Metallographic examinations of the Roman Republican weapons from the hoard from Grad near Šmihel

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Izvleček

Za metalografske preiskave je bilo izbranih pet predmetov iz zaklada rimskega orožja z Gradu pri Šmihelu, ki je datiran v konec 3. oziroma v prvo polovico 2. st. pr. Kr. Meč, katapultna konica in preprosta ost z nesimetrično konico imajo pretežno feritno ali feritno perlitno mikrostrukturo. Prav tako imata feritno mikrostrukturo vratova dveh pilumov s ploščatim nasadiščem. Konica enega od pilumov je bila kovaško zvarjena iz mehke (feritne) sredine in trše (perlitne) plasti na površini. Očitno je bila že pri najstarejših pilumih v rabi trda konica z mehkim vratom, kar je izpričano tudi v mnogo poznejših literarnih virih. Sorazmerno slabo kakovost orožja (mehko jeklo) razlagamo z naglico izdelave, oziroma s tem, da gre pri katapultnih konicah in preprostih osteh z nesimetrično konico verjetno za orožje za enkratno uporabo.

Ključne besede: Šmihel, 2. st. pr. Kr., rimska republikanska doba, zaklad, orožje, gladius, pilum, katapultni izstrelek, železo, metalografska preiskava

Abstract

Five objects were chosen for metallographic examinations from the hoard of Roman weapons found at Grad near Šmihel, dated to the end of the 3rd or in the first half of the 2nd centuries BC. The sword, catapult bolt, and simple rod with an unsymmetrical point predominantly have a ferrite or ferrite pearlite microstructure. The shafts of two *pila* with flat hafts also have a ferrite microstructure. The point of one of the *pila* is made from a soft (ferrite) center and a hard pearlite layer on the surface. Evidently the earliest *pila* already had a hard point with a soft shaft, as was noted in much later historical sources. The relatively poor quality of the weapons (soft steel) is explained by the rapidity of production, considering also that the catapult bolts and simple rods with an unsymmetrical point were probably weapons for one-time use.

Keywords: Šmihel, 2nd Cent. BC, Roman Republican period, hoard, weapons, *gladius, pilum*, catapult bolt, iron, metallographic examinations

1. INTRODUCTION

A hoard was found at the prehistoric hillfort of Grad near Šmihel that contained at least 473 iron objects. The majority consisted of Roman offensive weaponry: *pila*, javelins, catapult bolts, arrowheads, swords and many simple rods with triangular unsymmetrical heads. The hoard is dated to the end of the 3rd or in the first half of the 2nd century BC and it represents one of the earliest closed finds of weapons reliably known to be Roman. It is important for understanding the development of individual forms (particularly swords and *pila*) and offers a valuable insight into the Roman techniques of waging war in the period of the Republic. The fact that it was discovered at a settlement of the prehistoric Notranjska (Inner Carniola) cultural group can be explained as the result of one of the first military interventions in the southeastern Alpine region, through which the Romans established control over the trade route from Italy towards central Danubia and the northern Balkans (Horvat 2002).

Important metallographic investigations of steel[1] objects have been undertaken on Celtic weapons (e.g. Pleiner 1993) and on Roman weapons and tools from the end of the 1st century BC onwards (e.g. Pleiner 1970; Horstmann 1995). Weapons from the

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[1] There are no objects made of pure iron. There is always a use of steel, which is an alloy of iron and carbon as well as other alloy elements. The characteristics of steel depend on the contents of the alloy elements, the hot and cold working, and the heat-treament, the basis of which are phase transformations. Thus the expression “steel” is consistently used in the present article,

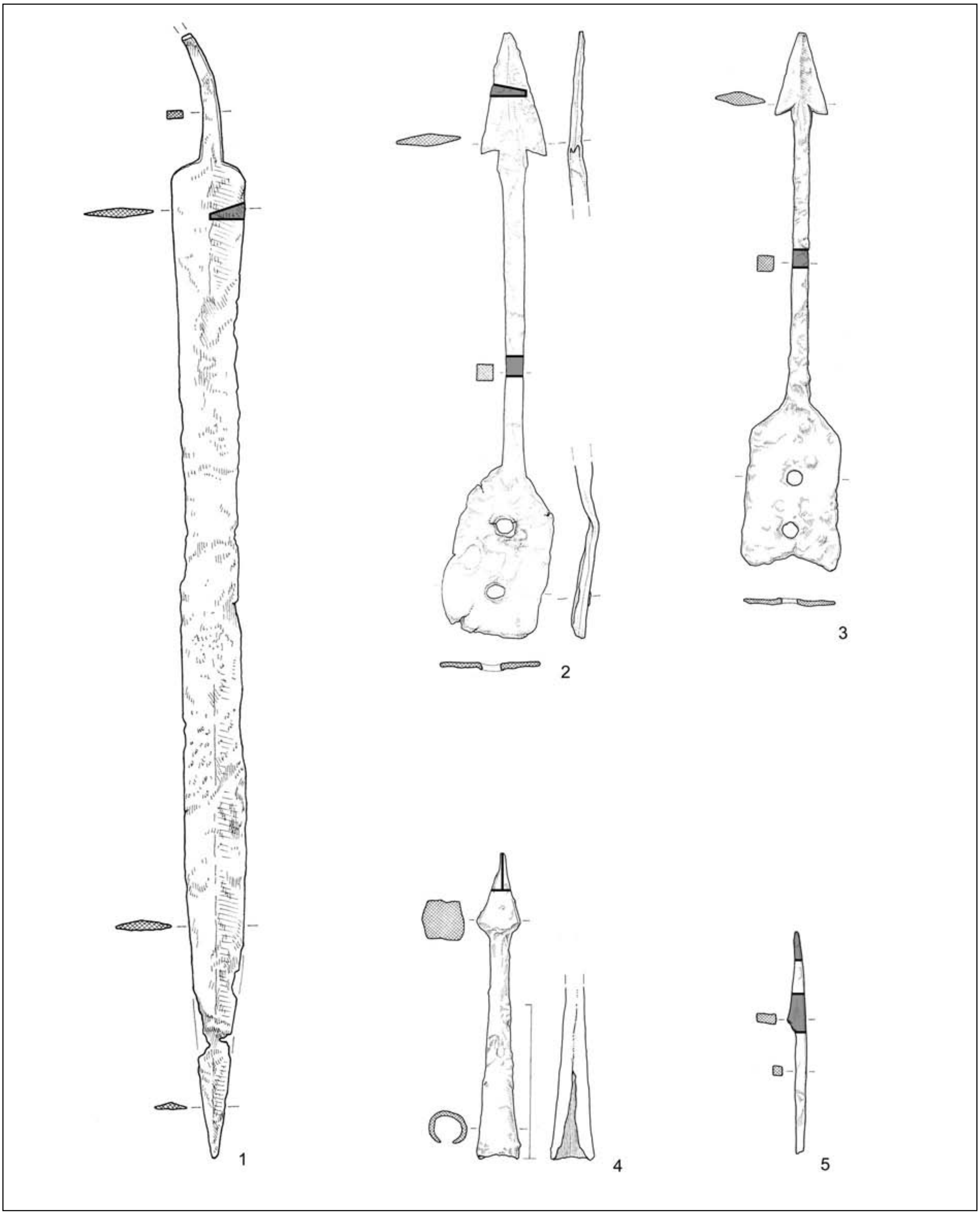

Fig. 1: Objects from the hoard with the places marked where the metallographic samples had been taken. Steel. 1 = 1:4, 2-5 = 1:2.
Sl. 1: Predmeti iz zaklada z označenimi mesti, kjer so bili izrezani metalografski vzorci. Jeklo. 1 = 1:4, 2-5 = 1:2.

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while also describing the microstructure. The expressions "soft steel" or "low carbon steel" are used for the ferrite microstructure, and the expressions "hard steel" or "high carbon steel" for the pearlite microstructure. This differs from part of the archaeological literature, where the expression "iron" is used for steel with a ferrite microstructure, and the expression "steel" for steel with a pearlite and martensite microstructure.
Some metallurgical expressions are explained at the end of the article.

Roman Republican period have previously not been included in metallographic examinations. Consequently all the data that we could acquire about the Roman weapons from Šmihel seemed very important. The intention was to acquire as much information as possible about the technology of making iron from ore and about the technology of manufacturing the weapons. One particular aim was to verify the conjecture of Alfons Müllner that one of the swords (*Fig. 1:* 1) had been manufactured in a special manner (Müllner 1892, 115-116; Müllner 1909, 49-50). We were also especially interested in the *pila*, as on the basis of classical literary sources it can be concluded that their points had been manufactured from a harder steel than their shafts (Schulten 1950, 1360-1364).

Metallographic examination methods are destructive, and thus the research was limited to the smallest possible number of samples. Five objects were chosen from the storerooms of the National Museum of Slovenia:

1. a sword - *gladius* (*Fig. 1:* 1), inv. no. P 3621 (Horvat 2002, Pl. 1: 1);
2. point of a *pilum* with a flat haft, type 1 (*Fig. 1:* 2), inv. no. P 3720 (Horvat 2002, Pl. 3: 3);
3. point of a *pilum* with a flat haft, type 1 (*Fig. 1:* 3), inv. no. P 3721 (Horvat 2002, Pl. 3: 4);
4. a catapult bolt (*Fig. 1:* 4), inv. no. P 3659 (Horvat 2002, Pl. 14: 2);
5. a simple rod with a triangular unsymmetrical point (*Fig. 1:* 5), inv. no. P 3702/1 (Horvat 2002, Pl. 16: 2).

The sword was chosen to verify Müllner's conjecture about a special technology of production. The hoard contains three types of *pila* with flat hafts, socketed *pila*, and incendiary *pila* (Horvat 2002, 129-133). From all these only two *pila* with simple flat hafts and a broad triangular point (type 1) were chosen for metallographic examination. As these were relatively large objects, it was hoped that the samples would also be sufficiently large to verify the hypothesis about the varied manufacture of the point and the shaft. Catapult bolts with a massive pyramidal point were characteristic of the Republican period, very widespread and thus also interesting from the technological standpoint (Horvat 2002, 133, 138). The hoard contained at least 265 simple rods, most of which were hammered on one side into an asymmetric triangular point. Their function has still not been entirely explained, but it is thought that they could be quickly manufactured heads for projectile weapons or points rammed into wooden obstructions (Horvat 2002, 135-137). One of the simple rods with an unsymmetrical triangular point was included in the metallographic analysis with the intention of examining the archaeological age of the object. Despite the destructiveness of the method, because of the large number of very similar rods it was possible to examine a relatively large metallographic sample from them.

Small samples were cut from the objects for analysis so as to cause the least amount of damage possible (*Fig. 1*). The metallographic examination was performed using optical and SEM (scanning electron microscope) and EPMA (electron probe microanalysis) examinations. The microhardness of the steel according to the Vickers hardness testing was measured with a load of 100 g. The samples were too small for chemical analysis in a quantometer, as the preparation of chips for classical chemical analysis would destroy the samples. Only sample no. 5 (P 3702/1; *Fig. 1:* 5) was large enough for quantometric analysis, although because of too high quantities of slag and nonmetallic silicate inclusions the results of the chemical analysis cannot be considered accurate.

2. THE METALLOGRAPHIC EXAMINATIONS

2.1 **Sword P 3621** (*Fig. 1:* 1)

Parallel oblique bands, 6 to 7 mm wide, are visible on the part of the sword where the surface layer has partly broken away (*Fig. 2*). This caused Müllner to suggest that perhaps the sword had not been forged from a single piece of metal, but rather using a technology similar to the damascene technique. A steel rod spirally wound with wire would have been forged into a sword with a double-edged blade. The bands of wire would be from a "bright grained steel" ("weisser körniger Stahl") of medium hardness. Two thin plates of gray steel ("grauer Stahl"), which is very hard, would be forged onto the surface. The core made of oblique bands would occasionally rust at the contact with the covering plates (Müllner 1892, 115-116; Müllner 1909, 49-50).[2]

A sample for metallographic examinations was cut in the upper part of the sword to its center (*Fig. 1:* 1). The sample is thin, and thus we could perform microstructural examinations only on the surface transverse to the axis of the sword.

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[2] Müllner 1909, 49, described another sword from Grad near Šmihel, which was preserved in the Windischgrätz Collection: the core would have been forged from a soft band that was covered on both sides by platelets of hard steel. The sword, which may or may not have been a part of the hoard, could not be identified; Horvat 2002, 128.

Fig. 2: Sword P 3621. Macro photograph of the upper part of the blade from both sides. Photo T. Lauko, National Museum of Slovenia.
Sl. 2: Meč P 3621. Makroposnetka zgornjega dela rezila z obeh strani. Foto T. Lauko, Narodni muzej Slovenije.

The surface of the sword has a layer of slag on one side, and a layer of rust on the other side and along the edge of the blade (*Fig. 3*). The slag comes from the process of ironmaking and can be noted on the micrograph as a gray phase in the crevices along the edge of the blade. The steel contained numerous relatively large nonmetallic inclusions of two types. The large inclusions that are multiphase in appearance are the remains of slag (*Fig. 3*). The second type of inclusions of a dark gray color that are vitreous phase in appearance is silicate (*Fig. 4*). Inclusions of both types are deformed in the direction of plastic deformation (forging) and sometimes lie along the boundaries of crystal grains (*Fig. 4; 5*). Very tiny globular nonmetallic inclusions were noted only at one place.

The slag on the surface and the inclusions of slag in the steel have a similar chemical composition. The inclusions are not homogenous and their composition changes from place to place.

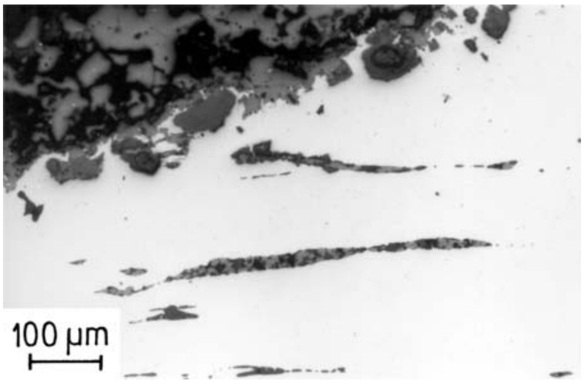

Fig. 3: Sword P 3621. Oxidized surface and multiphase inclusions of slag in the steel.
Sl. 3: Meč P 3621. Oksidirana površina in večfazni vključki žlindre v jeklu.

