

MJERENJE ELEKTRIČNIH SVOJSTAVA BAKRA I NJEGOVIH LEGURA KORIŠTENJEM U-I METODE

MEASUREMENT OF THE ELECTRICAL PROPERTIES OF COPPER AND ITS ALLOYS USING THE U-I METHOD

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SAŽETAK

Rad prikazuje mjerenje i usporedbu električnih svojstava materijala od bakra i nekih njegovih legura. Željelo se laboratorijskim ispitivanjem provesti provjera svojstava bakra kao vodiča u odnosu na neke druge materijale ili legure za istu primjenu. Rezultati koji su postignuti mjerenjem pokazali su da čisti bakar ima najbolju električnu provodnost od ostalih ispitivanih materijala. Uz to je pokazano i da se dodavanjem primjesa bakru pogoršavaju električna svojstva koja su bitna za njegovu upotrebu kao vodiča. Za ispitivanje svojstva materijala od bakra, mjedi i kositrenog lema korištena je za to izrađena ispitna maketa, uz svu potrebnu mjernu i ispitnu opremu. Ispitna maketa izrađena je od kartonske kutije koja predstavlja toplinsku komoru, s ciljem minimizacije toplinskih gubitaka. Primjenjuje se U-I metoda mjerenja otpora jer su se očekivale vrijednosti električnog otpora u rasponu 40-50 mΩ. Te vrijednosti su premale da bi se koristili neki drugi mjerni instrumenti za provedbu mjerenja.

Ključne riječi: bakar, mjed, kositreteni lem, žica, U-I metoda

ABSTRACT

The article deals with the measurement and comparison of the electrical properties of copper materials and some of their alloys. The aim was to carry out laboratory tests to verify the properties of copper as a conductor in comparison with some other materials or alloys for the same application. The results of the measurements showed that pure

copper has the best electrical conductivity among the other materials tested. It also showed that adding impurities to copper degrades the electrical properties that are important for its use as a conductor. To test the properties of the soldering materials copper, brass and tin, a custom-built test model with all the necessary measuring and testing equipment was used. The test model consists of a cardboard box that represents a heat chamber to minimise heat loss. The U-I method of resistance measurement is used because electrical resistances in the range of 40-50 mΩ are expected. These values are too small to use any other measuring instruments for the measurements.

Keywords: copper, brass, tin solder, wire, U-I method

1. UVOD

1. INTRODUCTION

Elemental copper occurs in the earth's crust as a metal in colours ranging from bright red to reddish brown [1, 2]. It is in a solid state at room temperature. In addition, it is one of the best-known and most widely used nonferrous metals. It is characterised by its mechanical properties as a relatively soft, but also very tough and ductile material [1, 2]. Copper can also be processed quite easily using forging, rolling and extruding processes. It is also frequently used as an auxiliary material in welding and soldering processes. In terms of electrical properties, it has the best thermal and electrical conductivity properties after silver [3]. However, its market price is

much more acceptable as it is much cheaper than silver, which is why it is widely used in electrical engineering for the production of conductors. It is also used as a material in generators, electric motors and transformers. Pure materials are very rarely used, so alloys are usually used to which certain impurities are added in order to maintain and improve certain properties.

In addition to pure copper, the alloy brass was also used in the tests. It is suitable for carrying out this laboratory measurement as it is one of the most important copper alloys and its electrical properties can be directly compared with those of pure copper.

In addition, the material tested is the so-called tin solder, i.e., a solder wire consisting of 99% tin and 1% copper, which is suitable for testing the electrical properties of alloys in which copper is only an impurity.

Each of the materials listed has different properties, such as electrical resistivity or the temperature coefficient of electrical resistance. The properties listed are among the most important in the field of electrotechnical materials. During the operation of electrotechnical products, considerable heating occurs, so that certain properties are required at certain temperatures.

