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Strojnícky časopis – *Journal of* MECHANICAL ENGINEERING,
VOL 74 (2024), NO 3, 121 - 130

STU SjF

MAKING OF BIMETALLIC SEMI-FINISHED PRODUCTS FOR THE PRODUCTION OF ELEMENTS FOR JOINING DISSIMILAR MATERIALS USING THE RESISTANCE ELEMENT SOLDERING

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Abstract: The contribution is devoted to the making of bimetallic semi-finished products for the production of elements, which are used to joining dissimilar materials, metal sheets to plastics, using the Resistance Element Soldering. During the making of bimetallic semi-finished products by gravity casting, defects occurred and, moreover, the proposed method of casting was not very productive. Therefore, centrifugal casting of bimetallic semi-finished products was proposed, which enables the production of a larger number of semi-products with higher quality in one casting cycle. The method was verified by preparing bimetallic semi-finished products Cu-Sn91Zn9 and Cu-Sn60Pb40. The non-destructive X-ray test proved the reliability of the centrifugal casting in the serial production of high quality bimetallic semi-finished products.

KEYWORDS: joining dissimilar materials, Resistance Element Soldering, bimetallic element, metal casting

1 Introduction

Due to the increased demands placed on the functionality, complexity and weight of structures, in many cases it is necessary to use combinations of different materials. In practice, two dissimilar materials with very different properties, such as metal and plastic, must be joined using suitable technology. Plastic materials are characterized by their versatility, low weight, corrosion resistance and favorable price [1-3]. Metals are usually used when excellent mechanical properties are required, e.g. strength and toughness, or certain physical properties such as high thermal or electrical conductivity [4,5].

Several joining technologies are used to join metal to plastic, e.g. gluing, mechanical joining and welding [6-13]. Each of them has its advantages and disadvantages, the use depends on the use of the joint.

The most used joining technologies include mechanical joining, in which the metal and plastic parts are joined with screws or rivets. This technology is simple and effective but increases the weight of the structure and can be prone to corrosion in the joint [8].

In recent decades, the use of glued joints has greatly expanded due to the development of high-strength and durable adhesives that can withstand both static and dynamic loads. This joint ensures a significant reduction in weight compared to a mechanical joint and a homogeneous distribution of stress during loading. The problem with glued joints is that the resulting joints are susceptible to degradation, for example due to humidity or temperature [6]. In addition, not all plastics can be glued.

Welding plastic to metal is a challenge, due to their different properties. One of the factors that most influence the use of welding to create this type of joint is their different melting temperature. To ensure a reliable joint of these materials, it is necessary to use special methods such as Laser-Assisted Metal and Plastic (LAMP) joining [13-17]. The joint is created by melting the plastic at the interface of the joined materials. Bubbles with high vapor

DOI: 10.2478/scjme-2024-0039, Print ISSN 0039-2472, On-line ISSN 2450-5471

pressure are formed in the molten plastic, which press the joined materials together (Fig. 1) [16]. The laser beam can heat the required contact surface through metal, or through plastic if it has a transparency of more than 60 %.

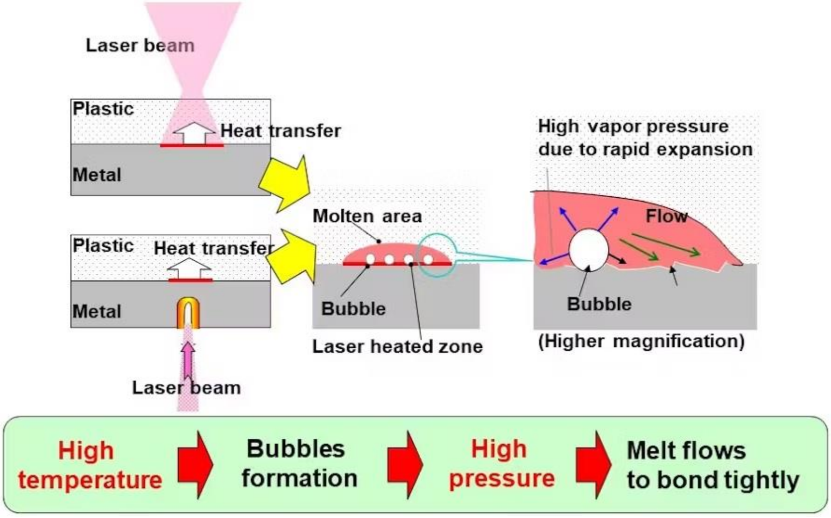

Fig. 1 The principle of joining metal-to-plastic by the LAMP joining method [16]

