RESEARCH ARTICLE – VÝZKUMNÝ ČLÁNEK

Metallography of medieval mining tools from Bohemian-Moravian Highlands

Metalografie středověkých hornických nástrojů z Českomoravské vrchoviny

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This study focuses on the technological examination of medieval mining chisels from the Bohemian–Moravian Highlands in the Czech Republic. The analysed artefacts originate from three silver-mining areas (Opatov, Čejkov, Utín) dated to the 13th and 14th centuries. Mining chisels belong among the most characteristic tools of underground extraction, yet their metallographic study has so far remained relatively limited. The presented research aims to contribute to a more detailed understanding of their manufacture, material composition and internal construction. Five chisels and a mallet of different sizes were selected to investigate potential technological variability. The selected assemblage includes both slender and robust chisels, allowing a comparison of technological choices in relation to tool size and presumed function. Full-length cross-sections were prepared to assess the composition of the bodies, points and striking heads, and to document forging procedures and applied heat treatment. Findings that individual chisels were adapted to the type of rock and work and that they were used not only for ore extraction but also for other mining activities expand our knowledge of toolmaking and offer new insights into technological approaches of medieval smiths working for mining communities in the Bohemian–Moravian Highlands.

medieval mining – Bohemian-Moravian Highlands – iron chisels – material analysis – metallography – blacksmithing

Tato studie se zaměřuje na technologický výzkum středověkých hornických želízek z Českomoravské vrchoviny. Analyzované artefakty pocházejí ze tří stříbrných revírů (Opatov, Čejkov, Utín) datovaných do 13. a 14. století. Přestože hornická želízka patří mezi nejcharakterističtější nástroje pro podzemní těžbu, jejich metalografické studium dosud zůstávalo poměrně omezené. Cílem předloženého výzkumu je přispět k podrobnějšímu pochopení jejich výroby, materiálového složení a vnitřní konstrukce. Pro zkoumání potenciální technologické variability bylo vybráno pět želízek různých velikostí a mlátek. Vybraná kolekce obsahuje štíhlá i robustní želízka, což umožňuje srovnání technologických možností ve vztahu k velikosti nástroje a předpokládané funkci. Pro posouzení složení těl, hrotů a konců želízek a pro zdokumentování postupů kování a technik tepelného zpracování byly provedeny řezy v celé délce předmětů. Zjištění, že jednotlivá želízka byla přizpůsobena typu horniny a druhu práce a používala se nejen k těžbě rudy, ale i k dalším hornickým činnostem, zpřesňují naše poznatky o výrobě nástrojů a nabízejí nové pohledy na technologické postupy středověkých kovářů pracujících pro hornické komunity na Českomoravské vrchovině.

středověké hornictví – Českomoravská vrchovina – želízka – analýza materiálů – metalografie – kovářství

Introduction

Chisels with handle holes represent the most frequent mining tools at the excavated medieval mining sites in Europe. Their shape remained basically unchanged during the medieval and Early Modern periods (*Mihok et al. 1998*; *Hebenstreit 2000*; *Hrazdil et al. 2007*; *Luna – Zimola 2007*; *Méaudre et al. 2023*). They have a square or rectangular neck, while

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handle holes tend to be small (with dimensions often less than 10 mm) and usually rectangular- or square-shaped; in some cases, they do not perforate the tool completely but extend only a few centimetres into the body. Metric and morphology indicate a high degree of standardisation, which is usually interpreted as evidence of specialised production and the increasing organisation of mining work. The fact that these artefacts cannot be dated prior to the 13th century raises the question of previous rock-breaking methods.

Very similar mining tools used to break rock in high and late medieval mines were iron wedges. Their blades are typically axe-shaped, but their overall morphology corresponds to that of handheld chisels. They could likewise have been used in the same manner as chisels (*Mihok et al. 1998*). They probably appeared as early as the 12th century (*Straßburger 2017*). Scrapers were also commonly used mining tools made from iron, and the earliest of them could be dated to the 12th century (*Smolnik 2016*; *Straßburger 2017*). These artefacts were found in mining areas that prospered mainly in the 13th century (*Schröder 2018*). Finally, picks have also been found at medieval mining sites dated to the 13th century (*Richter 1982*; *Mihok et al. 1998*). As was the case with handed chisels, there were different sizes of scrapers, which could have been used as chisels, too.

The use and size variations of these tools are captured by iconographic documents, such as the late medieval illuminations of Kutná Hora (*Studničková – Purš 2010*), Georgius Agricola's book from the mid-16th century (*Agricola Georgius*, *De Re Metallica*, VI, 150–151: *Hoover – Hoover 1912*), the *Schwazer Bergbuch* from the same period (*Bingener et al. 2006*), and in stone tile in Wirksworth Church in Derbyshire (*Hickey 2024*).

Weaknesses of past research and definition of issues

Metallographic analyses of chisels are relatively sporadic, not only in the Czech Republic but throughout Europe. While there are some notable studies (*Guillot et al. 1988*; *Mihok et al. 1998*; *Haubner – Strobl 2015*; *Méaudre et al. 2023*), researchers have usually examined specific sections rather than the entire artefact. These studies have often focused on selected areas, such as the points (*Haubner – Strobl 2015*) and heads of chisels (*Mihok et al. 1998*), except for work on chisels from the Pampailly region of central-eastern France (*Guillot et al. 1988*) and from Castel-Minier in south-eastern France (*Méaudre et al. 2023*).

With this in mind, we aimed to examine the entire length of the analysed artefacts to gain a comprehensive understanding of the tool's composition. The main goal of this study is to conduct a comparative analysis of the production of chisels from the Bohemian-Moravian Highlands. The observed differences in size and weight raise the question of whether these characteristics influenced the craftsmanship of these tools, which required the use of tough steel and hardening processes to withstand the difficulties of daily use in mining environments.

It is often postulated that the different sizes and weights of chisels were tailored to accommodate different types of rocks or specific mining conditions within the region (*Hrazdil et. al. 2007*). This paper aims to test the prevailing narrative about the manufacture of chisels, particularly, the practice of attaching hardened steel points to ferritic bodies by welding techniques. It also aims to identify differences in the production of various types of chisels.

Material

Geology and ore deposits

The Bohemian-Moravian Highlands are an extensive area of hills and low mountains situated in the south-central part of the Czech Republic, creating a border between Bohemia and Moravia. The area roughly coincides with the administrative borders of the Vysočina Region. (*Fig. 1*: A). The landscape of the Bohemian-Moravian Highlands is composed of crystalline metamorphic or igneous rocks of the Moldanubic with brown soils typical of sloping terrains that developed on the metamorphosed and consolidated sedimentary bedrock (*Cháb et al. 2007*). Deposits of polymetallic sulphide ores are developed in the central Highlands (*Houzar et al. 2021*).