The paper is a continuation of the research started in paper [4]. Here, the testing of the electrical properties of copper alloys, brass and solder is presented. The U-I resistance measurement method [5] was used because electrical resistances in the range of 40-50 m Ω are expected, which are too small for other measuring devices.

2. OPIS KORIŠTENE MJERNE OPREME ZA MJERENJE ELEKTRIČNIH VELIČINA I MJERNE LINIJE

2. DESCRIPTION OF THE MEASURING EQUIPMENT USED TO MEASURE THE ELECTRICAL QUANTITIES AND MEASURING LINE

Used measuring equipment: a CONRAD PS-302A laboratory power supply [6] (for regulating the current flowing through the wire), two VOLTCRAFT MXD-4660A digital bench

metres [7] and a model for carrying out laboratory tests. The laboratory power supply unit is shown in Figure 1 and the digital measuring device in Figure 2.



Slika 1 Laboratorijski izvor napajanja CONRAD PS-302A

Figure 1 Laboratory power source CONRAD PS-302A

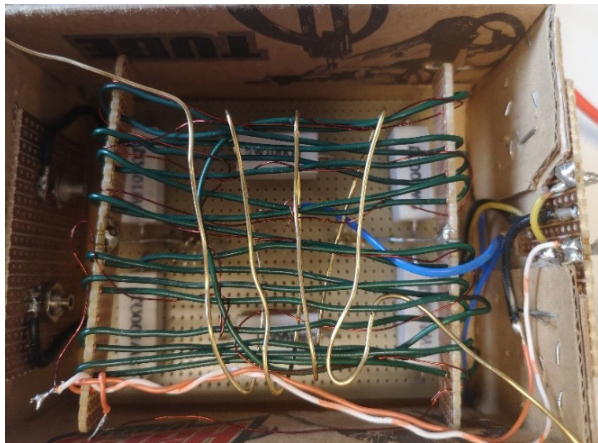


Slika 2 Digitalni mjerni instrument VOLTCRAFT MXD-4660A

Figure 2 Digital measuring device VOLTCRAFT MXD-4660A

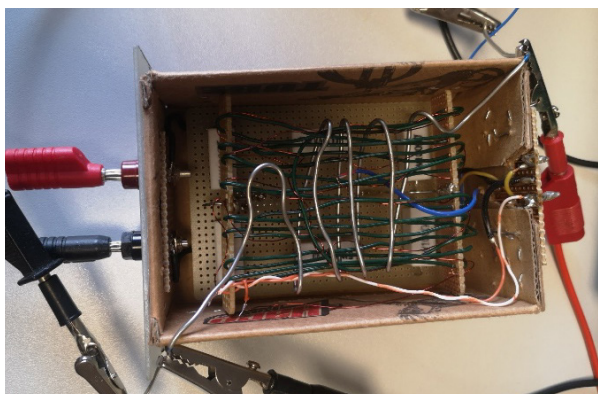
The laboratory model with the test wires is shown in Figures 3 and 4. The entire laboratory test is carried out under controlled conditions in a specially constructed model (made from a cardboard box) that simulates a heating chamber. The main components of the model are: a temperature sensor, which measures the temperature of the heated room, and a Vitroplast cover, which covers the model to prevent heat loss inside the model. The aim was to create the most realistic conditions possible in a thermally insulated room in order to minimise heat loss so that the measurement is as reliable as possible. This means that a sufficient amount of air must be ensured inside the model to create an atmosphere in which the temperature is approximately the same in all parts. For this purpose, we also use weights

that are placed on the Vitroplast shell to prevent the negative influence of the environment. In this way, we wanted the temperature of the wire inside the model to correspond as reliably as possible (closer to the value) to the temperature that the sensor displays as the temperature of the measured space.



Slika 3 Prikaz mjedene žice u maketi

Figure 3 Brass wire in a laboratory model



Slika 4 Prikaz žice od kositrenog lema u maketi

Figure 4 Tin solder wire in the laboratory model

To carry out the measurement, it is important to place the sensor at a point approximately in the central position in the measurement space. This gives the value of the average (mean) temperature for the observed wire. In the model, the wires are wound crosswise so that they are wound in the direction "up - down" or in the direction "zig - zag". Care must be taken to ensure that the non-insulated wires do not touch each other, as this can significantly affect the measurement results.