Another method that can be used to create a metal-to-plastic joint is ultrasonic welding [17,18]. This method allows joining through high-frequency oscillation of parts (20 to 40 kHz) with low amplitude (1 to 25 μm) and small pressing force in a very short welding time (0.1 to 1 second).

A new metal-to-plastic joining method is Resistance Element Soldering (RES) [19-21], which was developed from the Resistance Element Welding (REW). The difference between these methods is that while REW (Fig. 2) uses a single material element (weld rivet) for welding [22], RES uses a bimetallic element (Fig. 3) for soldering [23]. However, the joining principle (Fig. 2) is the same for both methods. The element with a cylindrical shaft and head ensures a lapped joint of the upper material (e.g. aluminum alloy or plastic in the RES) with the lower material (steel sheet). The opening in the upper material, into which the element is placed, defines the connection point and partially fixes the element before joining. To create a joint, resistance heating and clamping force are used, which are derived by welding gun for resistance spot welding (spot welder).

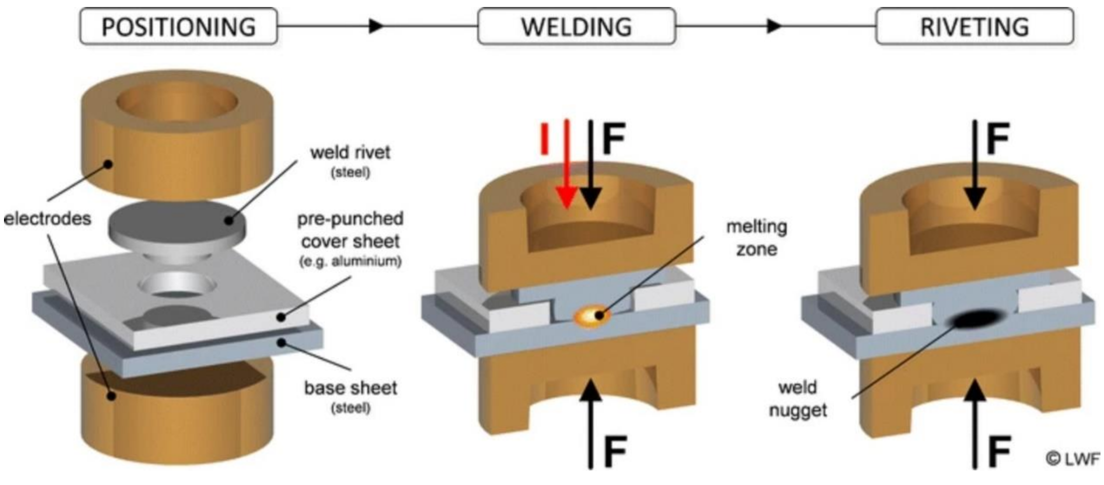

Fig. 2 The principle of joining by the REW [10]

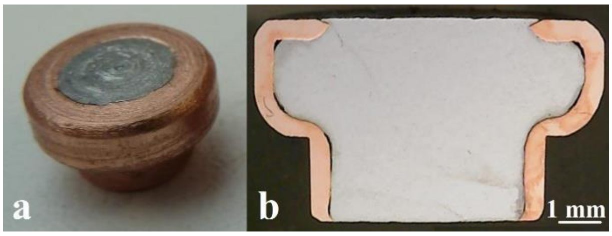

Fig. 3 Bimetallic elements for the RES (a – side view, b – cross section)

The join of materials by the RES is created by a combination of a fusion joint, which is created by resistance soldering of the bottom material (steel sheet) with the core of a bimetallic element (solder), and a shape-strength joint between the shell of the element and the upper material (plastic) [19-21]. The reason for using the soldering of the bimetallic element in the RES is that in the REW, when using a standard element made of steel or aluminum, thermal degradation of the plastic occurs.