Typical ores include sphalerite, pyrite, galena, arsenopyrite, and pyrrhotite, while chalcopyrite, stannite, pyrargyrite, cassiterite, and silver sulphosalts are less frequent; tetrahedrite, freibergite, and argentite occur only rarely. The gangue is composed of quartz with chlorite and dolomitic carbonate (*Dobeš – Malý 2001*). From Havlíčkův Brod ore district, the chisels found in the Utín mining site (*Hrubý et al. 2021*) have been chosen for the analysis (*Fig. 1*: B-1).

Mineralised structures in the Jihlava ore district are associated with so-called dislocation zones (*Fig. 1*: B). Ore minerals are represented by sphalerite, galena, less frequently chalcopyrite, arsenopyrite, pyrite and tetrahedrite. Gangue minerals are represented by barite and quartz (*Pluskal – Vosáhlo 1998*).

The ore structures in the Pelhřimov ore subdistrict in the west of the Bohemian-Moravian Highlands are found in the contact of metamorphic rocks (gneiss or paragneiss) and granites (*Fig. 1*: B). In the quartz ore veins striking NE–SW, pyrite, pyrrhotite, arsenopyrite, sphalerite, galena, tetrahedrite, and chalcopyrite can be mentioned. The uppermost subsurface parts can also contain acanthite (*Litochleb 1996*). From this ore district, the chisels found in the mining sites of Čejkov (*Fig. 1*: B-4) and Opatov (*Fig. 1*: B-2) have been chosen for analysis.

Historical context

Based on archaeological and archaeoenvironmental data, the initial medieval human impact on the Bohemian-Moravian Highlands dates from the 8th to the 11th century AD (*Hrubý et al. 2014*). Intensive colonisation began in the early 12th century and culminated in the 13th century (*Kaiser et al. 2020*; *Duffek et al. 2023*; *Hrubý et al. 2024*). In the mid-13th century, the Kingdom of Bohemia induced under the rule of the Přemyslid dynasty a 'silver boom' (*Hrubý et al. 2012*; *2016*; *2019*; *2021*), i.e. the intensive production of non-ferrous metals, especially of lead and silver, triggering unprecedented economic development and wealth in this region. The discovery and use of silver-bearing ores resulted after the mid-13th century in the significant development of mining, urban, and agrarian cultural landscapes in the Bohemian-Moravian Highlands (*Hrubý et al. 2014*; *Crkal et al. 2019*). The most important territorial owner in the 13th century was the king of Bohemia, who possessed the mining town of Jihlava, followed by the bishop of Prague, as well as Premonstratensian Želiv Abbey in the western part of this region.

Spatial and chronological context of the analysed artefacts

The medieval mining site Opatov (*Fig. 1*: B-2) is situated in the western part of the Bohemian-Moravian Highlands, where the land of Premonstratensian Želiv Abbey has been established since the 12th century. The analysed chisels were recovered between 2014 and 2020 as part of an assemblage of exclusively medieval metal artefacts found mostly during metal-detector survey in the vicinity of the mining shafts. A more accurate dating of the site is provided by the timbering of one of the shafts (*Fig. 1*: E), where dendrochronological measurements have shown the tree-felling dates to be 1266/1267 and 1267/1268 AD (*Kyncl 2015*).

The mining site Čejkov is located southwest of Opatov (*Fig. 1*: B-3). This area belonged to the Prague bishopric since the 12th century. Chisels and other various metal artefacts dated to the 13th and 14th centuries were also found here by a metal-detector survey around the shafts and heaps (*Hrazdil et al. 2007*; *Luna – Zimola 2007*).

The medieval mining area of Utín (*Fig. 1*: C) can be identified as the historical mine of *Mons Fagus* in Latin or *Buchberg* in German sources, first mentioned in 1258. The site is dominated by two linear clusters of shafts and heaps, indicating the NW–SE striking of the ore veins (*Fig. 1*: B). Magnetic prospection, carried out on adjacent fields, detected numerous anomalies, which can be interpreted mostly as pit houses and metallurgical facilities. The three analysed chisels were found during excavations of bloomeries and forges, which were situated immediately at the metallurgical workplace, which is a significant circumstance. According to archaeological findings, this context can be dated to the 13th and 14th centuries (*Hrubý et al. 2021*).

Analysed artefacts and their typology

The metal-detector surveys and rescue excavations between 2014 and 2020 produced a collection of 30 pieces of mining tools (chisels, picks, and wedges). Although this number is not large, it corresponds to the intensity and extent of mining activities in the given period. The finds are deposited in the collections of the Vysočina Museum in Jihlava. Five chisels and a mallet were selected for detailed analysis due to their different blacksmithing characteristics (*Tab. 1*). The set was deliberately divided into three more robust and three more slender specimens to compare the technological aspects of their production.

The basic typological classification is based on the shape of the body of the chisel. In Agricola's sixth book on mining and smelting, it is possible to find a description of four types of mining tools. Three types of chisels are morphologically identical, differentiated only in their lengths and widths; the last type of mining tool is a wedge (*Agricola Georgius, De Re Metallica*, VI, 150–151: *Hoover – Hoover 1912*). Even though the length of the depicted tools does not correspond to archaeological evidence, the width and thickness appear to be comparable (*Večeřa 2018*, 18, 30–31).

The first and numerically dominant type is characterised by maximum width in the area of the opening for the handle and a smooth tapering towards the tail and point (*Fig. 2*: C-0032, 0-0033; U502-1; *Luna – Zimola 2007*, 307, type A). This type can be associated with Agricola's description of chisels. The second and rarer type has a triangular shape. Its widest dimension is in the tail area and it tapers evenly towards the point (*Luna – Zimola 2007*, 307, type B). This variant is represented by two artefacts in the analysed set (*Fig. 2*: U-0107, U502-2).

