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THE INFLUENCE OF THERMAL EFFECTS ON ELASTOPLASTIC PROPERTIES OF Ti/Cu BIMETAL BARS OBTAINED BY EXTRUSION

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The article presents the results of the study of the elastic-plastic properties of bimetallic titanium/copper rods subjected to short-term thermal action in the temperature range of 600 °C–900 °C. The study used the impulse vibration excitation technique and a quasi-static tensile test. The final stage of the study was a microscopic SEM analysis of the interface. Macroscopic observations of the destruction surface were also carried out. Short-term annealing of the Ti/Cu bimetal caused a decrease in strength and proof stress, as well as an increase in ductility and diffusion. The destructive and dangerous processes were mainly at a temperature of 900 °C.

Keywords: Ti/Cu bimetal; elastoplastic deformation; impulse excitation technique, failure.

1. Introduction

The answer to the current global energy crisis in the processing industry is a metal-layered composite with multifunctional physical properties. Technological progress in the methods for joining different metals has made their permanent connections with each other easy and possible. This way, a new functional metallic material is obtained with important technical significance and unique operational properties. Examples here are bimetallic Ti/Cu bars used as anodes and cathodes in electrolysis processes (Bockris, 1981; Chawla & Gupta, 1993; O'Brien *et al.*, 2007) or as bus-bars in high-temperature electrolytic cells (Xu *et al.*, 2007). They are made of a copper core surrounded by a titanium layer. The advantage of this solution is the excellent electrical conductivity of copper and the high corrosion resistance of titanium to the aggressive action of many chemical compounds, especially those originating from acidic and chloride environments (Sanjurjo *et al.*, 1991). The inseparable layered composition of copper and titanium is also used in cryogenic and heat exchanger devices for thermal partitions (Bateni *et al.*, 2001; 2003) or in medicine when producing bone implants where, in addition to titanium, a layer of copper is introduced, providing antibacterial properties (Mahmoudi *et al.*, 2022) and others.

Bimetallic Ti/Cu rods are often made by explosive welding (Paul *et al.*, 2020) or extrusion (Xu *et al.*, 2007), which is thermally activated. The hydrostatic extrusion process of titanium-copper alloy bimetal is described in (Matsushita *et al.*, 1988), where the viscoplastic extrusion technique was used. In addition, important information on Ti/Cu extrusion can be found in

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(Lee *et al.*, 2007) and the co-extrusion process in (Xu *et al.*, 2007). The method of extrusion of rods intended for electrodes requires high loads and a correspondingly high temperature, which can cause the formation of intermetallic compounds at the interface of metal layers and thus reduce the bonding strength. During operation, the electrodes are exposed to thermal effects caused by the electric current flowing through them.

The risk of increased temperature in structural elements and installations made of Ti/Cu bimetal conducting high-density electrical current can cause an overheating effect, which results in a decrease in strength properties and may lead to premature destruction. The tests aimed to assess the effect of short-term exposure to a thermal medium in the temperature range of 600 °C–900 °C on the elastic-plastic properties of Ti/Cu bimetal rods. The condition of the Ti/Cu joint after annealing and the surface of the scrap samples after the tensile test were also evaluated. Research activities related to Ti/Cu bimetals should provide an answer to the question of how to reduce energy consumption, lower production costs in metallurgy, extend the service life, and protect bimetals against unforeseen results of thermomechanical effects. This work is based in part on the experimental data described in the research by Uścinowicz (2022) and extends them to include new research problems.

2. Material, specimens, and experimental setup

The research material was Ti/Cu bimetallic rods consisting of a copper core of ⌀8.8 mm thickness and a titanium coating of 1.6 mm thickness distributed concentrically around the core circumference. The average volume fraction of the bimetal components was $f_{\mathrm{Ti}} = 46\,\%$, $f_{\mathrm{Cu}} = 54\,\%$. The chemical composition of the Ti/Cu bimetal components was determined by the Shenzhen Jia Ping Titanium Industry Co. Ltd, and it is presented in Table 1.

Table 1. Chemical composition of the titanium (Ti) and copper (Cu) layers.