2 Experiment

The shell of the bimetallic semi-finished product for the production of elements (Fig. 4) must be made of a material with sufficient strength. Cu tubes with an outer diameter (d) of 6 mm, a wall thickness (s) of 0.5 mm and a length (h) of 80 mm were chosen for the experiments, which were annealed due to good formability into the shape of elements. The basic mechanical properties of the annealed Cu tubes are listed in Table 1. Two tin alloys suitable for soldering of steels, Sn60Pb40 and Sn91Zn9, were selected for the core of bimetallic semi-finished products (Table 2). These semi-products are later divided and formed into the shape of elements (Fig. 3) by volume cold forming.

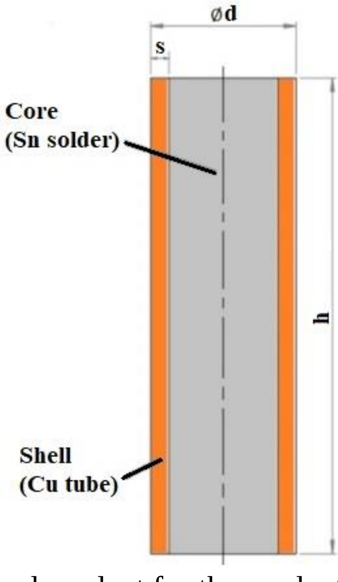

Fig. 4 Bimetallic semi-finished product for the production of elements for the RES

Table 1 Mechanical properties of the annealed Cu tube used for the shell of bimetallic semi-finished products

Material	Density ρ ($g.cm^{-3}$)	Yield strength R_e (MPa)	Ultimate tensile strength R_m (MPa)	Elongation at break A (%)
Cu	8.96	55.5	238	43.7

Table 2 Chemical composition and melting point (liquidus temperature) of solders used for the core of bimetallic semi-finished products

Material	Sn (%)	Pb (%)	Cu (%)	Zn (%)	Ag (%)	Sb (%)	Bi (%)	Cd (%)	Solidus / Liquidus (°C)
Sn60Pb40	59.5-60.5	40	0.08	0.001	0.1	0.2	0.1	0.002	183/190
Sn91Zn9	91	0.1	0.05	8.5-9.5	0.1	0.1	0.1	0.002	199/199

Bimetallic semi-finished products can be produced in different ways. One of the technologies that can be used is metal casting. Conventional gravity casting is the simplest and cheapest method. Therefore, the original proposal considered the gravity filling of Cu tubes (Fig. 5). The Sn91Zn9 solder was melted and overheated to a pouring temperature of 220 °C. The melt was cast in a continuous stream into the Cu tube placed in a two-part graphite insulating sleeve with a pouring cup, which were preheated together to a temperature of 220 °C. Immediately before casting, the inner surface of the Cu tube was flux coated to remove surface oxides and improve wettability. During casting, the end of the tube rested on a flat graphite plate with ambient temperature. After solidification of the solder in the Cu tube, the finished bimetallic semi-finished product was removed from the graphite sleeve and the pouring cup metal was removed by sawing. The semi-finished product prepared in this way was ready for division and forming.

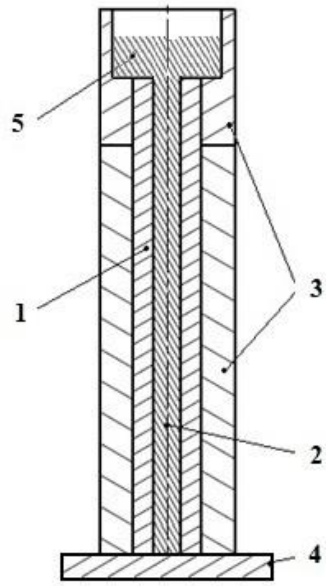

Fig. 5 Gravity casting of a bimetallic semi-finished product (1 – Cu tube, 2 – Sn melt, 3 – two-part graphite insulating sleeve, 4 – non-preheated graphite plate, 5 – pouring cup)

