A R C H I V E S O F M E T A L L U R G Y A N D M A T E R I A L S
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BIMETALLIC WIRES: TECHNOLOGY FOR THEIR MECHANICAL COLD CLADDING AND FUNCTIONAL PROPERTIES

DRUTY BIMETALOWE-TECHNOLOGIA MECHANICZNEGO PLATEROWANIA NA ZIMNO ORAZ WŁASNOSCI UŻYTKOWE

Technologies for the production of Fe/Cu and FeNi42/Cu type cladded wires, their physical and mechanical properties and some areas of application, have been presented. The paper outlines the mechanism and conditions of cladding a composite material consisting of two different metals with a circular cross-section, having a form of a tube with a core wire placed inside that tube in the process of mechanical bonding performed with the use of cold drawing and diffusive annealing. Analysis of the cladding process and results of related research and tests carried out have been presented. These technological tests, including bending, torsion test and flattening, and examination of mechanical properties, were aimed at evaluating quality of metallurgical bonding between bimetal components. Particularly important appeared to be microstructure examination carried out with the use of X-ray micro-analyser, which enabled to evaluate degree of atomic diffusion at the boundary between the metals joined. Tests were also made with coating the surface of FeNi42/Cu bimetallic wires with a thin layer of borax, Cu_2O copper oxide and nickel in order to check possibility of using them as lead-in wires in different light bulbs or electronic subassemblies. Production technology of bimetallic wires has been developed at the Institute of Non-Ferrous Metals under many research and development projects. Evaluation of their functional properties was made.
Keywords: bimetallic wires, mechanical cladding, functional properties

W pracy przedstawiono technologie otrzymywania drutów bimetalowych typu Fe/Cu oraz FeNi42/Cu, ich własności fizyko-mechaniczne, a także podano niektóre obszary zastosowania. Omówiono mechanizm i warunki platerowania kompozytu dwóch różnych metali o przekroju kołowym-rurka z umieszczonym w niej drutem rdzeniowym w procesie mechanicznego ich łączenia, wykorzystując operację ciągnienia na zimno i dyfuzyjnego wyżarzania. Przedstawiono analizę procesu platerowania w/w metali oraz zaprezentowano wyniki prób badawczo doświadczalnych w tym zakresie. Do oceny stopnia połączenia metalurgicznego składników bimetalu wykorzystywano zarówno próby technologiczne tj: zginanie, skręcanie, spłaszczanie oraz badania własności wytrzymałościowych. Ważne w tym zakresie okazały się badania mikrostruktury-szczególnie z wykorzystaniem mikroanalizy rentgenowskiej do oceny stopnia dyfuzji atomów na granicy strefy połączenia metali. Przeprowadzono także badania w zakresie nakładania cienkich warstw boraksu, tlenku miedzi Cu_2O oraz niklu na powierzchnię drutu bimetalowego FeNi42/Cu w aspekcie wykorzystywania tych drutów na doprowadzenia prądu w różnego typu żarówkach oraz podzespołach elektronicznych. Dokonano także oceny własności użytkowych drutów bimetalowych, których technologia wytwarzania opracowana została w Instytucie Metali Nieżelaznych w ramach realizacji szeregu prac badawczo–rozwojowych i wdrożeniowych.

1. Introduction

The Fe/Cu and FeNi42/Cu bimetallic cladded wires are composite materials consisting of two different metals metallurgically bonded during cold mechanical cladding process performed with the use of drawing operation and diffusive annealing. Typical cross-section of a bimetallic wire with the diameter of 1 mm obtained by this process is shown in Fig. 1.

