MANUFACTURING ASPECTS OF IRON AGE CERAMIC JUGS INVESTIGATED BY COMPUTER AIDED TECHNIQUES AND ANALYSES

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ABSTRACT

Two iron age ceramic jugs found in excavations in Dion, Greece, were investigated by means of computer tomography and 3D-laser scanning. The analysis of the solid objects' geometries provided by these techniques revealed significant information to clarify the applied manufacturing methods. A finite elements method based simulation of the jugs solid geometry and corresponding calculations contributed to the explanation of the jug's body deformation, developed during its shaping procedure.

KEYWORDS: Ancient pottery, Computer tomography (CT), 3D-laser scanning, FEM simulation

1. INTRODUCTION

The ceramic wine jugs Nr.1 and Nr.2 shown in Figure 1 were found by Prof. D. Pantermalis as offerings in ancient tombs in 1980 during excavations, about four kilometers to the west of Dion, one of the most important archeological sites of Greece. Both jugs possess a similar geometry with an almost spherical body and a wide neck with skewed cut away edge, characteristic of the ceramic pots of the early iron era in Macedonia (1,000 - 700 B.C.) /1,2/.

The geometry of jug Nr.1 was monitored by non-contacting computer supported X-ray tomography, to avoid any damage of the prototype, and to detect internal, invisible details. The measurement data gained by the tomographer were further processed to describe the jug geometry and to create a Finite Elements Method (FEM) computational model to explain deformations of the jug’s body developed during the shaping of the clay.

Figure 1: Early iron-period wine jug's with cut away necks.
Computer tomography is an innovative method used in many industrial, medical and other applications. Its advantage compared to scanning methods such as laser, CMM etc. is its ability to record both the external and internal geometrical features of the object. A computer guided tomography and its working principle is presented in the upper part of Figure 2. This device consists of two main units, the source of radiation producing the X-rays (Roentgen) and the detector. The specimen is rotated appropriately within the tomographer and multiple tomographies are performed at successive revolving positions. The method is based on the measurement of the X-radiation absorption by the object in various directions. When a satisfactory number of tomographies have been conducted, the reconstruction of the object’s external and internal surfaces is effected through a data computer analysis. In this way, the 3D object geometry can be visualized and partial or full sections at any position of its geometry can be obtained. In the described investigations, a computer tomographer was employed with a power of 250 KVA and a recording resolution precision of 10 μm.

The external geometry of jug Nr.2 was registered by laser non-contacting measurements. The applied portable laser scanner device is presented in the lower part of figure 2. The object is scanned with two laser beams and the data of the object geometry are recorded and displayed in a computer monitor. Through a full rotation by hand of the object, in conjunction with appropriate software the complete external geometry of the investigated jug Nr.2 be determined at an accuracy level of 90 μm.

![Figure 2: Recording object geometries, by computer tomography and 3D laser scanning.](image)
2. MANUFACTURING OF THE JUG

Pottery production is an additive process in which, the successive steps are recorded in the final object /3/. According to the results described in the present paper, the manufacturing of both ceramic jugs started with the shaping of the clay to form distinct components of the jug, namely the body, the neck and the handgrip; then joining together the individual clay parts the jug’s frame was accomplished, as schematically illustrated in Figure 3. The neck was partially cut out to give its final skew form.

Figure 3: Structural components of the investigated wine jugs.

It is notable that the external body geometry of both investigated jugs are almost identical, as shown in Figure 4.

Figure 4: Geometrical convergence and deviations between the two investigated jugs.
The corresponding geometrical data were obtained by processing the results of computer tomography and 3D-laser scanning, which were applied to measure jug Nr.1 and 2 respectively. The data were superimposed in order to detect relative dimensional deviations. Large deviations can be observed in the area of the neck and the handgrip, while in the region of the body both jugs possess almost the same geometry. This is confirmed in the cross section A and in the meridian section B-B illustrated in figure 4. The maximum deviation in this cross section is approximately 0.6 mm, and in the meridian section less than 0.8 mm. Taking into account that it is very difficult to attain such a geometrical convergence when forming the body contours both in horizontal and vertical directions by hand, even using a pottery wheel, it can be stipulated that probably the same concave spherical mold was used to shape the body clay. Further evidences, which strengthen this stipulation, will be presented in the following sections.