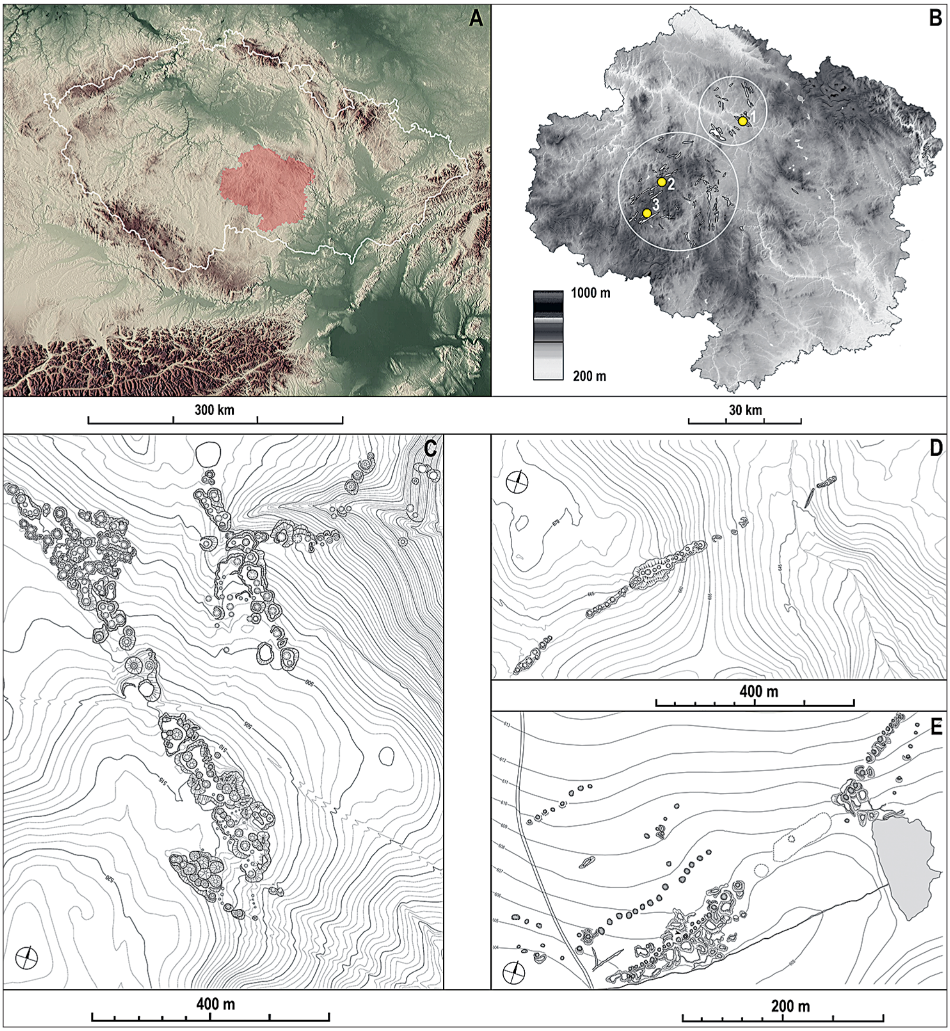

Fig. 1. A: The Vysočina Region in the Czech Republic. B: The Vysočina Region, showing the locations of the medieval chisels. 1 – Utín (historically known as Buchberg); 2 – Opatov; 3 – Čejkov. C: The Utín mining area (historically known as Buchberg). D: The Čejkov mining complex. E: The Opatov mining complex.

In the archaeological literature, chronological differentiation based on the size and weight of the tool is sometimes considered. Smaller specimens are hypothetically classified as belonging to the earlier period of the 13th–14th century, while larger and heavier pieces are usually considered to be products of the later stages of the 16th–18th century (*Hrazdil et. al. 2007*, 294–296, 302). However, it should be emphasised that this classification is rather artificial, as the variability in size and shape could reflect different work tasks, the individual preferences of miners, or different mining techniques (*Hrazdil et. al. 2007*, 302). A good example demonstrating the limits of such categorisation is the set of

Number	Site	Chronology	Point			Body			Head			Heat treated
			Microstructure	Hardness (HV) 30g load	Figure	Microstructure	Hardness (HV) 30g load	Figure	Microstructure	Hardness (HV) 30g load	Figure	
O-0005	Opatov	13–14th century	ferritic	100	3: a	ferritic	100		ferritic	130	3: b	no
O-0033	Opatov	13–14th century	martensitic-pearlitic	460	3: e	ferritic/ferritic-pearlitic	110–130	3: c–d	fearlitic/fearlitic-ferritic	235	3: f	yes (hardening)
C-0032	Čejkov	13–14th century	martensitic-pearlitic	505	4: c	ferritic/ferritic-pearlitic	96–130	4: a–b	spheroidised-pearlitic/ pearlitic	310	4: d	yes (hardening)
U-0107	Utín	13–14th century	martensitic	460	4: f	ferritic	100	4: e	pearlitic/cainitic	220–250	4: g–h	yes (hardening)
U-0502-1	Utín	13–14th century	pearlitic-ferritic	110–180	5: b	ferritic-pearlitic	110–180	5: a–d	ferritic-pearlitic	110–180		yes (tempering)
U-0502-2	Utín	13–14th century	martensitic-pearlitic	480	5: f	ferritic/pearlitic (Widmanstätten)	130–215	5: e–g	ferritic-cementitic	220	5: h	yes (hardening)

Tab. 1. A summary of the chisels, metallographic results and Vickers hardness test.

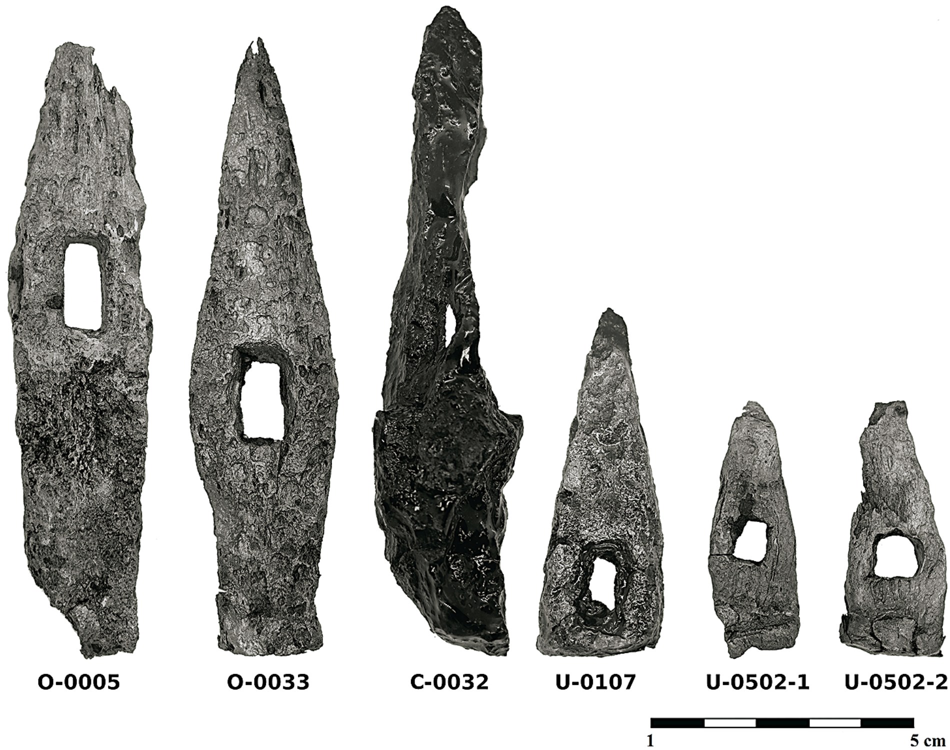

Fig. 2. Chisels and mallet used for metallographic analysis (photo by Filip Vološin).

irons from Banská Štiavnica (*Labuda 1997*, 131, tab. III), which is dated to the 13th century. Based solely on size, the set would fall into the younger group of the 16th and 18th centuries (*Luna – Zimola 2007*, 307). Similarly, different blacksmithing practices in the shaping and final finishing of the tool must also be considered as contributing factors (*Večeřa 2018*, 30–31).