Suitable bonding of two metals (copper and iron in this case) into a single product makes it possible to obtain wires exhibiting such mechanical and physical properties, which are the resultant of respective properties of constituent metals. An outer layer of this type of products is made of copper, which ensures appropriate corrosion resistance. The Fe/Cu cladded wires have been widely used in the manufacture of different types of cables and electric wiring such as concentric cables, telephone conductors, ground leads, in railway networks and military equipment, and in building engineering. Besides, the FeNi42Cu wires have thermal expansion coefficient comparable with that of glass, which is in favour of using them in vacuum-tight lead-in wires for light bulbs and in electronic circuits. These wires are suitably

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bonded to glass of specific properties and, in order to ensure vacuum-tightness of the joints obtained, surface of the wires is coated with a several micron thick layer of sodium tetraborate, copper oxide Cu_2O or nickel.

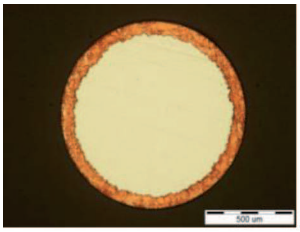

Fig. 1. Bimetallic cladded wire Fe/Cu 1 mm in diameter, obtained by mechanical cold cladding

Characteristic feature of the FeCu30 wires are their magnetic properties. Due to permanent bond of copper to steel this material is an outstanding theft deterrent since the steel core reduces the scrap value to that of steel. These reasons should be in favour of using bimetallic wires in various leads and cables, where they can easily replace products from solid copper.

2. Production technology of the Fe/Cu and FeNi42/Cu cladded wires – an outline

The concept of production technology of these wires, which has been patented by the Institute of Non-Ferrous Metals [1], is based on continuous forming of a copper tube inside which a core from steel or other metals (e.g. FeNi42) is placed, and simultaneous joining of the tube edges by the TIG welding process. Schematic diagram of this process is shown in Fig. 2.

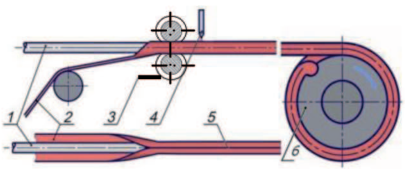

Fig. 2. Schematic diagram of the Fe(FeNi42)/Cu composite manufacture

1. Core wire Fe(FeNi42)
2. Strip from oxygen-free copper
3. Rolls for strip profiling and fastening on a core
4. Equipment for longitudinal welding of a copper tube formed on a core

Based on the concept of semi-product manufacture (i.e. of a composite material intended for cladded wires production) illustrated in Fig. 2, an experimental technological line has been designed and built using an equipment for the production of welded tubes from brass and copper, bought from "Warszawa" Rolling Mill. General view of this technological line is shown in Fig. 3.

Fig. 3. Technological line for fabrication of composites (semi-products) used for the production of bimetallic wires

The technological line shown in Fig. 3 is currently used at the Institute for the production of cladded wires Fe(soft steel)/Cu and FeNi42/Cu coated with a layer of borax, Cu_2O copper oxide or nickel, performed using the technologies developed at the Institute [2-5]. Technological flowchart of Fe/Cu wires production is shown in Fig. 4.

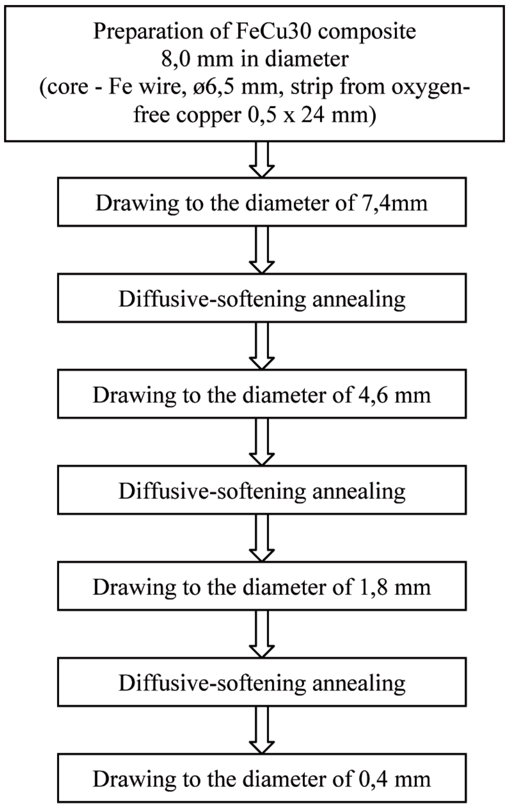

Fig. 4. Technological flowchart of the FeCu30 cladded wires production

Typical microstructure over cross-section of the FNi42/Cu bonded wires, 0,3 mm in diameter, borated and nickel-coated, is shown in Figs 5-6.

