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## Izdelava lite replike Negovske čelade Production of cast replica of Negova helmet

### Povzetek

V sklopu dveh študentskih projektov je sodelovalo več inštitucij in študentov. Namen projektov je bila analiza Negovske čelade iz 4. stol. pr. n. št. najdene v Podzemlju v Beli Krajini, kjer nas je zanimala tehnološka pot izdelave čelade. Namen projekta je bil tudi izdelava lite kopije čelade. Najdena čelada je bila izdelana s kovanjem bronza z 9 do 10 mas. % kositra in spajkanjem s svincem.

Pri izdelavi lite kopije je bila uporabljena tehnologija precizijskega litja, kjer smo na osnovi originalne konservirane čelade s pomočjo 3D tehnologij posneli original in natisnili pramodni čelade, izdelali silikonsko formo, voščeni model, keramično školjko in nato lito kopijo. Lita kopija čelade je bila nato še patinirana, da smo dosegli čim bolj pristen izgled kopije.

### Abstract

Several institutions and students participated in two student projects. The purpose of the projects was to analyze the Negova helmet from the 4th century BC, found in the Podzemlje in Bela Krajina, where we were interested in the technological path of helmet production. The purpose of the project was to produce a cast copy of the helmet and to manufacture a cast-reconstructed helmet. The found helmet was made by forging bronze with 9 to 10 wt. % tin and soldering with lead.

When creating the cast copy, the investment casting technology was used, where we recorded the original and printed the helmet prototype based on the original preserved helmet using 3D technologies, made a silicone mould, a wax pattern, a ceramic shell, and then a cast copy. The cast copy of the helmet was then patinated to achieve the most authentic appearance of the copy.

### 1 Uvod

Negovska čelada je tip čelade, ki se je pojavljal v našem prostoru razširjenem med Alpami, Donavo in Jadranskim morjem v pozni železni dobi, predvsem v 5. in 4. stol. pr. n. št.. Tip čelade je dobil svoje ime po kraju Negova, kjer so bile čelade podobnih oblik prvič najdene in sicer leta 1811 jih je Jurij Slaček pri oranju njive našel 26 [1]. Na slovenskem je bilo najdenih kar 49

### 1 Introduction

The Negova helmet is a type of helmet that appeared in our area, spread between the Alps, the Danube, and the Adriatic Sea in the late Iron Age, especially in the 5th and 4th centuries BC. The helmet type got its name from the place Negova, where helmets of similar shapes were first found, namely in 1811, Jurij Slaček found 26 of them while ploughing a field [1]. As many

čelad, največ na Dolenjskem iz dolenske halštatske skupine [2], analiziran predmet pa je bil najden na Pezdirčevi njivi v Podzemlju [3].

Sprva je bilo mnenje, da so bile čelade narejene z livarsko tehniko, kot pa se je pokazalo pri analizi predmeta te raziskave, so bile negovske čelade izdelane s tehniko kovanja in delno tudi spajkanja. Analizirana čelada je iz bronca z okoli 9 mas. % kositra 0,3 mas. % svinca in 0,1 mas. % mangana. Iz analiz mikrostruktur se vidi, da je mikrostruktura preoblikovana, saj je prisotna velika količina dvojčičnih mej, ki so posledica preoblikovanja. Iz analize oblike in velikosti kristalnih zrn ter vključkov je bila določena stopnja deformacije materiala [4]. S primerjanjem vzorcev, ki so bili liti z različnimi debelinami in preoblikovani pri različnih deformacijah, z vmesnimi žarjenji pri različnih temperaturah in časih, je bilo ugotovljeno, da je morala biti čelada izdelana iz surovca z obliko diska s premerom približno 200 mm in debelino najmanj 3,7 mm. Surovec je bil v čelado hladno skovan v več ciklih z vmesnimi žarjenji pri temperaturah okoli 650 °C vsaj 10 min [5],[6].

Cilj predstavljenega dela je bil narediti kopijo čelade. Ker pa je kovanje takih oblik zahteven in dolgotrajen proces, je bila uporabljena tehnologija precizijskega litja.