To increase productivity, an experimental plaster mold was designed and manufactured for centrifugal casting of four pieces of bimetallic semi-finished products in one casting cycle (Fig. 6). A laboratory centrifugal casting machine with speed control was used for casting. The plaster mold was clamped with two screws on the metal base plate of the machine and preheated together to a temperature of 120 ˚C. The Cu tubes were preheated to a temperature of 220 ˚C and before being inserted into the cavities of the plaster mold, they were coated from the inside with liquid flux SF-601, intended mainly for soldering copper alloys, nickel, and some steels with tin solders. After placing two Cu tubes and two blanking rods (to save solder during testing) in the lower part of the mold (drag), the mold was closed with the upper part (cope) and tightened with nuts. After spinning the mold at the selected revolutions, molten solder (Sn91Zn9 or Sn60Pb40) with a casting temperature of 220 ˚C was poured continuously through the central gating system into the Cu tubes. The melt flowed through Cu tubes to overflows (reservoirs, which are intended for gases and oxidized metal). After the end of pouring, centrifugation was active until the solder solidified in the pouring cup (approximately 5 minutes).

Casting was performed with Sn91Zn9 solder at a speed of 200, 300, and 400 rpm. Later, after evaluating the quality of the performed castings, one casting was performed with full use of the mold (four Cu tubes) with Sn60Pb40 solder at a speed of 300 rpm.

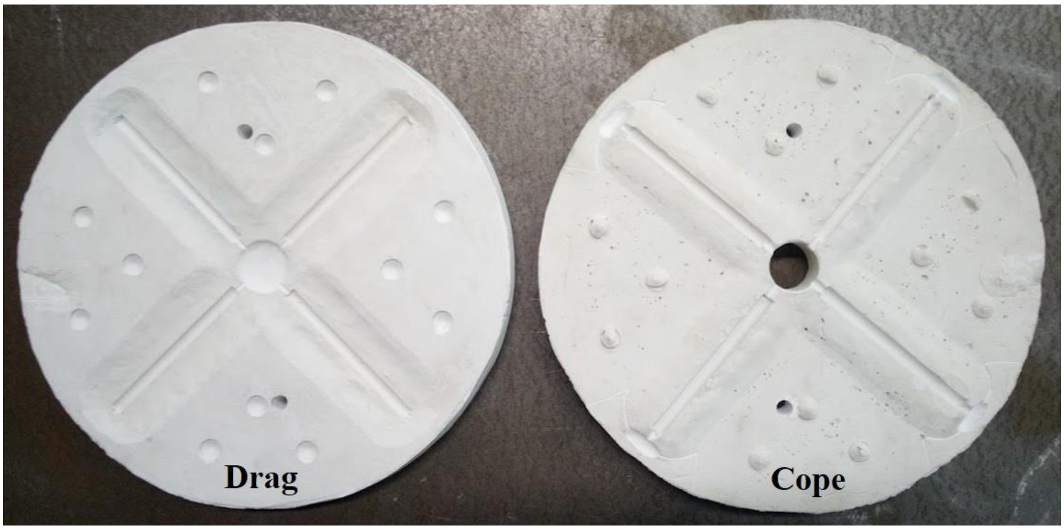

Fig. 6 Plaster mold with central gating system for centrifugal casting of four bimetallic semi-finished products in one casting cycle

All semi-finished products were checked by a non-destructive X-ray test to determine the cavities and misruns of the solder in the Cu tubes. The semi-finished products were then subjected to analysis of chemical composition by energy dispersive spectroscopy (EDS) with an Oxford Instruments X-Max analyzer, which is part of the JEOL JSM IT-300LV electron microscope. The chemical composition of the solder at the inlet to the tube and at the outlet from the tube was compared. The goal was to evaluate the segregation of solutes in the solder along the length of the semi-finished products, which during centrifugal casting is supported by the action of centrifugal force during solidification. Large differences in the composition of elements can result in fluctuations in the quality of the joints.

3 Results

Cu-Sn91Zn9 bimetallic semi-finished products that were cast by gravity in a graphite insulating sleeve did not show any signs of reduced quality at first sight, but differences in weight were observed. Therefore, these semi-finished products were subjected to a non-destructive X-ray test. It was found that during the production of bimetallic semi-finished products by gravity casting, cavities and misruns are created in the solidified solder (Fig. 7). These defects are mainly caused by gas entrapment during casting due to insufficient venting of the tubes, as the inlet also performed the function of the vent at the same time. Semi-finished products with defects result in the production of low-quality elements unsuitable for the RES (Fig. 8), therefore gravity casting designed in this way is not suitable for the making of bimetallic semi-products.