The analysed collection also includes a mallet that was used to strike the tail end of the chisel during work (*Fig. 2*: O-0005). The selection of analysed finds thus forms a representative sample capable of contributing to a better understanding of the technological, functional, and user aspects of these mining tools.

Methods of metallographic analysis

As many of the objects were affected by corrosion, measures were taken to ensure the preservation of the artefacts by storing them in a non-corroded state prior to analysis to prevent deterioration of the samples during the polishing process. The selected tools contained sufficient metal content to allow for comprehensive analysis and were subsequently sectioned along their length. Following this initial preparation, the samples were embedded in epoxy, polished to a mirror-smooth surface of 1 μm and etched with 2% nital. To reduce the risk of the rapid corrosion of the samples, an ethanol-based suspension was used during the polishing process to minimise surface degradation. The Vickers hardness test (QATM Qness 60 A+ EVO) was performed on reagents with known structures to evaluate the hardness of the declared structures. Chemical analysis using OES and SEM-EDS was performed on all artefacts, but did not yield any meaningful results.

Results

Mallet O-0005 is the tool discovered at the Opatov site. It stands out from the analysed samples as a remarkably heavy specimen. Initially, in accordance with common toolmaking practices of the period, the presence of hardened steel components was expected. However, this tool does not conform to that concept. Severe corrosion degraded the material integrity (*Fig. 3*: g; *Fig. 6*: O-0005) to such an extent that detailed metallographic analysis seemed to be almost impossible, as extensive voids (*Fig. 3*: a, g), islands of corrosion products, and slag inclusions hindered the polishing process. Subsequent etching revealed a pervasive ferritic iron structure (*Fig. 3*: a) extending along the entire length of the mallet, with corrosion primarily affecting the boundaries of the ferritic grains. A distinct area with a pearlitic structure was revealed on the left side of the chisel (*Fig. 3*: b), which, in this case, is associated with the heterogeneity typical of materials produced through the bloomery iron-smelting process, rather than with intentional improvement. Overall, the results suggest that the mallet was probably used in surface ore processing and was involved in post-mining activities such as crushing ore and slag, rather than playing a role in subsurface rock extraction. These results are further supported by hardness measurements, which show very low values of 100 HV at the working edges, and approximately 130 HV at the head (*Tab. 1*). These values correspond well to the predominantly ferritic microstructure and indicate the absence of intentional hardening of working edges.

Chisel O-0033 was discovered in 2019 through careful metal-detector prospection at the Opatov site. In the non-etched state, conspicuous linear inclusions consisting mainly of slag were documented along the entire length of the chisel, accompanied to varying degrees by corrosion products. Subsequent etching revealed a predominantly ferritic microstructure (*Fig. 3*: c) in the body of the artefact, which was clearly visible on the left-hand side. The right side showed a distinct ferritic-pearlitic microstructure (*Fig. 3*: d). The chisel point has a martensitic structure with pearlite along the boundaries of the martensitic grains (see *Fig. 3*: e). No weld line is visible between chisel point and body. This area is defined by a gradual transition from martensitic structure to predominantly ferritic body. The striking head of the chisel has a pearlitic and ferritic-pearlitic structure with flattened grains (*Fig. 3*: f) that indicate cold-working. This suggests that the chisel was struck by a hammer during use, which explains the wear associated with its prolonged use. Hardness measurement corresponds well to these observations, showing significantly higher values at the working edges of approximately 460 HV (*Tab. 1*). It confirms the presence of martensite and indicates hardening of the tool point. In contrast, the body of the chisel shows lower hardness values of approximately 110–130 HV, consistent with the ferritic and ferritic-pearlitic microstructure. The head shows values of 235 HV, which correspond to a pearlitic cold-worked structure.

Chisel C-0032 was discovered at the Čejkov mining and ore processing site. Before the etching, conspicuous linear inclusions consisting mainly of slag were observed along

