Mühlhans, Jörg; Kerbler, Lukas; Pomberger, Beate Maria

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Avar pellet bells from different sheet metals – Finds, experimental forging and acoustics

Avarské plechové rolničky z různých kovů. Nálezy, experimentální výroba a akustické vlastnosti

Jörg Mühlhans / Lukas Kerbler / Beate Maria Pomberger

Abstract

Pellet bells forged from metal sheets were common during the Avar period. Their investigation is part of the research project "Metallic Idiophones between 800 BC and 800 AD in Central Europe". A large amount of the pellet bells were forged from sheet iron, and the rest from copper and various copper alloy sheets. To find out the reason why sheet iron was preferred, different materials were used in forging experiments. While sheet copper and bronze were quite easily shaped, sheet iron needed much more force to be shaped into the swage block. Listening to the sounds of the three comparably-shaped pellet bells, they differ substantially in timbre and loudness. The analyses of the sound recordings showed no significant correlations between any of the calculated psychoacoustic parameters. The copper bell showed the lowest values, the bronze bell the middle and the iron bell the highest values. A possible explanation for the use of iron pellet bells could be found in magical-religious imagination and psychological warfare.

Key words

experimental archaeology, acoustics, psychoacoustics, sheet metals, Avar period, musicarchaeology

Abstrakt

Rolničky zhotovené z kovového plechu představují běžné nálezy z avarského období. Jejich zkoumání probíhá v rámci výzkumného projektu „Kovové idiofony z období mezi lety 800 př. n. l. a 800 n. l. ve střední Evropě". Většina rolniček byla vyrobena ze železného plechu, zbylé exempláře pak z plechu měděného či z různých slitin mědi. Při experimentální výrobě rolniček, která měla za úkol zjistit, proč byl pro jejich výrobu preferován právě železný plech, byly použity různé materiály. Zatímco měděný a bronzový plech byl snadno tvarovatelný, železný plech vyžadoval pro formování pomocí zápustky mnohem větší úderovou sílu. Zvuky rolniček přibližně stejného tvaru ukovaných z těchto tří materiálů se od sebe podstatně liší jak svou barvou, tak hlasitostí. Analýzy zvukových záznamů neprokázaly mezi vypočtenými psychoakustickými parametry žádné významné korelace. Nejnižší hodnoty vykazovala měděná, střední hodnoty bronzová a nejvyšší hodnoty železná rolnička. Možné vysvětlení pro používání železných rolniček je zřejmě potřeba hledat ve sféře magicko-náboženských představ a taktiky psychologického boje.

Klíčová slova

experimentální archeologie, akustika, psychoakustika, kovové plechy, avarské období, archeologie hudby

1. Introduction

The research project "Metallic Idiophones between 800 BC and 800 AD in Central Europe" investigates idiophones from the Early Iron Age, the Roman period and the Early Middle Ages. It is funded by the Austrian Science Fonds FWF and supported by the Natural History Museum Vienna, Austria (FWF Project T 1136-G, Hertha Firnberg grant). Within this interdisciplinary research project (*Pomberger et al. 2020*; *Pomberger et al. 2021; Grömer – Saunderson – Pomberger 2021*), pellet bells of the Avar period were investigated – among them 114 forged from sheet metal. In order to find out which material was used, chemical analyses were carried out. Ján Tirpák, Gemological Institute / University of Constantine the Philosopher in Nitra, SK (*Tirpák unpublished*) analysed the pellet bells of Slovakia, Bernadett Bajnóczi and Viktória Mozgai (*Bajnóczi – Mozgai 2020*), Institute of Geological and Geochemical Research / Research Centre for Astronomy and Earth Sciences Budapest (Hungarian Academy of Sciences) analysed Hungarian pellet bells and Mathias Mehofer (*Mehofer 2020*), VIAS /Vienna Institute for Archaeological Science /University of Vienna analysed pellet bells from Austria.

2. Pellet bells from archaeological contexts

Forged pellet bells from 21 Avar cemeteries were investigated. The majority of the pellet bells were found in burials of humans and a minority in horse burials. Children and women, sometimes also men, wore them attached to belts, around the wrists or on necklaces. The horses' bridles and probably also the breast collars could be decorated with pellet bells (*Pomberger et al. 2021*; *Pomberger et al. 2022*). The majority of the 114 investigated sheet pellet bells, 75 bells to be exact, were forged from sheet iron. The rest were made from bronze and copper and unanalysed copper alloy sheet. A few are gilded (see tab. 1; fig. 1). A detailed table of sheet metal pellet bells is available on the internet platform academia.edu (*Pomberger 2022*).[1]

They are composed of one piece of sheet metal, two vertical halves or two horizontal halves. Sometimes a narrow sheet belt seems to keep the two halves together. The eyelet is soldered on after joining together the two halves. Small pebbles, pieces of cinder or small bronze balls, serve as pellets (fig. 2). Six different base shapes can be determined: shape I, shape II, shape IV, shape VI, shape VII and shape IX, heart shaped (see fig. 3) (*Pomberger 2020*). Some have simple or cross-shaped sound slots and some have no sound slots at all. There are only a few sheet pellet bells with sound holes. The sizes of the pellet bells vary from 20 mm up to 40 mm with diameters from 20 mm up to 30 × 33 mm. The wall thickness is approximately 0.5 to 1 mm.

Usually, the iron pellet bells are heavily corroded. The moisture of the soil in burials strengthens the electrochemical process and an anodic reaction of iron dissolution takes place on the surface of the metal. The corrosion processes of metals in the soil are influenced, among other things, by the water, oxygen and salt content as well as the pH value of the soil. Mineral salts become deposited and change the chemical compositions on the surface (*Selwyn 2004*). Since the majority of the idiophones were forged from sheet iron and only a minority are made from copper alloy and copper, the question of why sheet iron was favoured arises.

