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RESTORATION OF BELLS AND ART PRODUCTS MADE OF COPPER ALLOYS

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ABSTRACT

The results of experimental work on the restoration of art castings from copper alloys are presented. It is shown that an individual approach is required during product repair, which is associated with the different chemical composition and presence of defects in the cast metal, the shape and size of the product, the need to adjust the chemical composition of welding consumables, etc. It is determined that when restoring bells, the most appropriate process for performing repair work is the process of manual argon-arc welding with a nonconsumable electrode (TIG process). It is shown that positive results in welding up cracks in church bells while ensuring their high acoustic properties are achieved with the correct choice of filler material. Coated-electrode welding can be recommended for welding up casting defects, as well as for manufacturing welded components of sculptures.

KEYWORDS: foundry bronzes, chemical composition, bell bronze, cracks, repair and welding technologies, metal-cored wire, coated electrodes

INTRODUCTION

Owing to their special physical-mechanical and technological properties, copper and its alloys are finding wide application in different sectors of industry and construction. There is not a single industry, where copper and its low and complex alloys are not used. High casting and decorative properties of the copper alloys have made them indispensable for many centuries (starting with the Bronze age) in the production of art and jewelry products: sculptures, monuments, decorations, etc.

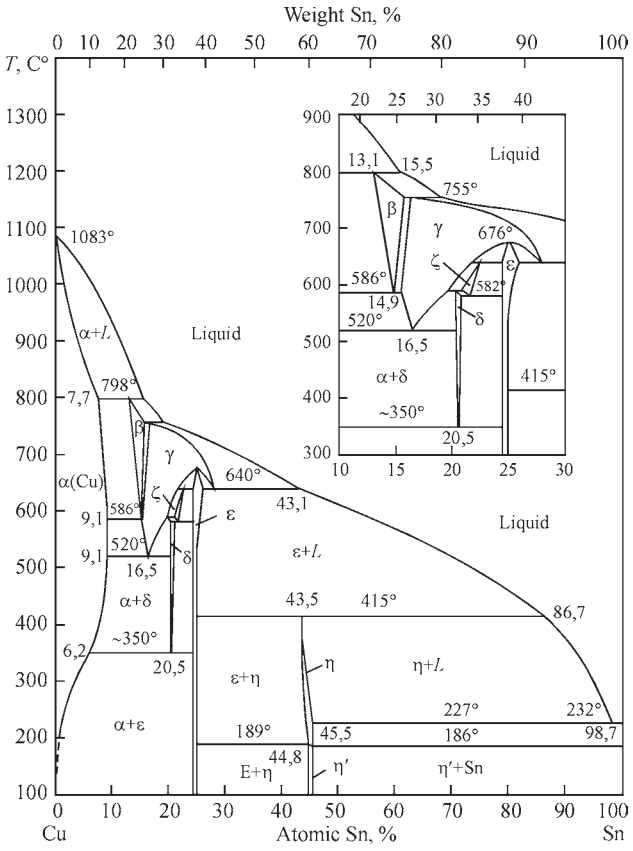


Figure 1. State diagram of Cu–Sn system [1, 2]

The most common alloy for these purposes is tin bronze of Cu–Sn–Zn–Pb system, which in the form of cast material has high fluidity, slight shrinkage, readily fills even complex casting moulds, ensures "bronze colour" of the products and their high corrosion resistance. The state diagram of copper-tin system is shown in Figure 1 [1, 2].

A characteristic feature of the structure of tin bronzes is the fact that during solidification the area of the solid α-solution becomes narrower and (α+β) eutectoid (its base is $Cu_{31}Sn_8$ electron compound with 32.53 wt.% Sn content) appears at Sn concentrations much smaller that it follows from the equilibrium state diagram [2]. This is due to the low rate of tin diffusion into copper, when at rapid transition of tin bronzes from the liquid into the liquid–solid and solid states the tin atoms do not have enough time to occupy all the nodes in the atomic lattice of the centers and crystals of the forming alloy. As a result, the crystals of the solid α-solution contain much less tin than it follows from the equilibrium diagram. Here, the molten alloy which did not crystallize, is enriched in tin in those parts of the ingot, which are the last to crystallize [3, 4]. With increase of the tin content the strength considerably increases and the ductility of the alloy decreases (Figure 2) [5].

Chemical composition of the casting bronzes for art castings is given in Table 1 [6, 7].