2.1. Forming the body

The cross (horizontal) sections of the body of jug Nr.1 shown in Figure 5a were obtained by appropriate evaluation of the computer tomographer results and they illustrate the external forms as well as the obtained wall thicknesses. The sections A, B and C represent jug’s body horizontal contours in the regions of shoulder, slightly under the maximum diameter and near the base respectively. The intended appearance and handling of the jug led to a thickening of some regions of the jug to enhance their strength in use, as for example near section A, where the neck is attached to the shoulder and the handgrip to the body. The walls in this region have to be strong enough to see the jug safely through drying stage, which can cause stresses, and to counteract the anticipated loads during the jug’s use. The wall thickness scatter which can be observed in figure 5b is significant large, on all horizontal sections. Although the external shape of all horizontal sections of the jug’s body converge very sufficiently to cyclic contours, the internal section geometry deviate much from circle peripheries because the wall thickness fluctuations. This is significant indication that no wheel was used to shape the clay, but the craftsman pressed the clay into a concave spherical mold, as it has been already stipulated.

![Diagram](image_url)

**Figure 5:**
- a: External form and the wall thicknesses of jug’s Nr.1 body.
- b: Average wall thickness distribution versus the distance from the jug’s base.
Furthermore, a longitudinal section of the jug’s body is shown in Figure 6. The imprints visible in the inner surface of the body shoulder in section A are about 15 mm apart, which corresponds approximately to the breadth of human fingers. Thus, it is reasonable to be assumed that the craftsman shaped the jug’s shoulder through lifting and pressing firmly the clay by his fingers into a prepared mold, to fit the clay to its interior concave surface. This mold could be a fragment from a broken jug. The craftsman did not smooth the inner surface of the body shoulder, most probably, because this surface would be invisible to the user of the jug after the neck joining. The lower body interior surface is less rough compared to the upper one, however imprints of larger dimensions were detected there too; they lead to the wall thickness deviations presented in figure 5b. Moreover, no rotational traces on the body interior surface were detected.

Concluding the described results, it can be stipulated that the craftsman has preformed a section of clay by patting or rolling it into a thin disc; then he pressed it firmly into a concave almost spherical mold, created perhaps from a broken jug body, which was manufactured using a pottery wheel to achieve almost cyclic cross sections and applying probably powdered clay to prevent sticking with the mold /3/. In this way on the one hand the external contours of sections A, B and C displayed in figure 5, do not deviate much from circles. On the other hand due to the material pressing into the mold, neither unique wall thicknesses nor cyclic contours were achieved, as revealed on the horizontal sections. Finally the low roughness of the body’s outer surface was attained by a smoothing tool, during an additional finishing procedure, probably after clay’s drying.

2.2. Forming the neck

The neck of the jug was built as a separate part. This is evident from the cross section displayed in Figure 7, where the transition between the smooth inner surface of the neck and the rougher inner surface of the body shoulder (interior corner point) is clearly visible. So after forming the neck, the craftsman would join the two parts together by pressing the clay in the lower neck region against the lip area of the body shoulder, thus creating one single part. Close inspection of the inner surface of the jug in the corner area of juncture between neck and body, which is illustrated in section AA of figure 7, shows small overflows of material created obviously during the joining procedure and possibly some final smoothing of the inner surface of the neck thereafter.

A meridian and a horizontal cross section of the neck are shown in Figure 8. Moreover the symmetry axis bb of the neck is displayed; its oblique position concerning the jug’s body axis aa is clearly visible. The corresponding inclination angle between aa and bb can be observed in section A-A; it amounts approximately to four degrees. The displacement of the neck’s symmetry axis to the corresponding one of the jug’s body amounts to ca. eleven millimeters on section B-B. The notable fluctuation of the neck wall’s thickness can be seen in section BB.

The almost elliptical form of the cross section external contour diverges significantly from a
Figure 7: Material overflow between body and neck of jug Nr.1.

Figure 8: Jug's Nr.1 neck geometry and its positioning on the body.
2.3. Forming the handgrip

An interesting finding is that the volume missing from the neck, to skew its orifice region, is practically equal to the volume of the handgrip. As displayed in Figure 9, the two volumes have been calculated and they amount to 17.438 mm$^2$ and 17.410 mm$^2$ respectively. Thus it could be possible that the handgrip was built out of the material removed from the neck. Obviously the craftsman cut that part of the neck out of the semi-finished jug by a string or a blade and then shaped it into a roll. After bending and forming it appropriately he joined its two ends with the jug’s shoulder and the neck.

