

REVERSE ENGINEERING OF A BRONZE AGE SOCKETED AXE

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Abstract: The details of the production technology of an artefact is always a question. Based on the technological knowledge of the given age, the results of archaeology and archeometallurgy a feasible production technology can be determined. This feasible production technology can be examined using computer simulation tools to find answers to open technological questions.

In this project, the casting technology of the Bronze Age is examined, based on the artefacts of the Hungarian National Museum, using archaeology, technology and theoretical tools. The multifunctional socketed axe tool is examined, the casting defects are analysed and the production technology is reproduced.

Keywords: artefact, reverse engineering, gravity casting technology, simulation

1. THE HISTORY OF AXES

The axe is one of the oldest tools used by mankind and the oldest axes were known as hand axes. The hand axe was a pear-shaped and roughly chipped stone tool brought to an even point, with a broad handle. Later, the axe was given a wooden handle, several different types of axes were developed, which may be divided into two main groups: Non-shaft-hole axes and shaft-hole axes.

The non-shaft-hole axes had no hole for the handle and were generally made from flint, greenstone or slate and in time had an evolution such as core axe, flake axe, thin-butted axe, round stone axe and hollow-edged axe.

The shaft-hole axes were made using various stones, although not flint, and were more likely to be status weapons or ceremonial objects. Types are the polygonal axe, double-headed battle-axe and the boat axe. [1, 2]

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1.1. The Socketed Axe

During the Bronze Age, stone axes began giving way to axes with a head made of mould cast copper or bronze, which initially were often pure copies of stone axes.

One type of Bronze Age axe is the socketed axe a wedge-shaped axe head with no shaft hole. The handle is instead fixed into a socket at the end part. Since the axe is made hollow and the handle is inserted into the head, a perfectly functional working axe can be made with minimal materials.

Socketed axes are widespread multi-functional tools of the Bronze Age world. Their stylistic appearance might differ from each other in certain areas of the continent but their main casting techniques show great similarities. In the archaeological material, the socketed axes are the ones which show the most characteristic casting defect types. Some of them have intensively porous inner structure, shifted parts, incomplete loops or amorphous patterns. Typical socketed axe geometry with handle reproduction can be seen in *Figure 1* [3].



Figure 1

Copper alloy socketed axe with modern handle, 1000–700 BC

2. THE SIMULATION PROCEDURE

A socketed axe is a metal object, where the production method was gravity casting. In this research computer-based simulation methods are used for the technology reconstruction of the casting process. Many modelling and simulation methods can be employed for gravity casting, including physical modelling and numerical methods. Most of the current modelling and simulation work is done using numerical methods that can be used to solve the appropriate partial differential equations for heat and fluid flow, using numerical algorithms. The following requirements are considered as essential parts of a casting simulation:

- correct geometric description of the domain,
- accurate thermodynamic phase data,
- accurate boundary conditions,
- proper material properties,
- a set of solvable equations describing the physical phenomena,
- experimental and numerical validation.

Generally, models solve equations for the temperatures and the fluid flow. To describe the complex phenomena correctly, good insight into the physics of liquid, semi-solid, and solid constitutive behaviour at high temperatures is required to decide which partial differential equations are best suited to describing the physical phenomena of interest. The parameters of these models should be realistic and physical. This implies very close interaction between controlled experiments of solidification or stress measurements of the high-temperature plasticity behaviour and process physics formulation. Accurate boundary condition and property data are essential if model results are to be representative.

The physical phenomena behind a technological problem should be identified and a mathematical model must be written. This mathematical model must be solved using an analytical or a numerical solution and the physical interpretation of this mathematical solution should be done for the technological solution. Especially in manufacturing processes such as casting, the misinterpretation of otherwise correct mathematical results could lead to wrong conclusions, and hence to no solution of the originating problem [4, 5].

In this research paper, the commercial software NovaFlow&Solid is used to solve the material- and heat transport processes. The method of simulation experiments can be seen in *Figure 2*.