According to the current standards, casting bronzes of CuSn5Zn5Pb5, CuSn4Zn7Pb5, CuSn4Zn4Pb17, CuSn3Zn12Pb5, CuSn6Zn6Pb3 grades also belong to

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alloys of this system. These bronzes are the best studied, and in our opinion, they can also be used as material for art casting (in one composition or another).

The given bronzes of BKh and CuSnZnPb grades belong to low-tin bronzes (≤5–6 % Sn), and at higher Sn concentration — to high-tin ones (CuSn8Zn4, CuSn10P1, CuSn10Zn2, CuSn108Zn10). Tin increases the mechanical properties (Figure 2) and corrosion resistance of the bronzes. The "bell" bronze well-known from ancient times also belongs to high-tin ones, its optimal composition being 20–23 % Sn, up to 2 % impurities, the balance being Cu [8]. It is this composition of bronze that ensures its sufficient strength and satisfactory sound qualities, which is particularly important in manufacture of such products as church bells.

Low-tin bronzes with zinc and lead additives are usually used for art casting. They improve the alloy casting properties, and facilitate the further machining of the products. A well-suited material for making art products (sculptures of various shapes, souvenirs, decorations, etc.) are also copper-based alloys, less expensive compared to tin bronzes: copper-zinc alloys (brasses), copper-aluminium alloys (aluminium bronzes), and silicon-manganese bronzes.

The given information as regards the alloys for art castings is necessary, first of all, for clear understanding what metal we are dealing with in the case of restoration repair of a product. The need to conduct such repair work arises both in the case of extending the service life of a product, and even at the production stage (welding up casting defects). Practical experience of welding cast bonzes shows that such alloys belong to the category of material with limited weldability, and their welding is a complex and critical operation.

THE OBJECTIVE

of the work is determination of the chemical composition and structural features of the damaged works of art from copper alloys and development of special welding consumables and welding technology on their base to restore the product integrity.

Beginning from the 50s of the previous century, PWI has conducted systematic studies of copper alloy weldability and development of the technological processes of their welding and surfacing. This work was usually performed with the purpose of solving the urgent problems of application of these materials in such sectors as mechanical engineering and shipbuilding, metallurgical and electrical engineering industry.

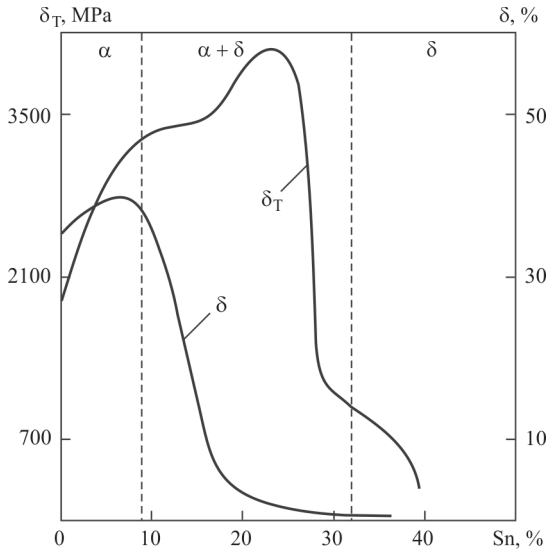


Figure 2. Dependence of mechanical properties of tin bronzes on tin content

Considering the available developments on welding consumables (flux-cored wires, coated electrodes) and technological processes of welding and surfacing of structural copper alloys, PWI Department of general problems of arc welding equipment and technology has conducted scientific-practical works on reconditioning and restoration of art castings from copper alloys. Results of some of them are given below.

RESTORATION OF CHURCH BELLS

Church bells which had to be restored had the characteristic classical shape (Figure 3).

As noted in work [9], the main criteria of the quality of church bells are their melodiousness and art design, as well as absence of defects (pores, cracks, nonmetallic inclusions), which can lead to their fast fracture. A detailed study of bell bronze demonstrated that it is exactly the copper alloy with 20–22.5 % tin (impurity content within 1–2 %) which has high acoustic properties in the cast untreated state. It should be noted that even a slight change of the chemical composition leads to significant changes in the structure and properties of bell bronze (Figure 4) [10].