Titanium (Ti) layer [%]							
Ti	Fe	C	N	H	0	others	
99.6	0.002	0.003	0.002	0.0005	0.001	0.391	
Copper (Cu) layer [%]							
Cu + Ag	Bi	Sb	As	Fe	Pb	S	others
99.9	0.03	0.002	0.004	0.005	0.004	0.005	0.05

Cylindrical samples of 110 mm length were made from Ti/Cu rods (Fig. 1). The geometric axis of the samples was consistent with the direction of the extrusion process. The test samples were divided into two groups. The first group contained samples without heat treatment, symbolically marked $T = 20\,^{\circ}\mathrm{C}$. Samples from the second group were independently heated in the furnace for 30 min to temperatures of 600 °C, 700 °C, 800 °C, and 900 °C, respectively. They were then annealed for 30 min and cooled in air to 20 °C.

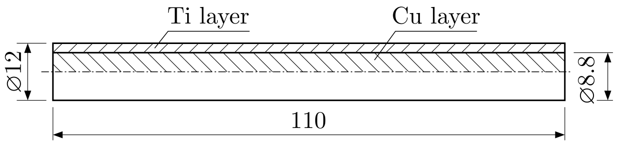

Fig. 1. Geometry of the Ti/Cu sample subjected to tensile tests and tests using the excitation impulse method.

The elastic properties of the tested bimetal were determined using the impulse excitation method (IME). The compact cylindrical shape of the Ti/Cu bimetal samples was helpful in measuring the elastic properties using an acoustic resonance frequency analyser (RFDA) from

IMCE NV. This (dynamic) method is described in the guide by Lord and Morrell (2006) and in the ASTM E1876-22 (2022) and ISO 12680-1 (2005) standards. With the help of this technique, Young's modulus E_d, the basic resonance frequencies χ_f, the internal friction parameters Q^{-1}, and the damping coefficient k were determined.

The essence of this method is to excite a mechanical impulse (impact with an impulse) and induce a mechanical wave (vibrations) in the tested sample subjected to 3-point bending. Induced vibrations have a frequency spectrum consistent with resonance frequencies and depend on the elastic properties of the material, its geometry, and density (mass). Next, with the help of an acoustic transducer (microphone), analog signals are transmitted to a computer and digitized. Unique mathematical algorithms using the Fourier transform calculate each frequency and attenuation from the detected frequency spectrum, assigning sinusoidal attenuated acoustic vibrations $x(t)$ to each frequency in the form:

$$x(t) = Ae^{-kt}\sin(2\pi\chi_f t + \varphi), \tag{2.1}$$

where A, φ – equation parameters, χ_f – basic resonance frequency during the bending mode, k – damping coefficient, t – time parameter. The selection of the appropriate value of the resonance frequency χ_f completed the process of determining the searched parameters.

The applied method experimentally confirmed the elastic constants of composites and other structurally complex materials (Uscinowicz, 2019; Song *et al.*, 2017; Stratigaki *et al.*, 2019; Yang *et al.*, 2012). The analysis of possible errors of this method is described in (Raggio *et al.*, 2010). This technique is so effective that it allows one to obtain quantitative information about the values of elastic constants and the integrity of samples (Roebben *et al.*, 1997).

Young's modulus for cylindrical Ti/Cu bimetallic samples with individually measured geometry and mass of specimen was determined from the following relationship (Lord & Morrell, 2006):

$$E_d = 1.6067 \cdot \left(\frac{L^3}{D^4}\right) m\,\chi_f^2\, H, \tag{2.2}$$

where E_d – Young's modulus, H – correction factor for flexural mode, m – sample mass, L, D – length and diameter of the cylindrical sample, respectively. Correction factor H was dependent on sample geometry and Poisson's ratio (Lord & Morrell, 2006). Young's modulus determined in the IME method was defined as dynamic and designated E_d.

