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Povratni inženiring artefaktov

Reverse Engineering of Artefacts

Povzetek

V tem prispevku smo z računalniško simulacijo in nedestruktivnimi metodami določanja lastnosti materialov proučili tehnologijo litja in napake pri litju artefakta – sekiro z očesom.

V Karpatski kotlini so se bronaste sekire začele širiti v zgodnji bronasti dobi. Bronaste sekire so najštevilčnejše v lokalnih najdbah iz pozne bronaste dobe (1500–900 pr. n. št.). Obstaja več vrst geometrij sekir, najpogostejše pa so tako imenovane sekire z očesom, ki jih najdemo v obrednih zakladih, naključnih najdbah in včasih kot grobne pridatke.

Proučevani artefakt sekire z očesom (Madžarski narodni muzej, prazgodovinska zbirka) je bil fizično analiziran. Kemična sestava je bila analizirana skozi analizo promptne aktivacije žarkov gama, tj. jedrsko analitično tehniko za nedestruktivno določanje elementarne in izotopske sestave. Zunanjo obliko in notranjo strukturo artefakta sekire z očesom smo proučili z nevtronsko radiografijo.

Na podlagi artefakta smo izdelali eksperimentalno repliko ulitka in virtualno geometrijo za podrobne raziskave. Razlog za izdelavo virtualne geometrije je, da so možnosti pregleda originalnega artefakta omejene in je mogoče uporabiti zgolj nedestruktivne metode. Eksperimentalna replika ulitka ni tako zelo omejena z vidika metod preiskav, vendar so lahko rezultati zaradi napak pri litju manj reprezentativni. Po drugi strani pa lahko virtualno geometrijo prosto proučujemo, virtualno lahko izvedemo več litij, možnosti različnih metod preskušanja pa so neomejene.

Z računalniško simulacijo smo preizkusili več primerov polnjenja in strjevanja ter preverili vpliv materiala forme in temperature taline na porazdelitev poroznosti. Analizirali smo pojave litja, povezane z geometrijo (modul), polnjenjem (zasnova ulivnega sistema, tok taline, gibanje taline v votlini, turbulenca, vnašanje zraka in položaj zračnih mehurčkov) in strjevanjem (mehanizem napajanja, nastanek krčilne poroznosti in čas strjevanja).

Rezultate simulacije smo potrdili s slikami nevtronske radiografije in analizo mikrostrukture z analizo mikroskopa s svetlim poljem in analizo diferencialnega interferenčnega kontrasta.

Ključne besede: Litje, bronasta doba, sekira z očesom, računalniška simulacija, povratni inženiring artefakta, povratni inženiring, tehnologija gravitacijskega litja, simulacija

Abstract

In this paper, the casting technology and casting defects of a socketed axe artifact were examined using computer simulation and non-destructive materials characterization methods.

The spread of cast bronze axes in the Carpathian Basin started in the Early Bronze Age. Bronze axes can be found in the highest number and selection in the local findings from the Late Bronze Age (1500-900 B.C.). There are several types of developed axe geometries, while the most common types are the so-called socketed axes, which can be found in ritual bronze treasures, scattered findings, and sometimes as grave annexes.

The examined socketed axe artifact (Hungarian National Museum, Prehistoric Collection) was physically analysed. The chemical composition was analysed by prompt-gamma activation analysis, which is a nuclear analytical technique for the non-destructive determination of elemental and isotopic compositions. The outer shape and the inner structure of the socketed axe artifact were examined by neutron radiography.

Based on the artifact an experimental casting replica and a virtual geometry were created for detailed investigations. The reason for the construction of the virtual geometry is that the examination possibilities of the original artifact are limited, only non-destructive methods can be applied. The experimental casting replica is less limited to examination methods, but because of the casting defects, the results can be less representative. On the other hand, virtual geometry is free to examine, several times can be cast virtually, and the possibilities of different testing methods are unlimited.

By the application of computer simulation, several filling and solidification cases were tested, and the effect of the mould material and melt temperature on the porosity distribution was examined. Casting phenomenon connected to the geometry (modulus), to the filling (gating system design, melt flow, movement of the melt inside the cavity, turbulence, air entrainment, and the position of air bubbles), and to the solidification (feeding mechanism, shrinkage formation and solidification time) were analysed.

The simulation results were validated by neutron radiography images and microstructure analysis using bright-field microscope analysis and differential interference contrast analysis.

Keywords: Casting, Bronze Age, socketed axe, computer simulation, reverse engineering artifact, reverse engineering, gravity casting technology, simulation

1 Zgodovina sekire

Sekira je eno prvih orodij, ki jih je uporabil človek, najstarejše sekire pa so bile znane kot ročne sekire. Ročna sekira je bila hruškasto oblikovano in grobo klesano kamnito orodje s širokim ročajem. Kasneje je sekira dobila lesen ročaj, razvitih je bilo več različnih vrst sekir, ki jih lahko razdelimo v dve glavni skupini: sekire brez očesa ter sekire z očesom. Sekire brez očesa niso imele luknje za ročaj in so bile običajno izdelane iz kremena, žada ali skrilavca ter so se sčasoma razvijale, kot so grobo obdelana sekira, sekira na kamnitih odbitkih, sekira s tankim rezilom, okrogla kamnita sekira in sekira s konkavnim rezilom. Za izdelavo sekir z očesom so uporabljali različne kamnine, vendar ne kremena, verjetno pa so se uporabljale

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, and 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 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.

ceremonialno in za prikazovanje statusa. Primeri so poligonalna sekira, dvoglava bojna sekira in sekira s čolnasto glavo [1, 2].

1.1 Sekira z očesom

V bronasti dobi so kamnite sekire postopoma zamenjale sekire z glavo iz bakra ali brona, ki so bile sprva pogosto v celoti kopije kamnitih sekir. Ena od vrst bronastodobnih sekir je sekira z očesom, ki ima klinasto obliko glave brez luknje za ročaj. Ročaj je v oko tako pritrjen na končnem delu. Ker je sekira votla in je ročaj vstavljen v glavo, je mogoče z minimalno količino materiala izdelati popolnoma funkcionalno in delujočo sekiro.