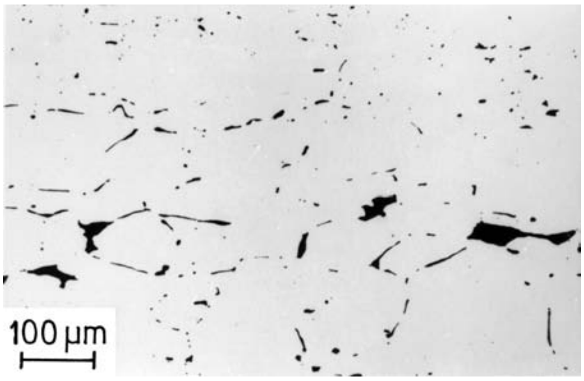

Fig. 4: Sword P 3621. Silicate inclusions in the core of the sword.
Sl. 4: Meč P 3621. Silikatni vključki ležijo na sredini tudi po mejah kristalnih zrn.

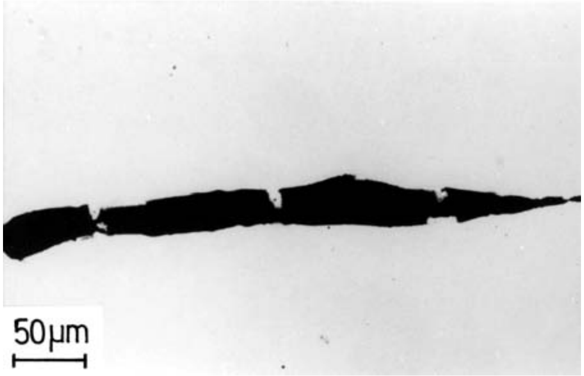

Fig. 5: Sword P 3621. The silicate inclusion elongated and cracked during forging.
Sl. 5: Meč P 3621. Silikatni vključek se je podaljšal in razpokal med kovanjem.

The composition of nonmetallic inclusions was qualitatively analysed by EPM. The elements in the inclusions of slag and in the silicate inclusions (the elements bonded to oxygen) are shown on

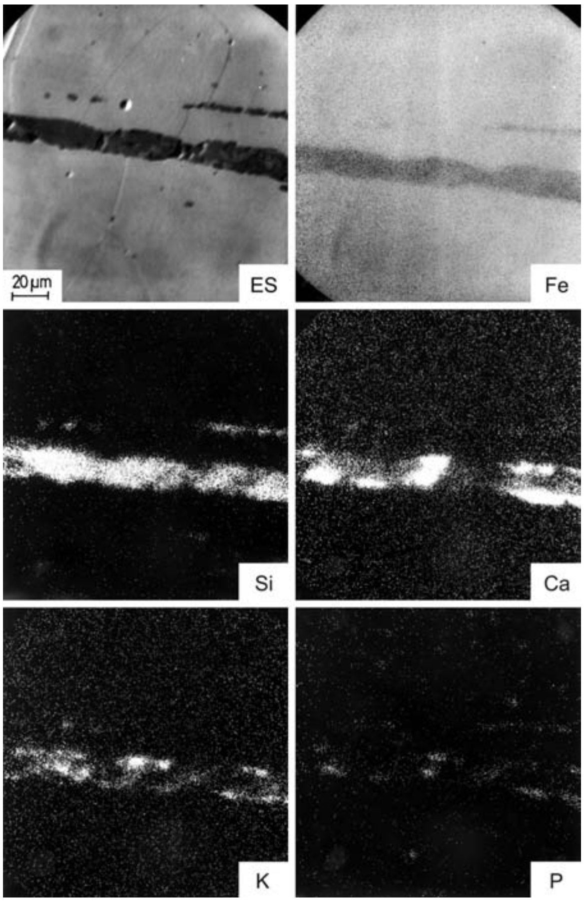

Fig. 6: Sword P 3621. Image of the electron composition (ES) and specific X-ray images of iron, silicon, calcium, potassium, and phosphorus in the inclusion of slag.
Sl. 6: Meč P 3621. Posnetek elektronske sestave (ES) in specifični X posnetki železa, silicija, kalcija, kalija in fosforja v vključku žlindre.

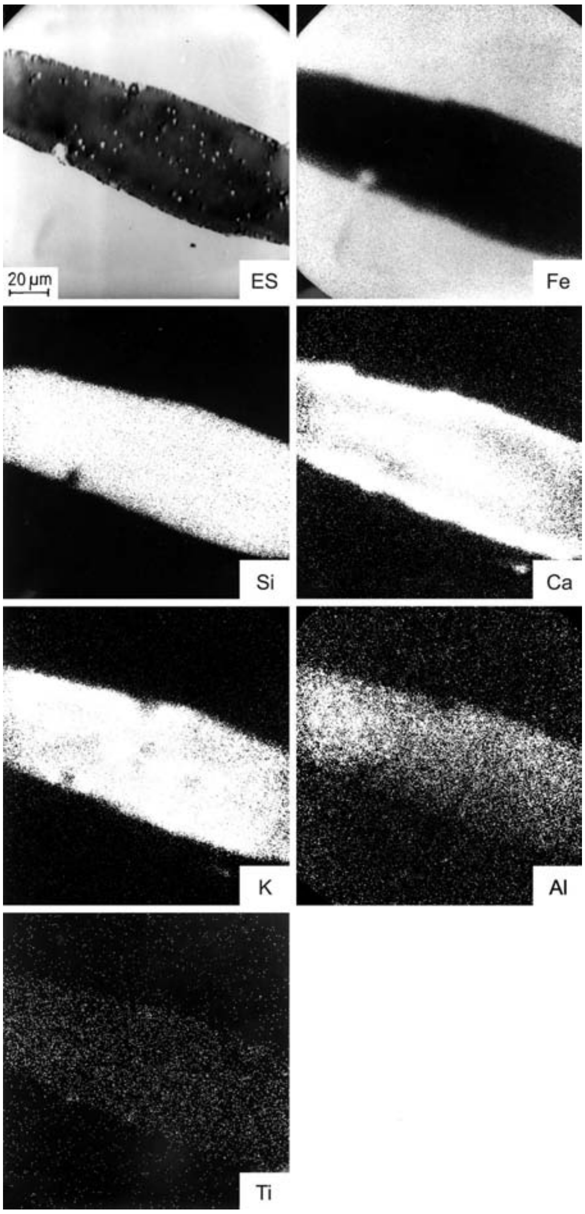

Fig. 7: Sword P 3621. Image of the electron composition (ES) and specific X-ray images of iron, silicon, calcium, potassium, aluminum and titanium in the silicate inclusion.
Sl. 7: Meč P 3621. Posnetek elektronske sestave (ES) in specifični X posnetki železa, silicija, kalcija, kalija, aluminija in titana na silikatnem vključku.

the ES backscattered electron image and specific X-ray images (*Fig. 6; 7*). The concentration of elements on the images is proportional to the relative density of white dots.

The slag (*Fig. 6*), which is non-homogeneous in composition, can be seen to contain large areas corresponding in composition to fayalite ($2FeO.SiO_2$). Individual places show great amounts of calcium and potassium, and small amounts of phosphorus. There is no iron in the silicate inclusions (*Fig. 7*). They contain much silicon, calcium, and potassium, some aluminum, and a little titanium. The composition of the inclusions is homogeneous in comparison to the slag inclusions.

The microstructure of the sword is varied in cross-section. The blade of the sword, rusty on the surface, has a quite ferrite microstructure (content of C under 0.01%) (*Fig. 8*). The crystal grains are polygonal and relatively large. The surface of the sword is decarburized, although not equally deeply on both sides. The band of ferrite of varied width is followed by a ferrite pearlite microstructure (*Fig. 9*). The center of the sword also has a ferrite pearlite microstructure (*Fig. 10*). The carbon content in this area is 0.3%. The form of the cementite lamellae (Fe_3C) in pearlite is shown on the SEM image (*Fig. 11*). Cementite lamellae are coarse and the interlamellar spacing (the total thickness of the cementite and ferrite lamellae in pearlite) is relatively large. A more precise

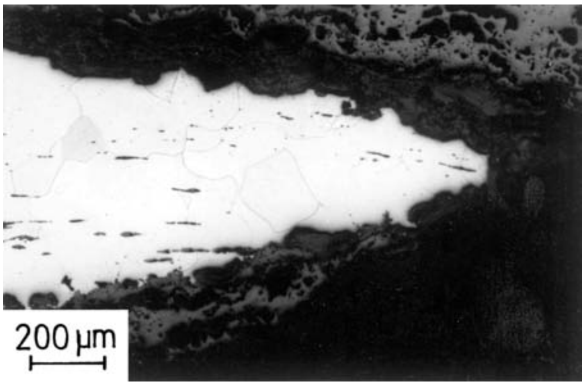

Fig. 8: Sword P 3621. Ferrite microstructure of the blade. A layer of corrosion products on the surface.
Sl. 8: Meč P 3621. Feritna mikrostruktura rezila. Na površini je plast korozijskih produktov.

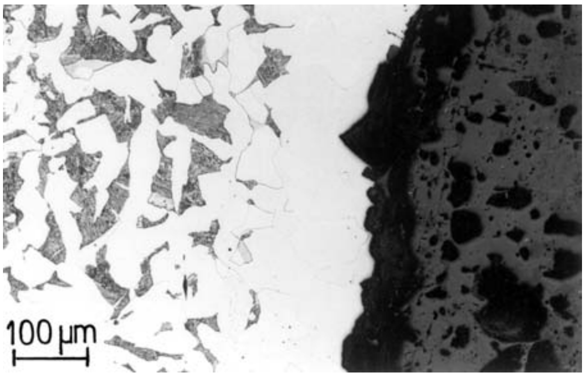

Fig. 9: Sword P 3621. Decarburized ferrite area along the surface merging into a ferrite pearlite microstructure.
Sl. 9: Meč P 3621. Razogljičeno feritno področje ob površini prehaja v feritno perlitno mikrostrukturo.

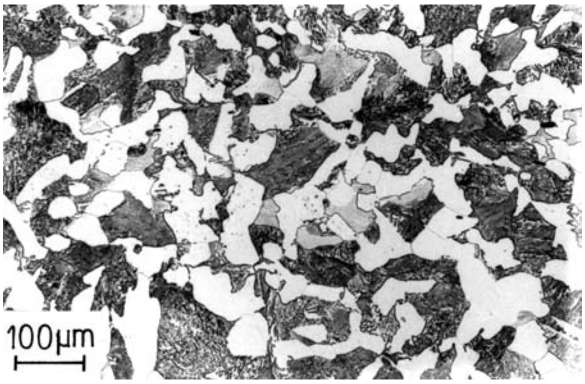

Fig. 10: Sword P 3621. Ferrite pearlite microstructure in the center of the sword.
Sl. 10: Meč P 3621. Feritno perlitna mikrostruktura na sredini meča.

examination of the sample showed tertiary cementite along the crystal grains boundaries in the area with a ferrite microstructure, and tiny precipitates in the ferrite matrix (*Fig. 12*).

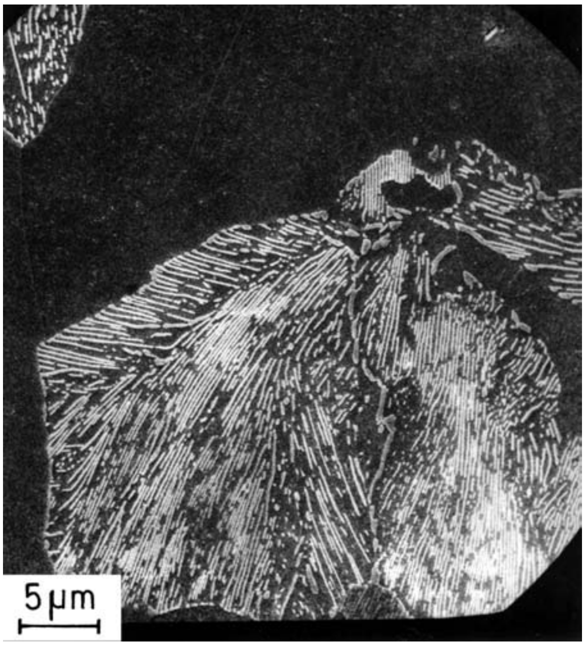

Fig. 11: Sword P 3621. SEM image of the ferrite pearlite microstructure.
Sl. 11: Meč P 3621. SEM posnetek feritno perlitne mikrostrukture.

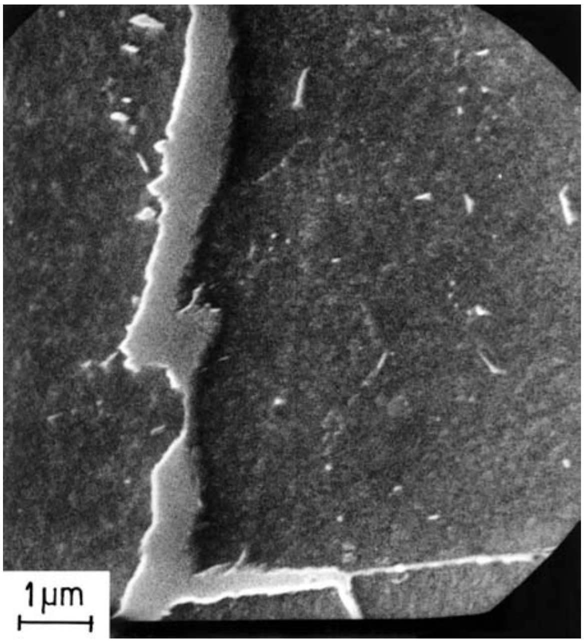

Fig. 12: Sword P 3621. Tertiary cementite at the ferrite grain boundary and tiny precipitates in the ferrite matrix.
Sl. 12: Meč P 3621. Terciarni cementit na meji feritnih zrn in drobni izločki v feritni matici.

The average micro-hardness of the steel was 87 HV on the edge of the sword, where the microstructure is ferrite. The micro-hardness in the area with a ferrite pearlite microstructure was greater, from 95 to 115 HV.

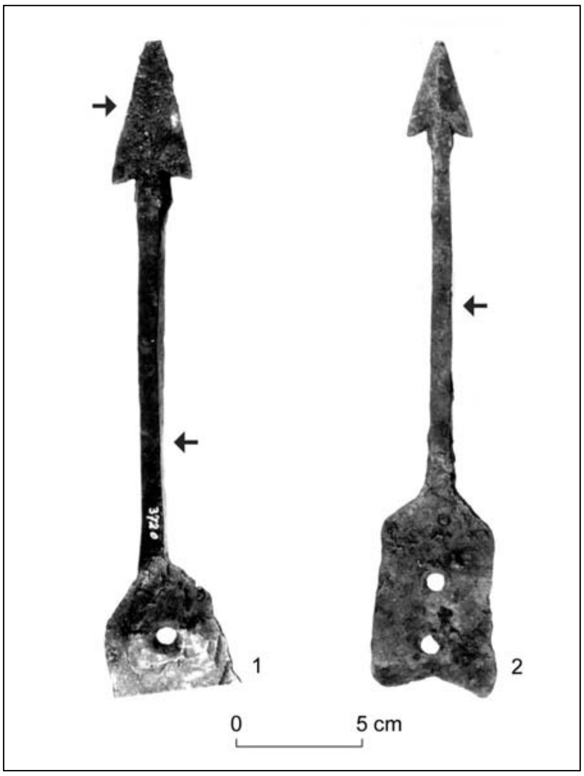

Fig. 13: Macro photograph of *pila* with the areas of metallographic examination marked. 1 pilum P 3720, 2 pilum P 3721.
Sl. 13: Makroposnetka pilumov z označenimi mesti metalografskih preiskav. 1 pilum P 3720, 2 pilum P 3721.