## 2 Eksperimentalno delo in rezultati

### 2.1 Izdelava 3D tiskanega modela

Analiziran predmet - negovska čelada je bil z namenom izdelave lite replike 3D skeniran. 3D geometrija je bila zajeta na dva načina in sicer s fotogrametrijo in s 3D skeniranjem. Za izdelavo digitalnega modela je bil pri fotogrametriji uporabljen program Agisoft Metashape. Digitalni

as 49 helmets were found in Slovenia, most of them in Dolenjska from the Dolenjska Hallstatt group [2], and the analysed object was found on the Pezdirc field in Podzemlje [3].

Initially, it was believed that the helmets were made using the casting technique, but as the analysis of the object of this research showed, the Negova helmets were made using the forging technique and partly also soldering. The analysed helmet is made of bronze with about 9 wt. % tin 0.3 wt. % lead and 0.1 wt. % manganese. Microstructure analyses show that the microstructure is deformed, as many twin boundaries are present, which are a result of deformation. The degree of deformation of the material was determined from the analysis of the shape and size of the crystal grains and inclusions [4]. By comparing samples that were cast with different thicknesses and deformed at different deformations, with intermediate annealing at different temperatures and times, it was found that the helmet must have been made from a blank with a disk shape with a diameter of approximately 200 mm and a thickness of at least 3.7 mm. The blank was cold forged into a helmet in several cycles with intermediate annealing at temperatures of around 650 °C for at least 10 min [5],[6].

The presented work aimed to make a copy of the helmet. However, since forging such shapes is a demanding and time-consuming process, a precision casting technology was used.

## 2 Experimental Work and Results

### 2.1 Production of a 3D Printed Model

The analysed object - a Negova helmet was 3D scanned to produce a cast replica. The 3D geometry was captured in two ways, by

model je bil izdelan na osnovi zajema s kamero Nikon D780 in objektivom Nikkor 24-70mm, 2,8. Fotografije so bile zajete z največjo možno globinsko ostrino in s čemer je bil omogočen najkakovostnejši postopek fotogrametrije. Izdelana sta bila dva izhodna digitalna modela in sicer eden pri veliki in drugi pri mali ločljivosti in tako sta bila pridobljena kakovostna modela za različne izhodne aplikacije.

3D skeniranje je bilo izvedeno z ročnim hibridnim 3D skenerjem, Shining 3D Einscan HX, kjer je bila uporabljena strukturirana svetloba. Pridobljen digitalni model je bilo potrebno očistiti in pripraviti za tisk, na način, da je postal vodotesen. Slika 1 prikazuje arheološko najdbo, model posnet s fotogrametrijo in 3D model pripravljen za tisk.

Za tisk modela čelade je bil uporabljen digitalni model, pridobljen s skenerjem. Tisk je bil izveden z belim PLA termoplastičnim filamentom, ki ga 3D tiskalnik slojno nanaša. Uporabljen je bil tiskalnik je Artillery Sidewinder X2 3D Printer. Naveden tiskalnik ima delovni volumen 300 mm × 300 mm × 400 mm tako, da je bil model natisnjen v velikosti 1:1. Pri tisku je bila uporabljena debelina sloja filameta 200 mikronov in premer šobe na ekstrudirni tiskalni glavi 400 mikronov. Notranja zapolnitev je bila 50 %.

## 2.2 Izdelava silikonske forme

3D natisnjen model čelade se je s kitanjem zgladil, da so se skrile vidne plasti nastale pri 3D tisku. Na podlagi tega modela, imenovanega pramodel, se je izdelala silikonska guma za izdelavo voščene modela čelade, ki je bil uporabljen pri precizijski tehnologiji litja. Uporabljena je bila silikonska guma Neukasil 1703 proizvajalca Altropol. Uporabljena je bila tudi komponenta

photogrammetry and by 3D scanning. The Agisoft Metashape program was used for photogrammetry to create a digital model. The digital model was created based on the capture with a Nikon D780 camera and a Nikkor 24-70mm, 2.8 lens. The photographs were captured with the maximum possible depth of field, which enabled the highest quality photogrammetry process. Two output digital models were created, one at high and the other at low resolution, thus obtaining high-quality models for various output applications.