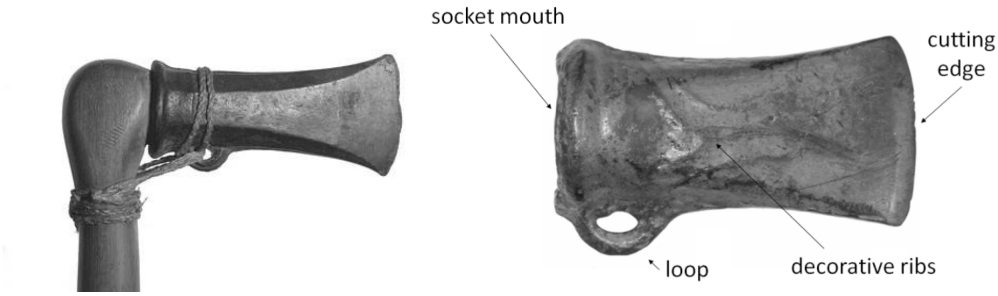
Sekire z očesom so bile v bronasti dobi zelo razširjeno in večnamensko orodje. Njihov videz se na nekaterih delih celine sicer razlikuje, vendar pa so glavne tehnike litja med seboj izredno podobne. V arheološkem gradivu so sekire z očesom tiste, pri katerih so jasne najznačilnejše napake pri litju. Nekatere med njimi imajo močno porozno notranjo strukturo, premaknjene dele, nepopolne zanke ali amorfne vzorce. Na Sliki 1 so prikazani

Types are the polygonal axe, double-headed battle-axe, and the boat axe [1, 2].

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 that show the most characteristic casting defect types. Some of them have intensively porous inner structures, shifted parts, incomplete loops, or amorphous patterns. Typical socketed axe geometry with handle reproduction and



Slika 1. Levo: Sekira z očesom iz bakrove zlitine s sodobnim ročajem (1000–700 pr. n. št.). Desno: Elementi sekire z očesom.

Figure 1. Left: Copper alloy socketed axe with modern handle (1000-700 BC). Right: Elements of the socketed axe.

tipična geometrija sekire z očesom in reprodukcijo ročaja kot tudi elementi sekire z očesom. [3].

2 Simulacijski postopek

Sekira z očesom je kovinski predmet, lit z gravitacijskim litjem. V tej raziskavi smo za tehnološko rekonstrukcijo postopka litja uporabili računalniško podprte metode simulacije. Za gravitacijsko litje lahko uporabimo številne metode modeliranja in simulacije, vključno s fizikalnim modeliranjem in numeričnimi metodami. Večina dosedanjega modeliranja in simulacij se izvaja z numeričnimi metodami, ki jih je mogoče uporabiti za reševanje ustreznih parcialnih diferencialnih enačb za toploto in pretok tekočin na podlagi numeričnih algoritmov. Naslednje zahteve veljajo za bistvene dele simulacije litja:

- pravilen geometrijski opis domene,
- natančni termodinamični podatki o fazi,
- natančni mejni pogoji,
- ustrezne lastnosti materiala,
- niz rešljivih enačb, ki opisujejo fizikalne pojave,
- eksperimentalno in numerično preverjanje.

Na splošno modeli rešujejo enačbe za temperature in pretok tekočine. Za pravilen opis zapletenih pojavov je potreben kakovosten vpogled v fiziko konstitutivnega vedenja tekočin, poltrdnih in trdnih snovi pri visokih temperaturah, da se lahko odločimo, katere parcialne diferencialne enačbe so najprimernejše za opis preiskovanih fizikalnih pojavov. Parametri teh modelov morajo biti realni in fizični. To pomeni močno interakcijo med nadzorovanimi poskusi strjevanja ali meritvami napetosti pri visokotemperaturnem plastičnem vedenju in oblikovanjem fizike procesa. Natančni podatki o mejnih pogojih in lastnostih

the elements of a socketed axe can be seen in Figure 1. [3].

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 technical reconstruction of the casting process. Many modeling and simulation methods can be employed for gravity casting, including physical modeling and numerical methods. Most of the current modeling 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 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 behavior 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 a very close interaction between controlled experiments of solidification or stress measurements of the high-temperature plasticity behavior and process physics formulation. Accurate boundary conditions so ključnega pomena za zagotovitev reprezentativnih rezultatov modela.

Določiti je treba fizikalne pojave za tehnološkim problemom in pripraviti matematični model. Ta matematični model je treba rešiti z analitično ali numerično metodo, za tehnološko rešitev pa je treba izvesti fizikalno interpretacijo te matematične rešitve. Zlasti pri proizvodnih procesih, kot je litje, lahko napačna razlaga sicer pravilnih matematičnih rezultatov privede do napačnih sklepov, na podlagi katerih ni mogoče razrešiti izvornega problema [4,5].

V tem raziskovalnem članku smo za reševanje procesov prenosa materiala in toplote uporabili komercialno dostopno programsko opremo NovaFlow & Solid. Metoda poskusov s simulacijo je razvidna iz Slike 2.

Med predobdelavo je prvi korak opredelitev geometrije sistema ulitka v diskretno število segmentiranih prostorninskih elementov za nadaljnje izračune.

Preden lahko rešimo enačbe, ki urejajo procese polnjenja in strjevanja, moramo imeti na voljo potrebne termofizikalne podatke o materialu. Poleg samih podatkov

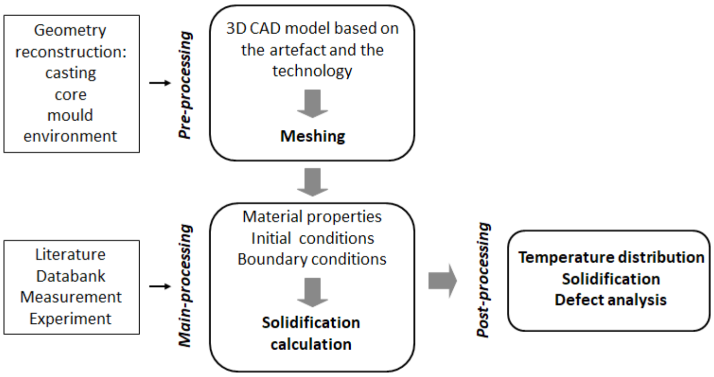
and property data are essential if model results are to be representative.