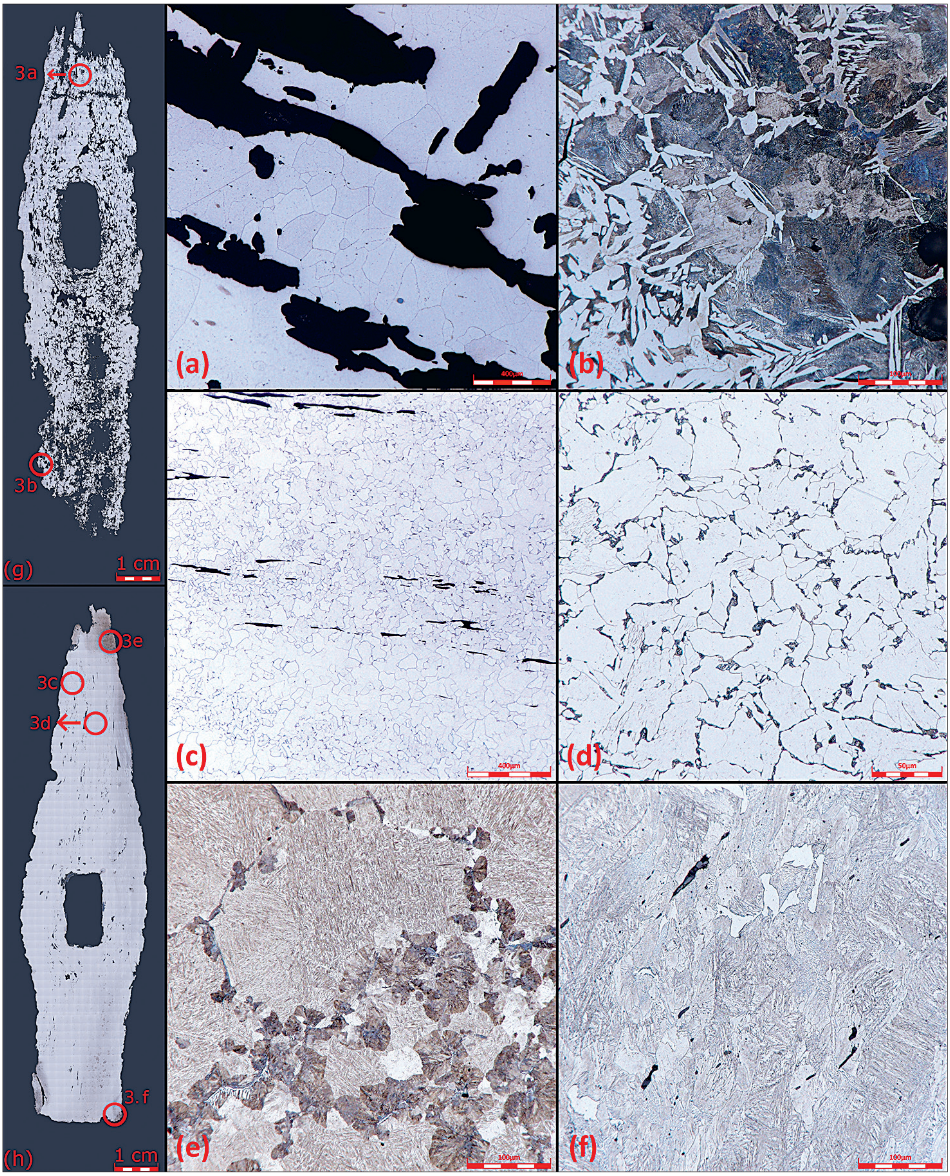

Fig. 3. Metallographic sections of mallet 0-0005 (g) and mining chisel O-0033 (h). Etched surface of mallet O-0005: a – ferritic structure; b – pearlitic structure. Etched surface of chisel O-0033: c – ferritic structure; d – ferritic-pearlitic structure; e – martensitic structure with pearlite formations along the edges of the martensitic grains; f – flattened pearlitic and ferritic-pearlitic structure.

its entire length, along with varying amounts of corrosion products. The preserved body of the chisel is characterised by ferritic (*Fig. 4*: a) and ferritic-pearlitic (*Fig. 4*: b) structures. These are separated by a slag line, indicating that two bars were welded together (*Fig. 6*: C-0032). The point shows martensitic grains with some pearlite at their boundaries

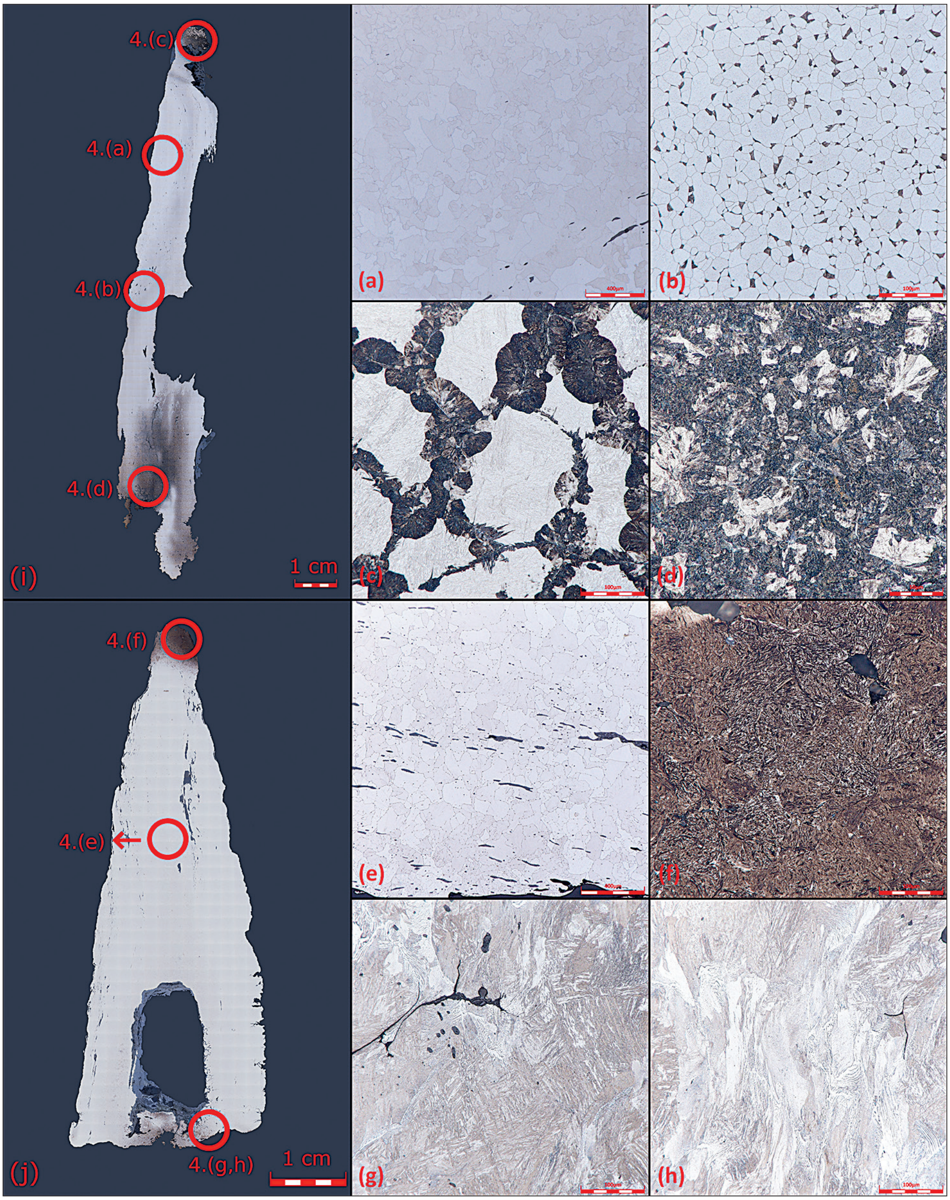

Fig. 4. Metallographic sections of mining chisels C-0032 (i) and U-0107 (j). Etched surface of chisel C-0032: a – ferritic structure; b – ferritic pearlitic structure; c – martensitic structure with radial pearlite grains bordering the edges of the martensitic grains; d – spheroidised-pearlitic structure. Etched surface of chisel U-0107: e – ferritic structure; f – martensite structure; g – pearlitic or bainitic structure; h – area has flattened grain of pearlite and ferrite.