Table 1. Composition of cast bronzes for art castings [6, 7]

Bronze grade	Sn	Zn	Pb	Cu	Additives				Application
					Sb	Fe	Al	Total	
BKh1	4–7	5–8	1–4	Bal.	1.0	1.0	0.1	3.0	Castings for busts and statues
BKh2	1–5	8–13	1–6		1.0	1.0	0.1	3.0	Large-sized decorative castings
BKh3	0,5–3	25–35	1–3		0.5	1.0	0.5	3.0	Small-sized decorative castings
Bell bronze	20–23	*	*		*	*	*	*	Bell castings

Notes. BKh1 — for producing busts, sculptures; BKh2 — for large-sized decorative castings; BKh3 — for small-sized decorative castings; * — not regulated, but not more than 2 %.

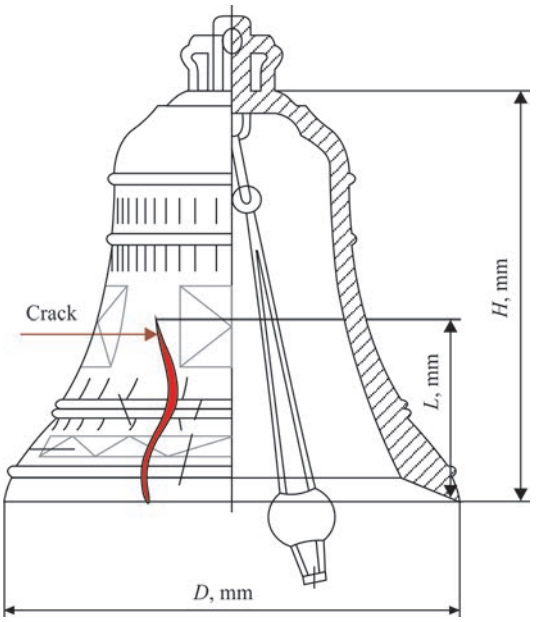


Figure 3. Generalized profile of the bells to be restored [8]

As shown by investigations [11], taking into account the service conditions (impact load, metal aging, atmospheric corrosion, etc.), the acoustic properties of bell bonze decrease abruptly. However, the bells become unfit for purpose the most often because of crack initiation in them (Figure 5).

Several bells of different size (and from different manufacturers) with exactly such defects were submitted for repair. Tables 2 and 3 give the data on overall dimensions of the bells and chemical composition of the bronze.

Visual inspection of the bells showed that the cracks initiate in the bell lower parts (bell percussion belt) and propagate upwards. It should be noted that in terms of design the bell walls have variable thickness: maximal in the percussion belt and much smaller in the upper part. So, the metal of the longest crack in K-2 bell was 8 mm thick in its upper part, and the metal of the percussion belt of K-3 bell was 48 mm thick. Crack welding up actually consists of making a butt weld of metal of a variable thickness, which is under rigid restraint.

It is known from published sources that soldering and welding methods are used in bell repair. The authors of [12] report that they managed to repair a bell with application of soldering, using copper-based powders as the filler material. In work [13], rods of similar bell material produced by casting were used. The authors of [14] in their applied research experiments on restoration of the integrity of bells of the 16th and 19th centuries used both the soldering and welding methods. Here, similar to work [15], prior to repair the bell was completely preheated and slowly cooled. Such a technology, however, is costly, and it does not always yield positive results. Therefore, in our opinion, a more rational and economically sounder welding process for performance of repair work on bell restoration is the TIG-process without preheating with application of special filler wires. Such metal-cored wires provide a weld metal close to the bell bronze by its composition, and to its acoustic properties, respectively.

The crack tip is traditionally drilled out before scraping (Figure 6). Taking into account the metal thickness, crack welding up is performed from both sides by multipass welds formed by deposition of small (8–10 mm) beads (Figure 7), each of them being additionally peened to lower the thermal stresses.