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 to 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.

During 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



Slika 2. Koncept poskusov s simulacijo.

Figure 2. Concept of the simulation experiments.

o materialu je treba opredeliti tudi druge pomembne parametre postopka. Določiti je treba začetne pogoje za neznane količine in mejne pogoje za neznanke. Vnesti je treba tudi druge pomembne informacije, da bi lahko upoštevali vse dejavnike, ki vplivajo na polnjenje in strjevanje ulitka.

Sledi glavna obdelava, ki je najzahtevnejši del numerične simulacije tako z vidika razvoja algoritmov kot v smislu zahtev za računalniško zmogljivost za reševanje vodilnih enačb. Tukaj je najbolj običajen pristop reševanje vseh osnovnih enačb, kar je predpogoj za simulacijo vseh ustreznih tehničnih problemov litja. Jasno je, da je za te izračune, v katerih se določajo primitivna polja, kot so temperature, odkloni, napetosti, hitrosti, tlak itd., potrebna rešitev diferencialnih enačb.

Naknadna obdelava obsega predstavitev rezultatov. Po opravljenih izračunih je treba ustrezno predstaviti osnovna polja (temperature, hitrosti, tlake, odklone, napetosti itd.).

3 Preiskovani artefakt

Proučevani artefakt je geometrija sekire z očesom iz Isaszega na Madžarskem (registracijska št.: Ha B1-B2/3). Kemična sestava sekire je 83 wt. % bakra (Cu), 11 wt. % kositra (Sn) in 6 wt. % antimona (Sb). Kemično sestavo smo analizirali z analizo promptne aktivacije gama žarkov, tj. jedrsko analitično tehniko za nedestruktivno določanje elementarne in izotopske sestave.

Z analizo promptne aktivacije gama žarkov je mogoče nedestruktivno analizirati kemično sestavo voluminoznih vzorcev. Predmet se obseva z nevtronskim snopom, žarke gama, ki nastanejo pri sevalnem zajetju nevtronov, pa hkrati zaznavamo z detektorjem iz germanija visoke čistosti.

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, and the 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 Artifact

The examined artifact is a socketed axe geometry from Isaszeg, Hungary (registration number: Ha B1-B2/3). 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 the non-destructive determination of elemental and isotopic compositions.

Prompt-gamma activation analysis is capable to analyse the chemical composition of voluminous samples non-destructively.

Večina elementov ima izotope, pri katerih poteka reakcija (n,γ), zato je s PGAA teoretično mogoče vse elemente razen helija analizirati brez predhodnih informacij o analitu. Temenske energije žarkov so značilne za elemente, ki so prisotni v vzorcu, medtem ko so intenzitete sorazmerne z njihovo količino. Vrednotenje spektra smo opravili s programsko opremo HYPERMET-PC, identifikacijo elementov in izračun koncentracije pa smo osnovali na katalogu spektroskopskih jedrskih podatkov in programski opremi ProSpeRo [6–8].

Notranjo strukturo artefakta sekire z očesom in poskusne replike ulitka smo proučili z nevtronskim slikanjem, ki predstavlja učinkovito metodo za analizo dragocenih primerkov in artefaktov. Tako 2-D nevtronska radiografija kot 3-D nevtronska tomografija s pomočjo transmisijskega slikanja dajeta informacije o notranji strukturi vzorca, pri čemer se meri oslabitev prehajajočega žarka. Tomografija je nadgradnja radiografije, pri kateri se preiskovani predmet vrti pod majhnimi koti, na podlagi serije projekcij pa je mogoče z matematičnim rekonstrukcijskim algoritmom izračunati tridimenzionalne informacije. S prikazom nabora 3-D podatkov je mogoče skozi digitalno obdelavo slik ustvariti tako imenovani prikaz virtualne resničnosti (karta). Karta prikazuje koeficient slabljenja nevtronov v materialu od točke do točke neodvisno od globine prodora. Meritve smo izvedli na fotogrametrični postaji RAD nevtronskega centra v Budimpešti s prostorsko ločljivostjo približno 250 μm [9].

Skupna količina poroznosti je 3,06 %. Geometrija artefakta in iz nje izhajajoče slike nevtronske radiografije so prikazane na Sliki 3.

Na podlagi artefakta smo s pomočjo računalniško podprtega oblikovanja ustvarili 3-D virtualni model. Za tehnološko analizo mora biti 3-D model sestavljen iz sekire,

The object is irradiated in a neutron beam, and the gamma rays from the radiative neutron capture are detected with a high-purity germanium detector, simultaneously. Most elements have isotopes that undergo the (n,γ) reaction, thus, in theory, all elements can be analysed with PGAA, except helium, without any prior information on the analyte. The gamma-peak energies are characteristic of the elements present in the sample, while the intensities are proportional to their quantity. The spectrum evaluation was done with the HYPERMET-PC software, the element identification and concentration calculation were performed based on the spectroscopic nuclear data catalog and the ProSpeRo software [6-8].

The inner structure of the socketed axe artifact and the experimental casting replica was examined by neutron imaging, which is an efficient method for analysing valuable artifacts. With the help of transmission imaging, both 2D neutron radiography and 3D neutron tomography give information about the inner structure of the sample measuring the attenuation of the passing beam. Tomography is the extension of radiography when the examined object is rotated at small angles, and based on the projection series the three-dimensional information can be calculated by a mathematical reconstruction algorithm. Displaying the 3D data set, using digital image processing, a so-called virtual reality representation (map) can be established. The map shows the neutron attenuation coefficient of the material from point to point independently from the depth of penetration. The measurements were implemented at the RAD imaging station of the Budapest Neutron Centre, with prox. 250 μm spatial resolution [9].