(*Fig. 4*: c). There is no clear weld line between the point and body; a gradual transition from a martensitic to a ferritic structure is visible. The area between the handle hole and the striking head of the chisel shows a partially spheroidised pearlite (*Fig. 4*: d), which appears to have formed unintentionally during the manufacturing process. This is the longest examined chisel with a hardened point that was intended for ore mining. The hardness measurement corresponded well to these observations, showing approximately 505 HV in the point area (*Tab. 1*). While the body of the chisel shows significantly lower values of about 96–130 HV, which correspond to the ferritic and ferritic-pearlitic microstructure, the hardness of the area between the handle hole and the head measured around 310 HV, which corresponds with the microstructure of spheroidised pearlite.

Chisel U-0107 is from the Utín mining site (*Fig. 1*: C). In a non-etched state, substantial linear inclusions were documented running down the entire length of the artefact, consisting mainly of slag, along with a smaller amount of corrosion products. These chains of inclusions indicate that three bars were welded together. Nital etching revealed a predominantly ferritic structure (*Fig. 4*: e) in the body of the chisel. The point consists of an acicular martensite (*Fig. 4*: f). No clear welded line is visible, just a gradual transition between the martensitic structure of the point and the ferritic body. A pronounced structure dominated by pearlite and/or bainite is visible between the handle hole and the head (*Fig. 4*: g), where a cold-worked structure with flattened pearlitic (bainitic?) and ferritic grains is also present (*Fig. 4*: h). Using this material for the head would be advantageous, as it can better withstand repeated hammer blows. The hardness measurement reflects a martensitic structure at the point of the chisel, with a recorded hardness of 460 HV (*Tab. 1*). The body shows lower values around 100 HV, corresponding to the ferritic structure. The head of the chisel shows intermediate values of around 210–250 HV, which correspond well with the pearlitic or bainitic structures and with cold deformation caused by repeated hammer blows.

Chisel U-0502-1 was at the Utín mining site (*Fig. 1*: C). Prior to etching, extensive linear inclusions were observed along the entire length of the chisel, primarily consisting of slag and, to a lesser extent, of corrosion products, clearly delineating the welded bars (*Fig. 5*: i, *Fig. 6*: U-0502-1). The side bars exhibit a predominantly ferritic structure (*Fig. 5*: a), while the central bar features a lamellar pearlitic structure with some proeutectoid acicular ferrite that transitions via a fully developed Widmanstätten ferrite to a ferritic structure (*Fig. 5*: b) along its length. This transformation was caused by decarburisation, likely resulting from prolonged exposure to high temperatures (above 600°C) in an oxidising atmosphere prior to the bar's use. Towards the side edges, the structure changes to a ferritic-pearlitic composition (*Fig. 5*: c, d). This chisel was made from several bars with various carbon contents. Bars with a pearlitic structure were probably selected intentionally for their suitable toughness, while the remaining bars were used without specific selection criteria and may have been sourced from scrap metal. Hardness measurements show relatively uniform values across the whole chisel, ranging from 110 HV to 180 HV (*Tab. 1*), which correspond to the observed structure and indicate that working parts were not hardened.

Chisel U-0502-2 comes from the same site and context as previously discussed chisel U-0502-1. In the non-etched state, significant linear inclusions were observed along the entire length of the chisel, consisting mainly of corrosion products and, to a lesser extent, of slag (*Fig. 5*: e, h; *Fig. 6*: U-0502-2). The body of the chisel consists of a ferritic structure

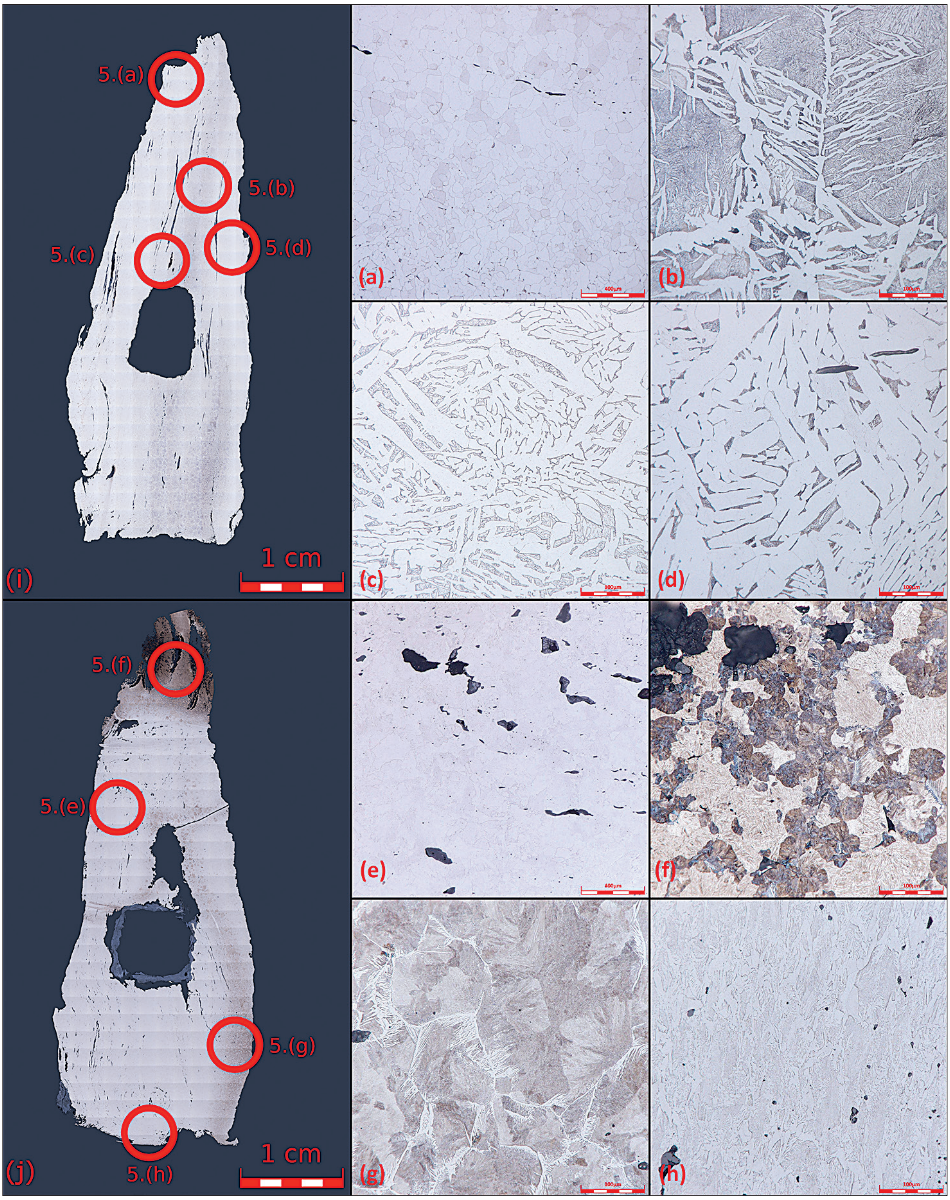

Fig. 5. Metallographic sections of mining chisels U-0502-1 (i) and U-0502-2 (j). Etched surface of chisel U-0502-1: a – ferritic structure; b – pearlitic-ferritic structure transitioning to Widmanstätten ferrite; c–d – ferritic-pearlitic structure. Etched surface of chisel U-0502-2: e – ferritic structure; f – pearlitic grain on the edges of martensitic grains; g – Widmannstätten ferrite features present at the edges of the pearlitic grain; h – flattened ferritic and ferritic-cementitic structure.

