METALLOGRAPHIC INVESTIGATION OF TWO MINER'S TOOLS FROM WADI KHALID/ FEINAN

by
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Introduction

During the 1984 field season in the Feinan district, a unique mining monument next to the survey of smelting and mining sites consisting of three shafts sunk parallel to each other was discovered and investigated. This "triple-shaft" (Pl. I, 1), discovered and excavated by Mr. Kasim Omari, mining engineer from the Natural Resources Authority (Omari 1983) is located in the middle of Wadi Khalid close to the modern trench cut in the copper ore deposit. Its internal reference no. is Wadi Khalid mine 2.

Two of the shafts which were heavily affected by tectonic events of the adjacent rift valley reached the copper mineralization in the Dolomite-Limestone-Shale Unit at a depth of at least 18 m (Hauptmann *et al.* 1985). These shafts were dated by pottery found in and around the back dumps to the Iron Age IIC. The third shaft (marked by an 'X' in Pl. I, 1) is different in that it has a more perfect shape and construction. It was sunk from a consolidated platform which, in turn, was accessible by two rows of steps carved in the rock. Due to the composition of the associated adjacent waste dump which consisted of pure sandstone, the shaft did not reach the ore horizon; it was apparently constructed for the purpose of prospection. The shaft was dated by a Roman coin to the first century AD. Two iron objects were found along with the coin. As shown by the chisel marks (Pl. I, 2), such tools were used in the construction of the steps, the platform and the shaft (Fig. 1). Iron tools used for work in mines have not been metallographically studied before. Therefore, it was gratifying to have the opportunity to study the metallography and the chemical composition of the products and, perhaps, to determine the special techniques the Roman blacksmith may have used in constructing mining tools.

Methods of Investigation[1]

Standard metallographic methods (cutting, grinding, polishing and etching), hardness determinations[2] along with Atomic Absorption Spectroscopy to determine the chemical composition were used. Samples were cut (Fig. 1) from both the pointed and opposite ends and mounted in a cold-setting resin to facilitate the grinding and polishing. Etching to remove the smeared metal due to the grinding and polishing was a 3% Nital (3 parts conc. nitric acid to 97 parts of ethyl alcohol).

Results

The microstructure of the "working" end of the chisel (Lz.-Nr. 20/1) is that of an eutectoid steel with a carbon concentration of *ca.* 0.7% (Pl. II,1). The chisel is homogeneously carburized over the entire section, i.e. to a depth of 3 mm. There is no transition zone visible between a carburized outer surface and a low carburized interior of the chisel. The pearlite[3] spacing suggests that the chisel was quickly cooled from the higher temperature phase region (austenite — see footnote 3). The hardness values (658, average of three measurements) are those of a

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[1] These studies were made at the Deutsches Bergbau-Museum. Financial assistance from the Deutsches Bergbau-Museum during the stay of R. Maddin was greatly appreciated.

[2] DPH (diamond pyramide hardness) using a 100g load.

[3] The eutectoid formed in the decomposition of the higher temperature phase (austenite) on cooling below 723°C. It consists of alternate layers of ferrite (pure iron) and iron carbide. The spacing of the layers is determined, primarily, by the cooling rate through the temperature 723°C.