3D scanning was performed with a handheld hybrid 3D scanner, Shining 3D Einscan HX, where structured light was used. The obtained digital model had to be cleaned and prepared for printing, in such a way that it became watertight. Figure 1 presents the discovery, model after photogrammetry, and model ready for 3D printing.

A digital model obtained with a scanner was used to print the helmet model. The printing was carried out with white PLA thermoplastic filament, which the 3D printer applies in layers. The printer used is the Artillery Sidewinder X2 3D Printer, with thermoplastic extrusion. The specified printer has a working volume of 300 mm × 300 mm × 400 mm, so that the model was printed in 1:1 size. The printing used a filament layer thickness of 200 microns and a nozzle diameter on the extrusion print head of 400 microns. The internal filling was 50%.

## 2.2 Making a Silicone Mould

The 3D printed helmet model was smoothed with putty to hide the visible layers created during 3D printing. Based on this model, called the master pattern, silicone rubber was produced to produce a wax pattern of



**Slika 1.** Arheološka najdba čelade (levo), model posnet s fotogrametrijo (sredina) in 3D model pripravljen za tisk (desno)

**Figure 1.** Archaeological find (left), model of photogrammetry (middle) and 3D model prepared for printing (right)



**Slika 2.** Natisnjena model čelade (levo), glajenje modela (sredina) in silikonska forma iz dveh delov (desno)

**Figure 2.** Printed helmet (left), smoothing of the 3D printed model (middle), and silicone rubber applied to the prototype (right)

za zagotavljanje tiksotropnih lastnosti silikona. Tako pripravljena silikonska guma je bila s čopičem, v debelin 5 mm, nanešena na pramodel. Zaradi velikosti in oblike pramodela je bil le ta s pomočjo gline razdeljen na dva dela, ki sta bila po sredini čelade – grebenu spojena. Silikonska guma je bila ojačana z mavčno kapo, ki je bila prav tako izdelana iz dveh delov, da je bilo omogočeno kasnejše odstranjevanje voščene modela. Uporabljen je štukaturni

the helmet, which was used in investment casting technology. The silicone rubber Neukasil 1703 from Altropol was used. A component was also used to ensure the thixotropic properties of the silicone. The silicone rubber thus prepared was applied to the master pattern with a brush, in a thickness of 5 mm. Due to the size and shape of the master model, it was divided into two parts with the help of clay, which were joined in the middle of the helmet - the crest. The silicone rubber was reinforced

mavec Stuckgips proizvajalca Saint-Gobain Formula. Postopek prikazuje slika 2.

### 2.3 Izdelava voščene modela in keramične školjke ter litje

S tako pripravljeno silikonsko gumo oz. silikonsko formo se je z nanašanjem voska izdelal voščeni model. Ta je bil iz dveh različnih voskov. Prva plast je bila iz tršega voska, ki zagotavlja zelo kvalitetno površino modela, druga plast pa je bila iz mehkejšega voska, ki se tali pri nižjih temperaturah in tako prepreči pokanje keramičnih školjk pri iztaljevanju voščene modela. Pred nadaljnjim postopkom izdelave keramične školjke smo na voščeni model namestili ulivni sistem in odzračevalni sistem (slika 3).

Keramična školjka je bila izdelana s potapljanjem voščene modela v suspenzijo Suspendaslurry® FS in s posipanjem s taljenim kremenom Rancosil različnih granulacij, proizvajalca Ransom & Randolph. Školjka je bila izdelana iz desetih slojev. Ko je bila keramična školjka zgrajena, je bil voščen model iztaljen v elektroporovni peči pri 400 °C, školjka pa še nadalje žgana pri temperaturi 1050 °C, da se je ustvarila keramična vez. V indukcijski peči je bila pripravljena talina bronza z 10 mas. % Sn. Pred litjem smo talino dezoksidirali s fosforjem, talina pa je bila ulita v vročo školjko pri 1250 °C. Ulitek je bil po ohlajanju odstranjen iz keramične školjke, ulivni sistem in zračniki odrezani, sledilo pa je še cizeliranje in priprava površine za patiniranje, kar prikazuje slika 4.

with a plaster cap, which was also made of two parts, to enable later removal of the wax pattern. The stucco plaster Stuckgips from Saint-Gobain Formula was used. Preparation process is shown in Figure 2.