The overall amount of porosity is determined as 3,06 %. The artifact geometry

Slika 3. Geometrija artefakta in rezultat nevtronske radiografije.

Figure 3. The geometry of the artifact and the result of the neutron radiography.

jedra, ulivnega sistema, forme in okolja. Na podlagi nevtronske radiografske analize smo ustvarili poenostavljeno geometrijo sekire (43 cm^3) brez ulivnega sistema, medtem ko smo jedro in formo ustvarili s pomočjo raznih funkcij v CAD programu. Na podlagi pregleda literature in poskusnih poskusov smo oblikovali dva ulivna sistema, ki lahko na realističen način zapolnita votlino brez večje turbulence: asimetrični ulivni sistem, kjer se ulivni sistem stika na eni strani geometrije, in simetrični ulivni sistem, kjer se ulivni sistem stika na obeh straneh geometrije.

Alternativno polnjenje v primeru asimetričnega ulivnega sistema v odvisnosti od časa je prikazano na Sliki 4. Čas polnjenja v primeru asimetričnega ulivnega sistema je 1,74 s, v primeru simetričnega ulivnega sistema pa 1,40 s. Lestvica predstavlja hitrost taline med 0,00 m/s in 1,00 m/s. Masni tok taline je bil 0,5 kg/s.

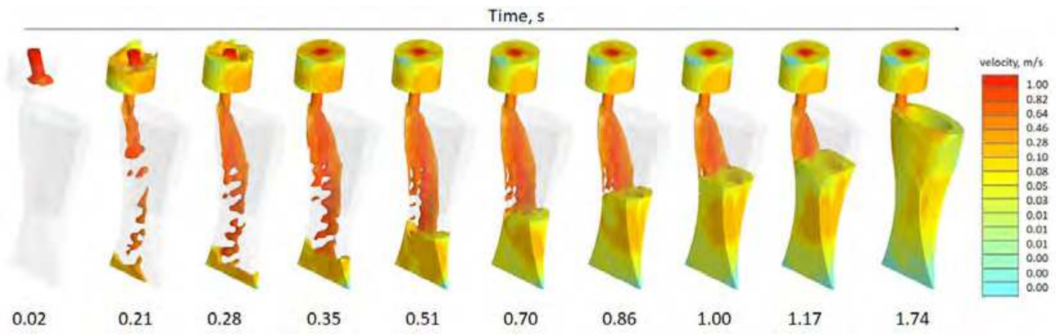
V obeh primerih talina med polnjenjem vstopa v ulivni sistem pod določenim kotom in z opredeljenim premerom curka taline. Iz ulivnega sistema vstopa talina v votlino skozi dovodni kanal in jo zapolni z gibanjem s prostim padom. Najvišja vrednost hitrosti toka je ~1,0 m/s, kar je več

and the resulting figures of the neutron radiography can be seen in Figure 3.

Based on the artifact a virtual model is created in 3D, using Computer-Aided Design. For the technical 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 cm^3), without a gating system, while the core and the mould are created using Boolean features. Based on a literature survey and trial experiments two gating systems are created which can fill the cavity in a realistic way without significant turbulence: Asymmetrical gating system, where the gating system contacts one side of the geometry, and symmetric gating system, where the gating system contacts both sides of the geometry.

The filling alternative of the asymmetric case can be seen in Figure 4. In the function of time. The filling time of the asymmetric case is 1.74 s, while the symmetric case is 1.40 s. The scale represents the velocity of the melt, between 0.00 m/s and 1.00 m/s. The pouring flow rate was 0.5 kg/s.

In both cases, during filling, the melt enters the gating system with a defined



Slika 4. Asimetrično polnjenje v odvisnosti od časa.

Figure 4. Asymmetric filling in the function of time.

od kritične hitrosti taline; to pomeni, da je tok turbulenten. Turbulentni tok vmešava nečistoče in oksidno plast v tok taline, kar lahko povzroči napake, imenovane bifilm [10]. Zrak v votlini se vmešava tudi v kovino. V primeru asimetričnega ulivnega sistema je bil čas polnjenja 1,74 s, v primeru simetričnega pa 1,4 s.

4 Proces strjevanja

Na podlagi arheoloških izkopavanj in pregleda literature [11, 12] smo pripravili 3-D model CAD poenostavljene geometrije sekire z ulivnim sistemom in jedrom. Nerešeno ostaja vprašanje o materialu forme, zato smo hkrati proučili dve možnosti:

- Zlitina je bila vlita v peščeno formo. Predpostavlja se uporaba forme za enkratno uporabo, ki jo je mogoče uporabiti samo enkrat.
- Zlitina je bila vlita v kamnito formo. Predpostavlja se uporaba trajne forme, ki jo je mogoče uporabiti večkrat. Pred litjem je bila kamnita forma obdana s peskom, ki ponazarja okolje, glej Sliko 5.

Zasnova eksperimentov (DoE) je razvidna iz Preglednice 1, v kateri je bila

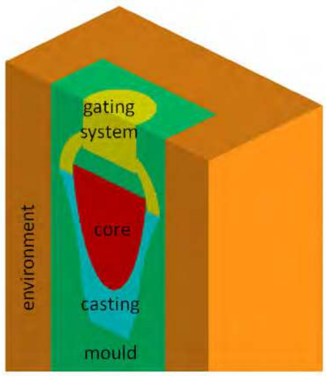
angle and with a defined melt stream diameter. From the gating system, the melt enters the cavity through the gates and fills the cavity with a free-fall movement. The highest value of the flow velocity is ~1.0 m/s, which is higher than the critical velocity of the melt, id est (?) the flow is turbulent. The turbulent flow mixes the impurities and the oxide layer of the melt into the metal stream, which can cause bifilm defects [10]. The air inside the cavity is also mixed inside the metal. In the case of asymmetric gating, the filling time was 1.74 s, in the case of symmetric gating, this value was 1.4 s.