In cross sections 1-1 up to 4-4 and in detail A, shown in Figure 10, is obvious that the material in the upper part of the grip is completely coherent. This is probably due to the good access the craftsman had to the upper part of the grip, which allowed him to knead the clay well enough to connect it flawlessly to the jug’s neck and shape its upper part. The air enclosures appearing in cross sections 5-5 and 6-6 in the lower handgrip region were probably occurred during the shaping of the roll to form the handgrip and remained, as no further shaping of the grip took place there. The hole opened in the body’s shoulder wall and the end of the grip stuck into it are clearly recognizable in view B and section C-C. The air enclosure in cross section 7-7 was obviously created while pressing material of the handgrip onto the surrounding body’s outer surface to shape a smooth juncture between handgrip and body’s shoulder.

3. DEFORMATION OF THE JUG’S BODY

The forming of the body, the neck and handgrip and the joining of these parts, should produce a symmetrical frame. However both investigated jugs Nr.1 and 2 exhibit an easily observed asymmetry, in the form of a tilt towards the side of the grip. Detailed examination of the geometry of the frame has shown that this deviation from symmetry is entirely due to deformation of the jug’s body, as explained in Figure 11. Two meridian cross sections of the part, section B through the handgrip and section A normal to B are illustrated in this figure. Comparison of the right (A2) with the left (A1) half of section A, as shown in the lower left part of the figure, where A2 is flipped in a fainter tone of grey over A1, shows no considerable divergence between the
Figure 10: Handgrip cross sections of jug Nr.1.

Figure 11: Detected body deformation of jug Nr.1.
two halves. The same kind of comparison between the front (B2) and the rear (B1) halves of section B in the lower middle part of the figure reveals a significant depression of the rear shoulder region, which for its upper inner edge is measured 5.6 mm downwards in the vertical and 2.4 mm rightwards in the horizontal direction. Since there is no considerable divergence between profile B2 and the profiles of section A, as demonstrated in the lower right part of the figure, it is evident that the deformation of the body from its initial symmetrical form consists alone of a deformation of the area around the junction of the grip.

4. EXPLANATION OF THE JUG’S BODY DEFORMATION BY FEM SUPPORTED CALCULATIONS

The handling of the ready jug frame i.e. body with neck up to the completion of the final product forming the neck skewing and joining the handgrip, consists of three distinct actions:

a. cutting out part of the neck,
b. opening a hole in the body and
c. attaching the handgrip to the body and to the neck.

To investigate thoroughly whether the observed jug’s body deformation was incurred during these treatments, the three actions have been simulated by means of finite elements method (FEM) and corresponding calculations, were conducted.

The jug’s geometry was described using the SOLIDWORKS modeler /4/. The initial almost rotationally symmetrical external form of the jug’s body, prior to the forming of the handgrip, was recreated from the geometrical form of the jug digitized by the tomographer, assuming no inclination of its axis of symmetry and a symmetrical form of the jug’s base. Under this assumption the initial form of the body was created as a rotationally symmetrical body through rotation of the profile B2 shown in figure 11. The FEM-discretization of the jug shown in Figure12 was implemented by DEFORM-software /5/ with 4 – node tetrahedral solid elements. The element mesh was generated automatically, with the additional application of the mesh window feature to attain a 6 times finer discretization in the area of the body hole, where the handgrip is attached to the body and the deformation was expected to be much higher.

The mechanical behaviour of the material – wet ceramic clay – was approached by the analytical model established for wet ceramic clay in /6/. The wet clay is assumed to obey the Herschel-Bulkley hardening rule, which for an isotropic material following the associative flow rule and the von Mises yield criterion takes the form:

![4-node tetrahedral solid elements](image)

Figure 12: FEM-discretization of jug’s geometry.
\[ \sigma_{pl} = \sigma_0 + k \dot{\varepsilon}_{eq}^n, \]  

(1)

where the flow stress \( \sigma_{pl} \) is the von Mises equivalent stress, \( \dot{\varepsilon}_{eq} \) the equivalent strain rate, \( \sigma_0 \) the yield stress, \( k \) the plastic flow consistency and \( n \) a flow exponent.

By substituting the material parameters’ values of \( \sigma_0 = 0.102 \) MPa, \( k = 0.37 \) Mpa \( s^{0.25} \) and \( n = 0.25 \) determined experimentally in /6/ for a common type of clay in Greece, eq.(1) becomes:

\[ \sigma_{pl} = 0.102 + 0.37 \dot{\varepsilon}_{eq}^{0.25} \]  

(2)

The friction between clay and forming tools was approached by the Tresca friction law:

\[ \tau_F = m \cdot \tau_{\beta}, \quad \tau_{\beta} = \frac{\sigma_{pl}}{\sqrt{3}} \]  

(3a, b)

where \( \tau_F \) is the friction stress, \( \tau_{\beta} \) the shear flow stress for a material obeying the von Mises yield criterion and \( m \) a constant friction factor, whose value in /6/ was determined as \( m = 0.46 \).