Forged Pellet Bells from Avar cemeteries **site**	**country**	**pellet bells total**	**iron**	**copper alloy**	**copper alloy gilded**	**bronze**	**bronze gilded**	**brass**	**copper**	**copper gilded**
Holiare	SK	4	4							
Nové Zámky	SK	4	4							
Komárno IX Lodenica	SK	16	5			2	6	1	1	1
Radvaň nad Dunajom, part Žitava (former Žitavská Tôň)	SK	18					18			
Keszthely	HU	12	11		1					
Keszthely-Városi temető	HU	5	5							
Keszthely-Dobogó	HU	1	1							
Pilismarót-Öregek-dűlő	HU	1	1							
Halimba Belátó domb	HU	13	13							
Szebény	HU	1		1						
Jászalsósszentgyörgy	HU	1	1							
Jánossomorja-Mosonszentmiklós	HU	1	1							
Jánoshida	HU	2	1	1						
Szob	HU	2	2							
Kölked-Feketekapu A	HU	1	1							
Gyenes	HU	9	8	1						
Lescentomaj	HU	2	2							
Zamárdi-Réti földek	HU	6	6							
Kaposvár 33	HU	5			5					
Wien-Csokorgasse	AT	9	8	1						
Edelstal (Nemesvölgy, Zemianska Dolina, Nikišdol)	AT	1	1							
total		**114**	**75**	**4**	**6**	**2**	**24**	**1**	**1**	**1**

Table 1. Forged pellet bells from Avar cemeteries of Slovakia, Hungary and Austria (B. M. Pomberger)

Tab. 1. Kované rolničky z avarských pohřebišť na Slovensku, v Maďarsku a Rakousku (B. M. Pomberger)

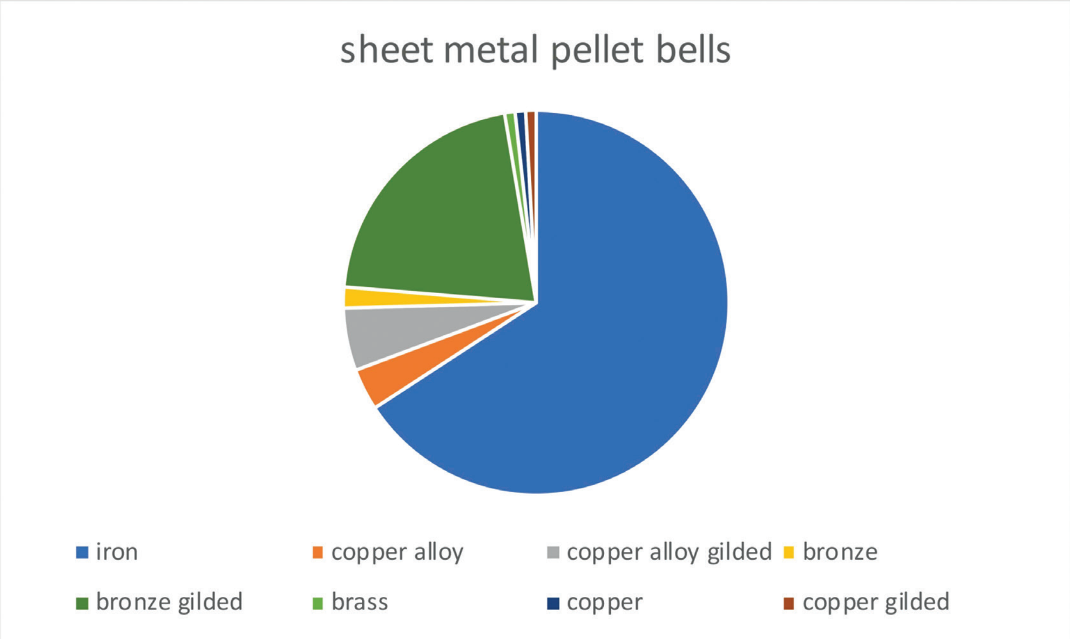


Fig. 1. Forged pellet bells and the distribution of materials (Graphic by B. M. Pomberger)

Obr. 1. Zastoupení jednotlivých materiálů plechových rolniček (graf B. M. Pomberger)

3. Research questions and methods

To answer the main research question – why sheet iron was favoured for sheet pellet bells – we have to find out firstly how the pellet bells were forged, and secondly what the differences in forging the various metals are. This should be answered by producing them in one shape and size from different metals as an experiment. Experimental archaeology is an approved method to gather scientific data using international standards (*Lammers-Keijser 2005*). Another question is how the materials influence acoustic and psychoacoustic parameters. Sound recordings were made in a recording studio at the MediaLab of the University of Vienna and then analysed. For all of the objects, a variety of acoustic and psychoacoustic parameters were calculated using ArtemiSuite (*Head 2022*), Praat (*Boersma – Weenink 2022*) and Audition (*Adobe Inc. 2022*).

4. Experimental reconstruction of pellet bells

Three pellet bells, made of the historically most commonly used metals (iron, bronze, copper) were forged into the same shape. The iron pellet bell from Komárno-Lodenice (A-6070, grave 110; fig. 4), which dates to the Late Avar period, served as a template for the reconstruction. The corroded original object has an oval shape (3.1 × 2.7 cm), cross-shaped sound slots, a belt around the horizontal axis and a perforated plate on top for attachment or handling. In some cases, solder residues (copper oxides) could be seen on the belts of iron pellet bells,