For brass and solder wires, the U-I method is used to measure resistance, as the expected resistances of 40-50 mΩ are outside the measuring range of

other instruments, e.g., an LCR instrument. Such a laboratory measurement is performed by passing a constant current through the wire (in our case 2A) and measuring the voltage.

3. OPIS MJERENJA KORIŠTENJEM U-I METODE

3. DESCRIPTION OF MEASUREMENTS USING THE U-I METHOD

The measurement using the U-I method (Figure 5) is described in the following steps:

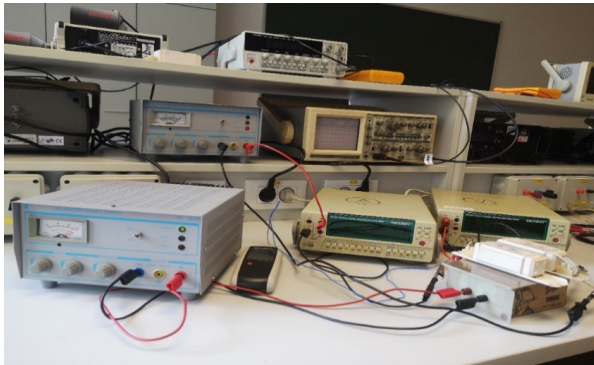
1. A digital bench device (for current measurement) is connected to the laboratory current source, and a current of 2 A is regulated by the laboratory current source. This current has a constant value (permissible range: 1.995 - 2.005 A, i.e., a deviation of 0.25% - within the accuracy of the measuring device, which is 0.3%). The other end is connected to the wire to be tested. The second digital bench metre is used to measure the voltage of the wire and is therefore connected to the wire (before connecting the crocodile clips of the ammeter to avoid the influence of contact resistance).
2. For each wire to be tested, the voltage must be measured at room temperature (room temperature is assumed). It is also used as the starting temperature. The voltage is measured with the MXD-4660A bench metre.
3. The measurement is then continued at higher temperatures by switching on additional measuring devices as follows. By heating with a heater (the heater is powered by a CONRAD PS-302A laboratory power supply), the voltage is measured for each of the tested wires at temperatures of 40, 60 and 80 °C. The measurement must be repeated a total of five times. Then the average value is calculated (to increase the reliability of the measurement results). The temperature is measured using a VOLCRAFT PL-120 T1 digital thermometer [8].

Note: since heating is a transient process (the temperature changes during heating), the electrical resistance value must always be measured at a slightly lower temperature than

the desired temperature during the measurement. For example, if the resistance is measured at a temperature of 50 °C, the measurement must start at a temperature of 49.5 °C. This eliminates the delay time during the measurement.

Instruction: The supply voltage is set to 21 V before the measurement. After the temperature has reached 40 °C, the voltage is increased to 27 V. When the temperature reaches 60 °C, the voltage is increased to 30 V. This ensures that the wires to be tested are in the heated air for a sufficiently long time and reach approximately the same temperature.

4. The measured voltage values at the measurement points at the required temperatures must be recorded in tabular form.
5. Based on the measured voltage values of the tested wires at the required temperatures and using the expressions (1), (2) and (4), the electrical resistance R , the specific electrical resistance ρ and the temperature coefficient of the electrical resistance α must be calculated. The calculated and measured values are presented in tabular form and in a diagram as a function of the temperature change: ($R = f(\vartheta)$, $\rho = f(\vartheta)$, $\alpha = f(\vartheta)$).