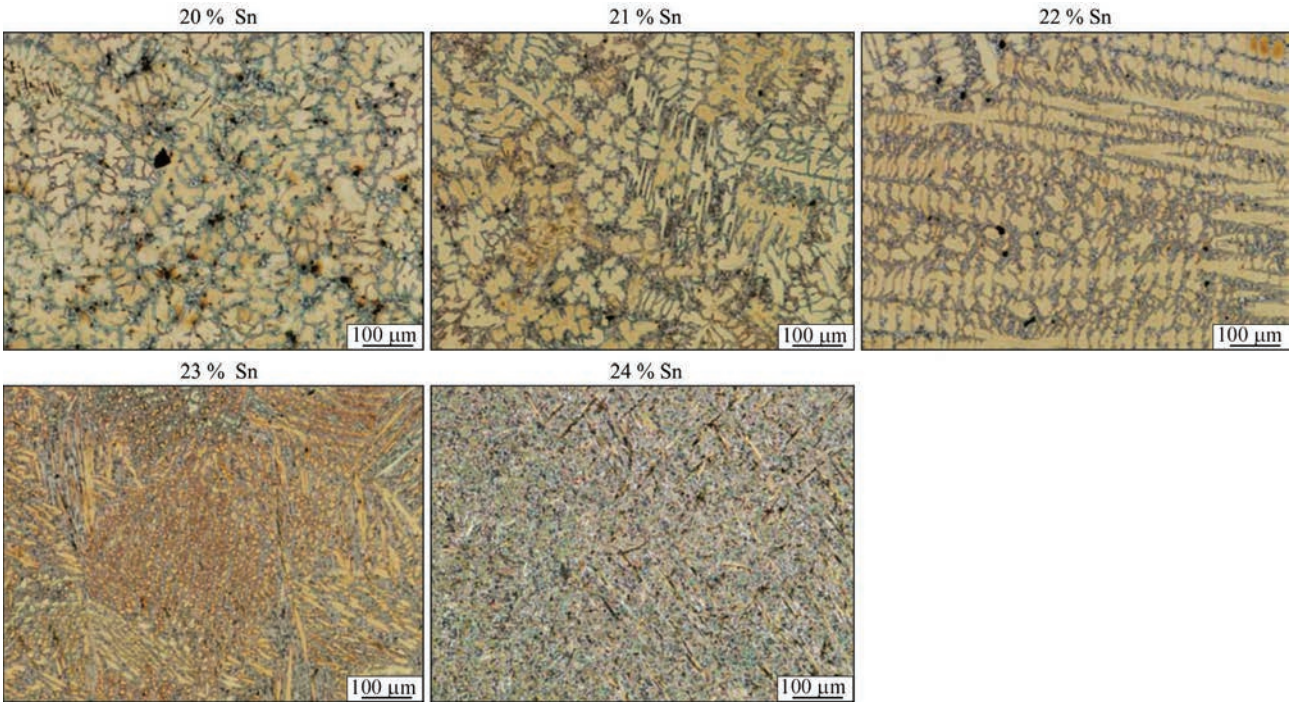


Figure 4. Microstructure of bronze with different tin content [10]