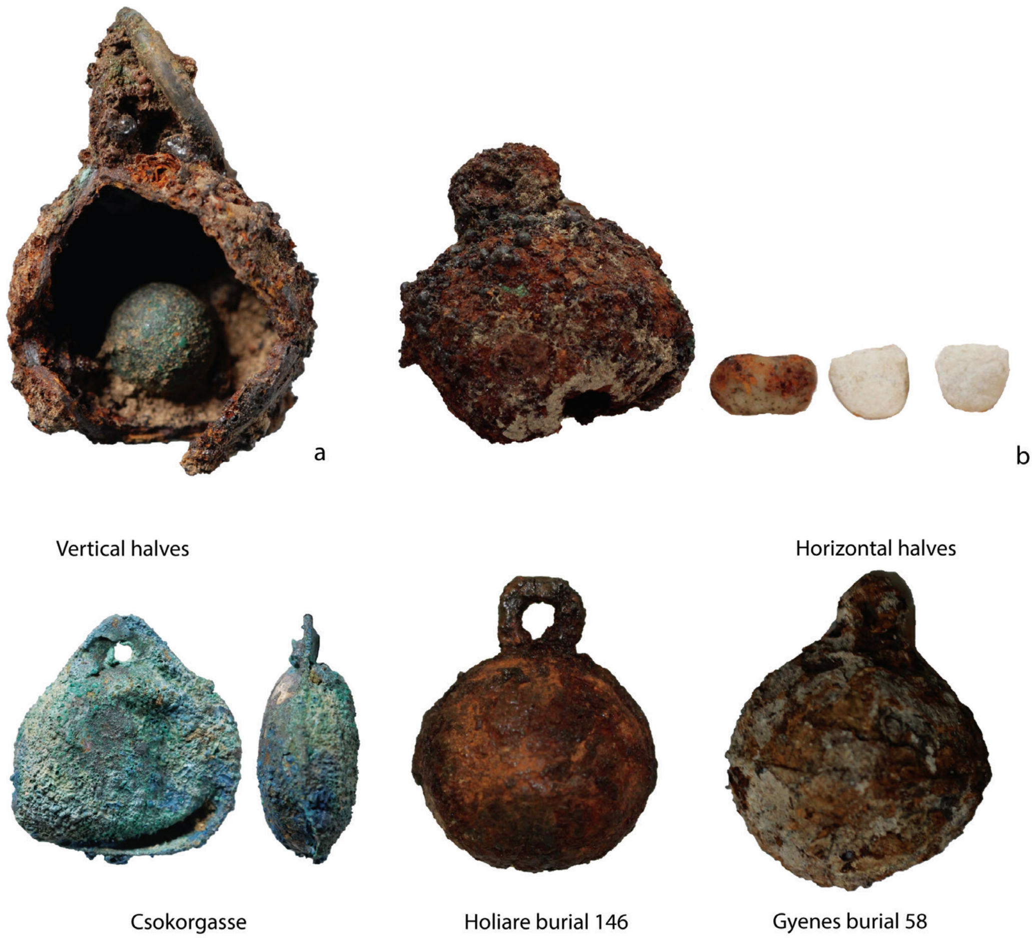


Fig. 2. The different kinds of rattle bodies and the composition of the pellet bells (Photos by B. M. Pomberger, L. Strainz)

Obr. 2. Různé tvary jader a struktura rolniček (foto B. M. Pomberger, L. Strainz)

so it can be assumed that these had been soldered together from two halves.

The reconstructed pellet bells were made from metal sheets of the same thickness (0.5 mm). The metals used were copper, bronze with 6 % tin and iron with 0.07 % carbon. The type of copper used has a densitiy of 8.94 g/cm³ (*Deutsches Kupferinstitut, Werkstoffdatenblatt Cu-DHP*), the bronze 8.82 g/cm³ (*Deutsches Kupferinstitut, Werkstoffdatenblatt CuSn6*) and the iron 7.90 g/cm³ (*Böhler Edelstahl, Werkstoffdatenblatt A500*, at 20 °C). At first, two round sheet metal discs were cut out of each material with tin snips (fig. 4: A). Using a swage block with hemispherical recesses and spherical punches of matching diameters, the round sheets were forged into hemispheres (fig. 4: B, C). This was done gradually from the largest hemispherical recess in the swage block to the recess with a 33 mm diameter. With the next smaller recess

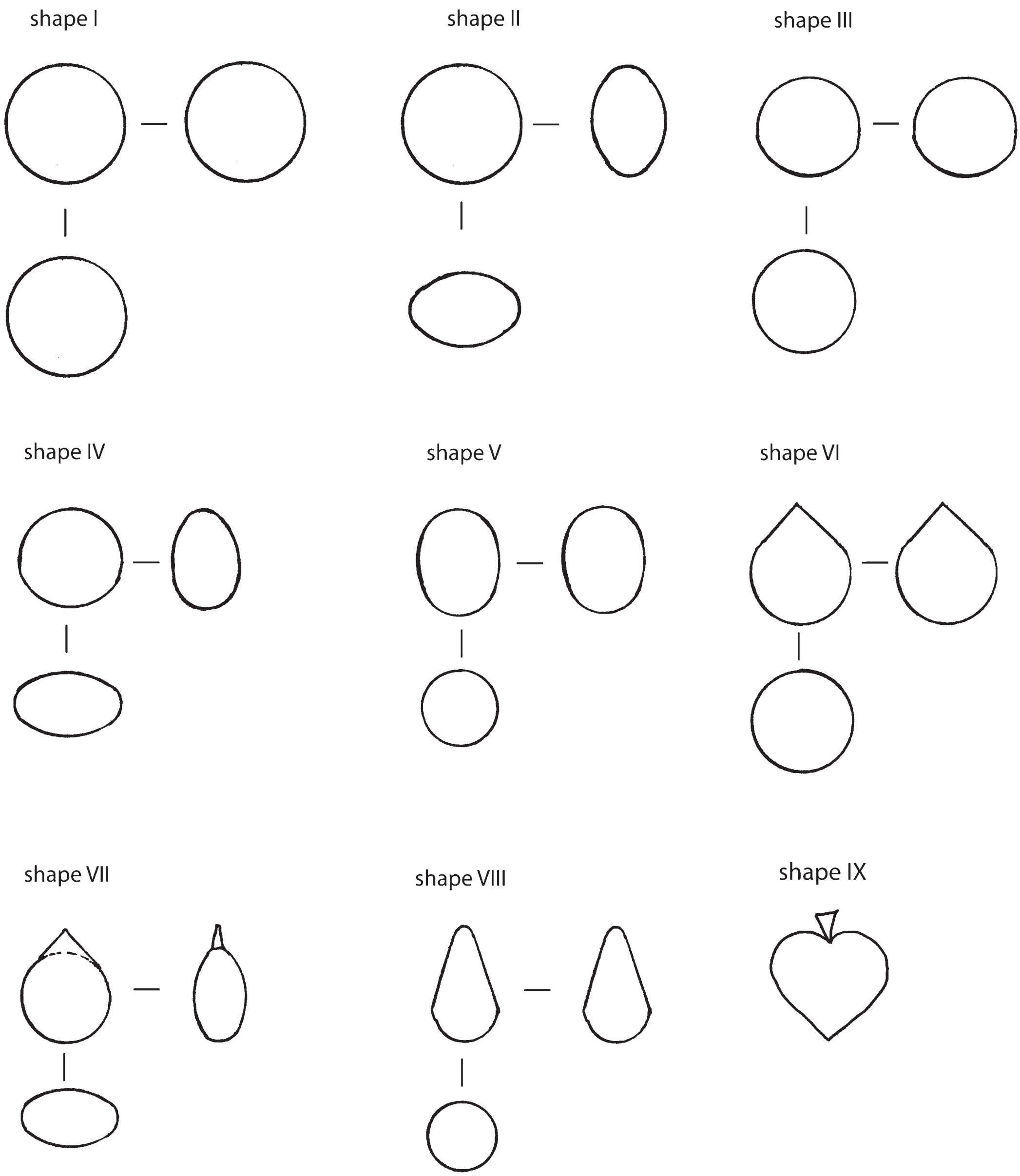


Fig. 3. Base shapes of forged pellet bells (Graphic by B M. Pomberger)

Obr. 3. Přední, spodní a boční profily kovaných rolniček (grafika B. M. Pomberger) of the available swage block, the hemispheres would have become too small, so the pellet bells are slightly larger than the originals. Between the change of the hemispherical recesses in the swage block, the hemispheres were annealed to relax the microstructure (fig. 4: D). For this purpose, the hemispheres made of copper and bronze were heated to a dark red glow and then quenched in water. Quenching in water is particularly important for bronze in order to avoid the brittle delta phase in the microstructure (*Scott – Schwab 2019*). The iron hemispheres were annealed and then allowed to cool slowly to relieve tensions and hardening caused by cold forging. With a set punch and a swage specially made for this purpose, the edges of the upper halves of the pellet bells were bent up (fig. 5: E). Afterwards the outer end of the edge was levelled again (fig. 5: F). So the upper halves got a belt shaped fold for joining the two halves together. A cross shape was sawn into the lower halves of the pellet bells and holes were drilled in at the sawn ends (fig. 5: G). A sheet metal plate with a drilled hole was riveted onto the upper halves of the pellet bells for an attachment or usage as a handle. Then the outside edges of the lower halves and the insides of the folds of the upper halves were sanded. Flux was applied to the sanded surfaces. A pebble weighing one gram was then placed in each pellet bell and the two halves were placed into each other. The halves were temporarily fixed together with iron wire. Then the pellet bells were soldered with high silver content hard solder that melts at 670 °C[2] (CFH, Werkstoffdatenblatt Hartlot SH320; fig. 5: H). Finally, the temporary wires were removed and the surfaces of the pellet bells were sanded and polished (fig. 6: I).