### 2.3 Production of a Wax Pattern and Ceramic Shell, and Casting

With the silicone rubber or silicone mould thus prepared, a wax pattern was produced by applying wax. This was made of two different waxes. The first layer was made of harder wax, which ensures a very high-quality surface of the model, and the second layer was made of softer wax, which melts at lower temperatures and thus prevents cracking of ceramic shells when melting the wax pattern. Before the further process of manufacturing the ceramic shell, we installed a pouring system and a venting system on the wax pattern (Figure 3).

The ceramic shell was made by immersing the wax pattern in Suspendaslurry® FS suspension and stuccoing it with Rancosil fused silica of various granulations, manufactured by Ransom & Randolph. The shell was made of ten layers. Once the ceramic shell was built, the wax pattern was melted in an electric resistance furnace at 400 °C, and the shell was further fired at a temperature of 1050 °C to create a ceramic bond. A bronze melt with 10 wt. % Sn was prepared in an induction furnace. Before casting, the melt was deoxidized with phosphorus, and the melt was poured into a hot shell at 1250 °C. After cooling, the casting was removed from the ceramic shell, the casting system and vents were cut off, followed by chiselling and preparation of the surface for patination. The process is presented in Figure 4.



**Slika 3.** Silikonska forma (zgoraj levo), nanašanje slojev voska na silikonsko formo (zgoraj na sredini), izdelan ulivni sistem z zračniki (zgoraj desno), cizeliranje voska (spodaj levo), pomakanje in polivanje voščenega modela s keramično suspenzijo (spodaj na sredini) in posipanje s kremenčevim peskom (spodaj desno)

**Figure 3.** Silicone mould (top left), applying layers of wax to the silicone mould (top middle), constructed gating system with vents (top right), chiselling of wax (bottom left), immersion and pouring of the wax model with ceramic suspension (bottom middle) and sprinkling with quartz sand (bottom right)



**Slika 4.** Prelivanje ostanka taline po ulivanju čelade (levo), čelada po ulivanju (na sredini), patinirana čelada (desno)

**Figure 4.** Pouring the leftover melt after casting the helmet (left), the helmet after casting (middle), patinated helmet (right)

## 2.4 Patiniranje izdelka

Proces patiniranja je bil izveden na podlagi predhodnega eksperimenta. Za eksperiment so bile ulite ploščice debeline 4 mm iz enake zlitine kot je bila čelada in tudi lita replika. Na ploščicah se je izvajal eksperiment patiniranja z začetno vodno raztopino žvepljenih jeter (kalijev sulfid), nato pa so sledili nanosi vodne raztopine amonijevega klorida in bakrovega sulfata. Po različnih razmerjih, časih in ponovitvah nanašanja raztopin za patiniranje je bil ugotovljen proces, ki je rezultiral v barvi patine podobne na originalu.

Po cizeliranju je bila čelada razmaščena, da je lahko sprejela patino. Prvi nanos je bila podlaga - temna patina iz žvepljenih jeter (kalijevega sulfida), sledilo je 15 nanosov mešanice amonijevega klorida in bakrovega sulfata z vodo, ki so v rednih presledkih dale žlahtno malahitno patino. V treh tednih premazovanja se je patina stabilizirala in trdno vezala na čelado. Zaščito za patinirano čelado smo izdelali iz čebeljega voska, ki smo ga na površino patinirane čelade nanесли v 5 % raztopini bencina in ga nato spolirali. Končana patinirana čelada je prikazana na sliki 4.