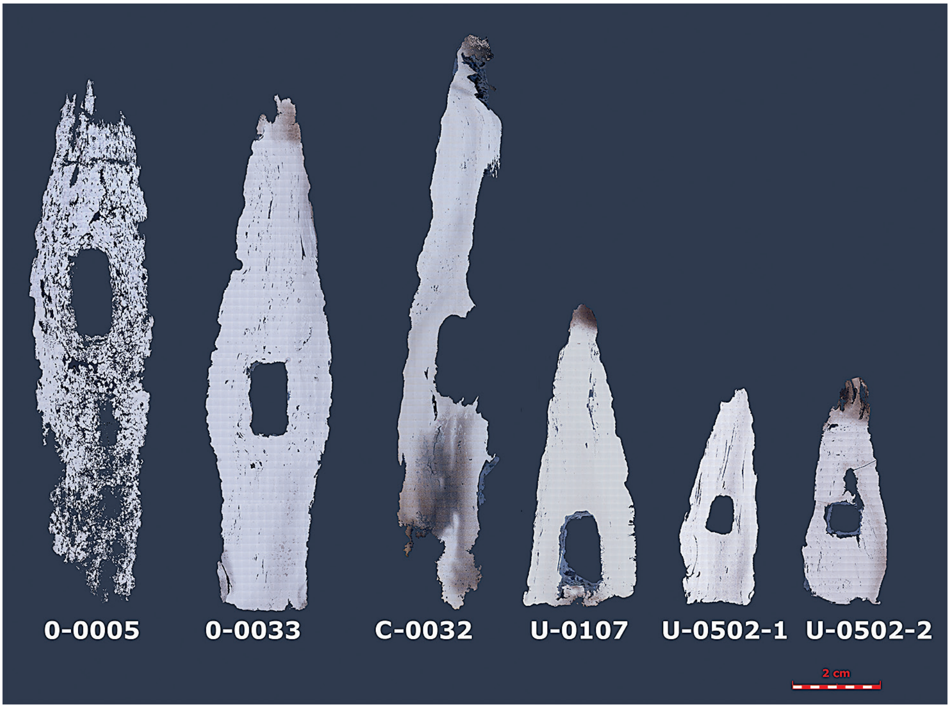

Fig. 6. Overall view of the etched surface of the analysed mining tools.

(*Fig. 5*: e). The point contains martensitic grains with pearlite at their boundaries (*Fig. 5*: f). The right side of the artefact shows pearlite and proeutectoid acicular (Widmanstätten) ferrite (*Fig. 5*: g). The head shows a cold-worked structure consisting of ferritic and ferritic-cementitic grains (*Fig. 5*: h).

Measurement of hardness in the point area shows values around 480 HV (*Tab. 1*), which corresponds to the martensitic structure. Lower values, about 130 HV, were measured in the body, corresponding to the ferritic and ferritic-pearlitic structure. The right side of the body shows a higher value around 215 HV, which aligns with pearlite and proeutectoid acicular (Widmanstätten) ferrite. The rear-end measurements show intermediate values around 220 HV represented by a cold-worked structure of ferritic and ferritic-cementitic grains.

Discussion

The use of chisels to break the rock was the most common method of ore extraction documented in the Bohemian-Moravian Highlands from the 13th century onwards (*Hrubý 2019*, 81). Metallographic analyses of medieval mining chisels from Banská Štiavnica, Slovakia, and 16th-century chisels from Leoben, Austria, have shown that the chisel points were rich in carbon and deformed. Additionally, these studies revealed that steel pieces were, or could be, welded onto the chisel bodies during repairs (*Mihok et al. 1998*, 493–511;

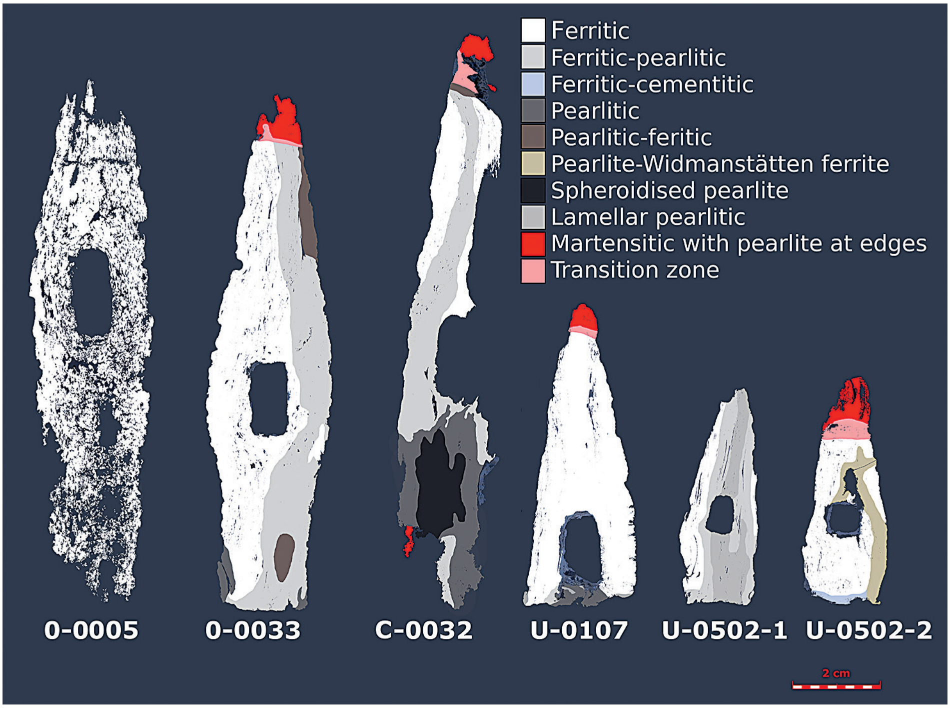

Fig. 7. Overall view of structures of analysed mining tools.

Haubner – Strobl 2015, 217–222). This practice could explain the frequent occurrence of broken-off points and chisels missing their points. In fact, Georgius Agricola noted that 16th-century miners used their chisels until they were completely worn out or destroyed (*Agricola Georgius*, *De Re Metallica*: *Hoover – Hoover 1912*).