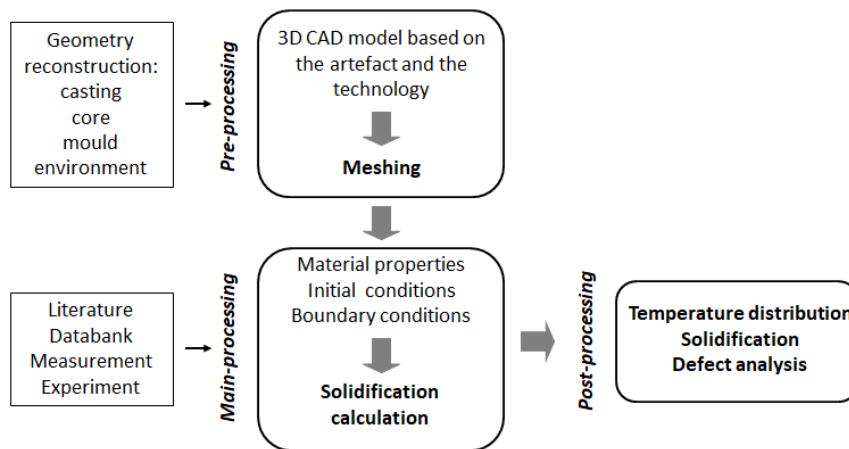


Figure 2
Concept of the simulation experiments

In Pre-processing the first step is to define the geometry of the casting system into a discrete number of segmented volume elements for the subsequent calculations.

Before the equations that govern the filling and solidification processes can be solved, the necessary thermophysical material data must be available. Apart from the material data themselves, other relevant process parameters have to be defined. Initial conditions for the unknown quantities and boundary conditions for the unknowns

must be defined. Other relevant information also needs to be input, so that all the factors that affect the filling and solidification of the casting can be accounted for.

Main-processing is the most demanding part of the numerical simulation follows in respect of both the algorithmic development and the requirements for computer capacity, solution of the governing equations. The most usual approach here is to solve all the basic equations, this being a prerequisite for simulating all relevant casting problems of a technical nature. It is clear that these calculations, in which primitive fields such as temperatures, displacements, stresses, velocities, pressure, etc. are determined, require the solution of the governing differential equations.

Post-processing is the presentation of the results. After the computations, the resulting basic fields (temperatures, velocities, pressure, displacements, stresses, etc.) should be presented appropriately.

3. THE EXAMINED ARTEFACT

The examined artefact is a socketed axe geometry (Ha B1-B2/3) from Isaszeg, Hungary. The chemical composition of the axe is 83 wt% copper (Cu), 11 wt% tin (Sn) and 6 wt% antimony (Sb). The chemical composition is analysed using prompt-gamma activation analysis, which is a nuclear analytical technique for non-destructive determination of elemental and isotopic compositions.

The artefact was analysed by neutron radiography where the overall amount of porosity is determined as 3.06%. The artefact geometry and the resulting figures of the neutron radiography can be seen in *Figure 3*.

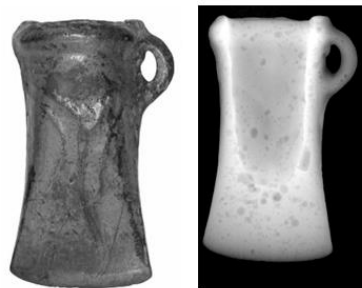


Figure 3

Geometry of the artefact and results of the neutron radiography

Based on the artefact a virtual model is created in 3D, using Computer-Aided Design. For the technology analysis, the 3D model must consist of the axe, the core, the gating system, the mould and the environment. Based on the neutron radiography analysis a simplified axe geometry is created (43 cm³), without gating system, while the core and the mould are created using Boolean features.

Based on a literature survey and trial experiments a gating system is created which can fill the cavity on a realistic way without significant turbulence. The result of the mould filling analysis [6] is not presented in this paper. Only the mould filling

defects will be presented to understand the simulation results. The geometry of the casting with the gating system and the 3D cut of the calculation domain can be seen in *Figure 4*.