Slika 5 Cjelokupna mjerna linija za U-I metodu
Figure 5 Complete measuring line for the U-I method

4. OPIS MJERENIH ELEKTRIČNIH VELIČINA

4. DESCRIPTION OF MEASURED ELECTRICAL QUANTITIES

The electrical quantities that are measured and tested are [4]: the electrical resistance R , the electrical resistance or specific electrical

resistance ρ and the temperature coefficient of the electrical resistance α .

a) Electrical resistance R - depends on the length l , cross-section S and conductor temperature ϑ , and is calculated according to:

$$R = \frac{\rho \cdot l}{S} \quad [\Omega] \quad (1)$$

where are:

ρ – specific electrical resistance $[\frac{\Omega \text{mm}^2}{\text{m}}]$,
 S – conductor cross-sectional area $[\text{mm}^2]$,
 l – conductor length $[\text{m}]$.

The initial temperature of the conductor is assumed to be the temperature in the test laboratory $\vartheta_0 = 28^\circ\text{C}$.

b) Electrical resistance or specific electrical resistance ρ - a property that a homogeneous material of a certain type with arbitrarily chosen dimensions imparts to a direct electric current at a certain temperature, and is calculated according to:

$$\rho = \frac{R \cdot S}{l} \quad [\frac{\Omega \text{mm}^2}{\text{m}}] \quad (2)$$

c) Temperature coefficient of electrical resistance (resistance) α - a number that describes the change in resistance of 1 Ω with a temperature change of 1 °C. It is calculated according to:

$$R_T = R_0 \cdot (1 + \alpha \cdot \Delta\vartheta) \quad (3)$$

where are:

R_0 $[\Omega]$ – conductor resistance at room (initial) temperature,

R_T $[\Omega]$ – conductor resistance at a certain measured temperature,

$\Delta\vartheta$ $[\text{°C}]$ – temperature difference.

$$\alpha = \frac{1}{\Delta T} \cdot \left(\frac{R_T}{R_0} - 1 \right) \quad (4)$$

The values of electrical resistance and the temperature coefficient of electrical resistance depend on the impurities added to the base material [1-3]. Pure metals have the lowest electrical resistance, while the addition of certain

impurities increases the electrical resistance. By increasing the proportion of certain impurities, the temperature coefficient of electrical resistance can sometimes take on a negative value (e.g., with resistive materials) [1]. Measurement errors within 5 % are to be expected due to imperfections.

d) Average voltage value \bar{U} - is calculated by dividing the sum of all calculated voltage values at 5 measuring points by the number of measuring points n :

$$\bar{U} = \frac{\sum_{i=1}^n U_i}{n} \text{ [mV]} \quad (5)$$

e) Average value of electrical resistance \bar{R} - is calculated by dividing the average voltage value \bar{U} by the value of the electric current I :

$$\bar{R} = \frac{\bar{U}}{I} \text{ [\Omega]} \quad (6)$$

f) Standard deviation σ - is a statistical term that denotes a measure of the dispersion of data in an observed set. It is interpreted as the average deviation from the mean, in absolute terms.

$$\sigma = \sqrt{\frac{\sum_{i=1}^n (R_i - \bar{R})^2}{n-1}} \quad (7)$$

where are:

n – number of measured points,

R_i [Ω] – conductor resistance in the i -th measurement point,

\bar{R} [Ω] – mean value of conductor resistance in all measured points.

g) Relative measurement error Δ – is the ratio of the absolute error according to the true value. It is expressed in percentages (%). It is calculated according to the following expression:

$$\Delta = \frac{|\bar{R} - R_i|_{max}}{\bar{R}} \cdot 100 \% \text{ [%]} \quad (7)$$

where are:

$|\bar{R} - R_i|_{max}$ [Ω] – the absolute value of the maximum difference between the mean value and the measurement at the i -th point.

5. REZULTATI MJERENJA

5. MEASUREMENT RESULTS

5.1. ULAZNE VRIJEDNOSTI ZA MJERENJE

5.1. INPUT VALUES FOR MEASUREMENT

Table 1 shows the input values for the measurement, which are: measured conductor length l [mm], conductor diameter d [mm] and conductor cross-sectional area S [mm²].