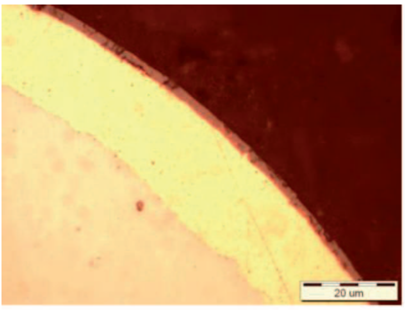

Fig. 5. Microstructure of a cross-section of bimetallic wire FeNi42/Cu- ø0,35 mm with a surface borax-oxide layer

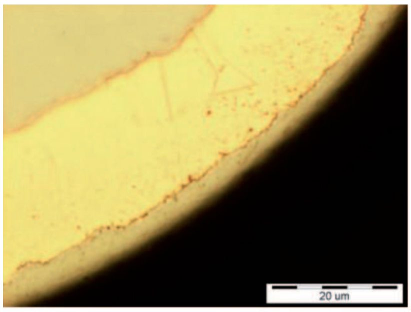

Fig. 6. Microstructure of a cross-section of bimetallic wire FeNi42/Cu -ø0,3 mm, nickel-coated

The research and tests are currently underway at the Institute aimed at developing production technology of new grades of Fe/Cu type bonded wires intended for application in electrical power systems for railway networks, and of the stainless steel/copper and copper/stainless steel type wires for application mainly in electrical engineering and electronics.

3. Theoretical background of bimetallic cladded wires manufacture in the processes of mechanical cladding and diffusive heat treatment

The bimetallic wire is a metallurgical connection of two different metals; one of which being a core wire and the second – an outer coating. Different methods are used to produce this kind of products, e.g. Fe/Cu or FeNi42/Cu. These methods are: (i) pouring liquid copper into a mould containing preliminarily heated steel core with suitably selected diameter, (ii) fastening of a steel core inside the copper tube by pressing followed by hot rolling under a sizing system, or cold drawing combined with diffusive annealing, (iii) joining of two copper strips on a heated steel core using a hot sizing process [6], which has been applied by leading world producers of bimetallic wires.

The technological process used at the Institute of Non-Ferrous Metals for bimetallic wires production is the following: first a suitable composite is prepared using technological line shown in Fig.3, and then the obtained semi-product is subjected to cold drawing with intermediate heat treatment. Diagram of the deformation region within a drawing die is shown in Fig. 7.

The deformation region, participating in "fastening" of the Fe(FeNi42)/Cu composite by drawing, can be divided into three zones:

- fastening zone, where a tube (cladding) is being deformed and placed onto a core wire,
- reducing zone, where only the change in thickness of cladding takes place, and
- zone of proportional deformation of both composite components

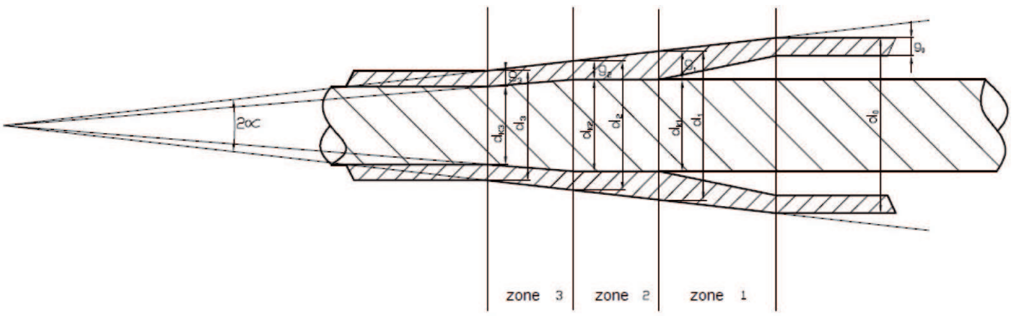

Fig. 7. Deformation zones in the process of drawing Fe(FeNi42)/Cu composite [7]