2.2 ***Pilum*** **P 3720** (*Fig. 1:* 2; *13:* 1)

The point of the *pilum* was roughly made, with clearly visible traces of forging without any additional finishing (*Fig. 13:* 1).

Two samples were taken from the *pilum* for metallographic examination, from the point (longitudinal), and from the shaft (longitudinal and transverse) (*Fig. 1:* 2).

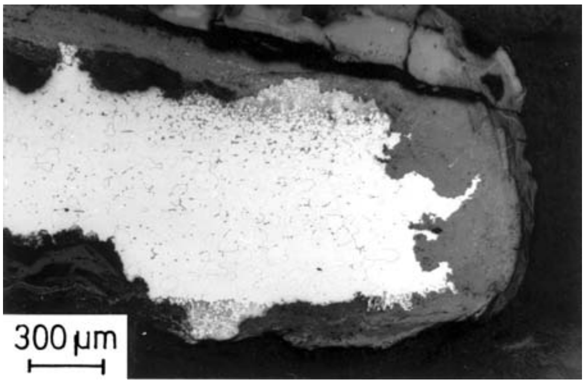

Fig. 14: Pilum P 3720. Microstructure of the edge of the point. The center is ferrite, and despite the corrosion damage it can be seen that the surface has a pearlite microstructure.
Sl. 14: Pilum P 3720. Mikrostruktura roba konice. Sredina je feritna, na površini pa se kljub korozijskim poškodbam opazi, da je ta perlitna.

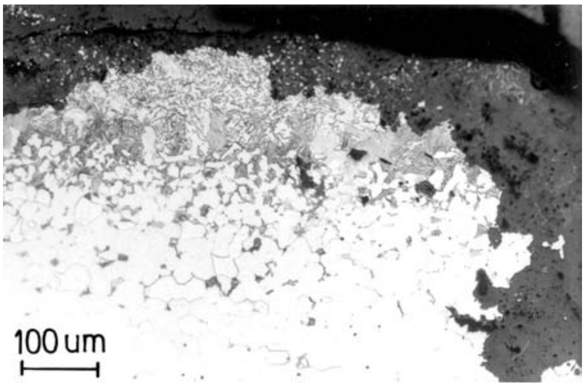

Fig. 15: Pilum P 3720. At greater magnification, corrosion products can be seen on the surface of the point, with the pearlite microstructure laying under it.
Sl. 15: Pilum P 3720. Pri večji povečavi se ob perlitni mikrostrukturi na površini konice opazijo korozijski produkti.

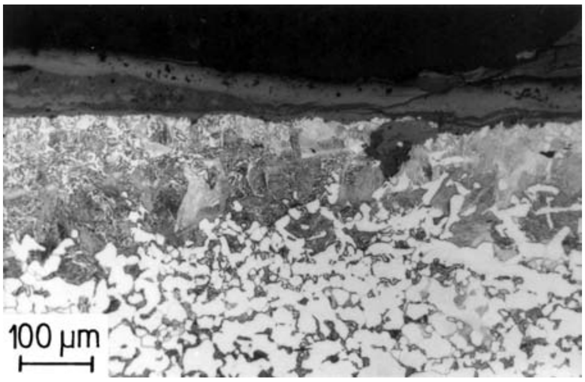

Fig. 16: Pilum P 3720. Pearlite microstructure along the surface of the point - 20 mm from the lateral edge.
Sl. 16: Pilum P 3720. Perlitna mikrostruktura ob površini konice - 20 mm od stranskega roba.

The point of the *pilum*, which is highly damaged because of corrosion, has a layer of rust. The steel in the middle of the point has a ferrite microstructure. Despite corrosion damage it can be seen that the microstructure of the surface layer was pearlite (0.7% C) (*Fig. 14; 15*). At 20 mm from the lateral edge of the point (interior limit area of the sample), the microstructure was quite pearlitic next the surface on one side (*Fig. 16*), while on the other side, which was heavily damaged by corrosion, the microstructure consists of ferrite and pearlite. The sharp boundary between the totally pearlite and ferrite microstructure indicates that the point of the pilum was forge welded from hard steel on the surface and a soft core.

The microstructure of the sample cut from the shaft is mostly ferrite, and only a small amount of perlite is present in individual bands in the center.

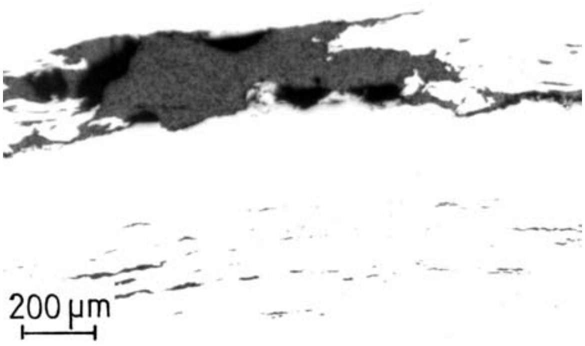

Fig. 17: Pilum P 3720. A large slag inclusion and a cluster of silicate inclusions.
Sl. 17: Pilum P 3720. Večji vključek žlindre in niz silikatnih vključkov.

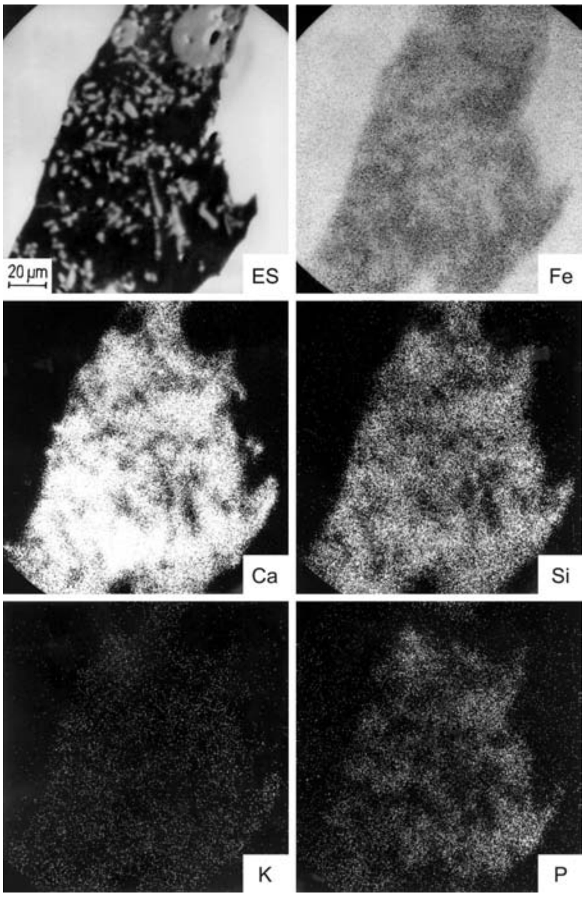

Fig. 18: Pilum P 3720. Image of the electron composition (ES) and specific X-ray images of iron, calcium, silicon, potassium, and phosphorus in the slag inclusion.
Sl. 18: Pilum P 3720. Posnetek elektronske sestave (ES) in specifični X posnetki železa, kalcija, silicija, kalija in fosforja v vključku žlindre.

The steel contained numerous relatively large nonmetallic inclusions of two types. The long inclusions, two-phase in appearance, are remains of slag. The other types of inclusions, of a dark gray color, are of the vitreous phase in appearance and are silicate. The silicate and the slag inclusions are elongated, as they were plastic at the forging temperature and were deformed longitudinally. The sample cut from the shaft of the pilum has more nonmetallic inclusions, which are mostly arranged in clusters. Inclusions of slag are larger than inclusions of calcium silicates (*Fig. 17*). The analysis of a large slag inclusion is shown on *Fig. 18*. Beside iron, the slag contains large amounts of calcium and silicon, some potassium, phosphorus and manganese. The slag

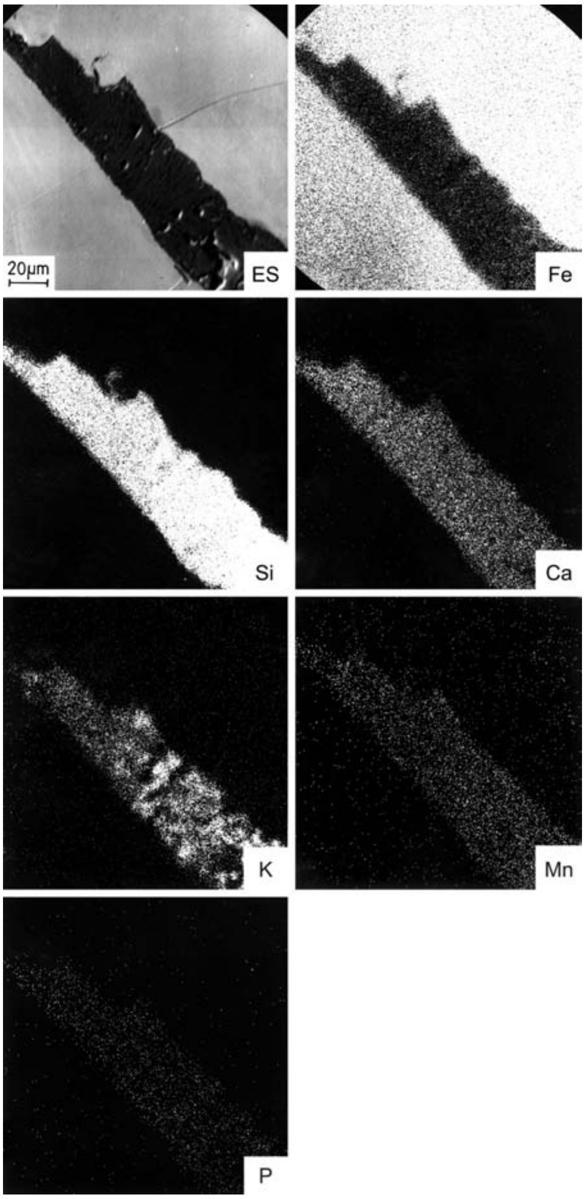

Fig. 19: Pilum P 3720. Image of the electron composition (ES) and specific X-ray images of iron, silicon, calcium, potassium, manganese and phosphorus in the silicate inclusion.
Sl. 19: Pilum P 3720. Posnetek elektronske sestave (ES) in specifični X posnetki železa, silicija, kalcija, kalija, mangana in fosforja na silikatnem vključku.

is two-phase. The pale gray phase is mostly iron and in composition corresponds to wüstite (FeO). The concentration of the other elements is greater in the darker phase. The silicate inclusions contain much silicon, calcium, and potassium, a little manganese, and traces of phosphorus (*Fig. 19*). These inclusions contain no iron.

The average microhardness of the steel with the ferrite microstructure is 88 HV. The quite pearlite area on the surface of the point is harder, the greatest value measured is 135 HV.

2.3 ***Pilum*** **P 3721** (*Fig. 1:* 3; *13:* 2)

The *pilum* was very roughly made, so that traces of forging are clearly visible (*Fig. 13:* 2).

The sample for metallographic analysis was taken from the shaft of the *pilum* (*Fig. 1:* 3). Microstructural examination was performed longitudinally and transversely. The surface of the sample is rusted and shallow corrosion crevices are seen along the crystal grain boundaries in several places. The layer of the steel along the surface consists of completely decarburised ferrite coarse grains. Below this layer, the ferrite microstructure, in which the crystal grains are smaller, contains numerous tiny precipitates. There are no precipitates in the center of the shaft. There are numerous nonmetallic inclusions of various sizes in this area, which in terms of composition are mostly slag, with fewer silicate inclusions. The morphological characteristics and composition of the nonmetallic inclusions of slag and silicates are identical to the inclusions of *pilum* P 3720.

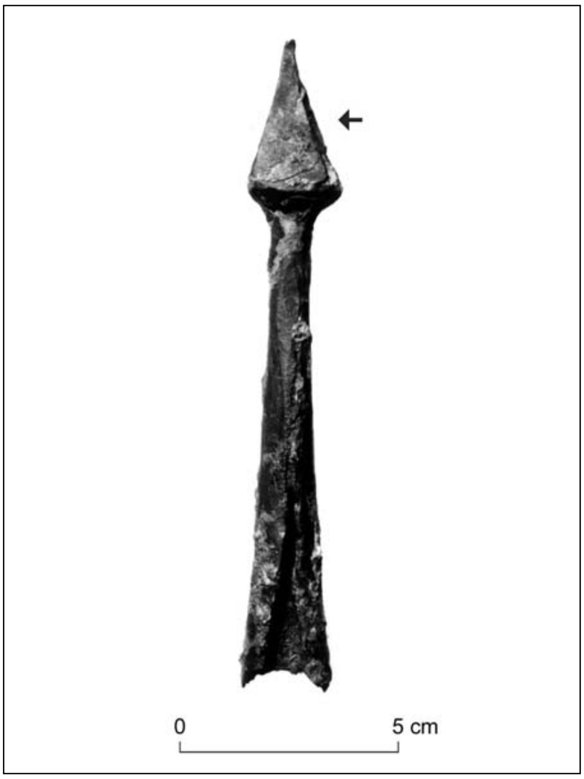

Fig. 20: Catapult bolt P 3659. Macro photograph with area of examination marked.
Sl. 20: Katapultni izstrelek P 3659. Makroposnetek z označenim mestom preiskav.

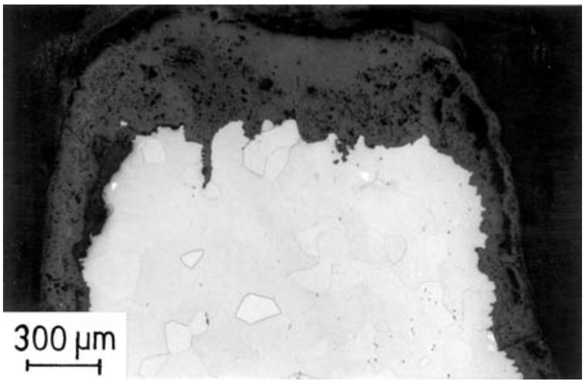

Fig. 21: Catapult bolt P 3659. Ferrite microstructure.
Sl. 21: Katapultni izstrelek P 3659. Feritna mikrostruktura.