4 Solidification Process

Based on archaeological excavations and literature survey [11, 12] 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:

- The alloy was poured into a sand mould. It supposes a so-called expendable mould where the mould is used only once.
- The alloy was poured into a stone mould.

kemična sestava zlitine izbrana na podlagi artefakta. Temperaturo litja smo preverili v več korakih, pri čemer smo korake opredelili na podlagi možnih najvišjih temperatur starih tehnik taljenja.



Slika 5. Predstavitev proučenih geometrij, prerez 3-D modela.

Figure 5. Representation of the examined geometries, 3D cut.

Pregleden vizualni prikaz strjevanja je prikazan na Sliki 6 v primeru poskusa A1 (forma za enkratno uporabo) in poskusa B6 (stalna forma) kot nasprotnih koncev polov

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 5.

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

The transparent visual representation of the solidification can be seen in Figure 6. in the case of the A1 experiment (expendable mold) and the B6 experiment (permanent mold) as opposite ends of the poles in terms of pouring temperature (1015 vs. 1100 °C). The scale refers to liquid phase 5–95 %.

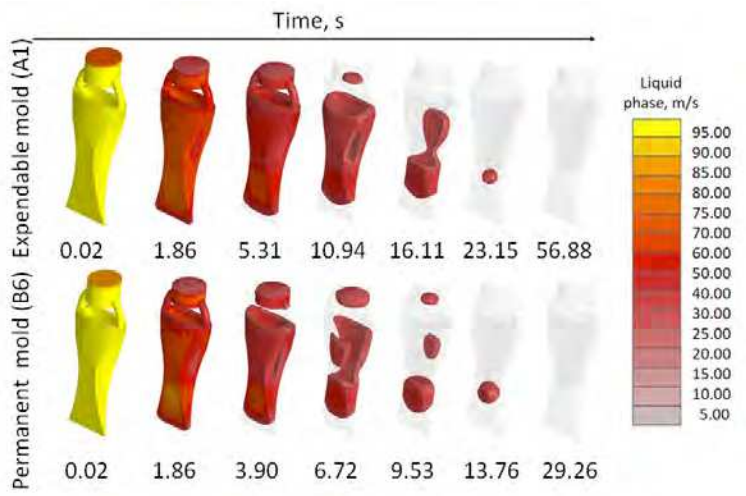
4.1 Result Analysis

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

Preglednica 1. Zasnova eksperimentov.

Table 1. Design of experiments.

	Forma za enkratno uporabo / Expendable mold					
	A1	A2	A3	A4	A5	A6
Začetna temperatura taline / Initial melt temperature (°C)	1015	1025	1035	1050	1070	1100
Forma / Mold	pesek / sand	pesek / sand	pesek / sand	pesek / sand	pesek / sand	pesek / sand
Okolje / Environment	pesek / sand	pesek / sand	pesek / sand	pesek / sand	pesek / sand	pesek / sand
	Trajna forma / Permanent mold					
	B1	B2	B3	B4	B5	B6
Začetna temperatura taline / Initial melt temperature (°C)	1015	1025	1035	1050	1070	1100
Forma / Mold	peščenjak / sandstone	peščenjak / sandstone	peščenjak / sandstone	peščenjak / sandstone	peščenjak / sandstone	peščenjak / sandstone
Okolje / Environment	pesek / sand	pesek / sand	pesek / sand	pesek / sand	pesek / sand	pesek / sand



Slika 6. Strjevanje ulitka v različnih pogojih.

Figure 6. Solidification of the casting in different conditions.

v smislu temperature litja (1015 proti 1100 °C). Lestvica se nanaša na tekočo fazo 5–95 %.

4.1 Analiza rezultatov

Med polnjenjem se mora zrak odstraniti iz votline. To je mogoče doseči z odzračevanjem ali z difuzijo zraka skozi formo, kar imenujemo prehajanje plina. Na podlagi analize polnjenja je mogoče ugotoviti, da talina blokira dovodni kanal, zato zrak ne more izstopiti skozi ulivni sistem. Brez odzračevanja zrak ne more zapustiti votline. Plinoprepustnost forme je odvisna od materiala, iz katerega je izdelana forma. Peščena forma za enkratno uporabo dobro prepušča pline, medtem ko je plinoprepustnost trajne kamnite forme skoraj ničelna. Te učinke je treba raziskati z analizo rezultatov.

Med strjevanjem se zlitina skrči, kar povzroča krčilno poroznost. Ulitek se strjuje brez napajalnika, čeprav lahko kovina v

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 of 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 experiments, 6 different melt temperatures were examined in both moulding methods. The question was the amount and the distribution of shrinkages, ulivnem sistemu omejen čas napaja ulitek. Preostanek kovine v votlini se strdi brez napajanja.

Zaradi teh učinkov se v geometriji pojavijo praznine, ki jih je mogoče izračunati na podlagi izračuna strjevanja.

V skladu s poskusi smo pri obeh načinih formanja preverili 6 različnih temperatur taline. Odprto je ostalo vprašanje količine in porazdelitve krčenja, na podlagi katerih bi lahko te vrednosti primerjali z analiziranimi rezultati artefakta, kjer je vrednost splošne poroznosti 3,06 %. Rezultati so prikazani v Preglednici 2.

Na podlagi analize poroznosti artefakta z nevtronsko radiografijo lahko skupno količino poroznosti (3,06 %) primerjamo z rezultati simulacije. Izmerjena vrednost je podobna kot pri naslednjih rezultatih simulacije:

- Peščena forma za enkratno uporabo s temperaturo litja 1070 °C.
- Trajna kamnita forma s temperaturo litja 1015 °C.