The internal friction parameter was used to evaluate the energy balance in the above-described method and was defined by the following relationship:

$$Q^{-1} = \Delta W/2\pi W, \tag{2.3}$$

where W, ΔW – the energy stored and lost in a unit of the volume of the vibrating medium during one period, respectively. The following relationship was used to calculate it:

$$Q^{-1} = k/\pi\chi_f. \tag{2.4}$$

The elastic-plastic properties were determined from uniaxial tensile tests. The tests were carried out on an MTS 809.10 testing machine. Specimens' deformations were measured using the ARAMIS 3D 4M optical strain measurement system from GOM, which applied digital image correlation technology. The samples were loaded at a strain rate of $\dot{\varepsilon} = 2\cdot 10^{-3}\,\mathrm{s}^{-1}$. Tensile tests were performed using the ASTM E8/E8M-22 (2022) technical standard on the same Ti/Cu bimetallic samples as on the RFDA device. The tests provided basic information on the elastic-plastic properties of the bimetal, i.e., Young's modulus E_s, the yield strength $R_{p0.2}$ corresponding to permanent deformations of 0.2 %, tensile strength R_m and the values of the specific work of uniform plastic deformation L_p and elastic deformation L_e corresponding to uniform strains. The quantities defining the change in the dimensions of the diameter ε_d in tensile tests and the reduction of cross-sectional area after the fracture (Z) of bimetal components were also determined.

3. Results of tests and discussion

The values of elastic properties of the Ti/Cu bimetal obtained from tests using the impulse excitation technique depending on temperature are shown in Figs. 2 and 3 and Table 2.

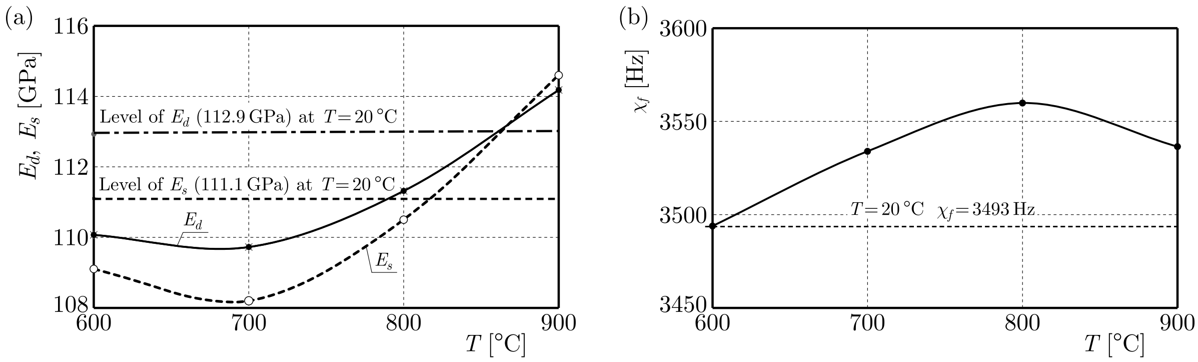

Fig. 2. Change of Young's modulus E_s and E_d (a) and resonance frequency χ_f (b) with increasing annealing temperature of the Ti/Cu bimetal.

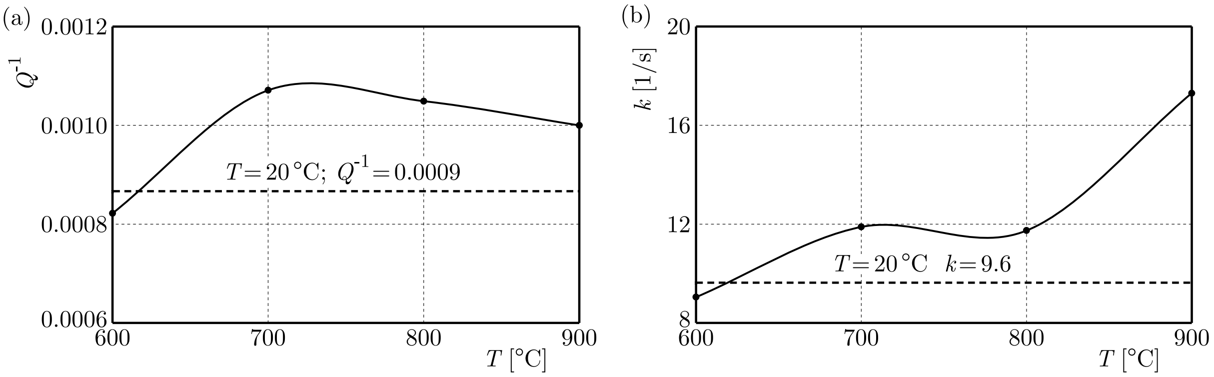

Fig. 3. Dependence of the internal friction parameter Q^{-1} (a) and the damping coefficient k (b) on the annealing temperature.