Tablica 1 Ulazne vrijednosti za duljinu, promjer i površinu poprečnog presjeka za mjedenu žicu i kositretni lem

Table 1 Input values for length, diameter, and cross-sectional area for brass wire and tin solder

	Brass wire	Tin solder wire
Length l [mm]	500	500
Diameter d [mm]	1	1,5
Cross-sectional area S [mm ²]	0,7854	1,7671

Table 2 shows the values of the temperature coefficient of electrical resistance for the tested temperature intervals for copper wire ([4]). Table 3 shows the values of electrical resistivity ρ for copper wire ([4]).

Tablica 2 Vrijednosti temperaturnog koeficijenta električne otpornosti prema promjeni ispitivane temperature za bakrenu žicu [4]

Table 2 Values of the temperature coefficient of electrical resistance according to the change of the tested temperature for copper wire [4]

$\Delta\theta$ [°C]	α [1/°C]
40 - 28	0,00350
60 - 40	0,00302
80 - 60	0,00323
80 - 28	0,00394

Tablica 3 Vrijednosti električne otpornosti ρ za bakrenu žicu [4]

Table 3 Electrical resistivity values ρ for copper wire [4]

Temperature θ [°C]	Electrical resistance of copper ρ_{Cu} [Ωm/mm ²]
28	0,0113
40	0,0118
60	0,0124
80	0,0133

5.3. IZMJERENE I IZRAČUNATE VRIJEDNOSTI ELEKTRIČNIH SVOJSTAVA ZA MJEDENU ŽICU

5.3. MEASURED AND CALCULATED VALUES FOR ELECTRICAL PROPERTIES OF BRASS WIRE

Table 4 shows the measured values of the measured voltage U [mV] at 5 measuring points and the calculated mean value of the electrical resistance \bar{R} [Ω] for the brass wire. A constant current of 2 A was used for the measurement. The table also shows the value of the average voltage \bar{U} [mV] at 5 measuring points. The last two columns of the table also show the values of the standard deviation σ and the relative measurement error Δ .

5.4. IZMJERENE I IZRAČUNATE VRIJEDNOSTI ELEKTRIČNIH SVOJSTAVA ZA ŽICU OD KOSITRENOG LEMA

5.4. MEASURED AND CALCULATED VALUES FOR ELECTRICAL PROPERTIES OF TIN SOLDER WIRE

The data display is structured in the same way as the previous measurement. Table 5 shows the measured values of the measured voltage U [mV] at 5 measuring points and the calculated mean value of the electrical resistance \bar{R} [Ω] for the solder wire. A constant current of 2 A was used for the measurement. The table also shows the value of the average voltage \bar{U} [mV] at 5 measuring points. The last two columns of the table also

Tablica 4 Izmjerene vrijednosti napona u 5 mjernih točaka, srednja vrijednost napona i srednja vrijednost električnog otpora za mjedenu žicu

Table 4 Measured voltage values at 5 measurement points, mean voltage value and mean electrical resistance value for brass wire

$I = 2A = \text{const.}$									
Temperature ϑ [°C]	Measured voltage U [mV]					\bar{U} [mV]	\bar{R} [Ω]	σ	Δ [%]
	U_1	U_2	U_3	U_4	U_5				
28	92,17	93,65	93,51	92,77	92,89	93,00	0,046	0,00030	1,793
40	93,44	94,48	95,21	94,09	94,34	94,31	0,047	0,00021	1,287
60	95,93	96,65	96,36	96,60	96,64	96,44	0,048	0,00013	0,677
80	98,73	99,11	98,94	98,83	98,79	98,88	0,049	0,00007	1,133

Tablica 5 Izmjerene vrijednosti napona u 5 mjernih točaka, srednja vrijednost napona i srednja vrijednost električnog otpora za žicu od kositrenog lema

Table 5 Measured voltage values at 5 measurement points, mean voltage value and mean electrical resistance value for tin solder wire