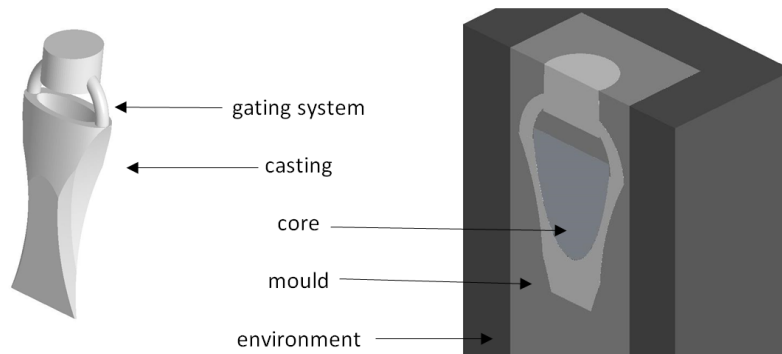


Figure 4
Examined geometries

4. SOLIDIFICATION ANALYSIS

Based on the archaeological excavation and literature survey [7, 8] the 3D CAD model of the simplified axe geometry with the gating system and the core is prepared. The pending question is the material of the mould, therefore two cases were examined simultaneously:

- A. The alloy was poured into a sand mould. It supposes a so-called expendable mould where the mould is used only once.
- B. The alloy was poured into a stone mould. It supposes a so-called permanent mould where the mould is used several times. Before pouring the stone mould was surrounded by sand which is symbolized by the environment, see *Figure 4*.

The Design of Experiments (DoE) can be seen in *Table 1*, where the chemical composition of the alloy was composed based on the artefact. The pouring temperature was examined in several steps, where the steps were defined based on the possible maximum temperatures of the ancient melting techniques.

Table 1
Design of experiments

Expendable mould	A1	A2	A3	A4	A5	A6
Alloy temperature	1,015 °C	1,025 °C	1,035 °C	1,050 °C	1,070 °C	1,100 °C
Mould	sand (20 °C)					
Environment	sand (20 °C)					
Permanent mould	B1	B2	B3	B4	B5	B6
Alloy temperature	1,015 °C	1,025 °C	1,035 °C	1,050 °C	1,070 °C	1,100 °C
Mould	stone (20 °C)					
Environment	sand (20 °C)					

The solidification of the Project A1 can be seen in *Figure 5*, where the scale is liquid phase: 5–95%.

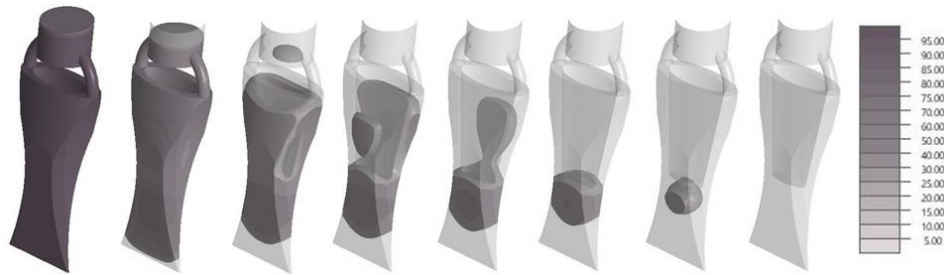


Figure 5
Solidification process

4.1. Result analysis

Although the mould filling analysis is not presented in this paper, but some results of it must be explained. During filling the air inside the cavity must leave. This can be done by venting or by the diffusion of air through the mould, which is called gas permeability. Based on the filling analysis it can be determined that melt blocks the gates, so the air cannot leave through the gating system. Without venting the air cannot leave the cavity. The gas permeability of the mould depends on the moulding material. The expandable sand mould has good gas permeability, while the permanent stone mould has nearly zero. By the result analysis, these effects must be investigated.