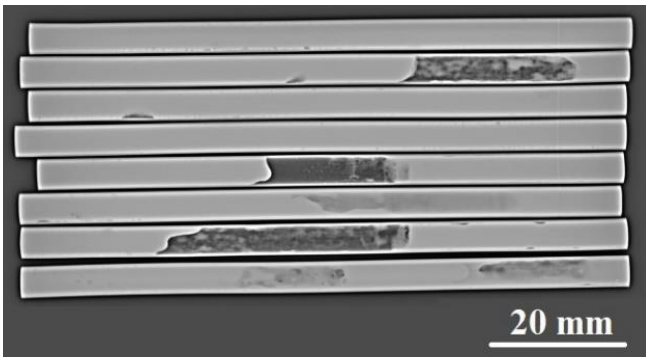

Fig. 7 X-ray image of Cu-Sn91Zn9 bimetallic semi-finished products made by gravity casting (dark areas in the core of the semi-finished products represent cavities and misruns)

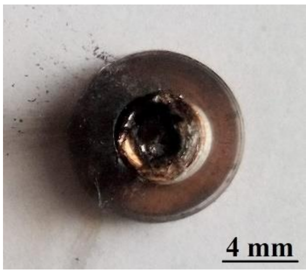

Fig. 8 Low-quality element with blowhole unmasked after joining using the RES

Centrifugally cast Cu-Sn91Zn9 bimetallic semi-finished products (Fig. 9) showed varying degrees of melt flow into the parting line of the mold (flashes), which increased after each casting due to degradation of the plaster mold and increased clearance between the mold parts. Flashes have no effect on the final quality of bimetallic semi-finished products. Due to saving solder material, this condition can be improved by tighter clamping using a larger number of screws or by making a new mold, which was confirmed later in the production of bimetallic semi-finished products Cu-Sn60Pb40 (Fig. 10).

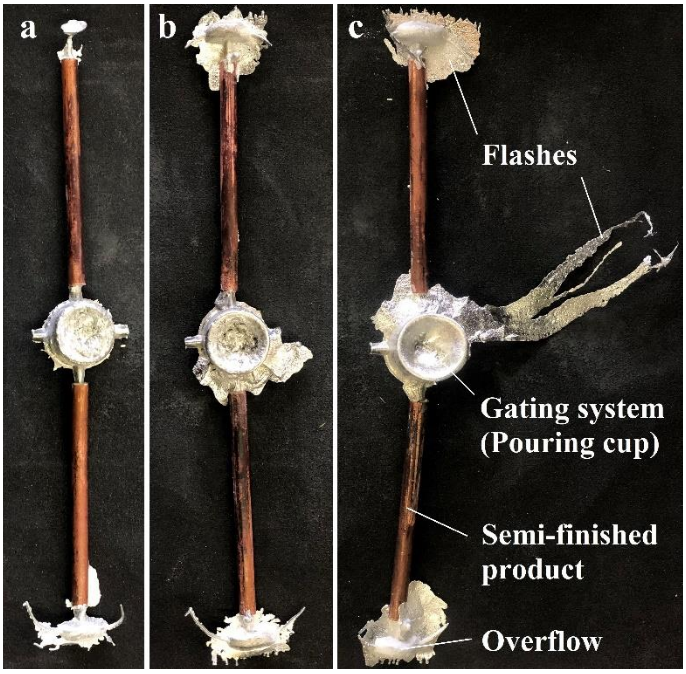

Fig. 9 Centrifugally cast bimetallic semi-finished products Cu-Sn91Zn9 at a speed of: a) 200 rpm, b) 300 rpm, c) 400 rpm