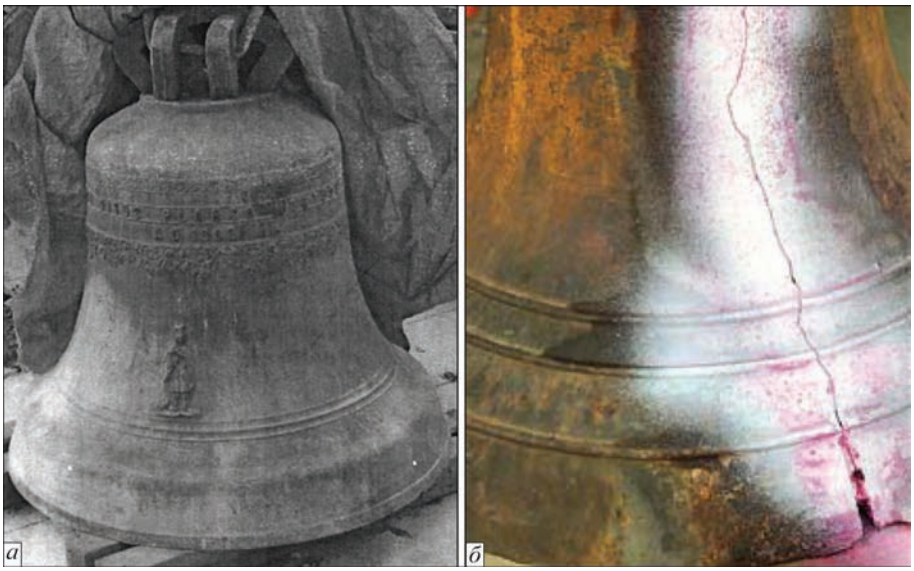


Figure 5. Appearance of a bell with the crack

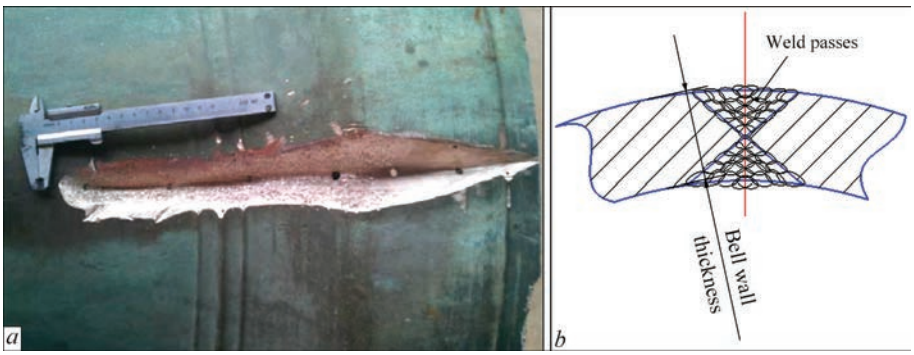


Figure 6. Appearance of a treated crack (*a*) and schematic of crack welding up (*b*)

Used as the shielding gas is argon. The welding mode parameters are as follows: I_w = 140–180 A, U_a = 10–15 V, Q_{Ar} = 10–15 l/min, d_{el} = 3.0–4.0 mm.

Of the three bells provided for repair bells K-1 and K-3 were successfully restored (Figure 8).

In bell K-2 which had the longest crack, a new crack of up to 200 mm length initiated during repair. Additional quality inspection of this bell after welding by the liquid penetrant testing revealed the presence of internal microcracks in the metal, which during welding up of a cut-out crack lead to further cracking of the bell (Figure 9, *a*). More over, pores formed in the HAZ metal (Figure 9, *b*).

Therefore, during assessment of the bell reparability a comprehensive diagnostics of its quality is required. Quality control of the restored bells and evaluation of their acoustic properties (character and

Table 2. Main overall dimensions of the bells

Bell	Height *H*, mm	Diameter *D*, mm	Crack length *l*, mm
K-1	250	300	90
K-2	400	465	230
K-3	490	580	160

Table 3. Chemical composition of the bronze

Bell	Sn, %	Zn, %	Pb, %	Cu, %
K-1	15.6–16.2	–	< 0.5	Bal.
K-2	17.0–17.8	1.3	< 1.0	
K-3	20.4–21.3	< 1.0	–	



Figure 7. Appearance of the weld

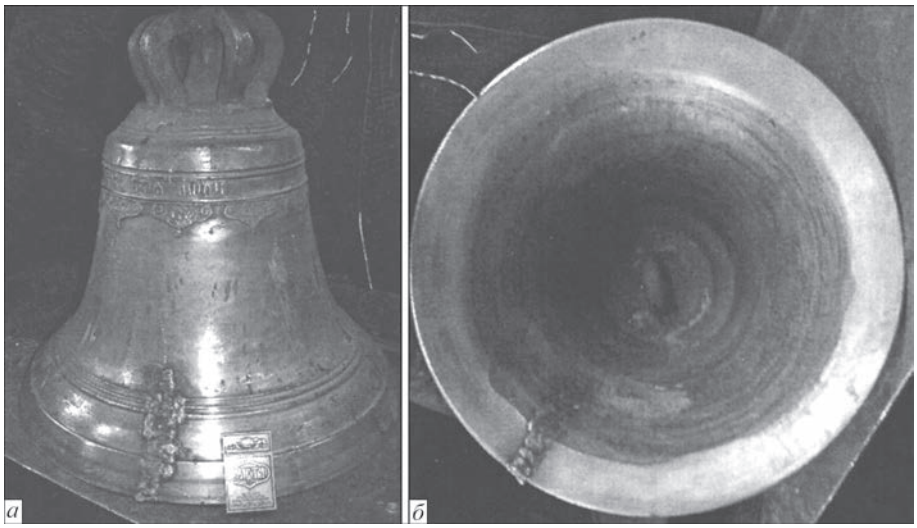


Figure 8. Restored bell K-3 from the outside (*a*) and the inside (*b*)