After the first pellet bell was forged from copper, the second was made of iron and the third of bronze. In order to create the required size, metal discs with a 44 mm diameter had to be cut out of the copper sheet. Then, an attempt was made to forge the iron pellet bell with the same cut-out diameter. But that way the hemispheres were not deep enough and the finished pellet bell was too ellipsoidal in shape. For the iron pellet bell, a cut-out diameter of 48 mm was required in order to obtain the same shape and dimensions as the copper pellet bell. This is because copper becomes thinner much faster when forged and therefore longer in all directions. Another reason could be that for the first pellet bell empirical values first had to be gathered and more hits with the punch were necessary to get the required shape. Accordingly, the copper pellet bell should actually have been forged from thicker sheet metal in order to have the same material thickness as the iron pellet bell in the end product. The bronze pellet bell in turn was also cut out to a diameter of 48 mm and met the requirements in shape and dimensions. In addition to the differences caused by forging, it was not possible to use exactly the same amount of solder for the three pellet bells either, so there are slight differences in weight. All in all, the bronze and the iron pellet bells in particular can be compared well to one another, while for the copper pellet bell it must be considered that forging made it thinner than expected.

In addition to the pellet bells made from two soldered halves, a bronze pellet bell was forged from one piece. This naturally has a different shape than the soldered ones, but it is similar in size (fig. 6: J). By comparing the pellet bell forged from one piece with the other pellet bells, it should be clarified whether the soldering has a negative effect on the sound. For the pellet bell forged from one piece, an almost cruciform shape (fig. 6: K) had to be cut out from a 0.5 mm thick sheet of bronze (CuSn6). First the upper part of the pellet bell was forged in the swage block with hemispherical recesses and with spherical punches of

original pellet bell A - 6070
from burial 110, Komárno IX

A - Cutting out the sheet metal disks

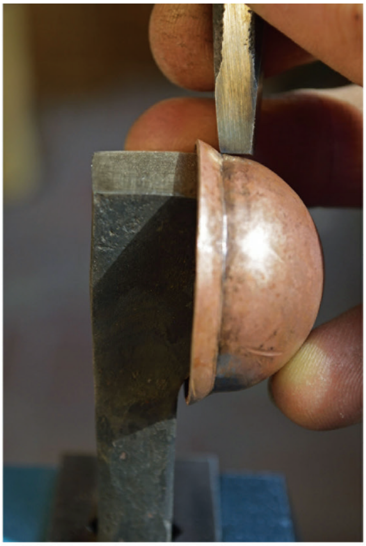
B - Forging into hemispheres in a swage block

C - Forged hemispheres

D - Annealing the hemispheres to relax the microstructure

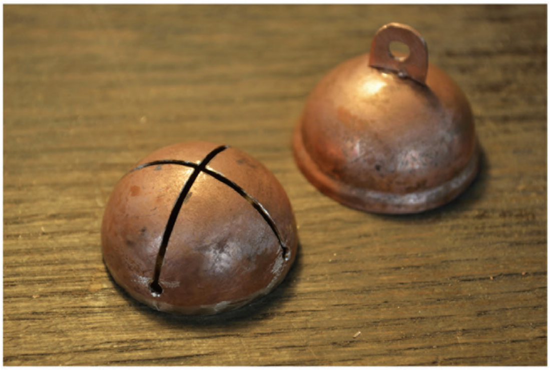
Fig 4. Forging the pellet bells, steps A–D (Photo by L. Kerbler)

Obr. 4. Výroba rolniček ze dvou částí, fáze A–D (foto L. Kerbler)



E - Setting up the edge of the upper half of a pellet bell

F - Levelling the outer end of the edge



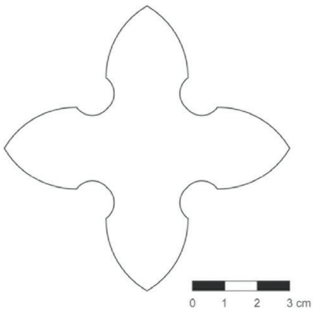
G - Sawed out lower half of a pellet bell and upper half with riveted metal plate

H - Soldering with high-silver content hard solder

Fig. 5. Forging the pellet bells, steps E–H (Photo by L. Kerbler)

Obr. 5. Výroba rolniček ze dvou částí, fáze E–H (foto L. Kerbler)

I - Finished pellet bells made from two soldered halves
copper - bronze - iron



J - Cruciform shape for a pellet bell forged from one sheet piece

K - Pellet bell forged from one piece of sheet

Fig. 6. Forged pellet bells, steps J–K (Photo by L. Kerbler)

Obr. 6. Rolničky kované ze dvou částí (I) a výroba jednodílných rolniček, fáze J–K (foto L. Kerbler)

L - Deformed surface of swage block by cold forging sheet iron

M - Deformed surface of spherical punch by cold forging sheet iron

Fig. 7. The deformed swage block and the surface of spherical punch deformed by cold forging of sheet iron (Photo by L. Kerbler)

Obr. 7. Opotřebená zápustka a povrch kulatého razidla deformovaný tvářením železného plechu za studena (foto L. Kerbler) matching diameters. Before the upper half was forged in the smaller diameters, the lower part with the later sound slots was completely forged in the swage. Forging was done gradually from larger to smaller diameters of the swage block and with intermediate annealing as previously described. Then the upper half was forged to the required size and a metal plate was riveted on top for attachment and handling. Afterwards a pebble was placed into the pellet bell and then the slightly opened sound slots were closed to the required extent.

Among the three different forged metals, copper is naturally the easiest to shape. But it becomes thinner much faster when forged. Bronze, on the other hand, has a higher resistance to deformation. Cold forged bronze holds its shape well and does not bend as easily with careless handling as copper does. The iron sheet naturally had the highest resistance to deformation during forging. Significantly more force had to be applied for the shaping. This also caused a higher wear of the working edges and the striking surfaces (fig. 7: L, M).

