 μm, 1 μm. The final polishing was performed with emulsion type OP-S (Struers) with grain size 0,2 μm.

Macroanalysis of the fabricated joints was realised on a light microscope type ZEISS STEMI 2000-C with image analyser Quick Photo Camera 2.3.

Microstructures of the soldered joints and transition zones were studied on a light microscope type Neophot 32 with the application of image analyser NIS - Elements, type E.

Identification of the transition zones was made by the use of EDX analysis on an electron scanning microscope type Vega TS 5130 MM with an X-ray microanalyser type INCA Energy 300.

The distribution of thermal fields during heating by electric resistance was identified by thermographic analysis. This was performed on FLIR P640 equipment. Processing and assessment of the measured values was performed by the use of the ThermaCAM Researcher 2.10 PRO software.

3 Results

3.1 DSC analysis of experimental solders

For the purpose of the elucidation of phase transformations and the exact determination of the melting interval of the studied experimental solders, differential calorimetry (DSC) was employed.

The melting interval of Sn3Ag solder was 221 °C to 222,9 °C. The DSC analysis also revealed binary eutectics with a melting point of 217,7 °C.

The Cu-Sn eutectics proved the presence of Cu in the solder [8]. A higher melting interval in the 226,8 to 228,7 °C range was achieved with Sn3Cu solder. Fig. 3 shows a record of the DSC analysis at the heating rate 1 K /min.

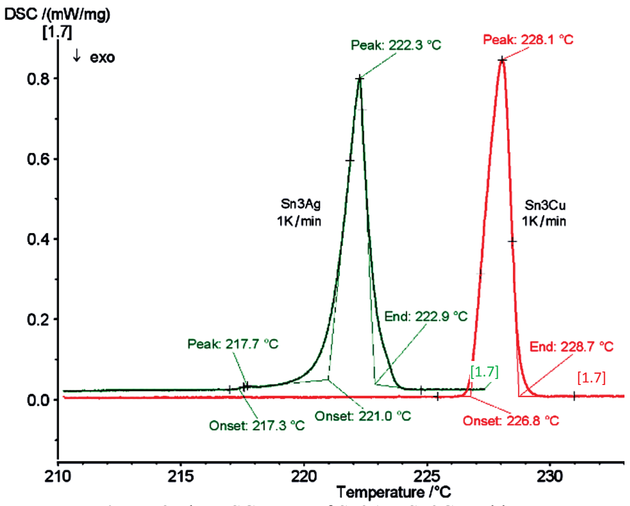

Figure 3 The DSC curve of Sn3Ag, Sn3Cu solders

3.2 Defects of soldered joints

Ten specimens fabricated by resistance heating and ten specimens fabricated by flame soldering were subjected to macroscopic and microscopic studies. The heating of copper tubes and bronze fittings by electric resistance lasted 12 s, whereas the flame heating took 31 s on average. The average thickness of the capillary clearance was 0,075 mm.

Visual inspection identified free visible defects in overlapped socket joints. Incomplete running-in of the solder (see Fig. 4a), and running-out of the solder from the inner side of the joint (see Fig. 4b) were observed most frequently.

Figure 4 Defects of soldered joints a) incomplete running-in of solder b) running-out of solder, c) voids in capillary clearance

Table 4 Comparison of formed defects

	Resistance soldering	Flame soldering
Number of cavities in the capillary gap	7	4
Incomplete running-in of solder	2	0
Running-out of solder from the inner side of the joint	1	0

Macroscopic analysis has shown that oblong voids (see Fig. 4c) were mostly formed in the capillary clearances of joints fabricated by both heating methods. The joints fabricated by use of resistance heating exerted a 43 % higher occurrence of voids than the case of flame heating. The overall number of defects occurring in soldered joints is shown in Tab. 4.

To identify the cause of the formation of the frequent oblong voids, a thermovision record was made of the heat transfer during the heating of the tubes by electric resistance. The heat transfer by conduction from the carbon electrodes to the external tube was observed. The oblong voids in the capillary clearings were formed due to the different temperatures of the outer and inner tubes. The different temperatures of the opposite walls in the capillary clearance cause a non-uniform filling of the capillary clearance. Fig. 5 shows an isothermal distribution of temperature after 12 s of heating the copper tubes. The difference in achieved temperatures, depending on the distance of the electrode from the bronze fittings, is shown in Fig. 6.