4.1. Simulation of cutting material out of the neck

In the representation of the action of cutting material out of the neck in Figure 13 the craftsman must had held the jug in a fixed position by pressing it with his hand against its base. As a result the body of the jug deforms under the pressure of the craftsman’s hand. In the simulation model

\[ \text{Figure 13: FEM-simulation of the craftsman’s action during material cutting out of the neck, and occurring body geometry.} \]
explained in the same picture the action of the craftsman’s hand is simulated by a 120° symmetrical jig matching exactly the outer profile of the jug around the connection line between neck and body. The cut away of the neck could cause negligible local deformations only. The force that probably could lead to a body deformation is the reaction of the craftsman’s hand, which is estimated about to 20 N. The results of the FEM-calculations are shown in the lower left part of the same figure. Practically no body deformation occurred. The comparison between left and right half of the meridian section of the body shows no considerable deformation of the body’s walls. Hence the body deformation could not develop during the cutting out of the neck craftsman action.

4.2. Simulation of the opening of the body hole

Figure 14 shows the most probable way, how the craftsman used a tool to open up the hole in the jug’s body shoulder. The hole with the deformed clay material is illustrated in the lower part of this figure. The hole opening took place below the joining area of the neck to the body to avoid a juncture damage.

The opening of the hole on the jug’s shoulder, as illustrated in the upper left part of Figure 15, was simulated with the aid of a FEM-model, displayed in the right upper part of this figure. The piercing object was assumed a cylindrical pin of 14mm diameter – the measured diameter of the hole in the body – ending over a 30 degrees cone to a spherical nib of 2 mm diameter, moving at a low speed of 10 mm/s along its axis normal to the jug’s shoulder surface. The counteracting hand of the craftsman was simulated as a fixed jig with an internal profile matching exactly the outer profile of the shoulder, extending symmetrically as to the pin over 120 degrees of the body’s circumference, at a height of 70 mm in the vertical direction from the jug’s base. In the FEM model both pin and jig were considered as rigid.

To facilitate the opening of the hole the normalized Cockcroft and Latham fracture criterion was applied. This is provided by the DEFORM-software, with a critical value for the damage factor of 0.105. The Tresca friction factor of 0.46 between plastically deforming clay and rigid forming surfaces was implemented through a constant shear friction. The results of the simulation are presented in the lower part of figure 15. As it can be observed in the meridian cross section B1 of the deformed body (lower part of the figure), which is superimposed on the same section of the initial part (B2), no considerable deformation was affected on the body as a result of the opening of the hole, apart from the overflow of material in a narrow zone around the hole in the inner surface of the body shoulder. Comparison of the calculated form of the clay overflow with that of the real object in the same figure, reveals satisfying similarity.

Figure 14: Opening of the body hole.
4.3. Simulation of joining the handgrip with the body

In the representation of the action shown in Figure 16, it is considered that the craftsman holds the jug down with his left hand while pressing the end of the handgrip against the body with the fingers of his right hand.

In the FEM simulation of this action the same jig as in section 4.1 and 4.2 was used to emulate the action of the left hand, whereas the pressure on the body by the craftsman’s fingers around the grip is simulated by a ring of 30 mm external diameter. In the FEM-model it was assumed that the forces of the left hand and the craftsman’s fingers around the grip equal to 17 N and 23 N respectively, leading to body’s deformations of the same order of magnitude, as the measured ones (see lower part of figure 16). The base and the rest of the body remained essentially undeformed. Hence the jug’s body deformation was developed when the craftsman tried to join the handgrip with the jug’s body, pressing clay material around the handgrip end, to close the hole and to enhance the strength of the juncture.

5. CONCLUSIONS

Innovative technologies such as of the computer tomography and laser 3D scanning enabled the precise recording of the solid geometry of ancient ceramic wine jugs of the early iron period. The attained results highlighted the craftsman’s actions and methods during the clay shaping and explained the reasons which led to jug’s deformations and asymmetries.

6. ACKNOWLEDGMENTS

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Figure 16: FEM-simulation of joining the handgrip with the body, caused body deformations, and their comparison with the measured ones of jug’s Nr.1 body.

7. REFERENCES

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