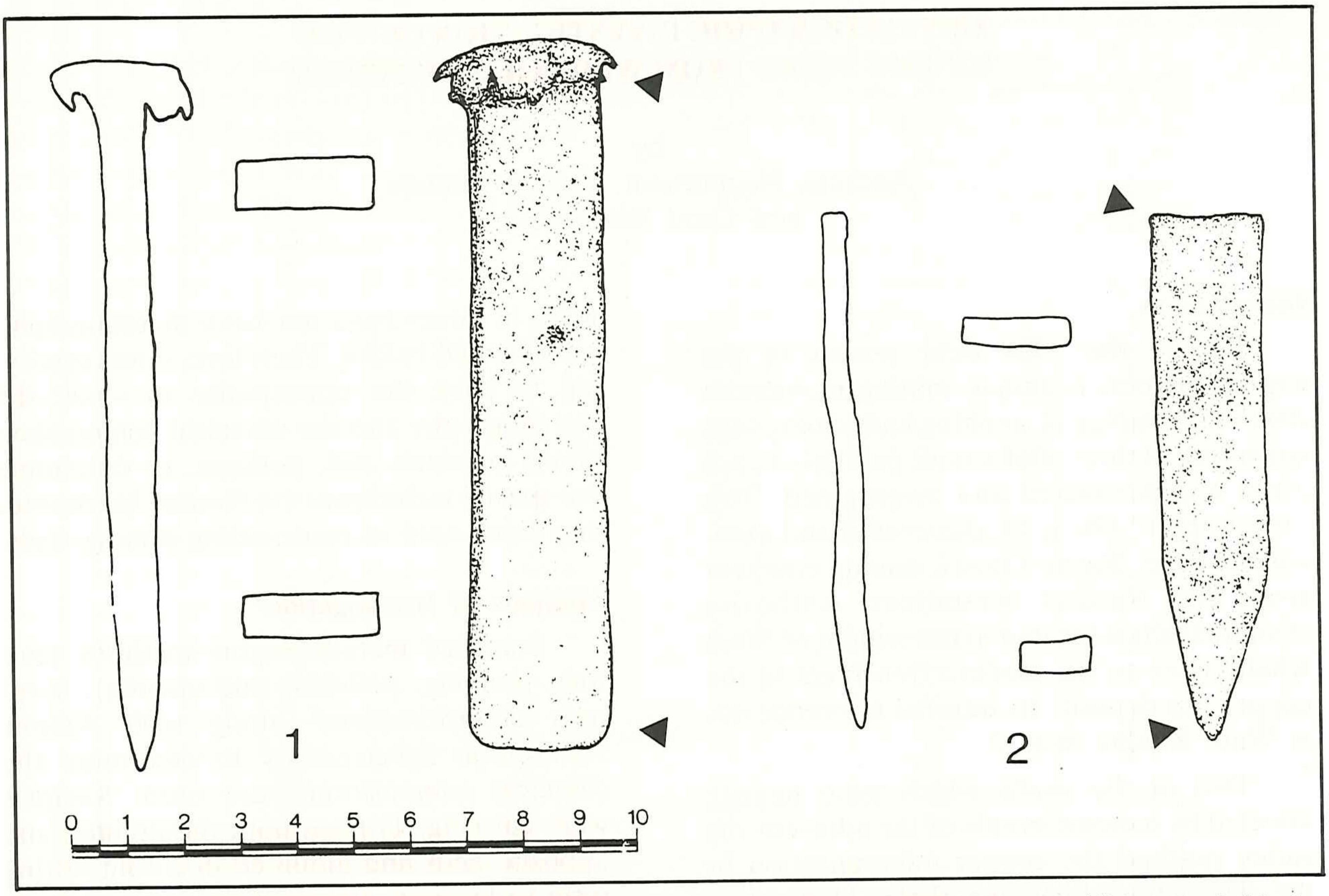

Fig. 1. Roman iron objects from the waste dump of the "triple-shaft". One of the tools (1) is a used chisel of eutectoid steel. The second object (2) is a semifinished chisel or knife. Lz.-Nr. 20 Deutsches Bergbau-Museum (Drawing A. Weisgerber).

quenched eutectoid or hypereutectoid steel. We did not observe martensite;[4] we assume, however, that either the attempt to produce the extremely hard martensite was unsuccessful or that the layer of martensite (which may have been quite thin) was lost due to corrosion over the millennia. Pl. II,2 and 3, at higher magnifications show also slag particles aligned perpendicular to the forging direction during the manufacture of the tool. Here the fine spacing of the pearlite in some areas is almost bainitic.[5]

The sample from the blunt end also shows an eutectoid steel (Pl. III,1). Here, too, the sample appears to be homogeneously carburized throughout the section, i.e. the composition and structure are that of a steel to at least 4 mm below the surface. The hardness values (347, average of three measurements), on the other hand, are considerably less in this part of the chisel but are consistent with a quickly cooled hypoeutectoid steel.

The chemical composition (Table 1) shows a steel with relatively high values of Mn, Cu and Ni. In amounts such as 0.5%, manganese has a slight effect on increasing the initial yield strength of iron; its effect on the rate at which cold forging hardens iron is greater, however. Both copper and nickel have only a slight effect on increasing the strength as well as increasing the resistance to corrosion. As much as 1.5% Mn (the amount present in chisel Lz.-Nr. 20/2, see below), on the other hand, increases the initial hardness as much as 25% and has a large effect on the rate at which cold forging increases its strength. Mn, Cu and Ni are typical elements associated with the mineralization in the Feinan area and could be—with caution—

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[4] The phase formed in the quenching of a carburized steel.

[5] A product formed when the cooling rate is not quite fast enough to form martensite.