Table 2. Quantities determined for Ti/Cu bimetal using the impulse excitation method.

Temperature [°C]	E_d [GPa]	E_s [GPa]	χ_f [Hz]	Q^{-1} [–]	k [1/s]
20	112.9 ±0.4	111.1 ±4.5	3493 ±43	0.0009 ±0.0002	9.6 ±1.0
600	110.1 ±0.4	109.1 ±3.2	3494 ±17	0.0008 ±0.0001	9.0 ±0.5
700	109.7 ±0.4	108.2 ±2.1	3534 ±29	0.0011 ±0.0001	11.9 ±1.2
800	111.3 ±0.4	110.5 ±4.5	3560 ±36	0.0010 ±0.0002	11.7 ±1.9
900	114.2 ±0.4	114.6 ±5.6	3537 ±42	0.0010 ±0.0003	17.3 ±2.2

Figure 2a shows the variation of Young's moduli determined from the tensile test (E_s) and tests using the impulse excitation method (E_d). It was found that values of Young's modules within a tested temperature range differed by several GPa and were small in the tensile test cases. The highest values of Young's modulus of the Ti/Cu bimetal were $E_d = 114.2$ GPa and $E_s = 114.6$ GPa, recorded for the temperature of 900 °C. They were 3 GPa higher than for temperatures $T = 600$ °C, 700 °C. The values of the E_d moduli of the samples annealed at temperatures $T = 600$ °C and 700 °C were similar. Starting from the temperature of 700 °C, the values of Young's moduli increased in a parabolic manner (Fig. 2a). This was partly the result of structural changes in the titanium and copper layer and was associated with the formation of intermetallic brittle phases. It should be emphasized that the values of Young's moduli after annealing in the temperature range of 600 °C–900 °C compared to the unannealed ones were small.

A significantly different nature of the changes, with the increase in the annealing temperature, was observed for the resonance frequencies χ_f (Fig. 2b). In the case of χ_f, the highest frequency value was found for the temperature $T = 800\,^{\circ}\mathrm{C}$ and the range of frequency changes, for all temperatures, was small and covered only 50 Hz. It was noticed that the resonance frequencies for the unannealed samples ($T = 20\,^{\circ}\mathrm{C}$) and those annealed at 600 °C were identical.

Observation of the internal friction parameter Q^{-1}, related to energy losses in a given continuous medium subjected to impulsive loading, provides very important information about changes occurring in the internal structure of the Ti/Cu bimetal. They are helpful in assessing the cohesion of metal layers, but also provide information about the effects of processes in the structure during and after annealing. The parameter Q^{-1} reached its maximum value for samples annealed at a temperature of 700 °C, and the course of its variation in the tested temperature range was strongly non-linear (Fig. 3a). The values of Q^{-1}, for samples annealed at 600 °C and 20 °C, were very similar. It should be noted that high values of Q^{-1} are not recorded for metals. However, their noticeable increase with temperature can be attributed to processes occurring in the copper and titanium layers, i.e., the emergence of metallic phases at the interface as a result of diffusion. Puškár (2001) stated that there is no linear dependence of $Q^{-1} = f(T)$ when the temperature in metals exceeds the temperature by 50 %–60 % of the melting point, which is considered the limit.

It is commonly known that annealing at elevated and high temperatures can lead to an increase in grain size, structural reconstruction, changes in dislocation movements and a decrease in internal friction in the case of copper and titanium. The acquired strain of metals in the extrusion process can be thermally reduced, which results in a decrease in strength parameters and an increase in the ductility of bimetal components. However, in the case under study, internal friction slightly increases with temperature at 700 °C, and its causes can be sought in forming an intermetallic diffusion zone at the interface (third layer), which changes the reactivity of bimetal to a mechanical impulse.

Figure 3b shows the changes in the damping coefficient k. The increase in its value for the temperature of 900 °C and the simultaneous decrease in Q^{-1} can be attributed to the allotropic transformation of titanium, which significantly affects the elastic properties of Ti/Cu.