Da bi se odločili, kateri način formanja in temperatura vlivanja sta primernejša, je treba raziskati tehnologijo bronaste dobe. Tehnologija zgodnjih peči in taljenja za doseganje višje temperature kovine je bila omejena. Na podlagi preiskav ostankov žlindre in poskusov reprodukcije je jasno, da je treba uporabiti najnižjo temperaturo

to be able to compare these values with the analysed results of the artifact, 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 1070 °C pouring temperature.
- Permanent stone mould with 1015 °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 1013 °C.

If the moulding method is examined there are several pieces of evidence that prove, that during the Bronze Age permanent mould was applied since unused and burned out mould fragments are excavated [13–14].

Preglednica 2. Izračunani rezultati.

Table 2. Calculated results.

	Forma za enkratno uporabo / Expendable mold					
	A1	A2	A3	A4	A5	A6
Začetna temperatura taline / Initial melt temperature (°C)	1015	1025	1035	1050	1070	1100
Krčenje / Shrinkage (vol. %)	2,92	2,977	3,035	3,04	3,069	3,161
	Trajna forma / Permanent mold					
	B1	B2	B3	B4	B5	B6
Začetna temperatura taline / Initial melt temperature (°C)	1015	1025	1035	1050	1070	1100
Krčenje / Shrinkage (vol. %)	3,071	3,128	3,184	3,135	3,244	3,253

litja, tj. temperaturo likvidusa zlitine 1013 °C.

Če proučimo način formanja, obstaja več dokazov, ki pravijo, da so v bronasti dobi uporabljali stalne forme, saj so izkopali neuporabljene in že uporabljene dele form [13–14].

5 Simulacija geometrije artefakta

Na podlagi rezultatov simulacije lahko ugotovimo, da material za formanje (in s tem hitrost strjevanja) ter temperatura litja pomembno vplivata na krčenje ulitka. Težava je, kako rezultate simulacije povezati z dejanskim artefaktom sekire z očesom.

5 Simulation of the Artifact Geometry

Based on the results of the simulation, the molding material (and therefore the solidification velocity) and the pouring temperature have a significant effect on the shrinkage behavior of the casting. The problem is how to feedback on the simulation results to the real socketed axe artifact.

The socketed axe artifact and the experimental casting part are examined with prompt-gamma activation analysis and neutron tomography. Based on the tomography results of the artifact, a 3D CAD geometry was created, which is suitable for the simulation analysis.

Preglednica 3. Zasnova eksperimentov artefakta sekire z očesom.

Table 3. Socketed axe artifact's DoE.

	Expendable mold					
	A1	**A2**	**A3**	**A4**	**A5**	**A6**
Initial melt temperature (°C)	1015	1025	1035	1050	1070	1100
Mold	sand	sand	sand	sand	sand	sand
Environment	sand	sand	sand	sand	sand	sand

	Expendable mold	
	C1	**C2**
Initial melt temperature (°C)	1015	1100
Mold	sand	sand
Initial mold temperature (°C)	20	20
	Permanent mold	
	D1	**D2**
Initial melt temperature (°C)	1015	1100
Mold	sandstone	sandstone
Initial mold temperature (°C)	20	20

	Permanent mold					
	B1	**B2**	**B3**	**B4**	**B5**	**B6**
Initial melt temperature (°C)	1015	1025	1035	1050	1070	1100
Mold	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone
Environment	sand	sand	sand	sand	sand	sand

Artefakt sekire z očesom in eksperimentalni del ulitka smo pregledali z analizo promptne aktivacije gama žarkov in nevtronsko tomografijo. Na podlagi rezultatov tomografije artefakta smo izdelali 3-D geometrijo CAD, ki je primerna za analizo s simulacijo.

Na podlagi zasnove eksperimentov virtualne geometrije (oglejte si Preglednico 1) smo ustvarili poenostavljeno zasnovo eksperimentov za artefakt sekire z očesom, ki je prikazana v Preglednici 3. V teh poskusih sta bili upoštevani najnižja (1015 °C) in najvišja (1100 °C) temperatura litja.

Proučena geometrija artefakta (prostornina: 20,533 cm^3) in 3-D izrez forme z votlino sta prikazana na Sliki 7.

Ulivni sistem sekire ni ustvarjen, predstavljena je zgolj točka litja taline z asimetričnim in simetričnim ulivnim sistemom. Polnjenje in strjevanje geometrije sta prikazana ločeno. Najprej smo preverili, ali forma med polnjenjem prenese ujete plinske mehurčke artefakta. Podrobna analiza polnjenja ni predstavljena. Začetne in mejne pogoje polnjenja forme smo določili, kot sledi:

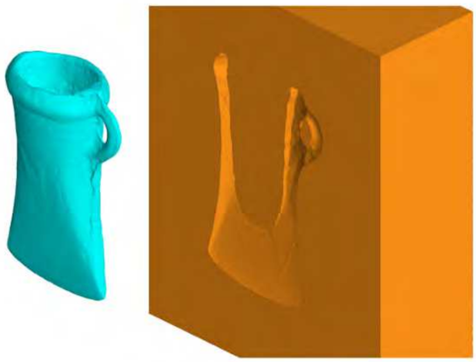
- Kemična sestava taline: 92 ± 0,5 m/m % bakra (Cu), 4,8 ± 0,4 m/m % antimona (Sb), 1,1 ± 0,1 m/m % arzena (As), 1,6 ± 0,07 m/m % niklja (Ni), 0,59 ± 0,03

Based on the DoE of the virtual geometry (see Table 1.) a simplified DoE is created for the socketed axe artifact, which can be seen in Table 3. In these experiments, the lowest (1015 °C) and the highest (1100 °C) pouring temperatures are adverted.

The examined geometry of the artifact (volume: 20,533 cm^3) and the 3D cut of the mold with the cavity can be seen in Figure 7.