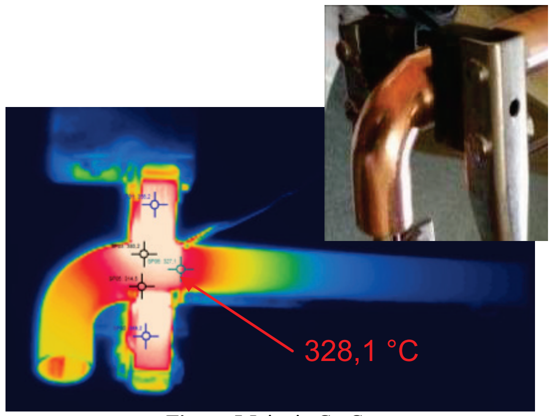

Figure 5 Joint in Cu-Cu

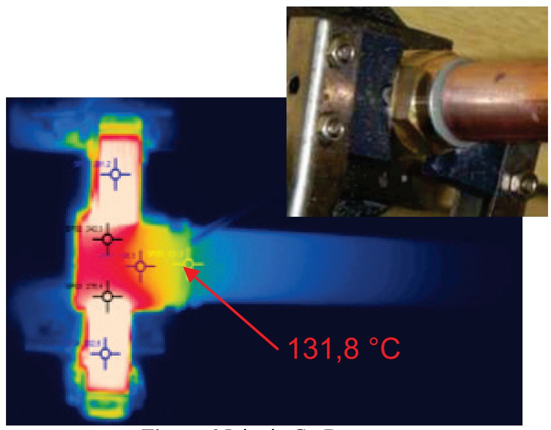

Figure 6 Joint in Cu-Bronze

3.3 IMC of soldered joints

Microstructural analysis of the transition zones in soldered joints has revealed the formation of IMC on the contact surfaces of copper substrates. The line course of Cu, Sn elements in the transition zone of the IMC is shown in Fig. 7. Two Cu_3Sn phases with the approximate composition (61,2 wt. % Cu and 38,8 wt. % Sn), and a Cu_6Sn_5 phase with the approximate composition (41,4 wt. % Cu, 58,6 wt. % Sn) were identified by EDX analysis.

The Cu_6Sn_5 phase is wettable and is in contact with the solder. The Cu_3Sn phase is non-wettable and is in contact with the copper substrate. These intermetallic phases are hard and brittle compounds [9].

Their existence in the contact surface, owing to interactions of solder and substrate, indicates that a sound metallurgical bond was achieved. Problems arise just at the point of IMC growth, due to which degradation of the mechanical properties of the soldered joints takes place.