Based on the tensile tests, basic information was obtained about the elastic-plastic properties of the bimetal under monotonic quasi-static loading, i.e., the limit stresses $R_{p0.2}$ corresponding to permanent deformations of 0.2 %, tensile strength R_m, the course of which is shown in Figs. 4a and 4b. It should be noted that both the yield strength and the strength of the Ti/Cu bimetal were significantly decreased due to heat exposure compared to the analogous parameters for unannealed samples. The decrease in the $R_{p0.2}$ value was almost 3.5 times, while the strength R_m decreased 1.6 times. The increase in temperature from 800 °C to 900 °C caused a decrease in strength of only 20 MPa.

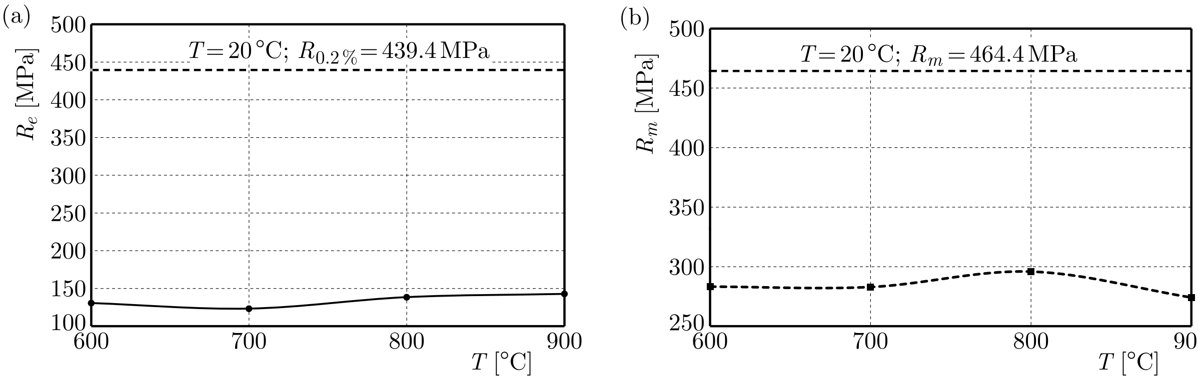

Fig. 4. Variation of the yield stress (a) and the strength (b) depending on the annealing temperature.

The effect of the decrease in strength due to annealing is the increase in the ductility of the bimetal, as evidenced by the increases in the value of the specific energy required for uniform plastic deformation of a unit of bimetal volume from $10.0\,\mathrm{MJ/m^3}$ for $T = 20\,°\mathrm{C}$ to $79.5\,\mathrm{MJ/m^3}$ for $T = 700\,°\mathrm{C}$ (Fig. 5b). The structural changes in the Ti/Cu bimetal samples at 900 °C caused a decrease in the L_p parameter almost 2.5 times compared to the value associated with the temperature of 800 °C. The values of basic mechanical properties determined from the tensile test are given in Table 3.

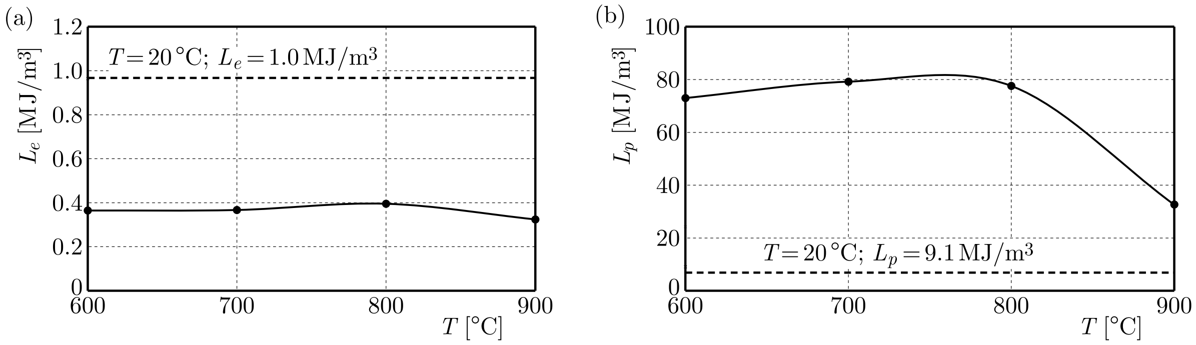

Fig. 5. Variation of the specific energy of the uniform elastic (a) and plastic (b) deformation depending on the annealing temperature.

Table 3. Average values of various mechanical properties obtained for Al/Cu bimetal.