5. The influence of materials on the acoustics of pellet bells

The timbre of bells and pellet bells (as well as probably all idiophones) is influenced by size/mass, material/alloy, shape, wall thickness and mode/place of excitation. In this study, the focus was primarily on the material's influence on the sound, so three objects were forged as similar as possible, from bronze, copper and iron. Two more pellet bells with slightly different shapes were made, one from a single sheet of bronze and an ellipsoidal one from iron. For an additional comparison on the influence of size/mass, eleven pellet bells made of brass different in size but similar in shape were bought and analysed. For all of the objects, a variety of acoustic and psychoacoustic parameters were calculated using ArtemiSuite (*Head 2022*), Praat (*Boersma – Weenink 2022*) and Audition (*Adobe Inc. 2022*). While the density of the used materials is known (see above), values for the wave velocity had to be taken from the literature (*Rose 2014,* 57) for similar materials. Stiffness, defined as the rigidity of an object, plays a major role in sounding objects, but is composed of the intrinsic stiffness of the material and the chosen geometry of the object itself (*Hort et al. 2014,* 1), thus unknown. JASP (*JASP Team 2022*) was used for statistical calculations.

First of all, the density and wave velocity, both longitudinal and shear, of 14 different metals/alloys that are likely to occur in musical instruments were extracted from Rose (*2014*, 57). Statistical calculations showed quite a high negative correlation between density and velocity, while the two given types of waves (longitudinal and shear) show a very strong and highly significant positive correlation (see tab. 2). Statistically, metals with higher density have lower velocity, however this does not apply to the small sample of the three materials in this study.

The density of cast iron is about 14 % lower than in the other two materials and the longitudinal wave velocity is about 23 % lower in bronze, which is the only alloy used. Shear velocity does not deviate as much.

5.1. Audio recordings

All of the objects were recorded in the studio of the "MediaLab" within the Faculty of Philological and Cultural Studies (University of Vienna). An Earthwork M30 measurement microphone was used with a Presonus c24 interface. Recordings were done at a 44.1 kHz sampling rate with 16 bit and calibrated using a Peaktech 8010 class II calibrator, the accu-

Material	Density (g/m³)	Wave velocity (m/s)	
		Longitudinal	Shear
Bronze	8.86	3530	2230
Copper	8.9	4660	2260
(Cast) Iron	7.7	4500	2400

Table 2. Density and velocity of longitudinal and shear waves for similar materials as given in Rose 2014, 57

Tab. 2. Hustota a rychlost podélných a příčných vln u podobných materiálů podle Rose 2014, 57

Pearson's Correlations		n	Pearson's r		p
velocity shear (m/s)	velocity longitudinal (m/s)	14	0.946	***	< .001
velocity shear (m/s)	density (g/cm^3)	14	-0.701	**	0.005
velocity longitudinal (m/s)	density (g/cm^3)	14	-0.615	*	0.019

* p < .05, ** p < .01, *** p < .001

Table 3. Pearson Correlation for density and velocity in 14 selected metals/alloys

Tab. 3. Pearsonova korelace mezi hustotou a rychlostí u 14 vybraných kovů/slitin

bell	weight	Leq	pitch	peak_f	loud	bright	sharp	rough	impuls	tonal
bronze	18.45	73.2	1614	1891	20.6	4736	4.69	0.07	1.12	21.18
copper	14.27	67.7	1560	2024	18.6	6901	4.4	0.03	0.94	17.18
iron	15.13	78.5	2060	1988	29.5	4427	5.19	0.02	0.94	22.56

Table 4. Acoustic and psychoacoustic parameters. Weight (grams), Leq (dB), pitch (Hz), peak (frequency, Hz), loudness (sone), brightness (spectral centroid, Hz), sharpness (acum), roughness (asper), impulsiveness (iu) and tonality (dB). Highest value in dark grey, lowest in white (J. Mühlhans)

Tab. 4. Akustické a psychoakustické parametry. Hmotnost (g), ekvivalentní hladina (dB), výška (Hz), maximální hodnota (frekvence, Hz), hlasitost (son), jas (spektrální centroid, Hz), ostrost (acum), drsnost (asper), impulzivnost (iu) a tonalita (dB). Nejvyšší hodnota označená šedě, nejnižší bíle (J. Mühlhans)

racy for the sound pressure level is thus about +/-0.3 dB. Since the characteristic sound of pellet bells is created by a constant ringing of the object, recordings were done this way too. 3 seconds with constant excitation were taken out for analysis after removing the content below 500 Hz with a 5th order Bessel high pass filter.

Acoustic parameters are spectral and temporal ones that can be measured objectively from the audio material. Sound pressure levels (L_{eq}, LA_{eq}, L_{peak}), partials, peak frequencies and RMS amplitude were also measured. Psychoacoustic parameters seek to objectify subjective human perceptions such as pitch, loudness, brightness, sharpness, roughness, impulsiveness and tonality and are calculated with complex algorithms.

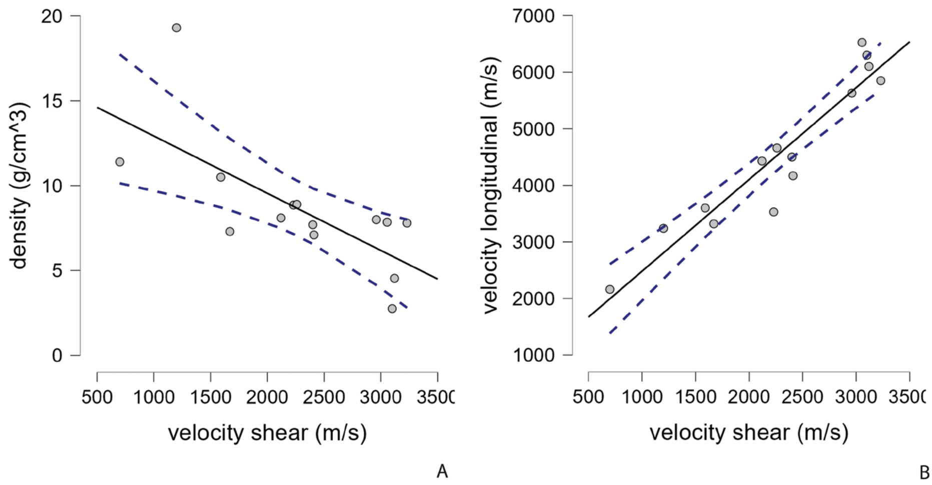


Fig. 8. A – Scatterplot for correlation between density and shear wave velocity of 14 metals with 95% confidence interval (dashed line). B – Scatterplot for correlation between shear and longitudinal wave velocity of 14 metals with 95% confidence interval (dashed line). (Graphic by J. Mühlhans)

Obr. 8. A – korelační diagram hustoty a rychlosti příčných vln u 14 druhů kovů s intervalem spolehlivosti 95 % (přerušovaná čára). B – korelační diagram rychlosti příčných a podélných vln u 14 druhů kovů s intervalem spolehlivosti 95 % (přerušovaná čára). (grafika J. Mühlhans)

5.2. Acoustic and psychoacoustic analyses

By ear, the three objects differ substantially in timbre and loudness, which is easily explained by the major differences in spectral distribution and strength of partials (see fig. 9). However, there are certain spectral patterns that can be seen in different frequency regions and can only be explained by the similar shape and size of the objects.