Based on the equation derived elsewhere [7,8]:

$$\ln\left(g_0/g_1\right) = \frac{\ln\left(d_0/d_1\right)^{2\Theta} - (1+k)\cdot\ln\left[\left(3k^2 + \left(d_0/d_1\right)^{2\Theta}\right)/\left(3k^2+1\right)\right]}{2k\Theta} \tag{1}$$

where:

g_0 – initial thickness of an outer layer (cladding),

g_1 –thickness of an outer layer at zone 1 exit,

d_0 – initial diameter of bimetallic semi-product,

d_1 – bimetal diameter at zone 1 exit,

$k = (d_0 - 2g_0) / d_0$ – relative internal diameter of the cladding at drawing die entrance,

$\theta = 1 + \mu \cdot ctg\alpha$ – arameter taking into account an effect of friction and die angle on the change of tube wall thickness before the contact with a core is reached (zone 1); when $7° \leqslant \alpha \leqslant 9°$ and $0.1 \leqslant \mu \leqslant 0.3$; neglecting of this effect introduces an error of below 5%,

the following relationships are valid at the exit from zone 1:

$$g_1 = d_1/2 - [(d_1/2)^2 \cdot g_0 \cdot (d_0 - g_0)/\lambda_1]^{0.5} \quad (2)$$

or

$$g_1 = [(d_{K1}/2)^2 + g_0 \cdot (d_0 - g_0)/\lambda_1]^{0.5} - d_{K1}/2, \quad (3)$$

where: d_{K1} – diameter of a core at the die entrance, which is usually $0{,}98d_{K0}$ (after cleaning of the surface). Elongation factor for zone 1 is:

$$\lambda_1 = g_0 \cdot (d_0 - g_0)/g_1 \cdot (d_1 - g_1) \quad \text{and} \quad (4)$$

$$\varepsilon_1 = 1 - 1/\lambda_1 \quad \lambda_1 = 1/(1 - \varepsilon_1). \quad (5)$$

If the fraction of relative deformation of an outer layer (in zone 1) is denoted by ε_{x1}, then:

$$\varepsilon_{x1} = 4g_1 \cdot (d_1 - g_1)/d_1^2 = 1 - [d_{K1}/(d_{K1} + 2g_1]^2. \quad (6)$$

The changes taking place in zone 2 can be determined assuming a maximum deformation of the cladding in this zone; i.e. $\varepsilon_2 = \varepsilon_{x1}$.

Then:

$$\lambda_2 = 1/(1 - \varepsilon_{x1}), \quad (7)$$

$$d_2 = d_{K1} + 2g_2 \quad \text{and} \quad (8)$$

$$\varepsilon_{x2} = 4g_2 \cdot (d_2 - g_2)/d_2^2 = 1 - [d_{K1}/(d_{K1} + 2g_2)]. \quad (9)$$

In the zone 3:

$$\lambda_3 = (d_2/d_3)^2, \quad (10)$$

$$d_{K3} = d_{K1}/\lambda_3^{0.5}, \quad (11)$$

$$g_3 = (d_3 - d_{K3})/2 \quad (12)$$

Assuming the experimentally determined acceptable outer layer deformation for the steel/Cu wires of $\varepsilon_{dop} \leqslant$ 35% (which corresponds to λ_{max}= 1.538), the following condition has been obtained:

$$\lambda_{dop} = \lambda_1 \cdot \lambda_2 \cdot \lambda_3 \leqslant \lambda_{max}. \quad (13)$$

An important research area related to cold cladding of the Fe(FeNi42)/Cu bimetals is an assessment of an effect of diffusive-softening annealing on the conditions in which formation of metallurgical bond between both metals takes place. Therefore, the process of atoms diffusion at the boundary between both cladded metals was also investigated under this work, and the results obtained are presented below.