## 3 Zaključki

Rezultat predstavljenega dela je replika negovske čelade iz 4. stol. pr. n. št., ki je bila narejena na podlagi najdene čelade v Beli Krajini. S postopkom 3D tehnologij je bila originalna restavrirana in konservirana čelada posneta, pripravljen 3D model in natisnjen pramodel. Na podlagi tega je bila izdelana silikonska guma, voščeni model ter keramična školjka - forma. Ulita je bila zlitina, enaka kot pri originalu, in sicer bron z 10 mas. % kositra. Po litju, cizeliranju in pripravi površine je bilo izvedeno

## 2.4 Patination of the Product

The patination process was carried out based on a previous experiment. For the experiment, 4 mm-thick plates were cast from the same alloy as the helmet, and also a cast replica. A patination experiment was carried out on the plates with an initial aqueous solution of sulfuric liver (potassium sulphate), followed by applications of aqueous solutions of ammonium chloride and copper sulfate. After different proportions, times, and repetitions of applying patination solutions, a process was established that resulted in a patina colour similar to the original.

After chiselling, the helmet was degreased so that it could accept the patina. The first coat was a base coat - a dark patina of liver of sulphur (potassium sulphide), followed by 15 coats of a mixture of ammonium chloride and copper sulphate with water, which at regular intervals gave a noble malachite patina. Within three weeks of coating, the patina stabilized and firmly bonded to the helmet. The protection for the patinated helmet was made of beeswax, which was applied to the surface of the patinated helmet in a 5% solution of petrol and then polished. Finished helmet is presented in Figure 4.

## 3 Conclusions

The result of the presented work is a replica of the Negova helmet from the 4th century BC, which was made based on a helmet found in Bela Krajina. Using the 3D technology process, the original restored and preserved helmet was photographed, a 3D model was prepared, and a prototype was printed. Based on this, silicone rubber, a wax pattern, and a ceramic shell mould were made. The alloy was cast, the same

patiniranje, ki je dalo podobno barvo in strukturo patine. Tako izdelana replika je že bila in bo predstavljena na več razstavah, končno mesto pa bo našla v Belokranjskem muzeju v Metliki.

Iz predstavljenega je razvidno, da se lahko tehnika precizijkega litja lahko uporablja v različne namene, tako industrijske kot tudi v razvoju in znanosti ter tudi v umetnosti in zgodovini.

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as on the original, namely bronze with 10 wt. % tin. After casting, chiselling, and surface preparation, patination was performed, which gave a similar colour and structure to the patina. The replica made in this way has already been and will be presented at several exhibitions and finally find its place in the Bela Krajina Museum in Metlika.

From what has been presented, the investment casting technique can be used for various purposes, both industrial and in development and science, as well as in art and history.

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### Literatura / References

- [1] Letos mineva natanko 210 let odkar so bile odkrite Negovske čelade. V: *Bakos* [dostopno na daljavo]. Obnovljeno 23.9.2021 [citirano 14.1.2025]. Dostopno na svetovnem spletu: <<https://www.bakos.si/zanimivosti/letos-mineva-natanko-210-let-odkar-so-bile-odkrite-negovske-celade/>>.
- [2] Negovska čelada. V: *NTF* [dostopno na daljavo]. Obnovljeno [citirano 14.1.2025]. Dostopno na svetovnem spletu: <<https://www.ntf.uni-lj.si/ntf/negovska-celada/>>.
- [3] Na Pezdirčevi njivi negovska čelada. V Obnovljeno [citirano 14.1.2025]. Dostopno na svetovnem spletu: <<https://belokranjski-muzej.si/post/504472/na-pezdircevi-njivi-negovska-celada>>.
- [4] Mödlinger, M. in Piccardo, P. Manufacture of Eastern European decorative tin–bronze discs from the twelfth century BC. *Archaeological and Anthropological Sciences*, Springer Science and Business Media LLC, 2013, let. 5, št. 4, str. 299–309.
- [5] Žerjav Jereb, B. Arheometalurška karakterizacija čelade iz pozne železne dobe : magistrsko delo. Univerza v Ljubljani, Naravoslovnotehniška fakulteta, 2023,. Dostopno na svetovnem spletu: <<https://repozitorij.uni-lj.si/Dokument.php?id=175512&lang=slv>>.
- [6] Cvek, Ž. Rekonstrukcija tehnološke poti izdelave negovske čelade iz podzemlja : magistrsko delo. Univerza v Ljubljani, Naravoslovnotehniška fakulteta, 2024,. Dostopno na svetovnem spletu: <<https://repozitorij.uni-lj.si/Dokument.php?id=194298&lang=slv>>.