Temperature [°C]	$R_{0.2}$ [MPa]	R_m [MPa]	L_p [MJ/m³]	L_e [MJ/m³]
20	464.4 ±6.4	464.4 ±9.6	9.1 ±1.5	0.96 ±0.15
600	283.2 ±5.3	283.2 ±6.9	73.0 ±5.3	0.36 ±0.06
700	283.9 ±4.1	283.9 ±6.0	79.2 ±6.9	0.37 ±0.04
800	295.9 ±5.9	295.9 ±7.4	77.5 ±6.2	0.40 ±0.03
900	274.1 ±7.2	274.1 ±8.5	36.6 ±4.3	0.32 ±0.05

In turn, when analysing the values of the specific energy of the elastic deformation L_e (Fig. 5a) necessary to deform a unit of volume, determined at the level of uniform deformation at the temperature $T = 20\,°\mathrm{C}$ and in the temperature range of 600 °C–900 °C, it should be stated that also here, as a result of heat action, a decrease of this parameter by 68 % occurred. In the tested temperature range of 600 °C–900 °C, the L_e values differed slightly, which does not correlate well with the distribution of Young's modulus values in this range (Fig. 2a).

The deformation capacity of the Ti/Cu bimetal during the tensile test can be monitored by observing the changes in the transverse deformation of the sample expressed by the relative change in its diameter ε_d. The variability of this quantity is shown in Fig. 6. To facilitate the assessment of the scale of deformation and its course, the test duration was normalized

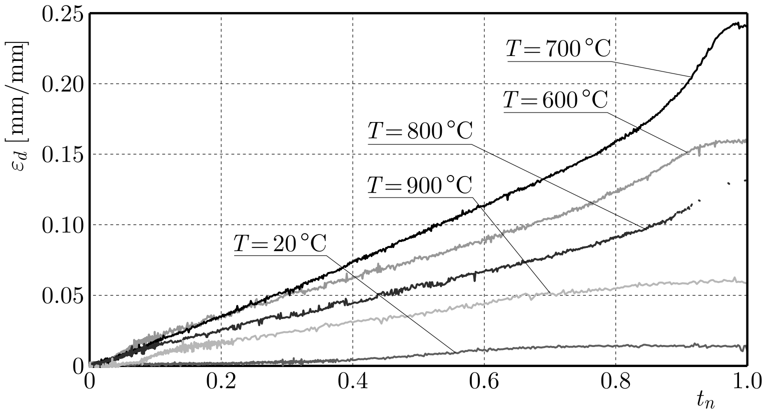

Fig. 6. Example variations of relative diameter deformation ε_d of Ti/Cu bimetallic samples throughout the tensile process.

by assuming the interval $\langle 0,1\rangle$ as the duration of the entire tensile process for tested samples. Assuming the same samples' deformation in the loading (axial) direction of the bimetal, including its Ti and Cu layers under different stresses in cross-sections, the most significant increase in elastic-plastic deformations of ε_d was observed in samples annealed at 700 °C; slightly lower values can be attributed to Ti/Cu samples for $T = 600\,^\circ\mathrm{C}$. Lower values ε_d with an increase in the normalized time t_n were observed in samples heated at $T = 800\,^\circ\mathrm{C}$ and 900 °C. This resulted from structural changes in the sample volume and the enlargement of the diffusion zone at the interface. Unannealed samples obtained the lowest ε_d values during stretching.

Important quantitative information allowing us to assess the influence of the annealing temperature on the tensile process and the destruction mechanism was the standard parameter Z [%] called the percentage maximum reduction of cross-sectional area after fracture. It described the change in the cross-sectional area of the samples at the fracture site related to the original area. The values of this parameter for the Ti/Cu bimetal components are shown in Fig. 7. The graph shows that the Ti/Cu bimetal components annealed at $T = 900\,^\circ\mathrm{C}$ are characterized by the minor reduction of the cross-section at the fracture site, which was about 41 % for copper and 45 % for titanium. It can, therefore, be assumed that the Ti and Cu components became more brittle after annealing at this temperature. In the 600 °C–800 °C temperature range, the Z constriction values for the individual bimetal components were similar and amounted to approximately 90 % for copper and 74 % for titanium, as observed. However, these values were higher than the corresponding Z values for the bimetal components for unannealed samples. In the case of titanium, this difference was 20 %. The more ductile metal in the composite was copper, which was the effect of final deformations just before the sample fracture.