The microhardness of the steel is 87 HV on the edge of the shaft of the *pilum*, where the microstructure is ferrite. The microhardness is somewhat greater in the center of the shaft, where precipitates in the ferrite are numerous. The greatest value measured is 95 HV.

2.4 **Catapult bolt P 3659** (*Fig. 1:* 4; *20*)

The sample for analysis was cut transversely on the point (*Fig. 20*). It was prepared for metallographic examination in a longitudinal direction (*Fig. 1:* 4). The point of the bolt has a completely ferrite microstructure (*Fig. 21*). Under greater magnification, grains can be noted of tertiary cementite precipitated along the ferrite grain boundaries. The ferrite grains contain tiny precipitates (*Fig. 22*). The microhardness of the steel is 92 HV.

The surface of the point is covered with a layer of scale (iron oxides, which were created on the surface during heating for forging), which is shallowly indented into the ferrite matrix along the crystal grain boundaries (*Fig. 23*). The analysis of the scale at the boundary with the steel is shown on *Fig. 24.* The scale contains only traces of calcium, potassium, and phosphorus, while the steel contains a small amount of nickel and traces of copper. The concentration of the nickel in the steel is increased in the boundary layer with the scale.

Nonmetallic inclusions in the steel are remains of slag and silicate inclusions. They are relatively

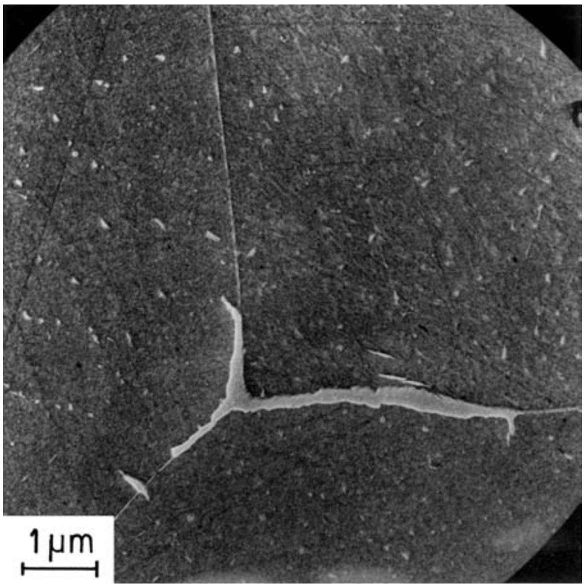

Fig. 22: Catapult bolt P 3659. Tertiary cementite at the boundary of three ferrite grains and tiny precipitates in the ferrite matrix.
Sl. 22: Katapultni izstrelek P 3659. Terciarni cementit na meji treh feritnih zrn in drobni izločki v feritni matici.

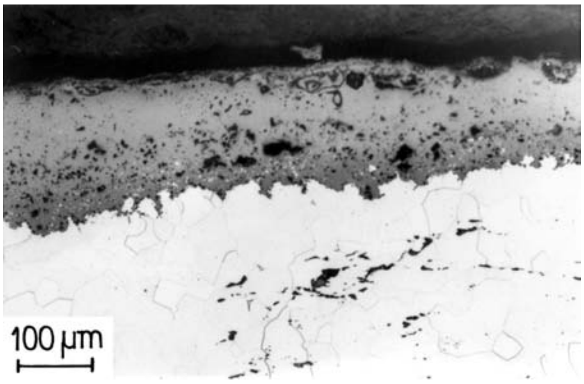

Fig. 23: Catapult bolt P 3659. Scale on the surface.
Sl. 23: Katapultni izstrelek P 3659. Škaja na površini.

large and are oriented variously because of deformation during hot forging. The slag inclusions are distinctly two-phase. The pale gray phase is iron oxide. The darker phase contains in addition to oxides of iron, also oxides of calcium, silicon, and potassium, as well as traces of phosphorus. The silicate inclusions contain no iron. They are composed of oxides of silicon, calcium, and potassium, with traces of aluminum, phosphorus, manganese, and sulfur.

2.5 **Simple rod with an unsymmetrical point P 3702/1** (*Fig. 1:* 5; *25*)

The hoard contained at least 265 simple rods of square section, hot forged at both ends into points.

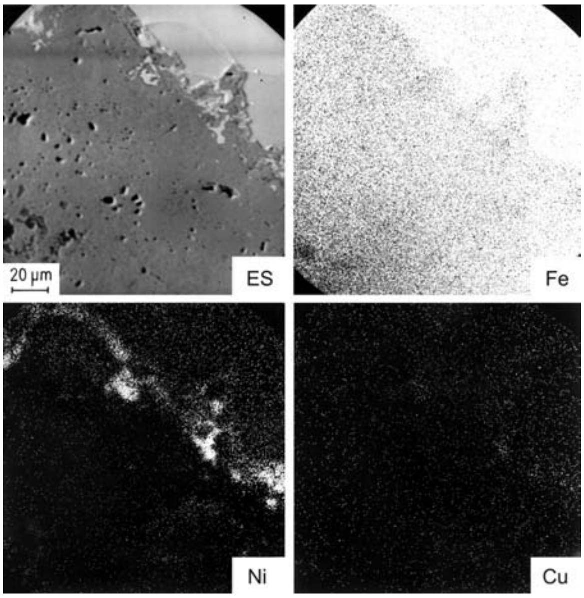

Fig. 24: Catapult bolt P 3659. Image of the electron composition (ES) and specific X-ray images of iron, nickel, and copper in the scale at the boundary with the steel.
Sl. 24: Katapultni izstrelek P 3659. Posnetek elektronske sestave (ES) in specifični X posnetki železa, niklja in bakra v škaji na meji z jeklom.

Most have a triangular tooth or prong on one side at approximately one third of the length, which continues into a point, while the other end has a spiked point - possibly for placing in a haft or socket.

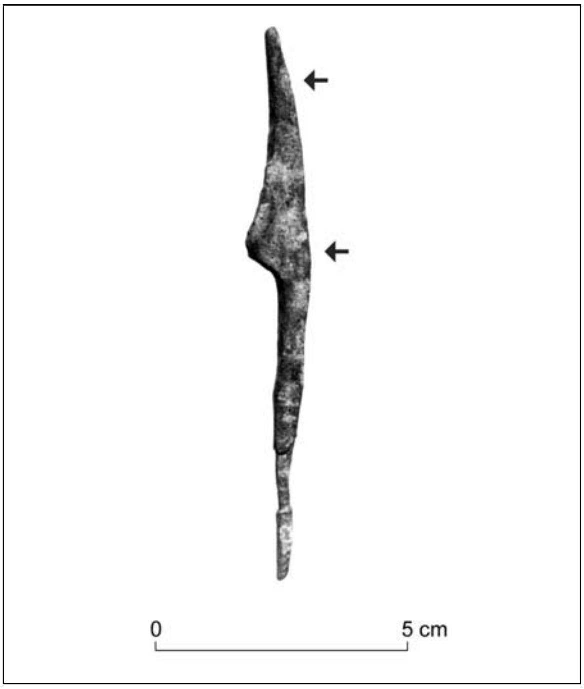

Fig. 25: Rod P 3702/1. Macro photograph with the area of examination marked.
Sl. 25: Ost P 3702/1. Makroposnetek z označenima mestoma preiskav.

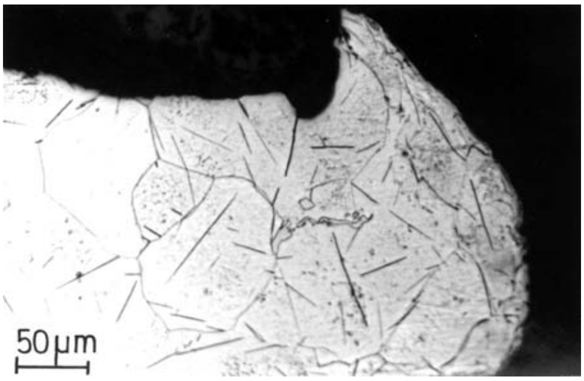

Fig. 26: Rod P 3702/1. Microstructure at the tip of the point.
Sl. 26: Ost P 3702/1. Mikrostruktura ob vrhu osti.

Fig. 27: Rod P 3702/1. Microstructure of the rod in a distance of 10 mm from the tip.
Sl. 27: Ost P 3702/1. Mikrostruktura osti v oddaljenosti 10 mm od vrha.

The sample for examination from rod P 3702/1 was taken from the area of the triangular tooth and from the tip of the point (*Fig. 1:* 5; *25*). Metallographic examination was performed in a longitudinal direction.

The steel at the tip has a ferrite microstructure, in which there are numerous precipitates, mostly of lamellar form, and partly also globular (*Fig. 26; 27*). Identical precipitates were noted on the catapult bolt P 3659. Tertiary cementite can also be noted along the boundaries of the crystal grains. The surface of the tip is covered with corrosion products. Shallow corrosive crevices along the grain boundaries extend into the metal matrix. In the area of the triangular tooth, scale was noted on the surface, although signs of corrosion processes (rusting) could also be noted. The density of precipitates is greater in the ferrite phase, increasing with the distance from the tip of the point. Pearlite grains can also be noted in the microstructure, containing coarse cementite lamellae that were created because of relatively slow cooling from the temperature of hot forging. These microstructure characteristics can be even more markedly noted on the SEM images (*Fig. 28; 29*).

The transition from the haft to the tooth is of steel with a ferrite pearlite microstructure (0.15% C), in which a distinct difference can be seen in the size of the crystal grains. The haft has a fine-grained recrystalized microstructure because of the greater deformation caused by forging. The degree of hot forming of the broader section (tooth of

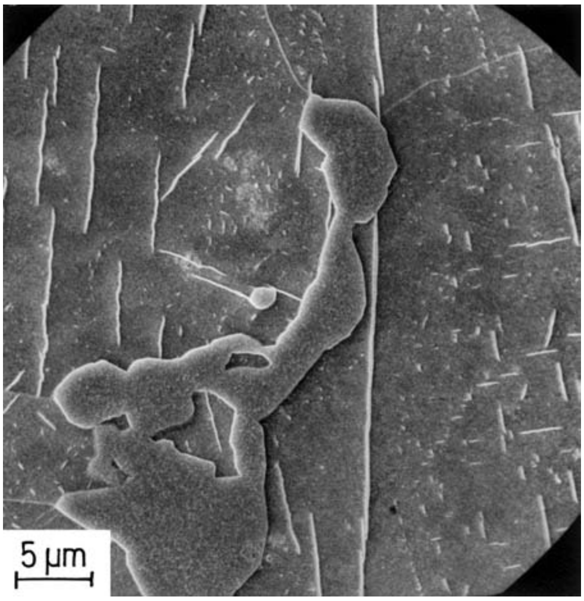

Fig. 28: Rod P 3702/1. Tertiary cementite and precipitates in the ferrite matrix.
Sl. 28: Ost P 3702/1. Terciarni cementit in izločki v feritni matici.

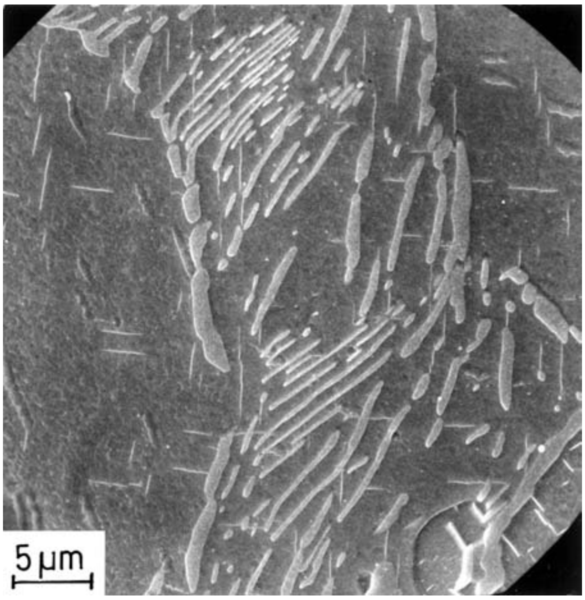

Fig. 29: Rod P 3702/1. Coarse cementite lamellae in the pearlite and in the precipitates in the ferrite.
Sl. 29: Ost P 3702/1. Grobe cementitne lamele v perlitu in izločki v feritu.

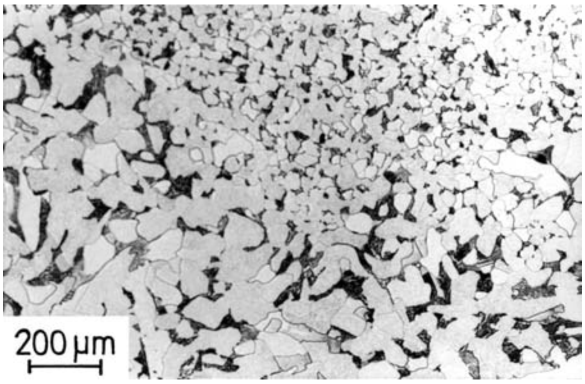

Fig. 30: Rod P 3702/1. Microstructure at the transition from the haft to the tooth of the rod.
Sl. 30: Ost P 3702/1. Mikrostruktura na prehodu iz nasadišča v zob osti.

the point) was lesser, and hence the crystal grains are larger (*Fig. 30*).

Just as for the other samples, two types of nonmetallic inclusions were noted in the steel, inclusions of multiphase slag and silicate inclusions. A relatively high content of manganese was observed in the slag (*Fig. 31*), in addition to iron, silicon, calcium, and potassium, as had been noted on the other samples. The pale gray phase in the slag represents iron oxides. Similarly, the silicate inclusions contained a high manganese content in addition to silicon, calcium, and potassium.

The microhardness of the steel at the tip of the point is 87 HV. The greatest microhardness values, from 110 to 115 HV, were measured in the area with the ferrite pearlite microstructure (at the transition from the haft to the tooth).