There are two rather weak and low partials (A) followed by two rather strong ones (B), one of them being the peak frequency. Next, a spectral valley with again quite weak partials (C) is followed by a very distinct group of four partials with ascending amplitude (D) where the two in the middle are very close to each other. On the high end (E), there is a number of partials quite similar in amplitudes. When compared with the spectra of the iron and the copper bell of slightly different shape, this structure (A–E) cannot be seen.

But interestingly, almost no significant correlations between any of the calculated parameters could be found. This spectral shift seems to influence the parameters in different ways, since some of them consider the human hearing curve while others do not. The human ear is particularly sensitive in the 2–5 kHz region (DIN ISO 226), if there is much spectral energy, sounds are likely considered as loud or sharp, while this does not influence level, pitch or brightness.

It seems that there are hardly any obvious patterns in parameters, i.e. that the heaviest bell would be the loudest, or the bell with the highest peak frequency is also the highest in pitch. Weight is negatively correlated with peak frequency ($r = -0.99$; $p = 0.044$) and longitudinal velocity ($r = -0.99$; $p = 0.041$) and pitch is positively correlated with loudness ($r = 0.997$;

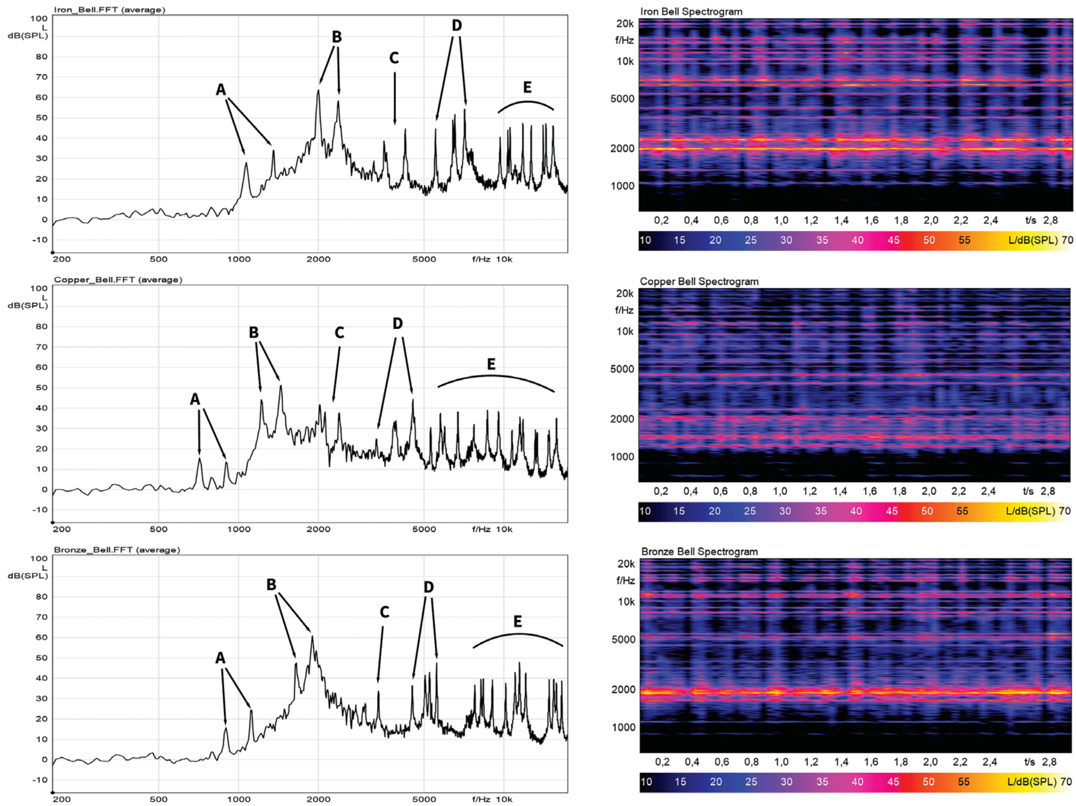


Fig. 9. Spectra (left) with marked similarities and spectrograms (right) for the three bells (Graphic by J. Mühlhans)

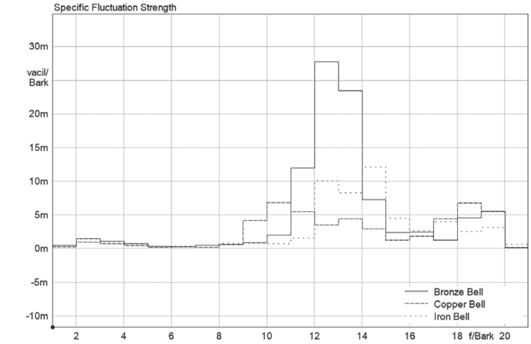
Obr. 9. Spektra (vlevo) s vyznačením podobností a spektrogramy (vpravo) pro tři zkoumané rolničky (grafika J. Mühlhans)

p= 0.048) and negatively with material density (r = -0.99; p = 0.044). Statistical significance, however, is hard to achieve with only three objects, but still there are some quite high (> 0.9) correlations just by means of the coefficient. Though this is more likely to be found out by calculating the values for the 11 bells that only differ in size/weight.

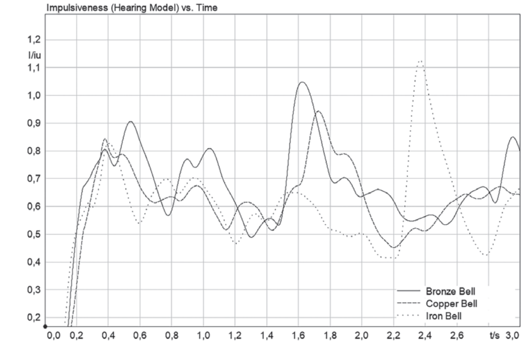
Table 4 shows the calculated parameters for the three pellet bells with colour highlighting (white = lowest value, dark grey = highest one). Besides no visible pattern, the copper bell has the most low values, the bronze one the most mid and the iron one the most high values. This shows that the influence of the material is quite complex, because density and stiffness must be taken into account (fig. 10).