The gating system of the axe is not created, only the gating point of the melt is represented with asymmetric and symmetrical gating. The filling and solidification of the geometry were handled separately. First, the mold filling is examined to be able to handle the entrapped gas bubbles of the artifact. A detailed analysis of the filling is not presented. The initial and boundary conditions of the mold filling were determined as follows:

- Chemical composition of the melt: 92 ± 0.5 m/m % copper (Cu), 4.8 ± 0.4 m/m % antimony (Sb), 1.1 ± 0.1 m/m % arsenic (As), 1.6 ± 0.07 m/m % nickel (Ni), 0.59 ± 0.03 m/m % silver (Ag) and 0.127 ± 0.006 m/m % cobalt (Co)
- Pouring temperature: 1015 and 1100 °C
- Mold material and temperature: sand, 20 °C
- Entering metal stream diameter: 4.5 mm
- Pouring flow: Σ 0.1 kg/s
- Calculated filling time: 1.67 s



Slika 7. Geometrija artefakta in prerez 3-D modela.

Figure 7. Artifact geometry and the 3D cut of the mold.

m/m % srebra (Ag) in 0,127 ± 0,006 m/m % kobalta (Co)

- Temperatura litja: 1015 in 1100 °C
- Material in temperatura forme: pesek, 20 °C
- Premer vhodnega curka kovine: 4,5 mm
- Tok litja: Σ 0,1 kg/s
- Izračunani čas polnjenja: 1,67 s

Pregleden vizualni prikaz strjevanja je prikazan na Sliki 8 v primeru poskusa C1 (forma za enkratno uporabo) in poskusa D2 (stalna forma) kot nasprotnih koncev polov v smislu temperature litja (1015 proti 1100 °C). Lestvica se nanaša na tekočo fazo 5–95 %.

Vzorci strjevanja so podobni pri obeh načinih formanja. Prvi strjeni del geometrije artefakta je na območju stranske zanke, ki mu sledita rezalni rob in ustje očesa. Zadnji strjeni del je težki del geometrije pod jedrom, ki se vede kot vroče mesto.

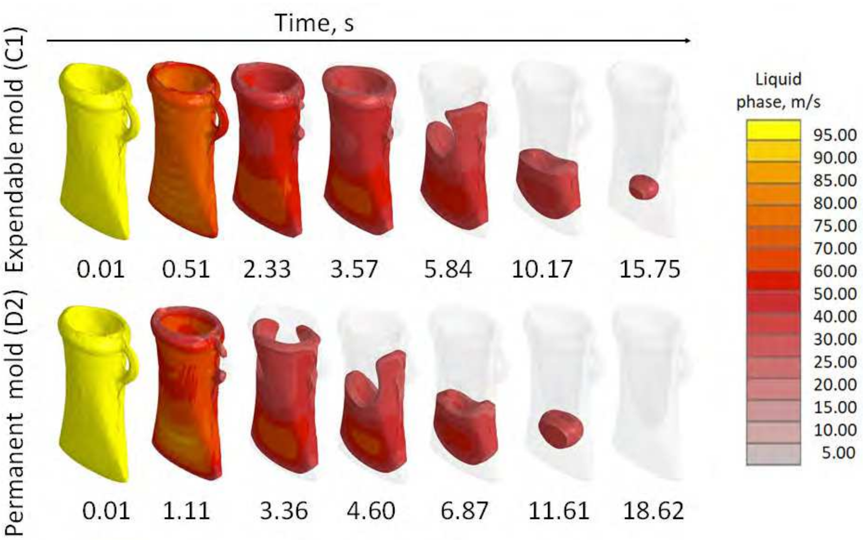
Najkrajši čas strjevanja ima različica D1 (forma iz peščenjaka, temperatura taline

The transparent visual representation of the solidification can be seen in Figure 8. in the case of the C1 experiment (expendable mold) and D2 experiment (permanent mold) as opposite ends of the poles in terms of pouring temperature (1015 vs. 1100 °C). The scale refers to liquid phase 5–95 %.

The solidification patterns are similar in both molding methods. The first solidified part of the artifact geometry is in the area of the side loop, which is followed by the cutting edge and the socket mouth. The latest solidified part is the heavy section of the geometry, under the core, which behaves like a hot spot.

The shortest solidification time belongs to the D1 version (sandstone mold, 1015 °C melt temperature) while the longest solidification time belongs to the C2 version (sand mold, 1100 °C melt temperature).

The empty spaces in the 2D cut mid-line view mean shrink holes. In all cases, at the area of the socket mouth, which has the highest position within the mold, the melt



Slika 8. Strjevanje artefakta sekire z očesom v različnih pogojih.

Figure 8. Solidification of the socketed axe artifact in different conditions.

Preglednica 4. Simulirane in izmerjene vrednosti poroznosti.

Table 4. Simulated and the measured porosity values.

	C1	C2	D1	D2
Simulirana poroznost zaradi krčenja / Simulated shrinkage porosity	2,84 %	3,69 %	2,80 %	3,66 %
S tomografijo izmerjena poroznost in poroznost zaradi plina / Tomography measured shrinkage and gas porosity	min. 3,1 – maks./ max 3,7 wt. % povprečna vrednost / mean value 3,4 wt. %			

1015 °C), najdaljši čas strjevanja pa ima različica C2 (forma iz peska, temperatura taline 1100 °C).

Prazni prostori v 2-D rezu na sredini črte predstavljajo lunker. V vseh primerih se talina na območju ustja očesa, ki leži najvišje v kalupu, strdi brez napajanja, kar povzroči nastanek lunkerja. Na sredini geometrije, tj. na območju težkega dela, je lunker, geometrija katerega je odvisna od vzorca strjevanja. Pri formah iz peščenjaka je na območju stranske zanke še ena napaka pri strjevanju. Simulirane in izmerjene vrednosti poroznosti so prikazane v Preglednici 4.

Simulirane vrednosti obsegajo samo poroznost zaradi krčenja, medtem ko obsegajo izmerjene vrednosti poroznost zaradi krčenja kot tudi zaradi plina. Za primerjavo ne le številčnih vrednosti krčenja, temveč tudi njegove porazdelitve, je treba simulirane slike primerjati z rezultati tomografije.