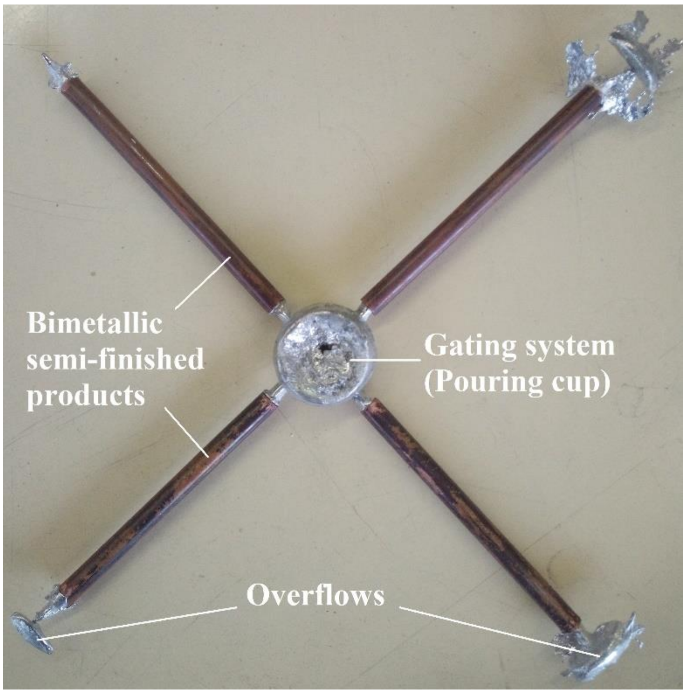

Fig. 10 Centrifugally cast bimetallic semi-finished products Cu-Sn60Pb40 at a speed of 300 rpm

Based on the X-ray images of bimetallic semi-finished products made by centrifugal casting (Fig. 11 and Fig. 12), it can be concluded that the centrifugal casting can eliminate the formation of defects in the core (Sn solder) of the semi-finished products. Therefore, it is suitable for their production.

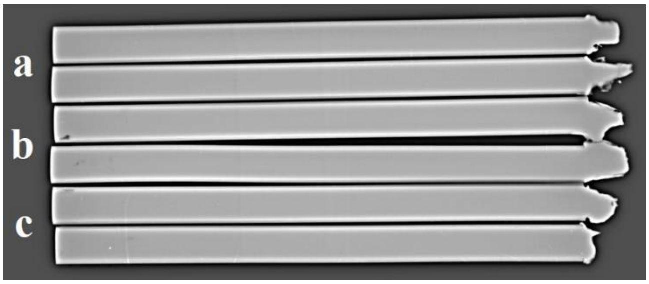

Fig. 11 X-ray image of bimetallic Cu-Sn91Zn9 semi-finished products made by centrifugal casting at a speed of: a) 200 rpm (2 pcs), b) 300 rpm (2 pcs), c) 400 rpm (2 pcs)

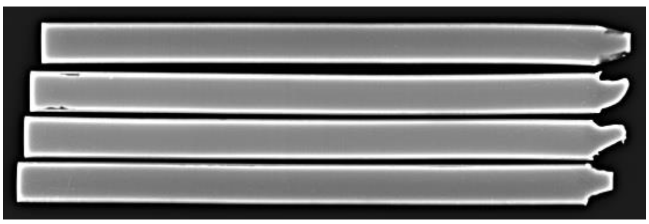

Fig. 12 X-ray image of bimetallic Cu-Sn60Pb40 semi-finished products made by centrifugal casting at a speed of 300 rpm

EDS analysis of the chemical composition (Fig. 13) was performed on both ends of each bimetallic semi-finished product. The presented values (Table 3 and Table 4) are the average of four measurements of the chemical composition. The results of the EDS analysis of the bimetallic semi-finished products show that during production by centrifugal casting there is an increased macroscopic segregation of zinc in the Sn91Zn9 alloy and lead in the Sn60Pb40 alloy (the gravity cast samples showed a difference in chemical composition from 0.1 to 0.3 wt. %). The influence of the speed of the mold during centrifugal casting on the amount of segregation of the solute was negligible in the used speed range from 200 to 400 rpm.