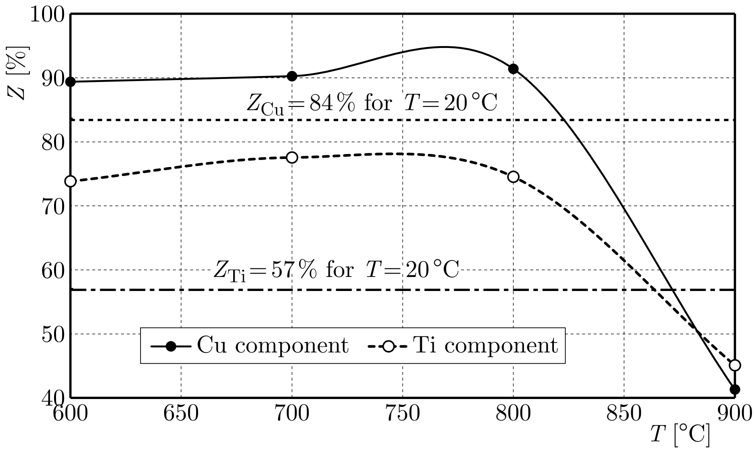

Fig. 7. Changes in the values of cross-sectional area Z after fracture of the titanium and copper layer depending on the annealing temperature measured on the sample scraps.

4. Microscopic and macroscopic observations of the Ti/Cu interface and fractures

For each sample tested, microscopic observations of the Ti/Cu bimetal layer connection zone were performed using a Phenom XL scanning microscope. At the same time, a linear analysis of its composition was performed immediately after annealing. The permanent connection of the copper and titanium layers in the Ti/Cu bimetal is crucial and has great significance for load transfer and operational task performance. No visible diffusion zone was observed in samples heated to 600 °C and 700 °C. However, in (Youn & Lee, 2020), the presence of a diffusion zone below 1 µm at a temperature of 450 °C was found. Only at 800 °C a narrow diffusion layer appeared (Fig. 8a) with an average thickness of 15.6 µm, which increased significantly at $T = 900\,^\circ\mathrm{C}$ (Fig. 8b) to a value of 31.7 µm. At temperatures of 800 °C and 900 °C, sporadic cracks appeared perpendicular to the interface (Fig. 8a). It seems that at annealing temperatures close to 900 °C the bond strength of the layers decreases significantly. This was accompanied

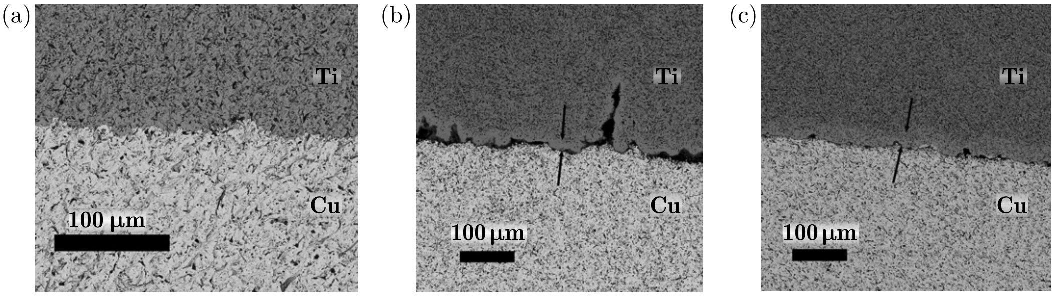

Fig. 8. Contact zone of titanium and copper in bimetal samples: (a) not annealed; (b) annealed at temperature $T = 800\,^\circ\mathrm{C}$; (c) annealed at temperature $T = 900\,^\circ\mathrm{C}$.

by an allotropic transformation of titanium, which changed from an HCP structure to a BCC structure, being more susceptible to diffusion processes. At this temperature, the tensile strength of the Ti/Cu bimetal decreased (Fig. 4b), making it less ductile (Fig. 5b). A similar nature of phenomena was observed by Lee *et al.* (2007) during the production of the Ti/Cu bimetal by the extrusion method.