5.3. Comparison of 11 bells from the same material

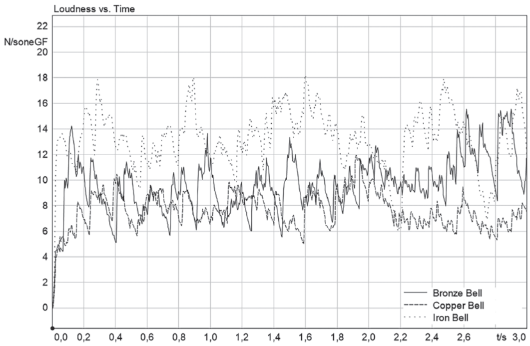
As a comparison, we take a look at the 11 bought bells that just differ in size/mass. Here we see a number of highly significant correlations. Weight is connected to level (r = 0.83;



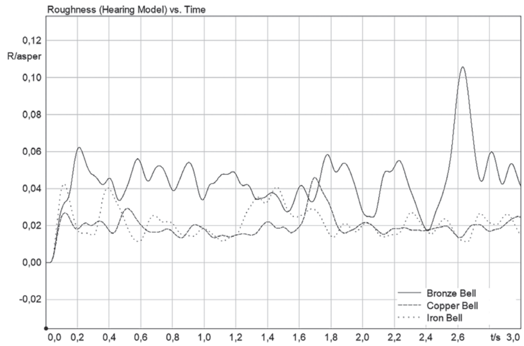
Specific Fluctuation Strength



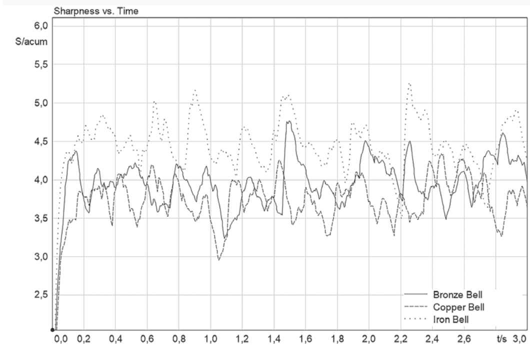
Impulsiveness



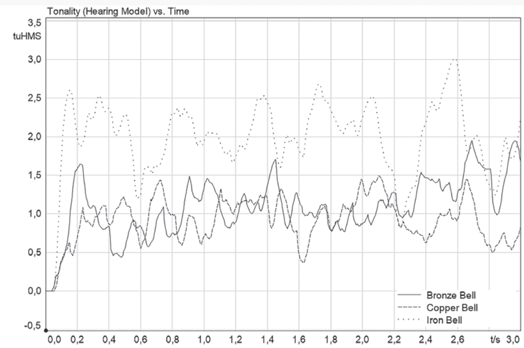
Loudness vs. Time



Roughness vs. Time



Sharpness vs. Time



Tonality vs. Time

Fig 10. Psychoacoustic parameters of the three pellet bells (Graphic by J. Mühlhans)

Obr. 10. Psychoakustické parametry tří zkoumaných rolniček (grafika J. Mühlhans)

Fig. 11. Cast brass pellet bells (Photo by J. Mühlhans, Graphic by B. M. Pomberger)
Obr. 11. Lité mosazné rolničky (foto J. Mühlhans, grafika B. M. Pomberger)

$p = 0.002$), roughness ($r = 0.81$; $p = 0.003$) and loudness ($r = 0.95$; $p < 0.001$) – which is also intercorrelated with level ($r = 0.95$; $p < 0.001$). There are also some mid correlations between level–roughness, level–tonality, sharpness–roughness and loudness–roughness, all in the range of $r = 0.62–0.72$, with $p < 0.05$. Some correlations are not so surprising, heavier bells of the same material are larger, thus louder and higher in level. Also they can oscillate more freely, so tonality in terms of tone to noise ratio increases. However, this does not explain why they are rougher and the rough ones also sharper (rough and sharp sounds are more likely to be rated as unpleasant).

5.4. Comparison of the two objects with the same materials but different shapes

Another interesting conclusion arises when comparing the two copper and iron bells for similarities. The two different bronze bells weigh 18.45 and 17.96 grams, the two iron bells 15.13 and 13.6 grams. Some parameters vary greatly between different shapes while others do between different materials.

While most bells are made of two pieces, soldered together around the middle, which thickens the material, the second bronze bell is made of one piece. Single hits create a decay time of normally 300–500 ms, whereas the one-piece copper bell goes up to about 1 400 ms. This section around the middle adds more material, which stiffens the object and blocks or dampens some lower modes.

Different materials have larger differences in level, loudness, pitch and tonality, smaller differences in brightness, impulsiveness and peak frequency and about the same variation in all the other parameters. This leads to the assumption that the former are more influenced by the material, while the latter are more dependent on the shape.

Table 4 shows that the iron bells scored higher in level/loudness, pitch and tonality. Since these parameters are beneficial for sound objects, this could be an acoustic explanation for the preferential use of iron for pellet bells in the Avar period.

These conclusions are as fragile as they are interesting because of the small number of compared objects. Another study with a comparison of six different alloys of bell and pellet bell replicas as well as standardised sound bars to reduce variations in wall thickness – or other parameters hard to control in handcrafted objects – is already in progress and will shed some more light onto the influence of the material on the timbre of bells and pellet bells.

5.5. Conclusions – acoustics and psychoacoustics

The shape of a sound object mostly influences the spectral distribution of partials. Even if the basic shape is the same but a slight variation occurs (such as the thinner middle section of the one-piece bell), the spectrum is altered. Material and size merely seem to shift the pattern in the spectrum and have an influence on the strength of single partials. Due to this, some correlations can be found between density/weight and wave velocity/peak frequency/pitch. Other psychoacoustic parameters are more dependent on the sensitivity of the human ear and depend less on the parameters mentioned above, but more on the spectral energy in the 2–5 kHz region, whatever the cause.

5.6. Discussion

Our findings provide a basis for more hypotheses and a more thorough examination of the influence of the material/alloy on the timbre of sound. While three materials in one shape (aside from some other comparisons) are a strongly limiting factor, we already extended the follow-up-study to six materials in three shapes. Especially in the search for significant effects, a comparison of 18 objects in total will deliver more solid data than only three.

Handcrafted objects, especially idiophones, are always unique from an acoustic point of view because slight variations can have quite an impact on acoustic parameters. However, little is known about the physical acoustics of historical sound objects, so we seek to create a larger base of knowledge to better understand the influence of historic materials/alloys on the timbre of sound.