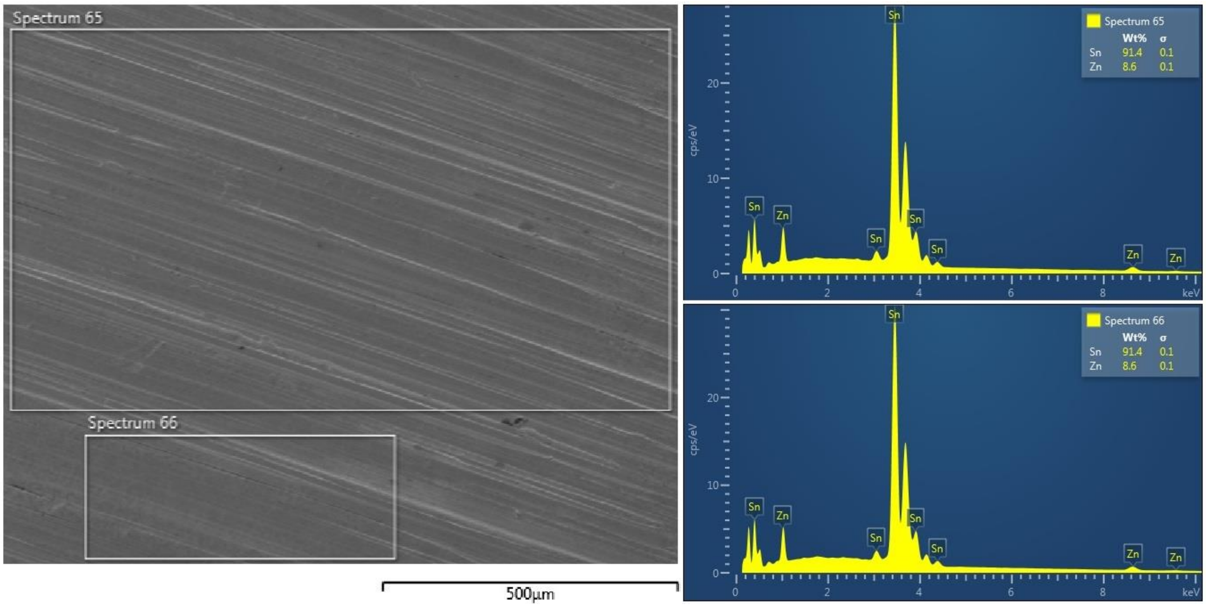

Fig. 13 EDS analysis of the solder at the end of the tube (outlet) of bimetallic Cu-Sn91Zn9 semi-finished product made by centrifugal casting at a speed of 400 rpm

Table 3 EDS analysis of Sn91Zn9 solder after centrifugal casting

Mold speed [rpm]	Inlet to the tube [wt. % Zn]	Outlet from the tube [wt. % Zn]	Segregation [wt. % Zn]
200	10.775 ± 0.960	9.375 ± 0.750	1.4
300	11.567 ± 0.665	9.9 ± 0.294	1.67
400	10.375 ± 0.217	8.775 ± 0.205	1.6

Table 4 EDS analysis of Sn60Pb40 solder after centrifugal casting

Mold speed [rpm]	Inlet to the tube [wt. % Zn]	Outlet from the tube [wt. % Zn]	Segregation [wt. % Zn]
300	46.525 ± 0.955	45.125 ± 1.176	1.4

Macroscopic segregation is a natural phenomenon in casting, but in the case of centrifugal casting it is supported by the action of centrifugal force. Large differences in the chemical composition of the solders along the length of the bimetallic semi-finished products can cause different quality of the elements and thus also different properties (e.g. strength) of the joints.

CONCLUSION

A method of making bimetallic semi-finished products Cu-Sn91Zn9 and Cu-Sn60Pb4 for the production of elements for Resistance Element Soldering (RES) using the principle of centrifugal casting was proposed and tested. Non-destructive X-ray tests showed that, unlike gravity-cast bimetallic semi-finished products, the bimetallic semi-finished products were centrifugally cast without cavities in the core, which enables the production of high-quality elements. The disadvantage of the centrifugal casting of bimetallic semi-finished products is the occurrence of higher segregation of solute in the used solders, which is caused by centrifugal force. This segregation can affect the mechanical properties of the joints.

ACKNOWLEDGMENTS

We would like to thank the supporters of the projects VEGA 1/0302/23, University Science Park of the Slovak University of Technology in Bratislava, ITMS code 26240220084, and Accord 2, ITMS code 313021BXZ1.

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