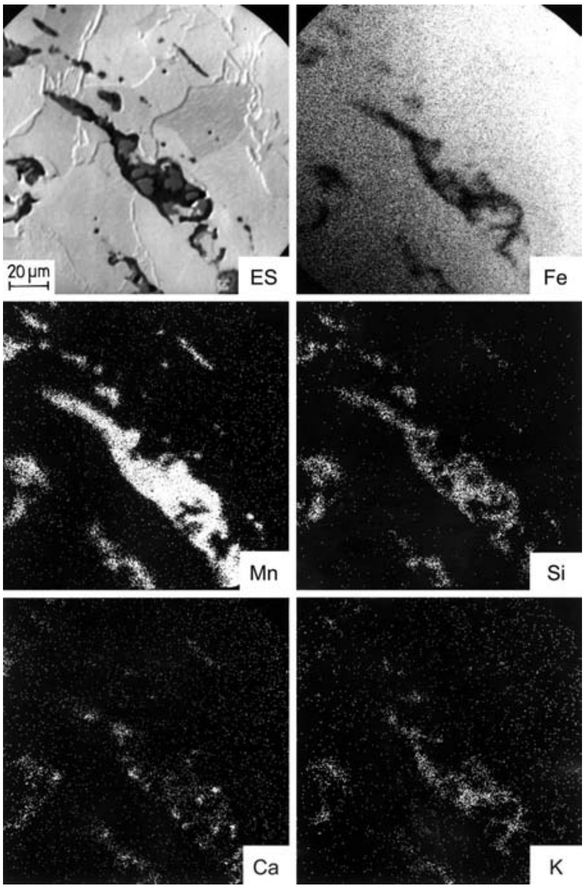

Fig. 31: Rod P 3702/1. Image of the electron composition (ES) and specific X-ray images of iron, manganese, silicon, calcium, and potassium in the slag inclusion.
Sl. 31: Ost P 3702/1. Posnetek elektronske sestave (ES) in specifični X posnetki železa, mangana, silicija, kalcija in kalija v vključku žlindre.

2.6 **Composition of the slag and the silicate inclusions**

Semi-quantitative analysis of the nonmetallic inclusions of slag and silicate inclusions was performed on the samples from the sword, catapult bolt, and rod.

The slag inclusions are non-homogeneous, and thus it is difficult to determine their composition with electron probe microanalysis. The average composition of the inclusions of slag in the sword and the rod is shown in *table 1*. The composition of the slag is similar, with a high FeO content, much SiO_2 and a little CaO, which is characteristic for bloomery ironmaking in a shaft furnace (Pleiner 2000, 251-253). The slag of the rod contains a relatively high content of manganese oxide, similar to the analyzed slag from the Roman period at Lölling (12.1% MnO; Neumann 1954, 36) and the slag in the loup from Magdalensberg (sample D, 36% MnO) in Austrian Carinthia (Straube 1996, 98-99). Iron ore from Carinthia and Burgenland is characterized by a high manganese content, which is also retained in the slag (Sperl 1985, 412-413; Straube 1996, 55, 98, 111).

Table 1: Composition of the slag in mass percentage.

Phase	Sword P 3621	Simple rod P 3702/1
FeO	52. 3	54.6
Fe_2O_3	-	-
SiO_2	32.3	19.6
Al_2O_3	1.4	1
CaO	7. 2	3
MgO	-	-
MnO	-	16.8
K_2O	1.5	0.8
P_2O_5	0.2	0.1
TiO_2	0.1	0.1
S	-	-

Table 2: Composition of the silicate inclusions in mass percentage.

Phase	Sword P 3621	Cat. bolt P 3659	Simple rod P 3702/1
MnO	0.6	0.8	32.5
SiO_2	50.1	49.5	40.5
Al_2O_3	7.6	4.3	1
CaO	29.3	33.2	21.5
MgO	-	-	0.4
K_2O	9	7	2.2
P_2O_5	1	1	0.6
TiO_2	0.4	< 0.1	0.4
S	-	< 0.1	-

The composition of the silicate inclusions analyzed in the samples from the sword, catapult bolt, and simple rod is given in *table 2.* The high contents of SiO_2 and K_2O meant that they had a low melting point and had plasticity at the forging temperature. The silicate inclusions of the rod contain a high fraction of MnO, just like the slag of the rod.

The contents of elements that are otherwise usually present in steel were also analyzed in the steel. The metal matrix is almost pure iron with only a very small manganese content (under 0.1%).

3.0 **DISCUSSION**

Iron was made in shallow pit and shaft furnaces up to the late Middle Ages in Europe. To successfully smelt forgeable (ductile) iron and to work it knowledge was required, which is significantly different than today, when numerous examination methods and experiments are available to determine the suitable quality of steel. The iron had to have a low carbon content (to 0.7% C) to achieve a plasticity that would allow it to be forged. A sufficiently high temperature and gas for reduction (CO) were gained with the combustion of charcoal. With low carbon content in the iron, part of the FeO (melting point 1377°C) remained in the slag, in which because of the presence of SiO_2 fayalite was created ($2FeO.SiO_2$), which has a low melting point (1217°C). Successful low temperature production of iron (1200°C) occurred only with tiny grained ore. Reduced metallic particles coalesced together at higher temperatures into a large doughy clump, from which most of the slag was removed by forging. The presence of CaO increases the melting point of slag, and MnO and K_2O decreases it. The ore thus had to contain under 10% CaO. Iron from shaft furnaces was inhomogeneous, and the carbon content was varied. The iron was decarburized or carburized, depending on the atmosphere, during heating on the forging hearth (Craddock 1995, 234 ff.).

The metal matrix of all the examined samples was quite pure iron with a relatively low carbon content (0.01 to 0.3% C). The steel of the simple rod has more manganese than the other samples, while the steel of the catapult bolt has traces of nickel and copper. This indicates that the steel from which the weapons were made had been acquired from iron ores with different trace elements.

The steel contained two types of nonmetallic inclusions, inclusions of slag and silicate inclusions.

The slag inclusions result from the process of ironmaking from ore (the reduction of iron oxides) and are two-phase. The phase that corresponds to wüstite in composition (FeO), has a higher melting point and during solidification of the slag solidifies first, and thus has a prevalently dendritic microstructure. The other phase has less iron, and contains large amounts of silicon and calcium, a little potassium, aluminum, and manganese, as well as traces of phosphorus and titanium. A high manganese content was noted only in the slag inclusions of the steel of the simple rod (P 3702/1).

The second type of nonmetallic inclusions consists of silicates with high contents of calcium and potassium. The aluminum, titanium, phosphorus, manganese, and sulfur contents are low, or are present only as trace elements. A higher manganese content was noted for the inclusions of the simple rod (P 3702/1). As the silicate inclusions do not contain iron, they probably did not come from the ore. It is our opinion that they could derive from the walls of the smelting furnaces, which contained silicates rich in potassium (clay). Part of the potassium entered into the slag and into the silicate inclusions from the charcoal.

The examined objects were well forged. The microstructural characteristics that would indicate quenching were not noted on any of the samples. Nor were signs of cold deformation noted on the objects, which is also one of the technologies of hardening the surface and increasing the total hardness.

3.1 **Sword**

The blade of the sword from the hoard has a quite ferrite microstructure on the surface (under 0.01% C), while the center has a ferrite pearlite microstructure (0.3% C). The ferrite grains along the blade are essentially larger than elsewhere on the surface of the sword, as well as the grains of the ferrite pearlite microstructure in the core. The crystal grains are also larger in comparison with the crystal grains on the other samples, which indicates that the sword was forged at a relatively high temperature (ca 1000° C). The boundary between the ferrite and ferrite pearlite microstructure did not exhibit oxide inclusions that would indicate the production of the sword from several bands or wound wires. The surface of the sword is corroded to such an extent that on the basis of metallographic analysis it cannot be established if lamellae of a harder steel were forged onto the surface. A sample for examination was taken from only one spot on the sword, but nonetheless we consider that it was most probably made from one piece or perhaps from several bands or wires with an approximately equal carbon content. Such an explanation is also confirmed by the layer of slag on one side of the sword, which remained on the surface of the product and prevented the rusting of the steel, which has a ferrite microstructure in this area. Thus Müllner's hypothesis can be rejected that the sword had been made from several bands and layers (Müllner 1892, 115-116; Müllner 1909, 49-50). The surface of the sword was subjected to decarburization during heating for forging. The blade thus has a relatively low hardness (87 HV) and the weapon cannot be considered a top rate product.

3.2 **Pila**

The point of *pilum* P 3720 has an area with a strongly pearlite microstructure (0.7% C) lying under corrosion products. The pearlite area continues into a strongly ferrite core. The surface of the point of the pilum is badly damaged by corrosion, although the pearlite microstructure on the surface and the sharp transition to the ferrite region in the core indicate that the *pilum* point P 3720 was forge welded of hard and soft steel. Hard steel with a high carbon content is less resistant to corrosion, and thus the surface of the weapon was more damaged by corrosion. The shafts of both *pila* (P 3720, P 3721) have a ferrite microstructure with a very small element of a pearlite phase, meaning that in contrast to the point of *pilum* P 3720, they had been made from a single piece of soft steel.

3.3 **Catapult bolt and simple rod**

The point of the catapult bolt and the simple rod have a strongly ferrite microstructure, and only on the thickened part of the rod (the tooth) the microstructure consists of ferrite and pearlite (0.15% C). Both objects were forged from non-homogeneous blanks with varied carbon contents, but the iron was decarburized during heating for forging in a blacksmith's hearth.

The ferrite of both objects exhibited more or less distinctive precipitation of tertiary cementite along the crystal boundaries and precipitation of tiny, mostly lamellar carbides from the matrix. Precipitation could occur only during extremely slow cooling.

3.4 **The place of the Šmihel weapons in technological development**

The majority of the important processes of forging were already known in the Hallstatt period in central Europe and in the Mediterranean, although the technological knowledge was not equally distributed. Individual combinations of hard and soft steel occasionally appear, and only exceptionally do we come across quenching and secondary carburization (Pleiner 1962, 50-63, 259-261; Tylecote 1992, 52-53; Craddock 1995, 238, 260).

Bloomery advanced greatly in the La Tène period (Pleiner 1962, 64-101, 261-267). The metallographic analysis of 122 Celtic swords has shown that the steel was mostly heterogeneously carburized. The knowledge of forging was at various levels, and thus the swords were of varied quality. Only 36% of the analyzed swords were made entirely of soft steel with a carbon content under 0.3% (ferrite or ferrite pearlite microstructure). Swords forged from one piece of steel are rare, the majority were forged from several layers, which were of identical or varied quality. More than half of the swords had at least one blade from middle carbon (0.3-0.5% C; ferrite-pearlite microstructure) or high carbon steel (0.6-0.8% C; pearlite microstructure). Some swords were made entirely from middle or high carbon steel, while the majority was produced from alternating low, medium, and high carbon steel. The various systems of arranging the layers indicate that the majority of smiths were uncertain in distinguishing between soft and hard steel. Secondary carburization of a blade was rare, and quenching and cold forging were not applied (Pleiner 1993).

In the lands of the Norican Kingdom, present day Carinthia and Burgenland, ironmaking was prominent owing to the greater carbon content (Schaaber 1963; Sperl 1985; Straube 1996). Tools and weapons from such steel appeared in this area as early as the Hallstatt period (Plöckinger 1976). The production of hard steel was very widespread in the late La Tène and Roman periods. The production of and trade in steel was controlled by the Romans from the middle of the 1st century BC (Dolenz 1996; Dolenz 1998).

In the Roman Imperial period, the production of iron increased greatly, and the knowledge of carburization and quenching spread. The Roman weapons and tools include exceptional, very good, and plain products, the latter predominating (Schaaber 1963; Pleiner 1970; Tylecote, Gilmour 1986, 18-108; Tylecote 1992, 65-68). The high level of knowledge of the materials and bloomery procedures can be seen above all in the weapons (Tylecote 1992, 65-68). The best daggers of the Augustan period were made so that the center and the blades were particularly hard, and between them lay bands composed of alternating strips of hard and soft steel (lamellar damascene). The blade of the dagger from Oberaden was first quenched, and then tempered at a raised temperature. Such weaponry had excellent mechanical properties; it was hard and tough (Pleiner 1970, 118-120, 128-130; Horstmann 1995; Westphal 1995; Lang 1995). The swords between the Augustan period and the 2nd century AD have a more simple structure. They were composed of several layers of identical, carburized steel. Quenching and tempering were used on the blades (Williams 1977, 78; Biborski et al. 1987; Lang 1988; Lang 1995, 127; Dieudonné-Glad, Parisot 1998). Pattern welding or true damascening of swords appear in greater amounts from the end of the 2nd century onwards (Ypey 1984, 195 ff.; Tylecote 1992, 66-68).

The weapons from Šmihel stand out in terms of their microstructural characteristics and low hardness (87 - 135 HV). The hardness of the blades of the Celtic swords was from 170 to 577 HV (Pleiner 1993, 138-140, 149-150), and products made of Norican steel can have even greater hardness (Schaaber 1963), as was true of the cutting edges of the better Roman Imperial period weapons and tools (Pleiner 1970; Horstmann 1995; Dieudonné-Glad, Parisot 1998). The analysis has proven that the weapons from the Šmihel hoard were certainly not high quality products. Almost all of them were produced from soft steel (ferrite, ferrite and pearlite), the only exception being the point of *pilum* P 3720, whose surface was forge welded with hard steel (pearlite). A high quality of weapons would particularly be expected of the Roman army in a period of extensive expansion, which was in contrast to the results of our research. It can be hypothesized that the highest quality Roman products of the Republican period most probably were no poorer than the contemporary Celtic products. But very likely the production of weapons in the Roman military workshops in the 2nd century BC was not at the level known from the Augustan period. It can be conjectured that the manner of production of the Šmihel weaponry from exclusively soft steel had been deliberately chosen. The causes of this could be various. On the one hand, this could reflect the lack of a harder steel. The Norican kingdom, which was later an important source of hard steel, was neither economically nor politically tied closely to the Roman state at the end of the 3rd or in the first half of the 2nd century BC. On the other hand and even more likely, the choice of material was predicated by a desire for the quickest production of weapons. Thus a softer steel in a single piece was deliberately chosen. It can be seen on the *pila* that they were merely forged and the surface was not later worked more finely with a file and grindstone. The simple rods and catapult bolts were mainly weapons for one-time use, and too great an investment of labor wasn't worthwhile. Objects from soft steel are also easier to repair. Simple repairs could be carried out by the owner himself, while a damaged piece of hard steel required repair by a smith (Sim 1992, 115-116). A catapult bolt, even if made from soft steel, probably caused sufficient harm. Practical experiments have shown that swords made from soft steel could also be used in battle (Pleiner 1993, 163-164). Spear heads and arrowheads of soft steel were sufficiently hard for using in hunting. They could pierce a shield, but not the best kinds of armor (Tylecote, Gilmour 1986, 109).