4. An effect of the conditions of drawing and diffusive-softening annealing on the formation of metallurgical bond in bimetals

During the tests aimed at developing production technology for the Fe/Cu and FeNi42/Cu bimetallic wires quality of a bond between copper cladding and a steel core was evaluated. The results of this evaluation have been presented in a number of unpublished reports prepared mainly in relation with quality control of new grades of products ordered by foreign customers. Exemplary results illustrating chemical composition changes within a bond region, obtained by X-ray microanalysis (JCXA 733 system) are presented in Table 1.

TABLE 1

The FeCu30 bimetallic wire (ø 0,4 mm), core from soft steel with carbon content <0,06%, annealed at the temperature of 600^0C for 3 hours

	Distance from joint boundary [μm]											
	Cu region						Fe region					
	20	10	5	3	2	1	1	2	3	5	10	20
Fe	0.27	0.54	1.15	2.25	2.52	4.19	the rest					
Cu	the rest						34.09	25.04	1.50	0.87	0.23	0.16

For quick quality evaluation of a bond between the core and outer cladding simple technological tests are also used. One of them consists in bending a fastened wire in both sides under the right angle until the wire is broken. Observation of a fracture at magnification of 10x should not reveal any core-cladding discontinuity. Another method for continuity control consists in wire twisting around its own axis: there can be no ply separation or cladding cracks. It is also possible to carry out wire flattening tests followed by checking continuity of layers on the wire cross-section.

5. Summary and conclusions

As a result of research and implementation tests conducted over many years [1-5, 9] original technology for the production of bimetallic cladded wires Fe(FeNi42)/Cu, which is based on cold cladding and diffusive-softening annealing, has been developed. Works have been carried out aimed at adapting of an existing technological line for thin-walled tubes manufacture by continuous TIG welding to the production of Fe/Cu composite as a semi-product for cladded wires manufacture. Over more than ten years of its operation, this line was permanently improved and modernized so that it has become an experimental installation suitable for small-scale production of different-type cladded wires and for developing technologies for the production of new grades of bimetallic products in a form both of wires and strips. Based on this line a new one with higher performance and greater capacity can be designed and built. Bimetallic cladded wires produced using the technologies developed, mainly FeNi42/Cu type wires with and without surface coating, were subjected to extensive certification examination and tests conducted by renowned world producers of light bulbs and lighting equipment, and in a majority of cases respective quality certificates have been granted. Also in case of Fe/Cu-type bimetallic wires designed for concentric cables, electronic equipment or telephone wiring, their good performance was reported by end-users. A vast majority (90%) of bimetallic wires produced at the Institute are exported.

In order to maintain high quality of products it is necessary to modernize the drawing equipment, particularly that used at the initial processing stage. This applies mainly to multi-die drawing machines enabling more efficient conducting of the production process.

Analysis of results from this research, experimental tests and pilot-scale production leads to the following conclusions:

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- Technology for the production of bimetallic cladded wires, which has been developed and patented by the Institute of Non-Ferrous Metals, made it possible to commence specialist production of these products, particularly FeNi42/Cu wires without coating, ϕ0.25–ϕ1.5 mm in diameter, borated and surface-oxidized wires from 0.30 to 0.80 mm in diameter, and nickel-coated wires from 0.20 to 0.50 mm in diameter,
- The Institute has gained extensive experience in the production of Fe/Cu type bimetallic wires incorporating a core from soft steel, from 0.4 to 1.8 mm in diameter,
- The present technological background and equipment owned by the Institute makes it possible to undertake new research and implementation works aimed at developing technology and production start-up of new grades of cladded wires, e.g. stainless steel/copper, copper/stainless steel, soft steel/nickel in type, and of cladded wires containing precious metals, for instance nickel-palladium type.

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