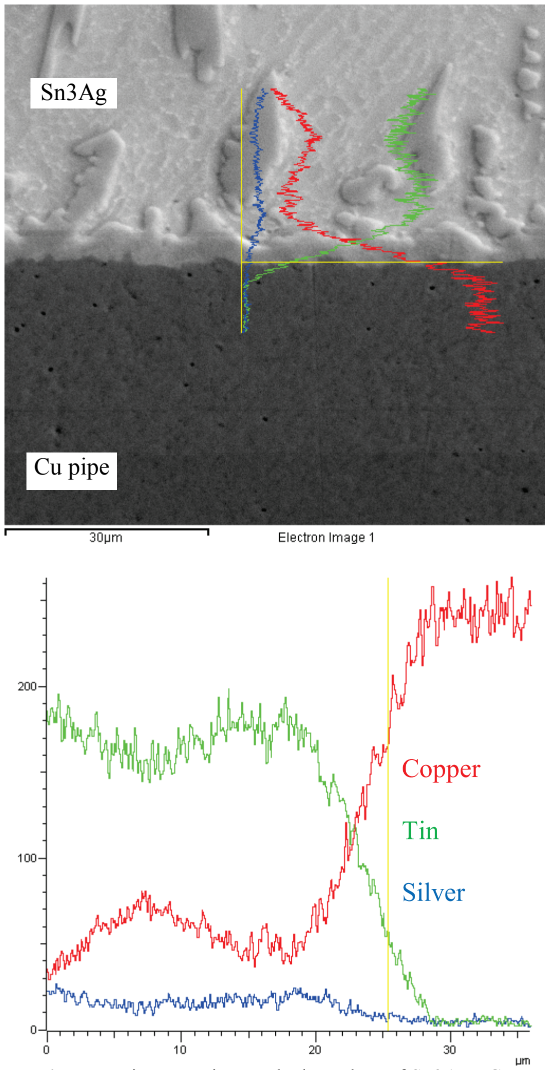

Figure 7 Line scanning on the boundary of Sn3Ag - Cu

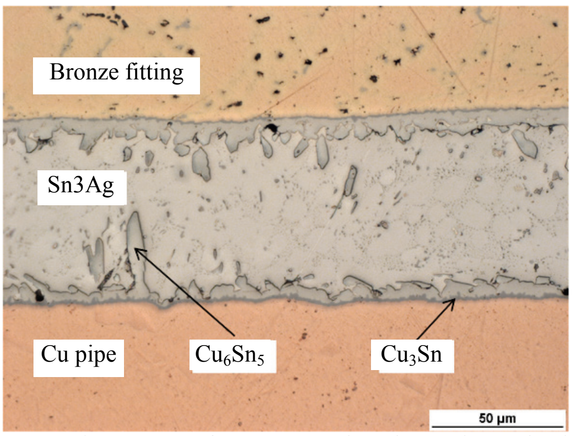

Figure 8 Microstructure of Cu-Sn3Cu-Cu boundary, resistance heating

The morphology and the thickness of the IMC were studied by optical microscopy. The average IMC thickness varied from 1,6 to 4,5 µm. In the case of joints soldered by electric resistance (Fig. 8) a wider and more particulated zone of Cu_6Sn_5 phase occurrence was observed than in the case of flame soldering (Fig. 9). The average IMC thickness depending on the heating procedure is shown in Fig. 10.

The size and shape of the IMC is affected by the soldering parameters (soldering temperature and time) and also the chemical composition of the solder. The IMC thickness grows exponentially with soldering temperature and linearly with soldering time.

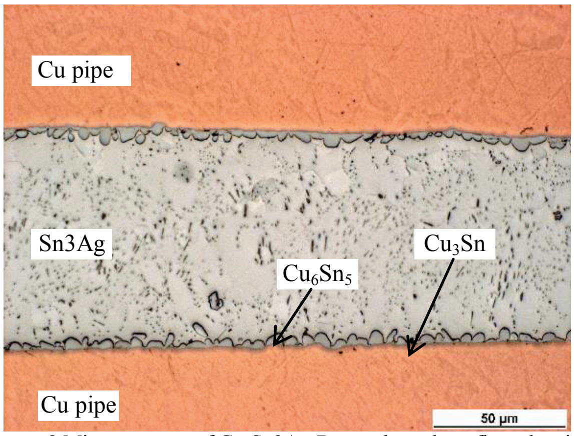

Figure 9 Microstructure of Cu-Sn3Ag-Bronze boundary, flame heating

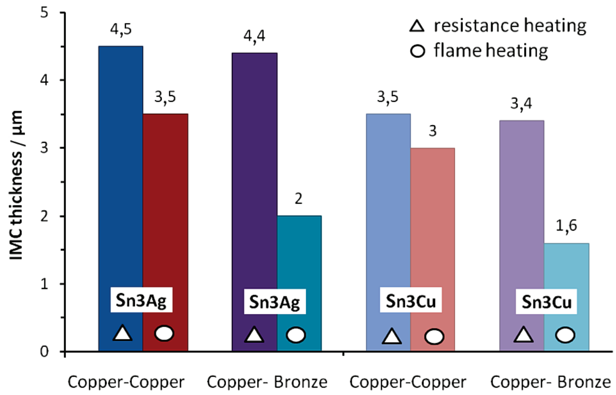

Figure 10 Average thickness of IMC

4 Conclusion

The DSC analysis has revealed the melting point of Sn3Ag solder to be in the temperature interval 221,0 to 222,9 °C. The Sn3Cu solder has shown the melting point to be within the temperature range 226,8 to 228,7 °C.

Macroscopic analysis has identified the most frequent defects occurring in soldered joints - the voids in capillary clearance. The joints fabricated by the use of resistance heating exerted a 43 % higher occurrence of void formation than the joints soldered by flame.

The mechanism of the defect formation was identified by the use of thermovision. Void formation was affected by heat transfer between the electrodes and the heated tube (factors: maximum temperature and shape of electrodes, final pressing of electrodes, material and diameter of tubes) as well as by the heat transfer between the outer and inner tubes (factors: calibration of tubes, thickness of tubes, distance of electrodes from the soldering zone).

The results of EDX analysis have revealed the dilution of copper on the tube surface in the tin matrix, accompanied by the formation of Cu_3Sn and Cu_6Sn_5

intermetallic phases. A region of copper solubility in the tin matrix of solder was formed on the boundaries of the analysed joints by the reaction diffusion mechanism.

The average IMC thickness on the joint boundaries of specimens soldered by flame is 36 % lower than the average IMC thickness in the case of resistance soldering. The IMC thickness was affected by the achieved temperature and the time of resistance soldering.

The resistance soldering is safer as it excludes application of a naked flame. Resistance soldering allows the joining of the tubing in environments where application of a naked flame is excluded. However, its disadvantage in comparison to flame heating is its poor accessibility to the soldering location.

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5 References

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