The manner of producing *pila* is particularly interesting, as it is also mentioned by several classical sources. Polybius noted in the first half or the middle of the 2nd century BC that a soldier armed with a light javelin would thrust it into the enemy's shield, thus bending the javelin so that the shield became unusable (Poly. VI, 22, 4). Such light javelins with characteristic damage to the points were identified in the Šmihel hoard (referred to as socketed pila with a pin-shaped point; Horvat 2002, 133). They were not subjected to metallographic analysis. Later historical sources report for other forms of *pila* that deformation was also desirable upon hitting an obstruction. Marius in the war against the Cymbri (at Vercellae in 101 BC) replaced one of two iron rivets with which the metal part of a *pilum* was attached to the wooden helve with a wooden one. Upon thrusting into the shield, the joint with the helve loosened, the *pilum* bent, and the shield became unusable (Plut. Mar. 25). Marius' experiment was probably short-lived. Gaius Julius Caesar noted that in the battle with the Helvetii in 58 BC the iron *pila* bent in the enemy's shields (Caes. bell. Gall. I 25, 3). On the basis of this report, it has been thought that a new element was introduced in the period between Marius and Caesar: the point of the *pilum* was made of hard steel, and the shaft from soft steel (Schulten 1950, 1360). Appian, who wrote in the 2nd century AD, specifically stated that the complete *pilum*, with the exception of the point, was made from soft steel (Appian Celt. 1). He was probably describing the *pila* of his time, although the text is related to the battle with the Celts in 358 BC (Schulten 1950, 1363). Arrian (2nd century AD) also wrote that the long and thin iron of a *pilum* would bend from the blow to the enemy's defensive equipment (Arrian, contra Alanos 17).

The Roman army used several types of *pila* in the period when the Šmihel hoard was formed. The simple socketed *pila* with a pin-shaped point had a clearly offensive function, as probably also did the long *pila* with a flat haft (forms 2 and 3 from Šmihel). The damage indicates that the points often bent from blows to obstacles. The short *pila* with a flat haft, with a wide point with barbs and a massive shaft (form 1 from Šmihel), probably had a different function. Connolly explained them as a distinctly defensive weapon, which did not deform quickly (Connolly 1997, 44; Horvat 2002, 138). This thesis was confirmed by the greater weight of the objects and the lack of damage. The metallographic examination of a *pilum* of type 1 established that the point was cladded with a layer of harder steel. Although the *pila* were merely forged and were not finely worked later, care was evidently taken in the production of the points. The combination of hard point - soft shaft probably did not occur because of a wish for quick deformation of the shaft. Rather this would confirm Connolly's idea that this type of short *pilum* was actually a defensive weapon that a soldier would have by his side for a longer time and that had to be durable.

The analysis of the Šmihel *pila* thus proves that the points of the *pila* were forged from hard steel and the shafts from soft steel, at least as early as the first half of the 2nd century BC. It also shows that this manner of production was not related merely to a desire for the shaft to bend under a blow, but rather to raise the quality of the weaponry. As a rather later example of this combination, Appian's description from the 2nd century (Appian Celt. 1) can be mentioned, as well as the analysis of a Roman period arrowhead from Wanborough in Britannia that had a hard point (martensite, 390 HV) welded to a soft shaft (Tylecote, Gilmour 1986, 109-110). The exact degree to which such technology was widespread cannot be established merely on the basis of the scarce research.

Explanation of some metallurgical expressions:

Cementite (Fe_3C) - iron carbide with a high hardness of 860 HV.

Ferrite - a solid solution of carbon in iron with a maximal 0.018% of carbon at ambient temperature, low hardness, about 95 HV.

Forge welding - a joint created by forging a connection between two types of steel.

Pearlite - a lamellar compound of cementite and ferrite steel with a content of 0.80% carbon is eutectoid steel with a totally pearlite microstructure and hardness of 210 HV.

Secondary carburization - increasing the carbon content in the surface layers while heating the steel for forging; it occurs through the gaseous phase.

Scale - oxides of iron and to a lesser extent alloy elements that were created on the surface of a product during heating for forging.

Slag - basic and acidic oxides, which are a product of gangue, additives, and oxidations of metals.

Acknowledgements

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Metalografske preiskave rimskega republikanskega orožja iz zaklada z Gradu pri Šmihelu

1. UVOD

Na prazgodovinskem gradišču Grad pri Šmihelu je bil najden zaklad, ki je vseboval vsaj 473 železnih predmetov. Glavnino je sestavljalo rimsko napadalno orožje: pilumi, kopja, osti katapultnih izstrelkov, osti puščic, meči in množica preprostih osti z nesimetrično trikotno konico. Zaklad je datiran v konec 3., oziroma v prvo polovico 2. st. pr. Kr. ter predstavlja eno najzgodnejših zaključenih najdb orožja, ki je zanesljivo opredeljeno kot rimsko. Pomemben je za razumevanje razvoja posameznih oblik (predvsem mečev in pilumov) in nudi dragocen vpogled v rimsko tehniko vojskovanja v času republike. Dejstvo, da je bil odkrit na naselbini prazgodovinske notranjske kulturne skupine, lahko razložimo kot sled enega prvih vojaških posegov v jugovzhodnoalpski prostor, s katerim so Rimljani vzpostavili nadzor nad trgovsko potjo iz Italije proti srednjemu Podonavju in severnemu Balkanu (Horvat 2002).

Številne metalografske preiskave jeklenih predmetov[1] so potekale na keltskem orožju (npr. Pleiner 1993) ter na rimskem orodju in orožju (npr. Pleiner 1970; Horstmann 1995). Niso pa nam poznane metalografske preiskave orožja iz rimskega republikanskega obdobja. Tako smo lahko sklepali, da bodo vsi podatki, ki jih bomo dobili za rimsko orožje s Šmihela, zelo pomembni. Želeli smo dobiti čim več informacij o tehnologiji pridobivanja jekla iz rude in o tehnologiji izdelave predmetov. Posebej smo želeli preveriti domnevo Alfonsa Müllnerja, da je bil eden od mečev (*sl. 1:* 1) izdelan na poseben način (Müllner 1892, 115-116; Müllner 1909, 49-50). Zanimali so nas tudi pilumi, saj na osnovi antičnih literarnih virov lahko sklepamo, da so bile njihove konice narejene iz tršega jekla kot vratovi (Schulten 1950, 1360-1364).

Metalografske preiskovalne metode so destruktivne, zato smo se omejili na čim manjše možno število vzorcev. Iz depoja Narodnega muzeja Slovenije smo izbrali pet predmetov:

1. meč - *gladius* (*sl. 1:* 1), inv. št. P 3621 (Horvat 2002, t. 1: 1);

2. ost piluma s ploščatim nasadiščem, oblika 1 (*sl. 1:* 2), inv. št. P 3720 (Horvat 2002, t. 3: 3);

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[1] Predmetov narejenih iz čistega železa ni. Vedno se uporablja jeklo, ki je zlitina železa in ogljika ter drugih legirnih elementov. Lastnosti jekla so odvisne od vsebnosti legirnih elementov, plastične predelave v vročem in hladnem ter toplotne obdelave, katere osnova so fazne transformacije. V članku zato dosledno uporabljamo izraz "jeklo", s tem da opišemo tudi mikrostrukturo. Za feritno mikrostrukturo uporabljamo izraza "mehko" oziroma "nizkoogljično jeklo", za perlitno mikrostrukturo pa "trdo" ali "visokoogljično jeklo". To je drugače kot v delu arheološke literature, kjer se uporablja izraz "železo" za jeklo s feritno mikrostrukturo ter izraz "jeklo" za jeklo s perlitno in martenzitno mikrostrukturo.
Nekateri metalurški izrazi so pojasnjeni na koncu članka.

3. ost piluma s ploščatim nasadiščem, oblika 1 (*sl. 1:* 3), inv. št. P 3721 (Horvat 2002, t. 3: 4);

4. ost katapultnega izstrelka (*sl. 1:* 4), inv. št. P 3659 (Horvat 2002, t. 14: 2);

5. preprosta ost s trikotno nesimetrično konico (*sl. 1:* 5), inv. št. P 3702/1 (Horvat 2002, t. 16: 2).

Meč smo izbrali zaradi preverjanja Müllnerjeve domneve o posebni tehnologiji izdelave. V zakladu so štiri različice pilumov s ploščatim nasadiščem, pilumi s tulastim nasadiščem in zažigalni pilumi (Horvat 2002, 129-133). Med vsemi temi smo za metalografsko preiskavo izbrali le dva piluma s preprostim ploščatim nasadiščem in široko trikotno konico (oblika 1). Ker gre za sorazmerno velika predmeta, smo upali, da bodo tudi vzorci dovolj veliki, da lahko preverimo predpostavko o različni izdelavi konice in vratu. Katapultni izstrelki z masivno piramidalno konico so značilni za republikansko dobo, zelo razširjeni in zato zanimivi tudi s tehnološkega stališča (Horvat 2002, 133, 138). V zakladu je bilo vsaj 265 preprostih osti, ki so večinoma na eni strani skovane v nesimetrično trikotno konico. Njihova funkcija še ni do konca razjasnjena, domnevamo pa, da je šlo za ost preprostega, na hitro narejenega izstrelka oziroma za konice, zabite v lesene ovire (Horvat 2002, 135-137). V metalografske preiskave smo vključili eno od preprostih osti z nesimetrično trikotno konico zato, da bi lahko preverili antični izvor predmeta. Zaradi številnih zelo podobnih osti pa smo lahko preiskali, kljub destruktivni metodi, sorazmerno velik metalografski vzorec.

Na predmetih smo za preiskave izrezali majhne vzorce, tako, da smo jih čim manj poškodovali (*sl. 1*). Metalografske preiskave so obsegale optično in SEM mikroskopijo (scanning elektronski mikroskop) in elektronsko mikroanalizo (EPMA). Na vzorcih smo izmerili tudi mikrotrdoto jekla po Vickersu z obtežbo 100 g. Vzorci so bili premajhni, da bi jih lahko kemično analizirali v kvantometru, pri pripravi ostružkov za klasično kemično analizo pa bi vzorce uničili. Le vzorec št. 5 (P 3702/1; *sl. 1:* 5) je bil dovolj velik za kvatometrsko analizo, vendar zaradi prevelike količine žlindre in nekovinskih silikatnih vključkov, rezultati kemične analize niso bili realni.

2. METALOGRAFSKE PREISKAVE

2.1 **Meč P 3621** (*sl. 1:* 1)

Na rezilu meča, kjer je površinski sloj deloma odpadel, so vidni vzporedni poševni pasovi, široki od 6 do 7 mm (*sl. 2*). Zaradi teh značilnosti je Müllner predpostavil možnost, da meč ni bil skovan iz enega kosa, temveč po tehnologiji podobni damasciranju. Jekleno palico spiralno ovito z žico naj bi skovali v meč z dvostranskim rezilom. Pasovi žice naj bi bili iz "svetlega zrnatega jekla" ("weisser körniger Stahl") srednje trdote. Na površino naj bi prikovali dve tanki jekleni plošči iz sivega jekla ("grauer Stahl"), ki sta zelo trdi. Jedro iz poševnih trakov naj bi ponekod na meji s krovnimi ploščami rjavelo (Müllner 1892, 115-116; Müllner 1909, 49-50).[2]

V zgornjem delu meča smo v širini do sredine izrezali vzorec za metalografske preiskave (*sl. 1:* 1). Vzorec je tanek, zato smo lahko naredili mikrostrukturne preiskave le na površini, ki leži prečno na os meča.

Na površini meča je na eni strani plast žlindre, na drugi strani in ob robu rezila pa plast rje (*sl. 3*). Žlindra izhaja iz procesa izdelave jekla in se na mikroposnetku opazi kot siva faza v zajedah ob robu rezila. V jeklu so številni sorazmerno veliki nekovinski vključki dveh vrst. Večji vključki, ki so po videzu večfazni, so ostanki žlindre (*sl. 3*). Druga vrsta vključkov temno sive barve, ki so po videzu steklasta faza, pa so silikati (*sl. 4*). Vključki obeh vrst so deformirani v smeri plastične deformacije (kovanja) in ponekod ležijo po mejah kristalnih zrn (*sl. 4; 5*). Le na enem mestu smo opazili zelo drobne globularne nekovinske vključke.

Žlindra na površini meča in vključki žlindre v jeklu imajo podobno kemično sestavo. Vključki niso homogeni in njihova sestava se spreminja od mesta do mesta.

Nekovinske vključke smo kvalitativno ploskovno analizirali. Na *sl. 6* in *7* so prikazani posnetki elektronske sestave in specifični X posnetki elementov v vključkih žlindre in silikatnih vključkih (elementi so vezani na kisik). Koncentracija elementov na posnetkih je sorazmerna gostoti belih pik.

V žlindri (*sl. 6*), ki je po sestavi nehomogena, se opazijo večja področja, ki po sestavi ustrezajo fajalitu ($2FeO.SiO_2$). Na posameznih mestih je veliko kalcija in kalija ter malo fosforja. V silikatnih vključkih (*sl. 7*) ni železa, vsebujejo pa veliko silicija, kalcija in kalija, nekaj aluminija ter malo titana. Sestava teh vključkov je v primerjavi z vključki žlindre homogena.

Mikrostruktura meča je po preseku različna. Rezilo meča, ki je na površini rjasto, ima popolnoma feritno mikrostrukturo (vsebnost C pod 0,01 %) (*sl. 8*). Kristalna zrna so poligonalna in sorazmerno velika. Površina meča je razogljičena, vendar ne na obeh straneh enako globoko. Različno širokemu pasu ferita sledi feritno perlitna mikrostruktura (*sl. 9*). Sredina meča ima feritno perlitno mikrostrukturo (*sl. 10*). Vsebnost ogljika je v tem področju 0,3 %. Na *sl. 11* je na SEM posnetku prikazana oblika cementitnih lamel (Fe_3C) v perlitu. Cementitne lamele so grobe in medlamelarna razdalja (skupna debelina cementitne in feritne lamele v perlitu) je sorazmerno velika. Pri natančnejšem pregledu vzorca smo opazili terciarni cementit po mejah kristalnih zrn v področju s feritno mikrostrukturo, v feritni matici pa drobne izločke (*sl. 12*).

Na robu meča, kjer je mikrostruktura feritna, smo izmerili povprečno mikrotrdoto jekla 87 HV. Mikrotrdota je v področju s feritno perlitno mikrostrukturo višja, od 95 do 115 HV.

2.2 **Ost piluma P 3720** (*sl. 1:* 2; *13:* 1)

Ost piluma je bila grobo izdelana, z jasno vidnimi sledovi kovanja, brez dodatne finejše obdelave (*sl. 13:* 1).

Na pilumu smo izrezali dva vzorca za metalografske preiskave, na konici (vzdolžna smer) in na vratu (vzdolžna in prečna smer) (*sl. 1:* 2).

Na konici piluma, ki je zaradi korozije močno izžrta, je plast rje. Jeklo ima na sredini konice feritno mikrostrukturo. Ob površini pa se kljub korozijskim poškodbam opazi, da je bila mikrostruktura površinske plasti perlitna (0,7 % C) (*sl. 14; 15*). Tudi 20 mm od stranskega roba konice (notranji rob vzorca) je mikrostruktura ob površini na eni strani popolnoma perlitna (*sl. 16*), na drugi strani, ki je močno korozijsko poškodovana, pa feritno perlitna. Ostra meja med popolnoma perlitno in feritno mikrostrukturo kaže, da je bila konica piluma kovaško zvarjena iz trdega jekla na površini in mehke osnove na sredini.