Simulacijski algoritem skrbi za krčenje pri strjevanju s pomočjo parametra na neprekinjeni lestvici, ki prikazuje vrednost krčenja zaradi strjevanja znotraj območja. Po drugi strani pa so krčenje in plinske poroznosti s pomočjo tomografije predstavljene kot odsotnost materialov. Ta različna vidika je mogoče približati z grafičnimi orodji.

Skupni prikaz izmerjenih in simuliranih vrednosti je na Slikah 9 in 10 na območju težkega dela geometrije. Zelena črta predstavlja mejo 10-odstotnega krčenja, solidifies without feeding, which causes shrink holes. In the middle of the geometry, at the area of the heavy section, there is a shrink hole, whose geometry depends on the solidification pattern. In the case of the sandstone molds, there is one further solidification defect in the area of the side loop. The simulated and measured porosity values can be seen in Table 4.

The simulation values contain only the shrinkage porosity, while the measured values contain the shrinkage and the gas porosity. To compare not only the numerical values of the shrinkages but their distribution of them, the simulated images must be compared to the tomography results.

The simulation algorithm handles the solidification shrinkages with the help of a parameter along a continuous scale, which demonstrates the value of solidification shrinkages inside an area. On the other hand, with the help of tomography, the shrinkage and gas porosities are represented as a lack of materials. The two different aspects can be approximated by graphical tools.

The common representation of the measured and simulated values can be seen in Figure 9. and 10. in the area of the heavy section of the geometry. Green lines represent the border of the 10 % of shrinkage, the yellow line represents the border of the 40 % shrinkage and the red circles represent the position of the gas bubbles.

rumena črta predstavlja mejo 40-odstotnega krčenja, rdeči krogi pa položaj plinskih mehurčkov.

1. Simulirano krčenje pri strjevanju.
2. Položaj plinskih mehurčkov.
3. Simulirano krčenje pri strjevanju in plinski mehurčki.
4. Meje krčenja in plinskih mehurčkov so nanesene na tomografski posnetek.

Rezultate smo potrdili z analizo mikrostrukture z mikroskopom s svetlim poljem in analizo diferencialnega interferenčnega kontrasta.

1. Simulated solidification shrinkages.
2. Position of the gas bubbles.
3. The simulated solidification shrinkages and the gas bubbles.
4. The borderlines of the shrinkages and the gas bubbles are superposed to the tomography.

The results were validated by microstructure analysis using bright-field microscope analysis and differential interference contrast analysis.

Slika 9. Simulirano in izmerjeno krčenje, 1015 °C (C1).

Figure 9. Simulated and measured shrinkages, 1015 °C (C1).

Slika 10. Simulirano in izmerjeno krčenje, 1100 °C (D2).

Figure 10. Simulated and measured shrinkages, 1100 °C (D2).

6 Sklepi

Uporabljene metode testiranja materialov so primerne za pregled artefaktov, medtem ko je računalniška simulacija ustrezno orodje za reprodukcijo tehnologije litja.

V primeru proučevane geometrije sekire z očesom smo model CAD artefakta izdelali na podlagi rezultatov točkovnih oblakov nevtronske tomografske rekonstrukcije. Vrednosti kemične sestave kot vhodnih parametrov simulacije so bile določene s tehniko analize promptne aktivacije žarkov gama. Ustreznost simulacijskih izračunov je mogoče primerjati in potrditi z rezultati metod analize notranje strukture in metalografije.

Na podlagi rezultatov testiranja materialov in simulacij je verjetno, da je bila sekira z vdolbino ulita z asimetričnim ulivnim sistemom, kar potrjujejo tudi rezultati mikroskopskih posnetkov.

Na podlagi rezultatov simulacij je bila sekira z nastavkom ulita v trajno formo, kar potrjujejo tudi arheološki dokazi.

Vlivanje kovinske taline je potekalo z minimalnim pregrevanjem, kar ustreza znanju o tehnikah taljenja iz bronaste dobe.

6 Conclusions

The applied materials testing methods are suitable for the examination of artifacts, while computer simulation is an adequate tool for the reproduction of the casting technology.

In the case of the examined socketed axe geometry, the CAD model of the artifact was created based on the point clouds results of the neutron tomographic reconstruction. The values of the chemical composition, as input parameters of the simulation, were determined using the prompt-gamma activation analysis technique. The adequacy of the simulation calculations can be compared and validated by the results of the inner structure analysis methods and the metallography.

Based on the results of the materials testing and the simulations it is probable that the socketed axe was cast using an asymmetric gating system, which statement was also confirmed by the results of the microscope images.

Based on the results of the simulations, the socketed axe was cast into a permanent mold, which statement was also confirmed by the archaeological evidence.

The pouring of the metal melt was carried out with a minimal superheat, which statement is based on the melting techniques of the Bronze Age.

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AKTUALNO / CURRENT

Pregled livarskih prireditev v letu 2023

Datum dogodka	Ime dogodka	Mesto in država
29.–30. 03. 2023	4th Molding Material Forum	Clausthal-Zellerfeld, Nemčija
29.–31. 03. 2023	Metals, Extrusion, Foundry (METEF)	Bologna, Italija
27.–28. 04. 2023	65. Österreichische Gießereitagung	Schladming, Avstrija
08.–09. 05. 2023	Gießtechnik im Motorenbau	Magdeburg, Nemčija
16.–18. 05. 2023	New Trends in Metallic Materials Processing	Bukarešta, Romunija
17.–19. 05. 2023	65. Mednarodni sejem tehnike in XV International Mineral Processing and Recycling Conference (IMPRC)	Beograd, Srbija
12.–13. 06. 2023	Industrijski forum IRT 3000	Portorož, Slovenija
12.–16. 06. 2023	Mednarodni sejem metalurgije in livarstva (GIFA)	Düsseldorf, Nemčija
13.–15. 09. 2023	**63. IFC Portorož 2023**	**Portorož, Slovenija**