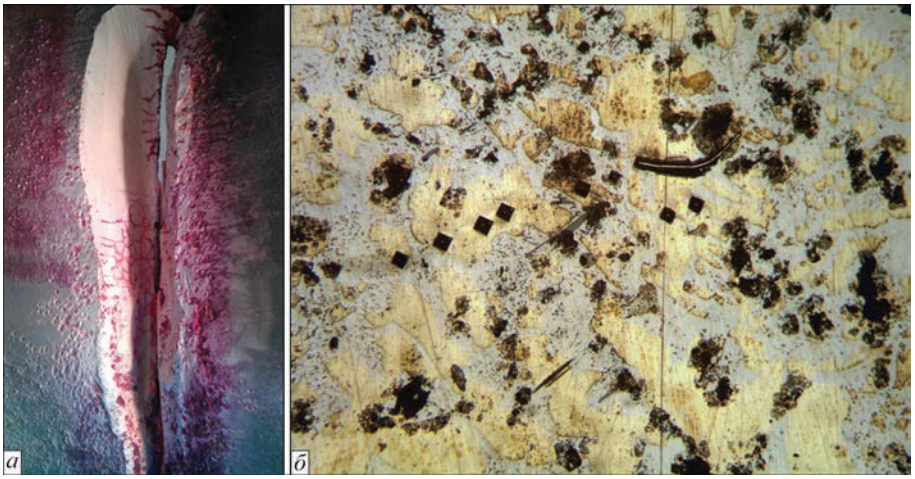


Figure 9. Defects in the HAZ: microcracks (*a*), pores (dark areas of an irregular shape) (*b*)



Figure 10. Statue of Bathing Venus (National Arboretum "Sofiivka", Uman, Ukraine)

melodiousness of the bell's sound) confirmed the possibility and expediency of repairing the church bells by the developed technologies and application of special metal-cored wires.

RESTORATION OF THE BRONZE BOWL OF "SOFIIVKA" ARBORETUM

The management of the National Arboretum "Sofiivka" (Uman) turned to PWI with the request to render technical assistance in restoration of a rare piece of art — the 19th century bronze bowl. This bowl was installed near the statue of Bathing Venus (Figure 10), was filled with spring water, which then by a granite underwater channel flowed to the lower pond. The bowl handles were decoratively made in the form of snakes [16].

"Scrap metal hunters" tore the bowl off its pedestal, and cut up the handles into 14 parts. Several "snakes" parts could not be found (Figure 11).

One of the conditions for repair was the need to achieve a decorative colour of the weld metal close to that of the bowl. In keeping with the data of mass-spectral analysis, the bowl was made from cast bronze of CuSnZnPb type. The most rational for its



Figure 11. Parts of the bronze bowl



Figure 12. Bronze bowl after restoration (*a*) and 5 years after its installation in the National Arboretum "Sofiivka" (*b*)

repair, similar to bell repair, is the use of TIG process with filler material of the type of metal-cored wire of the respective composition.

In addition to welding the damaged parts, the snake fragments which could not be found, were produced. In addition, it was necessary to make a special manual tool to produce "scales" on the surface of welded-in "snake" parts and the welds.

Figure 12 shows a photo of the restored bowl, which returned to its historical place to "Sofiivka" Arboretum.

WELDING OF MONUMENT FRAGMENTS

In the production of castings such as monuments, busts and other large-sized sculptures there arises the need to join their individual fragments. Also urgent is the problem of welding up the casting defects, forming during the product manufacturing. Modern MIG/MAG, TIG, as well as MMA welding technologies are successfully used to perform such work. Under the conditions of individual production — sculptor's workshop, mounting



Figure 13. Monument to V.I.Tolubinskyi with a broken off arm (*a*) and after coated electrode welding (*b*)

site, etc. — the MMA process, not requiring any special equipment, is the most rational. Such is the case, for instance, of repair of the monument to V.I. Tolubinskyi, academician of the AS of Ukr.SSR (Figure 13), from which the arm (in two places) and the scroll were broken off during a fall from the pedestal.

Taking into account the chemical composition of the material from which this monument was made, and PWI achievements on development of copper-based coated electrodes [17–19], a test batch of electrodes was made. Performance of welding operations on repair of this product confirmed the high quality of the weld and coincidence of the weld colour with that of the base metal, which is important in such cases.

CONCLUSIONS

1. The chemical composition and structural features of damaged works of art from copper alloys were studied. It was found that the chemical composition of the sculptures, particularly those, which were produced more than a century ago, does not always correspond to the established regulatory documents of today, leading to the need for an individual approach to development of welding consumables during sculpture repair.

2. Special metal-cored wires and coated electrodes were developed, which ensure both high values of welded joint strength, and their required decorative properties.

3. Conducted research and experimental work on restoration of cast products from copper alloys, including bell bronzes, and derived positive results allow a significant expansion of the application of repair-welding technologies in the practice of restoration of such products.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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