$I = 2A = \text{const.}$									
Temperature ϑ [°C]	Measured voltage U [mV]					\bar{U} [mV]	\bar{R} [Ω]	σ	Δ [%]
	U_1	U_2	U_3	U_4	U_5				
28	85,33	85,61	85,55	86,12	86,38	85,80	0,043	0,00010	0,779
40	89,68	89,85	89,71	90,07	90,23	89,91	0,045	0,00005	0,356
60	95,78	94,29	95,68	95,74	96,17	95,53	0,048	0,00033	1,781
80	102,36	101,14	102,25	102,11	103,47	102,27	0,051	0,00028	1,441

show the values of the standard deviation σ and the relative measurement error Δ .

5.5. IZRAČUNATE VRIJEDNOSTI TEMPERATURNOG KOEFICIJENTA ELEKTRIČNE OTPORNOSTI

5.5. CALCULATED VALUES OF THE TEMPERATURE COEFFICIENT OF ELECTRICAL RESISTANCE

Table 6 shows the calculated values of the temperature coefficient of electrical resistance for brass and tin solder wires, according to expression (4). The first column shows the temperature ranges for which they were calculated.

Tablica 6 Izračunate vrijednosti temperaturnog koeficijenta električne otpornosti za mjedenu žicu i žicu od kositrenog tema u 4 temperaturna intervala

Table 6 Calculated values of the temperature coefficient of electrical resistance for brass wire and tin solder wire in 4 temperature intervals

$\Delta\theta$ [°C]	α_{brass} (brass) [1/°C]	$\alpha_{\text{tin solder}}$ (tin solder) [1/°C]
40 - 28	0,00181	0,00387
60 - 40	0,00106	0,00333
80 - 60	0,00104	0,00313
80 - 28	0,00125	0,00358

6. DISKUSIJA DOBIVENIH REZULTATA

6. DISCUSSION ON OBTAINED RESULTS

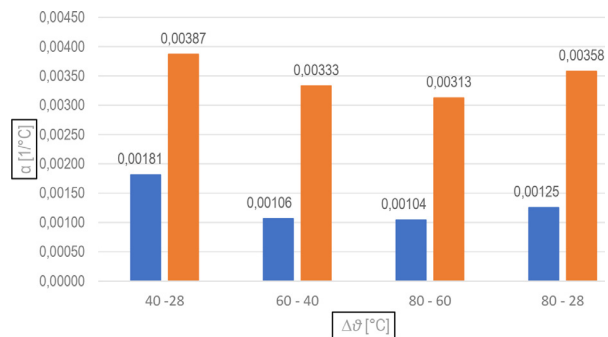
According to the diagram shown in Figure 6, the difference between the temperature coefficients of the electrical resistance for brass wire (orange colour) and solder wire (blue colour) is shown graphically using a histogram. This shows that brass has a lower temperature coefficient than solder for all observed temperature intervals. From this it can be concluded that the resistance of solder increases more with increasing temperature.

A direct comparison of the temperature coefficients of tin-soldered wires with brass wires using an analytical method leads to the following results.

Using tabulated data, the resistance of brass wire changes by a factor of 3,8 with temperature changes, whereas it changes by a factor of 2,9 when measured. The reason for this lies in the inadequacies of the measurement. The tabulated values for the coefficients $\alpha_{\text{tin solder}}$ and α_{brass} are taken from the literature [9]. The calculated values according to the measured data for the same coefficients $\alpha_{\text{tin solder}}$ and α_{brass} are taken from Table 6 for $\Delta\theta = 52$ °C (80-28 °C).

$$\alpha_{\text{tin solder}}/\alpha_{\text{brass}} = 0,00497/0,0013 \approx 3,8 - \text{table value,}$$

$$\alpha_{\text{tin solder}}/\alpha_{\text{brass}} = 0,00358/0,00125 \approx 2,864 \approx 2,9 - \text{measured value.}$$



Slika 6 Usporedba temperaturnih koeficijenata električnih otpornosti ispitivanom U-I metodom

Figure 6 Comparison of temperature coefficients of electrical resistance tested by the U-I method

Table 7 shows the calculated values of the specific electrical resistance ρ for brass and tin solder wire as a function of a specific temperature.