Na vzorcu izrezanem iz vratu je mikrostruktura večinoma feritna, le na sredini je v posameznih pasovih tudi malo perlita.

V jeklu so številni sorazmerno veliki nekovinski vključki dveh vrst. Dolgi vključki, ki so po videzu dvofazni, so ostanki žlindre. Druga vrsta vključkov temno sive barve je po videzu steklasta faza in so silikati. Ti vključki, kot tudi vključki žlindre, so razpotegnjeni, ker so bili na temperaturi kovanja plastični in so se deformirali v vzdolžni smeri. Nekovinskih vključkov, ki so večinoma razpore-

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[2] Müllner 1909, 49, opisuje še en meč iz Gradu pri Šmihelu, ki se je nahajal v Windischgrätzovi zbirki: jedro naj bi bilo skovano iz mehkega traku, ki ga z obeh strani pokrivata plošči iz trdega jekla. Meča, katerega pripadnost zakladu je vprašljiva, ni bilo mogoče identificirati; Horvat 2002, 128.

jeni v nizih, je več na vzorcu izrezanem iz vratu piluma. Vključki žlindre so večji kot vključki kalcijevega silikata (*sl. 17*). Na *sl. 18* je prikazana ploskovna analiza večjega vključka žlindre. Žlindra vsebuje poleg železa veliko kalcija in silicija, nekaj kalija, fosforja in mangana. Žlindra je dvofazna. V svetlo sivi fazi je predvsem železo in po sestavi ustreza wüstitu (FeO). Koncentracija ostalih elementov je večja v temnejši fazi. V silikatnih vključkih je veliko silicija, kalcija in kalija, malo mangana in sledovi fosforja (*sl. 19*). V teh vključkih železa ni.

Povprečna mikrotrdota jekla s feritno mikrostrukturo je 88 HV. Popolnoma perlitna področja na površini konice so trša, najvišja izmerjena vrednost je 135 HV.

2.3 **Ost piluma P 3721** (*sl. 1:* 3; *13:* 2)

Pilum je zelo grobo izdelan, tako da so jasno vidne sledi kovanja (*sl. 13:* 2).

Vzorec za metalografske preiskave smo izrezali na vratu piluma (*sl. 1:* 3). Mikrostrukturne preiskave smo naredili v vzdolžni in prečni smeri. Površina vzorca je rjasta in na nekaterih mestih so po mejah kristalnih zrn plitve korozijske zajede. Plast jekla ob površini je popolnoma razogljičena in je feritna, kristalna zrna pa so groba. Pod to plastjo se v feritni mikrostrukturi, v kateri so kristalna zrna drobnejša, opazijo številni drobni izločki. Na sredini vratu izločkov ni. V tem območju so številni različno veliki nekovinski vključki, ki so po sestavi predvsem žlindra, manj pa je silikatnih vključkov. Morfološke značilnosti in sestava nekovinskih vključkov žlindre in silikatov je enaka kot pri vključkih piluma P 3720.

Mikrotrdota jekla je na robu vratu piluma, kjer je mikrostruktura feritna, 87 HV. Na sredini vratu, kjer so v feritu številni izločki, je mikrotrdota malo višja. Največja izmerjena vrednost je 95 HV.

2.4 **Ost katapultnega izstrelka P 3659** (*sl. 1:* 4; *20*)

Vzorec za preiskave smo izrezali prečno na konici (*sl. 20*), vzorec za metalografske preiskave pa smo pripravili v vzdolžni smeri (*sl. 1:* 4). Konica izstrelka ima popolnoma feritno mikrostrukturo (*sl. 21*). Pri večji povečavi se opazijo zrna terciarnega cementita izločena po mejah ferita, v feritnih zrnih pa so drobni izločki (*sl. 22*). Mikrotrdota jekla je 92 HV.

Na površini konice je plast škaje (oksidi železa, ki so nastali na površini pri ogrevanju za kovanje), ki se po mejah kristalnih zrn plitvo zajeda v feritno matico (*sl. 23*). Ploskovna elektronska mikroanaliza škaje na meji z jeklom je prikazana na *sl. 24*. V škaji so le sledovi kalcija, kalija in fosforja, v jeklu pa je malo niklja in sled bakra. Koncentracija niklja je v jeklu povišana na mejni plasti s škajo.

Nekovinski vključki v jeklu so ostanki žlindre in silikati. So sorazmerno veliki in zaradi deformacije pri vročem kovanju različno orientirani. Vključki žlindre so izrazito dvofazni. Svetlo siva faza je železov oksid, v drugi temnejši fazi pa so poleg oksidov železa še oksidi kalcija, silicija in kalija ter sled fosforja. V silikatnih vključkih ni železa. Po sestavi so to oksidi silicija, kalcija in kalija, v sledovih pa so prisotni še aluminij, fosfor, mangan in žveplo.

2.5 **Preprosta ost z nesimetrično konico P 3702/1** (*sl. 1:* 5; *25*)

V zakladu je bilo vsaj 265 preprostih osti kvadratnega preseka, ki so na obeh koncih skovane v konico. Večina ima na približno tretjini dolžine na eni strani trikoten zob, ki prehaja v špičast vrh, na drugem koncu pa je daljša konica - mogoče nasadišče.

Na osti P 3702/1 smo za preiskave izrezali vzorca v področju trikotnega zoba in na vrhu konice (*sl. 1:* 5; *25*). Metalografske preiskave smo naredili v vzdolžni smeri.

Ob vrhu ima jeklo feritno mikrostrukturo, v kateri so številni izločki, ki so večinoma lamelarne oblike, deloma pa so tudi globularni (*sl. 26; 27*). Enake izločke smo opazili na konici katapultnega izstrelka P 3659. Po mejah kristalnih zrn se opazi tudi terciarni cementit. Površina konice je prekrita s korozijskimi produkti, plitve korozijske zajede pa se po mejah zrn širijo v kovinsko matico. V področju trikotnega zoba je na površini škaja, vendar se tudi tu opazijo znaki korozijskih procesov (rjavenje). Z oddaljenostjo od vrha konice se veča gostota izločkov v feritni fazi. V mikrostrukturi se opazijo tudi perlitna zrna, v katerih so grobe cementine lamele, ki so nastale zaradi sorazmerno počasnega ohlajanja. Te mikrostrukturne značilnosti se še izraziteje opazijo na SEM posnetkih (*sl. 28; 29*).

Na prehodu iz nasadišča v zob osti ima jeklo feritno perlitno mikrostrukturo (0,15 % C), v kateri se izrazito opazi razlika v velikosti kristalnih zrn. Na območju nasadišča so rekristalizirana kristalna zrna zaradi večje deformacije pri kovanju manjša. Stopnja predelave širšega dela (zoba osti) je bila manjša, zato so kristalna zrna večja (*sl. 30*).

Kot na ostalih vzorcih, smo tudi na tem opazili v jeklu dve vrsti nekovinskih vključkov, vključke večfazne žlindre in silikatne vključke. V žlindri smo poleg železa, silicija, kalcija in kalija, ki smo jih določili že na ostalih vzorcih, opazili tudi sorazmerno visoko vsebnost mangana (*sl. 31*). Svetlo siva faza v žlindri je oksid železa. Podobno smo tudi v silikatnih vključkih določili poleg silicija, kalcija in kalija visoko vsebnost mangana.

Mikrotrdota jekla je ob vrhu osti 87 HV. Najvišje vrednosti mikrotrdote, od 110 do 115 HV, smo izmerili v področju s feritno perlitno mikrostrukturo (na prehodu iz nasadišča v zob).

2.6 **Sestava žlindre in silikatnih vključkov**

Na vzorcih meča, katapultnega izstrelka in preproste konice smo semikvantitativno analizirali nekovinske vključke žlindre in silikatne vključke.

Tab. 1: Sestava žlindre v masnih odstotkih.

Faza	Meč P 3621	Preprosta ost P 3702/1
FeO	52,3	54,6
Fe_2O_3	-	-
SiO_2	32,3	19,6
Al_2O_3	1,4	1
CaO	7,2	3
MgO	-	-
MnO	-	16,8
K_2O	1,5	0,8
P_2O_5	0,2	0,1
TiO_2	0,1	0,1
S	-	-

Vključki žlindre so nehomogeni, zato je z elektronsko mikroanalizo težko določiti njihovo sestavo. V *tabeli 1* je podana povprečna sestava vključkov žlindre v meču in preprosti osti. Sestava žlinder je podobna, visoka je vsebnost FeO, veliko je SiO_2 in malo CaO, kar je značilno za železo, pridobljeno v jaškastih pečeh (Pleiner 2000, 251-253). V žlindri osti je sorazmerno visoka vsebnost manganovega oksida, v čemer je podobna analizirani žlindri iz rimske dobe v Löllingu (12,1 % MnO; Neumann 1954, 36) in žlindri v volku s Štalenske gore (vzorec D, 36 % MnO) na avstrijskem Koroškem (Straube 1996, 98-

Tab. 2: Sestava silikatnih vključkov v masnih odstotkih.

Faza	Meč P 3621	Kat. izstrelek P 3659	Preprosta ost P 3702/1
MnO	0,6	0,8	32,5
SiO_2	50,1	49,5	40,5
Al_2O_3	7,6	4,3	1
CaO	29,3	33,2	21,5
MgO	-	-	0,4
K_2O	9	7	2,2
P_2O_5	1	1	0,6
TiO_2	0,4	< 0,1	0,4
S	-	< 0,1	-

99). Za železove rude s Koroške in Gradiščanskega je značilna večja vsebnost mangana, ki se ohrani tudi v žlindri (Sperl 1985, 412-413; Straube 1996, 55, 98, 111).

Sestave silikatnih vključkov analiziranih v vzorcih meča, katapultnega izstrelka in preproste osti so podane v *tabeli 2.* Zaradi visoke vsebnosti SiO_2 in K_2O imajo nizko tališče in so na temperaturi kovanja plastični. V silikatnih vključkih preproste osti pa je, enako kot v žlindri, visoka tudi vsebnost MnO.

Tudi v jeklu preiskanih vzorcev smo analizirali vsebnost elementov, ki so sicer običajno prisotni v jeklu. Kovinska matica je praktično čisto železo, v katerem je le zelo majhna vsebnost mangana (pod 0,1 %).

3.0 DISKUSIJA

Do visokega srednjega veka so v Evropi pridobivali jeklo v talnih in jaškastih pečeh. Za uspešno pridobivanje kovnega (duktilnega) jekla in njegovo predelavo je bilo potrebno znanje, ki je bilo bistveno drugačno, kot ga imamo danes, ko so na voljo številne preiskovalne metode in eksperimenti, s katerimi lahko zagotovimo ustrezno kvaliteto jekla. Plastično jeklo, ki se ga je dalo kovati, je moralo imeti nizko vsebnost ogljika (do 0,7 % C). Dovolj visoko temperaturo in plin za redukcijo (CO) so dobili z zgorevanjem oglja. Pri nizki vsebnosti ogljika v železu je ostal del FeO (tališče 1377 °C) v žlindri, v kateri je zaradi prisotnosti SiO_2 nastal fajalit ($2FeO.SiO_2$), ki ima nizko tališče (1217 °C). Uspešno nizkotemperaturno pridobivanje železa (1200 °C) je potekalo le pri drobnozrnati rudi. Reducirani delci kovine so se pri višjih temperaturah združevali v večjo testasto kepo, iz katere so s prekovanjem odstranili večino žlindre. Prisotnost CaO je tališče žlindre zviševala, MnO in K_2O pa zniževala. Ruda je morala zato vsebovati pod 10 % CaO. Jeklo iz jaškaste peči je bilo nehomogeno, vsebnost ogljika je bila različna. Med ogrevanjem na kovaškem ognjišču se je železo, odvisno od atmosfere, razogljičilo ali naogljičilo (Craddock 1995, 234 ss).

Kovinska matica vseh preiskanih vzorcev je zelo čisto železo s sorazmerno nizko vsebnostjo ogljika (0,01 do 0,3 % C). Jeklo preproste osti ima več mangana, kot ga je v drugih vzrocih, jeklo katapultnega izstrelka pa ima v sledovih nikelj in baker. To kaže, da je bilo jeklo, iz katerega je bilo narejeno orožje, pridobljeno iz železovih rud, ki so imele različne spremljajoče elemente.

V jeklu sta dve vrsti nekovinskih vključkov, vključki žlindre in silikatni vključki.

Vključki žlindre izhajajo iz procesa pridobivanja železa iz rude (redukcija železovih oksidov) in so dvofazni. Faza, ki po sestavi ustreza wüstitu (FeO), ima višje tališče in se je pri strjevanju žlindre strdila prva, zato ima večinoma dendritno obliko. Druga faza ima manj železa, vsebuje pa veliko silicija in kalcija, malo kalija, aluminija in mangana ter sledove fosforja in titana. Le v vključkih žlindre v jeklu preproste osti (P 3702/1) smo opazili tudi visoko vsebnost mangana.

Druga vrsta nekovinskih vključkov so silikati z visoko vsebnostjo kalcija in kalija. Vsebnost aluminija, titana, fosforja, mangana in žvepla je nizka, oz. so ti elementi prisotni le v sledovih. Višjo vsebnost mangana smo opazili v vključkih preproste osti (P 3702/1). Ker silikatni vključki ne vsebujejo železa, verjetno ne izvirajo iz rude. Mnenja smo, da lahko izvirajo iz obzidave talilne peči, ki je vsebovala silikate bogate s kalijem (glina). Del kalija je prišel v žlindro in silikatne vključke tudi iz oglja.

Predmeti so kovaško kvalitetno izdelani. Mikrostrukturnih značilnosti, ki bi kazale na kaljenje nismo opazili na nobenem od preiskanih vzorcev. Na predmetih tudi nismo opazili znakov hladne deformacije, ki je tudi ena od tehnologij utrditve površine in s tem povečanja trdote.