Much information about the change in the plastic properties of the Ti/Cu bimetal due to annealing is provided by macroscopic observation of scrap samples created as a result of their rupture during tensile tests. Figure 9 presents photographs of characteristic traces of the scrap surface after the release of elastic energy due to destruction. The most severely degraded surface is the sample heated at 900 °C (Fig. 9e), where traces of the formed brittle Ti/Cu interphase layers are visible. The decomposition of the coating composed of titanium and intermetallic compounds could also be observed here. It had a different shade of grey and a characteristic fragmented structure, indicating brittleness. The mechanism of destruction in this case was different than for the unheated samples or those heated at temperatures of 600 °C and 700 °C. For these samples, it could be seen that the copper core, initially cylindrical, undergoes a ductile fracture (in a bundle), creating a characteristic cup and cone fracture. In the case of the bimetallic sample heated at 900 °C, the copper core was slippery (shear form), and the cross section was slightly deformed. The separating fracture had a mixed character in samples heated at $T = 800\,^\circ\mathrm{C}$.

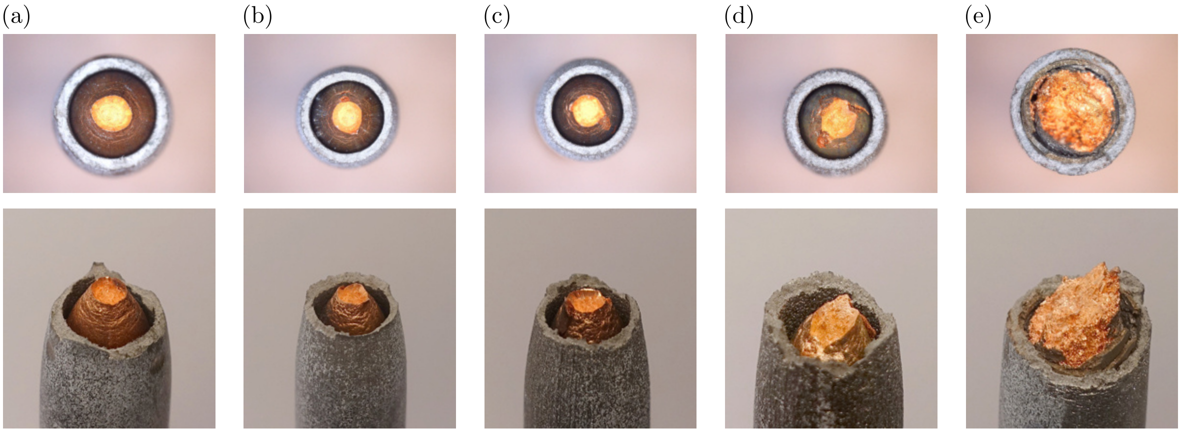

Fig. 9. Examples of surface zones of sample scraps formed as a result of the separation of samples during stretching after heating at the temperature: (a) 20 °C; (b) 600 °C; (c) 700 °C; (d) 800 °C; (e) 900 °C.

5. Conclusions

1) In the temperature range of 600 °C–800 °C, Young's modulus values determined for the Ti/Cu bimetal from tensile tests were slightly lower than the analogous values obtained from tests using the impulse excitation method and all oscillated in the range of 108 GPa–

111 GPa. The highest value of Young's modulus was found for samples annealed at $T = 900\,^{\circ}\mathrm{C}$ and amounted to over 114 GPa.

2) The increase in the value of internal friction Q^{-1} with increasing temperature (above 700 °C) can be attributed to the emerging of the diffusion zone at the boundary of the copper and titanium layers in the bimetal structure. The unannealed sample and the sample annealed at temperature $T = 600\,^{\circ}\mathrm{C}$ have similar Q^{-1} values. Annealing the Ti/Cu bimetal in the range of 600 °C–800 °C resulted in a multiple increase in the demand for energy for plastic deformation of a volume unit. For samples annealed at 900 °C, a significant decrease in this parameter was noted.
3) It was found that 30-minute heat exposure to Ti/Cu bimetal in the range of 600 °C–800 °C deteriorates strength properties, significantly lowering the yield point and increasing ductility, which reduces the bimetal's ability to work under load. The temperature of 900 °C threatens the safe use of bimetal, causing irreversible structural changes and accelerating processes leading to destruction.

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