Tablica 7 Izračunate vrijednosti za određene temperature vrijednosti električne otpornosti za žice od mjedi i kositrenog lema

Table 7 Calculated values for specific temperatures of specific electrical resistance values for wires of brass and tin solder

Temperature θ [°C]	Electrical resistance of brass ρ [Ωmm ² /m]	Electrical resistance of tin solder ρ [Ωmm ² /m]
28	0,0723	0,1520
40	0,0738	0,1590
60	0,0754	0,1696
80	0,0770	0,1803

In addition, analytical relationships are given for the electrical resistance of brass wire to copper

wire and for the temperature coefficient of the electrical resistance of copper wire to brass wire. All this was calculated at a measured initial temperature of 28 °C. The relationship values are rounded to the first higher integer value.

$$\begin{aligned} \rho_{brass(28)} / \rho_{copper(28)} &= 0,0723 / 0,0113 \approx 6,4 \\ \alpha_{copper(28)} / \alpha_{brass(28)} &= 0,0035 / 0,00181 \approx 2 \end{aligned}$$

Figure 6 and Table 7 show that brass wire has a lower electrical resistance than solder tin, i.e. it has better electrical conductivity. A comparison of the electrical values of the materials tested using the U-I method with those determined using an LCR measuring device [4] shows that copper has the lowest electrical resistance of all materials, followed by brass, steel, tin and finally cegas for the same wire length and cross-sectional area. The properties of steel and cegas materials were analysed in [4]. As a result, copper has the best electrical conductivity of all the materials analysed. According to the results of measurements at the same temperature, copper has almost 6,4 times lower electrical resistance, but the electrical resistance of brass changes less with temperature than the electrical resistance of copper, which is related to the fact that copper has a temperature coefficient of electrical resistance almost 2 times higher than brass, which means that its electrical resistance changes more with temperature. A direct comparison between a copper alloy (brass) and an alloy in which copper is only an impurity (solder) also shows that the addition of impurities to copper reduces the electrical conductivity of the material and that a low copper content in the alloy does not significantly improve the electrical conductivity.

7. ZAKLJUČAK

7. CONCLUSION

As a material used in electrical engineering, copper has the best electrical and thermal conductivity properties after silver. It is therefore interesting for investigations and tests as well as for comparison with other electrotechnical materials.

In this article, the electrical properties of two copper alloys, brass and solder, are analysed.

The U-I method of resistance measurement was used because the values of electrical resistance are too small to be measured with other measuring devices. A model for testing the electrical properties of materials with increasing temperature was created to carry out the measurements. All the necessary measuring and testing equipment was used for the measurements.

The paper comes to the following conclusions:

- Brass wire has a lower electrical resistance than tinned solder wire, i.e., it has better electrical conductivity.
- Copper wire has the lowest electrical resistance of all materials, followed by brass and tin solder wire (for the same wire length and cross-sectional area).
- Copper wire has almost 7 times lower electrical resistance, but the electrical resistance of brass wire changes less with temperature than the electrical resistance of copper wire.
- A direct comparison of copper wire with brass wire and tinned solder wire shows that the addition of impurities to copper reduces the electrical conductivity of the material and that a low copper content in the alloy does not significantly improve the electrical conductivity.
- During the measurement, a low scattering of the data and a slight deviation from the calculated average value of the electrical resistance were observed at all 5 measuring points.
- The expected measurement errors due to imperfections are in the region of 5 %.
- The UI measurement method can serve as an aid in the selection of a conductive material, when, in addition to good electrical conductivity, other known properties are also important, such as hardness, resistance to high temperatures, etc.

ZAHVALA

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