During solidification the alloy shrinks which causes shrinkage cavities and porosities. The casting solidifies without a riser, although the metal in the gating system can feed the casting for a limited time. The rest of the metal in the cavity solidifies without feeding.

These effects will result in empty places inside the geometry, which locations can be calculated based on the solidification calculation.

According to the DoE, 6 different melt temperatures were examined in both moulding methods. The question was the amount and the distribution of shrinkages, to be able to compare these values with the analysed results of the artefact, where the value of the overall porosity is 3.06%. The results can be seen in *Table 2*.

Based on the neutron radiography porosity analysis of the artefact the overall amount of porosity (3.06%) can be compared with the simulation results. The measured value is analogous to the following simulation results:

- Expendable sand mould with 1,070 °C pouring temperature.
- Permanent stone mould with 1,015 °C pouring temperature.

To decide which moulding method and which pouring temperature is more feasible the technology of the Bronze Age must be investigated. By the early furnace- and melting technology to reach a higher metal temperature was limited. Based on the investigation of the residual slags and the reproduction experiments it is clear

that the lowest pouring temperature must be applied, the liquidus temperature of the alloy is 1,013 °C.

Table 2
Calculated results

Expendable mould	A1	A2	A3	A4	A5	A6
Alloy temperature	1,015 °C	1,025 °C	1,035 °C	1,050 °C	1,070 °C	1,100 °C
Solidification time	56.88 s	57.98 s	59.15 s	61.35 s	61.63 s	67.47 s
Shrinkage	2.92%	2.977%	3.035%	3.04%	3.069%	3.161%
Permanent mould	B1	B2	B3	B4	B5	B6
Alloy temperature	1,015 °C	1,025 °C	1,035 °C	1,050 °C	1,070 °C	1,100 °C
Solidification time	25.03 s	25.51 s	25.03 s	26.91 s	27.85 s	29.26 s
Shrinkage	3.071%	3.128%	3.184%	3.135%	3.244%	3.253%

If the moulding method is examined there are several pieces of evidence which prove, that at the Bronze Age permanent mould were applied since unused and burned out mould fragments are excavated in a lot of places, see *Figure 6* [9].



Figure 6
Permanent mould from the Early Bronze Age

Based on these statements, the B1 Project is examined in details, where the mould is permanent stone mould and the pouring temperature is 1,015 °C. The amount of shrinkages is 3.071%.

The shrinkages of the geometry in 3D sections along the X-axis can be seen in *Figure 7*, where the scale is shrinkage 1–90%.

The 3D view of the shrinkages in *Figure 7* is not a detailed representation of the calculation results. To do this, the 3D geometry must be cut in 2D sections, that can be compared to the neutron radiography results. In this paper, only the middle cut of the geometry is presented, while the analysis of the geometry was complete.

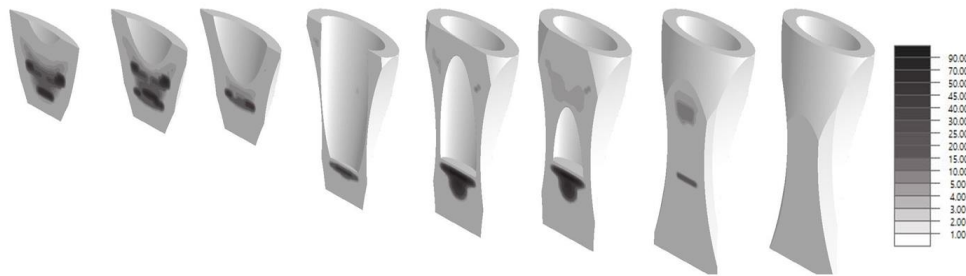


Figure 7
3D sections of the shrinkages

The question is how the simulation software represents the shrinkage results. By using a scale the feasibility of shrinkages can be displayed, which means that in the different areas how many amounts of shrinkages occur.

Next question is the gas entrapment during solidification. The gas bubbles can be seen on the 2D cut as smooth-surfaced round empty places. In the simulation, only the theoretical distribution of the bubbles can be seen.