3.1 **Meč**

Rezilo meča iz zaklada ima na površini popolnoma feritno mikrostrukturo (pod 0,01 % C), sredina pa je feritno perlitna (0,3 % C). Feritna zrna ob rezilu so bistveno večja kot tista drugod na površini meča in zrna v feritno perlitni mikrostrukturi v jedru. Kristalna zrna so tudi večja v primerjavi s kristalnimi zrni na ostalih vzorcih, kar kaže, da je bil meč kovan pri sorazmerno visoki temperaturi (okoli 1000 °C). Na meji med feritno in feritno perlitno mikrostrukturo nismo opazili oksidnih vključkov, ki bi kazali na izdelavo meča iz več trakov oz. žic. Površina meča je korodirana v taki meri, da na osnovi metalografskih preiskav ne moremo ugotoviti, če je bila na površino prikovana lamela iz tršega jekla. Iz meča smo izrezali vzorec za preiskave le na enem mestu, vendar smo mnenja, da je bil ta najverjetneje izdelan iz enega kosa ali morda iz več trakov oz. žic s približno enako vsebnostjo ogljika. Tako razlago potrjuje tudi plast žlindre na eni strani meča, ki je ostala na površini izdelka in je preprečila rjavenje jekla, ki ima na temu področju feritno mikrostrukturo. Torej lahko zavrnemo Müllnerjevo hipotezo, da je bil meč sestavljen iz več trakov in plasti (Müllner 1892, 115-116; Müllner 1909, 49-50). Površina meča se je med ogrevanjem za kovanje razogljičila. Rezilo ima zato sorazmerno nizko trdoto (87 HV) in orožje ne predstavlja vrhunskega izdelka.

3.2 **Piluma**

Na konici piluma P 3720 ležijo pod korozijskimi produkti področja s popolnoma perlitno mikrostrukturo (0,7 % C), ki nato prehaja v popolnoma feritno jedro. Površina konice piluma je korozijsko močno poškodovana, vendar perlitna mikrostruktura na površini in oster prehod v feritno področje v jedru kažeta, da je bila konica piluma P 3720 kovaško zvarjena iz trdega in mehkega jekla. Trše jeklo z višjo vsebnostjo ogljika je korozijsko manj obstojno, zato je površina orožja korozijsko bolj poškodovana. Vratova obeh pilumov (P 3720, P 3721) imata feritno mikrostrukturo z zelo majhnim deležem perlitne faze, torej sta, v nasprotju s konico P 3720, narejena iz enega kosa mehkega jekla.

3.3 **Katapultni izstrelek in preprosta ost**

Konica katapultnega izstrelka in preprosta ost imata popolnoma feritno mikrostrukturo, le na odebeljenem delu osti (zob) je mikrostruktura feritno perlitna (0,15 % C). Oba predmeta sta bila skovana iz nehomogenega surovca z različno vsebnostjo ogljika, ali pa se je železo med ogrevanjem za kovanje na kovaškem ognjišču razogljičilo.

V feritu obeh predmetov smo opazili bolj ali manj izrazito izločanje terciarnega cementita po kristalnih mejah in izločanje drobnih, večinoma lamelarnih karbidov iz matice. Izločanje je lahko potekalo le pri zelo počasnem ohlajanju.

3.4 **Mesto šmihelskega orožja v tehnološkem razvoju**

V srednji Evropi in v Sredozemlju so že v halštatskem obdobju poznali večino pomembnejših postopkov kovanja, čeprav tehnološko znanje ni bilo enakomerno razširjeno. Posamič se pojavljajo že namerne kombinacije trdih in mehkih jekel, le izjemoma pa srečamo kaljenje in sekundarno naogljičenje (Pleiner 1962, 50-63, 259-261; Tylecote 1992, 52-53; Craddock 1995, 238, 260).

V latenski dobi je železarstvo močno napredovalo (Pleiner 1962, 64-101, 261-267). Metalografske analize 122 keltskih mečev so pokazale, da je bilo jeklo večinoma heterogeno naogljičeno. Kovaško znanje je bilo na različni višini, zato so tudi meči različne kakovosti. Samo 36 % raziskanih je bilo narejenih v celoti iz mehkega jekla z vsebnostjo ogljika pod 0,3 % (feritna, oziroma feritno perlitna mikrostruktura). Meči skovani iz enega kosa jekla so redki, večina jih je skovanih iz več plasti, ki so enake ali različne kakovosti. Več kot polovica mečev je imela vsaj eno rezilo iz srednje ogljičnega (0,3-0,5 % C; feritno-perlitna mikrostruktura) ali visokoogljičnega jekla (0,6-0,8 % C; perlitna mikrostruktura). Nekaj mečev je v celoti izdelanih iz srednje oziroma visokoogljičnega jekla, večinoma pa so se menjavali trakovi nizko, srednje in visokoogljičnega jekla. Raznolikost shem sestavljanja plasti kaže, da je bila večina kovačev nezanesljiva v ločevanju med mehkim in tršim jeklom. Sekundarno naogljičenje rezil je bilo redko, kaljenja in hladnega kovanja pa niso uporabljali (Pleiner 1993).

Na ozemlju Noriškega kraljestva, na Koroškem in Gradiščanskem, so pridobivali jeklo, ki je izstopalo zaradi višje vsebnosti ogljika (Schaaber 1963; Sperl 1985; Straube 1996). Orodje in orožje iz takšnega jekla se na tem območju pojavlja že v halštatskem času (Plöckinger 1976). V poznolatenskem in rimskem obdobju pa je bila proizvodnja trdega jekla zelo obsežna. Proizvodnjo in trgovino z jeklom so od sredine 1. st. pr. Kr. že nadzorovali Rimljani (Dolenz 1996; Dolenz 1998).

V rimskem cesarskem obdobju se je proizvodnja jekla zelo povečala, znanje naogljičenja in kaljenja se je širilo. Med rimskim orožjem in orodjem srečamo vrhunske, zelo dobre in preproste izdelke, ki daleč prevladujejo (Schaaber 1963; Pleiner 1970; Tylecote, Gilmour 1986, 18-108; Tylecote 1992, 65-68). Visoka raven poznavanja materiala in kovašta se vidi predvsem na orožju (Tylecote 1992, 65-68). Najboljša bodala avgustejskega obdobja so bila izdelana tako, da so bili sredina in rezili še posebej trdi, med njimi pa sta ležala pasova, sestavljena iz izmeničnih trakov trdih in mehkih jekel (lamelni damast). Rezilo bodala iz Oberadna je bilo najprej kaljeno, sledilo je popuščanje na povišani temperaturi. Takšno orožje je imelo odlične mehanske lastnosti, bilo je trdo in žilavo (Pleiner 1970, 118-120, 128-130; Horstmann 1995; Westphal 1995; Lang 1995). Meči med avgustejskim obdobjem in 2. st. po Kr. imajo preprostejšo strukturo. Sestavljeni so bili iz več plasti istovrstnega, naogljičenega jekla. Na rezilih je bilo uporabljeno kaljenje in popuščanje (Williams 1977, 78; Biborski et al. 1987; Lang 1988; Lang 1995, 127; Dieudonné-Glad, Parisot 1998). Vzorčasto varjenje (pattern welding) oziroma pravo damasciranje mečev se pojavlja v večjem številu od konca 2. st. dalje (Ypey 1984, 195 ss; Tylecote 1992, 66-68).

Šmihelsko orožje po svojih mikrostrukturnih značilnostih in nizki trdoti (87-135 HV) izstopa. Trdota rezil keltskih mečev je od 170 do 577 HV (Pleiner 1993, 138-140, 149-150), izdelki iz noriškega jekla pa imajo lahko tudi višje trdote (Schaaber 1963) in prav tako tudi rezilni deli boljšega rimskega cesarskodobnega orožja in orodja (Pleiner 1970; Horstmann 1995; Dieudonné-Glad, Parisot 1998). Preiskave so torej pokazale, da orožje iz šmihelskega zaklada nikakor ne sodi med vrhunske izdelke. Izdelano je skoraj v celoti iz mehkega jekla (ferit, ferit in perlit), izstopa le konica piluma P 3720, katere površina je kovaško varjena s tršim jeklom (perlit). Za rimsko armado v času močne ekspanzije bi, nasprotno z rezultati naših preiskav, še posebej pričakovali kakovostno orožje. Predpostavljamo, da vrhunski rimski izdelki republikanskega obdobja najbrž niso bili slabši od keltskih izdelkov. Zelo verjetno pa v 2. st. pr. Kr. izdelava orožja v rimskih vojaških delavnicah še ni bila na takšni višini kot v avgustejskem obdobju. Domnevamo, da je bil način izdelave samo iz mehkega jekla pri šmihelskem orožju namerno izbran. Vzroki za to so bili lahko različni. Po eni strani morda zaradi pomanjkanja tršega jekla. Noriško kraljestvo, ki je bilo pozneje pomemben vir trdega jekla, konec 3. oziroma v prvi polovici 2. st. pr. Kr. še ni bilo trgovsko in politično tako tesno povezano z rimsko državo. Še verjetneje pa je izboru materiala botrovala želja po hitrejši izdelavi orožja in so zato namenoma izbrali mehkejše jeklo v enem kosu. Na pilumih se vidi, da so bili samo kovani, niso pa bile površine pozneje fino obdelane s pilo in brusi. Pri preprostih osteh in katapultnih konicah gre večinoma za orožje za enkratno uporabo, zato se prevelik vložek dela ni izplačal. Predmete iz mehkejšega jekla je tudi lažje popravljati. Enostavna popravila lahko naredi lastnik sam, medtem ko poškodovan kos iz trdega jekla zahteva popravilo pri kovaču (Sim 1992, 115-116). Katapultni izstrelek, čeprav iz mehkejšega jekla, je verjetno povzročil dovolj škode. Praktični preiskusi so pokazali, da so bili tudi meči narejeni iz mehkega jekla uporabni v boju (Pleiner 1993, 163-164). Sulice in puščične konice iz mehkejšega jekla so bile dovolj trdne za uporabo pri lovu, prav tako so lahko prebile ščit, ne pa tudi najboljših vrst oklepov (Tylecote, Gilmour 1986, 109).

Posebej je zanimiv način izdelave pilumov, ker ga omenjajo tudi nekateri antični viri. Polibij poroča v prvi polovici oziroma sredini 2. st. pr. Kr., da so se tanka kopja lahko oboroženih vojakov zarila v sovražnikov ščit in se upognila, tako da je postal ščit neuporaben (Polib. VI, 22, 4). Opisana kopja z značilnimi poškodbami konic smo identificirali tudi v šmihelskem zakladu (imenovali smo jih pilumi s tulastim nasadiščem in konico v obliki igle), vendar jih nismo metalografsko analizirali (Horvat 2002, 133). Mlajši zgodovinski viri poročajo, da je bil tudi pri drugih oblikah pilumov zaželjen upogib ob udarcu v oviro. Marij je v bojih proti Kimbrom (pri Vercelah leta 101 pr. Kr.) eno od obeh železnih zakovic, s katerima je bil kovinski del piluma pritrjen na leseno toporišče, nadomestil z leseno. Spoj s toporiščem se je ob zadetku v ščit razrahljal, pilum se je upognil in ščit je postal neuporaben (Plut. Mar. 25). Marijev eksperiment je bil verjetno kratkega veka. Gaj Julij Cezar poroča, da se je v bitki s Helveti leta 58 pr. Kr. železo pilumov zapognilo v sovražnikovih ščitih (Caes. bell. Gall. I 25, 3). Na podlagi tega poročila so domnevali, da naj bi se v času med Marijem in Cezarjem uveljavila novost: konica piluma iz trdega železa ter vrat iz mehkega (Schulten 1950, 1360). Šele Apijan, avtor iz 2. st. po Kr., izrecno piše, da so bili celotni pilumi, razen konice, narejeni iz mehkega železa (Apijan Celt. 1). Verjetno opisuje pilum svojega časa, čeprav je besedilo povezano z bitko s Kelti leta 358 pr. Kr. (Schulten 1950, 1363). Tudi Arijan (2. st. po Kr.) opisuje, da se je dolgo in tanko železo piluma zapognilo ob udarcu v sovražnikovo obrambno opremo (Arrian, contra Alanos 17).

V času nastanka šmihelskega zaklada, je rimska vojska uporabljala več vrst pilumov. Izrazito napadalno funkcijo so imeli preprosti pilumi s tulastim nasadiščem in konico v obliki igle ter verjetno tudi dolgi pilumi s ploščatim nasadiščem (obliki 2 in 3 s Šmihela). Poškodbe kažejo, da se je konica pogosto upognila ob udarcu v oviro. Kratki pilumi s ploščatim nasadiščem, s široko konico z zalustmi in masivnim vratom (oblika 1 s Šmihela), pa so verjetno imeli drugačno funkcijo. Connolly jih razlaga kot izrazito obrambno orožje, ki se ni hitro deformiralo (Connolly 1997, 44;

Horvat 2002, 138). Poleg masivne izdelave potrjuje njegovo tezo tudi odsotnost poškodb. Z metalografsko preiskavo piluma oblike 1 smo ugotovili, da je bila konica platirana s plastjo tršega jekla. Čeprav so bili pilumi samo kovani in niso bili pozneje fino obdelani, so se očitno potrudili pri izdelavi konice. Sestava trda konica - mehek vrat se verjetno ne pojavlja zaradi želje po hitri deformaciji orožja. Prej bi potrjevala Connollyjevo domnevo, da ne gre res za defenzivno orožje, ki ga je imel vojak dalj časa pri sebi in je moralo biti bolj trpežno.

Analiza šmihelskega piluma torej dokazuje, da so konice pilumov kovali iz tršega jekla, vratove pa iz mehkejšega, vsaj že v prvi polovici 2. st. pr. Kr. Kaže tudi, da ta način izdelave ni bi povezan le z željo po upogibu vratu ob udarcu v oviro, temveč bolj z dvigom kakovosti orožja. Kot precej mlajši primerjavi lahko omenimo Apijanov opis iz 2. st. (Apijan Celt. 1) in analizo rimskodobne puščične osti iz Wanborougha v Britaniji, ki je imela trdo konico (martenzit, 390 HV) prikovano na mehek vrat (Tylecote, Gilmour 1986, 109-110). Kako splošno je bila razširjena takšna tehnologija, pa na podlagi redkih raziskav seveda ne moremo ugotoviti.

Razlaga nekaterih metalurških izrazov:

Cementit (Fe_3C) - železov karbid s trdoto 860 HV.

Ferit - trdna razstopina ogljika v železu z najvišjo vsebnostjo 0,018 % ogljika pri sobni temperaturi; trdota je nizka, 95 HV.

Kovaško varjenje - z deformacijo nastane pri kovanju med dvema vrstama jekla popolen spoj.

Perlit - lamelarni kompozit cementita in ferita; jeklo z vsebnostjo 0,80 % ogljika je eutektoidno jeklo s popolnoma perlitno mikrostrukturo in trdoto 210 HV.

Sekundarno naogljičenje - povečanje vsebnosti ogljika v površinski plasti med ogrevanjem jekla za kovanje; poteka preko plinske faze.

Škaja - oksidi železa in v manjši meri legirnih elementov, ki so nastali na površini izdelka med ogrevanjem za kovanje.

Žlindra - bazični in kisli oksidi, ki so produkt jalovine, dodatkov in oksidacije kovin.

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