All the chisels from the Bohemian-Moravian Highlands selected for metallographic analysis are, except for mallet O-0005, of good quality and made of deliberately chosen materials that could withstand daily use in the mines. The points were intentionally made of steel with a martensitic (O-0033; C-0032; U-0107; U-0502-2) or pearlitic-ferritic (U-0502-1) structure to increase durability (*Fig. 7*). This approach is similar to that employed in other tools, whose working parts must resist excessive wear, such as knives, agricultural implements or wood-cutting tools (*Tylecote – Gilmour 1986*, 93; *Blakelock – McDonnell 2007*). The pointed part of a chisel is subjected to considerable stress during mining, often leading to breakage. Consequently, new points had to be welded onto or into the bodies of the chisels during repairs. Evidence of such repairs was observed in the case of finds from Castel-Minier in south-eastern France (*Méaudre et al. 2023*, 20) and Banská Štiavnica, and Špania Dolina in central Slovakia (*Mihok et al. 1998*, 503). An intriguing observation is that each chisel in this study with a hardened point or steel structure has a steel bar with a pearlitic-ferritic structure on one side, with occasional occurrences of martensite (*Fig. 6*, O-0033, C-0032, U-0502-2). This may indicate that the semi-finished ingots from which the chisels were made were specially made for the production of these tools and the use of harder material in the body of the tool was intentional. Such features are also documented in other studies of similar materials across Europe (*Guillot et al. 1988*; *Mihok et al. 1998*; *Méaudre et al. 2023*, 80). Interestingly, there is no evidence of tempered or welded-in points (*Fig. 6*, O-0033, C-0032, U-O502-2), as no clear wedge-shaped weld lines were observed in any of the analysed chisels from the Bohemian-Moravian Highlands. Instead, only a gradual transition from martensitic to ferritic structures was detected. The weld region is not visually distinguishable; it is characterised by a smooth, gradual transition between the ferritic body and martensitic point. This may indicate either an exceptionally high-quality weld or the formation of a diffuse bonding zone. No sharp weld line or abrupt change in microstructure is evident, resulting in a gradual transition area rather than a clearly defined weld boundary. Welded-in points have been documented on chisels from Pampailly (*Guillot et al. 1988*, 646–652) and Castel-Minier (*Méaudre et al. 2023*, 79–81).

The material requirements for the chisel bodies were clearly less stringent than those for the points. While the carbon content of the bodies was appropriate, the metal frequently contained numerous large slag inclusions. A cold-worked structure observed in the striking heads of chisels (O-0033; U-0107; U-0502-2) results from their usage. Intentionally cold-worked artefacts are rather uncommon in the Middle Ages (*Tylecote – Gilmour 1986*; *Mihok et al. 2003*; *Blakelock – McDonnell 2007*; *Thomas et al. 2016*; *Larreina – Quirós 2018*, 1306–1323), and cold-worked structures generally reflect how the artefacts were used (*Swiss – McDonnell 2003*). In our case, it confirms that the heads of the chisels were constantly struck with a hammer during mining activities. The practice of using mining chisels in this way is depicted in medieval illuminations, referred to by Agricola in 1556 (*Agricola Georgius*, *De Re Metallica*: *Hoover – Hoover 1912*). Additionally, similar features were documented on chisels from Špania Dolina and Banská Štiavnica (*Mihok et al. 1998*, 409–507) and Castel-Minier (*Méaudre et al. 2023*, 20).

Although the material chosen was of good quality, the amount of large slag inclusions suggests that the internal structure of the bodies of the artefacts was not as important as the points of the chisels. The reason why the points were welded in this way is that this part of the tool was subjected to considerable stress during mining; the points commonly broke off, and new ones were then welded into the body. This feature is observable on points from Castel-Minier (*Méaudre et al. 2023*, 20), Banská Štiavnica and Špania Dolina (*Mihok et al. 1998*, 503). Curiously, none of the chisels (0-0033, C-0032, U-0107, U-0502-1, U-0502-2) from this analysis has a point that is just tempered, not with wedged point, as has been demonstrated for chisels from Pampailly (*Guillot et al. 1988*, 646–652) and Castel-Minier (*Méaudre et al. 2023*, 19–21). We can conclude that the preferred constructions of mining chisels varied throughout Europe and that these tools were produced on a nearly mass scale, with slight differences, yet generally serving the same purpose. As these artefacts had to be produced quickly and cheaply, they are commonly made from materials of very poor purity (*Guillot et al. 1988*, 646–652; *Mihok et al. 1998*; *Haubner – Strobl 2015*, 217–222; *Méaudre et al. 2023*, 19–21).

Overall, the hardness measurements (*Tab. 1*) correspond closely to the metallographic observations. While some tools show clear evidence of intentional hardening of the working areas (point and head, O-0033; C-0032; U-0107; U-0502-2), reflected in high hardness values and martensitic microstructures, others were produced from relatively soft ferritic iron without deliberate heat treatment (O-0005; U-0502-1). These differences most likely reflect both technological choices and specific functional requirements of the tools used in mining and ore-processing activities.

Even though chemical analysis using OES and SEM-EDS was performed, it did not yield any meaningful results from which conclusions could be drawn. Rapid corrosion prevented SEM-EDS analysis, and the artefacts' matrix heterogeneity, with slag inclusions, prevented OES measurements. These analyses do not represent a suitable method for this type of material. Future work should therefore focus on Wavelength-dispersive X-ray spectroscopy (WDS) for more suitable data.

Conclusion

This study is one of the initial steps towards reconstructing the technological approach to the production of medieval mining chisels from the Bohemian-Moravian Highlands and, more generally, in Central Europe.

The metallographic analyses revealed that the chisel bodies were made of poor-quality metal, suggesting that these tools were regarded as consumables, intended for heavy use and at risk of significant wear or loss. Of the six samples, four had points of quench-hardened steel and predominantly ferritic iron bodies (O-0033, U-0502-2, C-0032, U-0107). There appears to be no weld line between chisel points and bodies. This might be due to the high-quality welding that has resulted in a diffuse bonding zone with a gradual transition between high-quality points and soft ferritic bodies. One chisel point (U-0502-1) was made from a predominantly pearlitic-ferritic steel, but quench hardening was not documented. Mallet O-0005 was primarily iron, including its working parts. These findings imply that individual chisels were adapted to the nature of the rock and the type of work for which they were intended. In addition, this variation may indicate that the chisels were used not only for ore extraction, but also for other mining activities, such as crushing ore or slag before smelting, as evidenced by the historical sources. In the future, further chemical analyses (WDS) will be conducted, which will contribute to a more detailed understanding.

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