In *Figure 8*, the calculated shrinkages can be seen on the right side, where the 10% and 50% values are rounded with iso-lines. These lines are copied to the left side of the figure, where the same 2D cut can be seen of the artefact geometry, where both shrinkages and air entrapments are visible. Shrinkage scale: 1–90%.

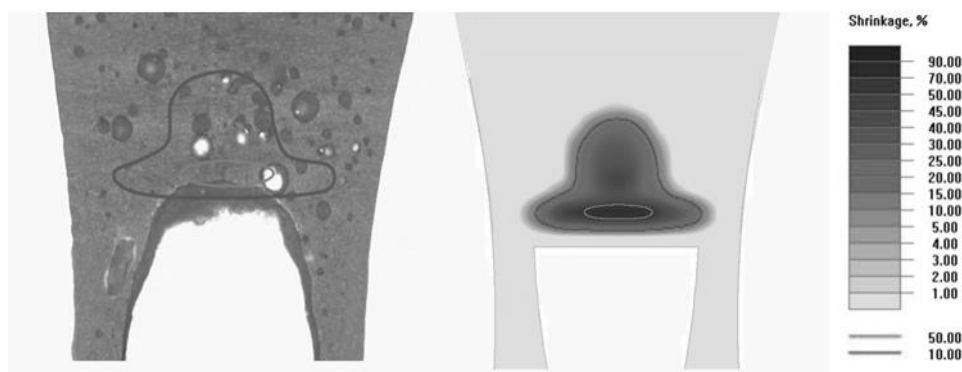


Figure 8
2D cut of the axe and the calculated shrinkages

In *Figure 9* the calculated shrinkages and the distribution of gas bubbles can be seen on the right side, where the 10% and 50% values are rounded with iso-lines. The circles highlight the aggregation of the gas bubbles. This line is copied to the left side of the figure, where the same 2D cut can be seen of the axe geometry. Shrinkage scale: 1–90%.

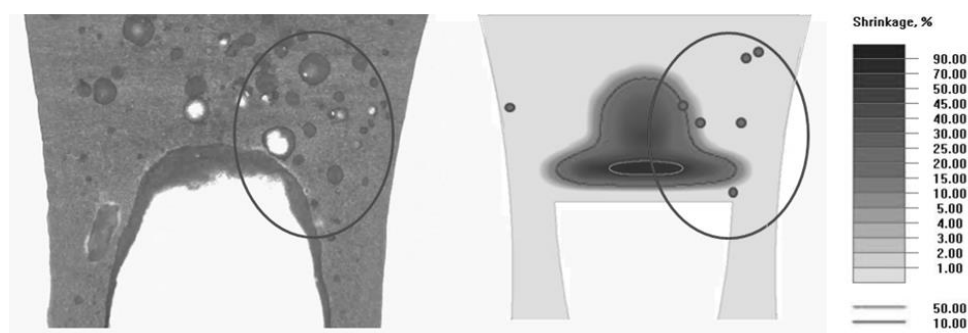


Figure 9
2D cut of the axe and the calculated shrinkages and gas bubbles

In both cases, it is clear that the distribution of shrinkages and gas bubbles are homologous in case of simulation and neutron radiography results. These distributions need further analysis e.g. image analysis to be able to run a quantitative analysis.

SUMMARY

In this paper, a socketed axe geometry is examined with computer simulation, where the details of the production technology are analysed. In this case, reverse engineering of an artefact means the reconstruction of the casting technology by computer simulation.

A socketed axe geometry from the Bronze Age is examined from middle Hungary, where the geometry is analysed with neutron radiography.

Based on the artefact a simplified 3D CAD geometry is created where the possible gating system designs were tested and analysed.

12 possible solidification experiments were run, where the effect of the mould material and the pouring temperature was examined on the shrinkages.

The shrinkages were compared with the figures of the neutron radiography and the results are interpreted.

The future goal is to create a method by the help of which the graphical values can be translated into numerical ones.

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