6. First conclusions

Avar pellet bells were forged from sheet copper, bronze and iron. Copper and bronze sheets are easier to press into shape than iron. The latter shows the highest resistance to deformation during forging and probably holds the shape longest. In our small study, the iron pellet bell showed the highest level/loudness as well as the highest pitch and tonality. Since these parameters are beneficial for sound objects, this could be an acoustic explanation for the preferential use of iron for bells in the Avar period. Evidence of iron smelting places during the 8th and 9th centuries AD is known in western Hungary (*Gömöri 1978; Gömöri 1980; Gömöri 2000*) and Burgenland, eastern Austria (*Kerbler – Krainz 2013; Mehofer 2004; Mehofer 2010*). Iron ore deposits are located in the Oberpullendorf Basin in Burgenland (*Schönlaub 2000,* 51–53) and in the Komitat of Győr-Sopron, western Hungary. The values of the various metals in the Early Middle Ages have not yet been investigated, as far as the authors know. Therefore, we cannot say if iron was cheaper than copper and if this also could be a reason for the large amount of pellet bells made from sheet iron. On the other hand, we have to consider that weapons and tools were forged from iron, for example sabres, arrowheads and knives. All these iron tools were used in combat. They intended to injure and kill the enemies and protect the fighter. Pellet bells are very often interpreted as apotropaic amulets but also as jewellery and toys for children. If they were used as apotropaic amulets, they may have worked similarly to weapons against evil forces in the imagination of the people and therefore the weapons' material had to be used. Furthermore, pellet bells are noise instruments (*Haid 2001*). Noise instrumentes are often used in psychological warfare.

7. Summary

Pellet bells first appear in the Avar Khaganate during the middle of the 7th century. They were not only cast in various copper alloys, but also forged mainly from iron, copper and copper alloy sheets. Children, sometimes also women and men, wore them attached to belts or ribbons around the waist, on ankles or on necklaces. The authors wanted to find out why iron sheet was favoured for producing forged pellet bells. Therefore, experiments were carried out and three idiophones of the same shape were made from copper, bronze and iron sheet. Furthermore, two idiophones, one from one piece of bronze sheet and an oval iron sheet bell were forged. The experiment showed that copper and bronze sheets are quite easily shaped, whereas shaping cold iron sheet requires more strength. This circumstance is due to the material density. But it also gives the object more resistance to deformation. Listening to the sounds of the three comparably shaped pellet bells made of sheet copper, bronze and iron revealed that they differ substantially in timbre and loudness. The analyses of the sound recordings showed no significant correlations between any of the calculated psychoacoustic parameters. The copper bell showed the lowest values, the bronze bell the middle and the iron bell the highest values. Comparing pellet bells of the same material and shape but of different sizes showed that heavier objects are louder and higher in level. Ore was mined and old metal was recycled in the Avar Khaganate, but there is no knowledge about the values of the different metals, which could give a hint for the preference of iron. We maybe have to look for an explanation of the preferred use of iron pellet bells in magical-religious imagination. If pellet bells were apotropaic amulets and should protect the wearer against evil forces in the imagination of the people, they should work like weapons and therefore the weapons' material, iron, had to be used.

1) https://www.academia.edu/72304784/Table_Pellet_bells_forged_from_metal_sheet_Avar_Period_Early_Middle_Ages_Europe_Table_PombergerBM

2) https://www.klasand.si/docs/FONTARGEN%20sales%20program.pdf (Access: 22.2.2022).

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Avarské plechové rolničky z různých kovů. Nálezy, experimentální výroba a akustické vlastnosti

Avarské plechové rolničky z různých kovů – nálezy, experimentální výroba a akustické vlastnosti. Na území Avarského kaganátu se rolničky objevily poprvé v polovině 7. století. Kromě litých exemplářů zhotovených z různých slitin mědi se zde vyskytovaly i kované plechové rolničky ze železa, mědi a měděných slitin. Děti a někdy také ženy a muži je nosili připevněné k opaskům nebo stuhám kolem pasu, na kotnících či jako součást náhrdelníků. Autoři příspěvku se pokoušeli zjistit, proč byla převážná většina kovaných rolniček zhotovena ze železného plechu. Pro experimentální účely byly vyrobeny tři rolničky stejného tvaru ze tří různých druhů plechu – měděného, bronzového a železného. Kromě toho byly zhotoveny ještě dva další kované idiofony – rolnička z jednoho kusu bronzového plechu a oválná rolnička ze železného plechu. Experiment prokázal, že měděný a bronzový plech je snadno tvarovatelný, zatímco tváření železného plechu za studena vyžaduje mnohem větší sílu. Je to způsobeno hustotou použitého materiálu, která však zároveň poskytuje výrobku větší odolnost proti deformaci. Při poslechu tří pokusných rolniček přibližně stejného tvaru ukovaných z měděného, bronzového a železného plechu bylo zjištěno, že jejich zvuky se od sebe podstatně liší jak svou barvou, tak hlasitostí. Analýzy zvukových záznamů neprokázaly mezi vypočtenými psychoakustickými parametry žádné významné korelace. Nejnižší hodnoty vykazovala měděná, střední hodnoty bronzová a nejvyšší hodnoty železná rolnička. Porovnání různě velkých rolniček stejného tvaru zhotovených ze stejného materiálu ukázalo, že těžší exempláře vydávají hlasitější zvuk o vyšší intenzitě. Je známo, že v Avarském kaganátu se těžila ruda a použité kovy se recyklovaly, ale bohužel nevíme nic o tehdejší hodnotě jednotlivých kovů, která by nám mohla napovědět, proč bylo jako materiál pro výrobu rolniček preferováno právě železo. Možné vysvětlení můžeme pravděpodobně hledat ve sféře magicko-náboženských představ. Pokud byly rolničky v představách tehdejších lidí vnímány jako apotropaické amulety, tedy svého druhu zbraně, které měly svého nositele chránit před zlými silami, bylo logické zhotovit je ze železa, z něhož se zbraně obvykle vyráběly.

Dr. Jörg Mühlhans, BA MA

- Universität Wien
  MediaLab der Philologisch-Kulturwissenschaftlichen Fakultät
  Althanstraße 14, Rotunde, Stiege H, Ebene I, A – 1090 Wien
  joerg.muehlhans@univie.ac.at

Lukas Johannes Kerbler, BA MA

- ARMET Archäologie & Archäometallurgie e.U.
  Mühlstraße 35, A-2070 Obernalb
  armet@gmx.at

Mag. Dr. Beate Maria Pomberger

- Naturhistorisches Museum Wien
  Prähistorische Abteilung
  Burgring 7, A – 1050 Wien
  beatemaria.pomberger@gmail.com