Table 1: Chemical composition of the iron tools. Lz.-Nr. 20/1a is from the cutting edge, 20/1b from the blunt end of the chisel. Lz.-Nr. 20/2a is from the pointed end of the semifinished tool.
Values given in wt.-% if not µg/g. n.s. = not sought for.

Lz.-Nr.	20/1a	20/1b	20/2a
Fe (%)	96.0	97.1	94.5
C (%)	0.7	0.7	< 0.01
Mn (%)	0.469	0.465	1.579
Cu (%)	0.254	0.255	0.132
Ni (%)	0.152	0.149	0.109
Co	125	130	215
Cr	970	820	1610
Ti	< 20	< 20	40
V	< 20	< 20	< 20
P	<100	<100	800
Si	50	n.s.	n.s.
As	260	270	290

indicative of a smelting of local iron-rich ores. On the other hand, the steel is nearly free of other trace elements and especially phosphorus is very low. This is in contrast to the high phosphorous (and carburized) iron inclusions which apparently are typical not only for copper slags from Feinan (Hauptmann *et al.*, in prep.), but for the entire ore district of Wadi ‘Arabah (Roman 1990). Obviously, such inclusions are formed by smelting copper ores plus gangue/flux rich in phosphorus under high reducing conditions.

Two samples from the second chisel (Lz.-Nr. 20/2) were similarly cut from the working and the blunt ends and studied accordingly. Both ends show the same microstructure which, in contrast to the chisel 20/1, is that of a slightly carburized bloomery iron with only a small amount of carbon (estimated at *ca.* <0.01%, Pl. III, 2). In both samples, the hardness values are that of a soft ferritic iron (115 for the pointed end and somewhat harder, 155, at the blunt end). Both values are those for this type of bloomery iron.

The chemical composition (Table 1) is very similar to that for the chisel 20/1 except for Mn which measures 1.579%. This amount of manganese is most likely responsible for the relatively high DPH (normally expected to be in the order of 80-100). Also Cr has about double the level as the other artefact.

Discussion

The discovery of both iron tools (chisels) in the waste dump of the “triple shaft” indicates that they were used for mining work. The results of the metallographic studies show that they represent different stages in the manufacture of the chisels — a completed and an intermediate stage. The object, 20/1, is a fully formed and (heat-treated) chisel. The far harder working end of this chisel suggests to us that the heat treatment, probably involving the repeated immersion of this end into the hearth in order to forge to the desired shape, increased the carbon content (cementation) and, hence, the hardness after attempts at quenching.

Numerous experimental studies show that higher carbon contents in iron objects may result from long-time carburization (standard carbon diffusion while the object is at higher temperatures, Shewmon 1963) in a forge. These studies are in accord with numerous metallographic studies carried out on Roman edge tools (for an overview see e.g. Tylecote 1986) and suggest that the blacksmiths during this period have been able to convert a bloomery iron into a steel for further conversion into a hardened product. As the metallography of the chisel 20/1 revealed no carbon gradient near the surface, it is not possible to draw definite conclusions on the manufacturing of this tool.[6] In any event, because of its hardness, this chisel would have been an effective tool. The object, (20/2), in the shape of a chisel (or a knife) and broken towards the blunt end, appears to be in the process of having been manufactured. The bloomery microstructure and shape suggest to us that the objects are

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[6] Straube (1985), in a critical review paper on the theories of the bloomery process, even considered the possibility of a primary steel production in ancient times, at least for Roman smelting activities at the Magdalensberg/Austria.

first shaped into their form and are followed by heat treatment. In contrast to chisel 20/1, this object is the result of the first stage in a process that would involve carburization to be followed by a stage during which the sharp end of the tool would be further carburized and quenched.

Local treatment of iron tools or even their manufacture is supported by many finds of smithing slags in the hills and valleys where Roman mines are located, e.g. at Qalb Ratiye and Wadi al-Abiaḍ. Such slag-cakes are formed during the carburizing and sharpening of tools used in the mines. They may also represent an earlier stage of the treatment of iron, e.g. the heating of a bloom to remove slag or charcoal inclusions. The two objects, therefore, along with the smithing residues are clear evidence that tools, not necessarily completed tools, were delivered to the mines in the Feinan area; the semi-finished tools were then further shaped and heat-treated by the blacksmith at the mine. Evidence for a local smelting of iron ores for the Roman period, as it was performed during the Early Islamic period, needs further investigation.

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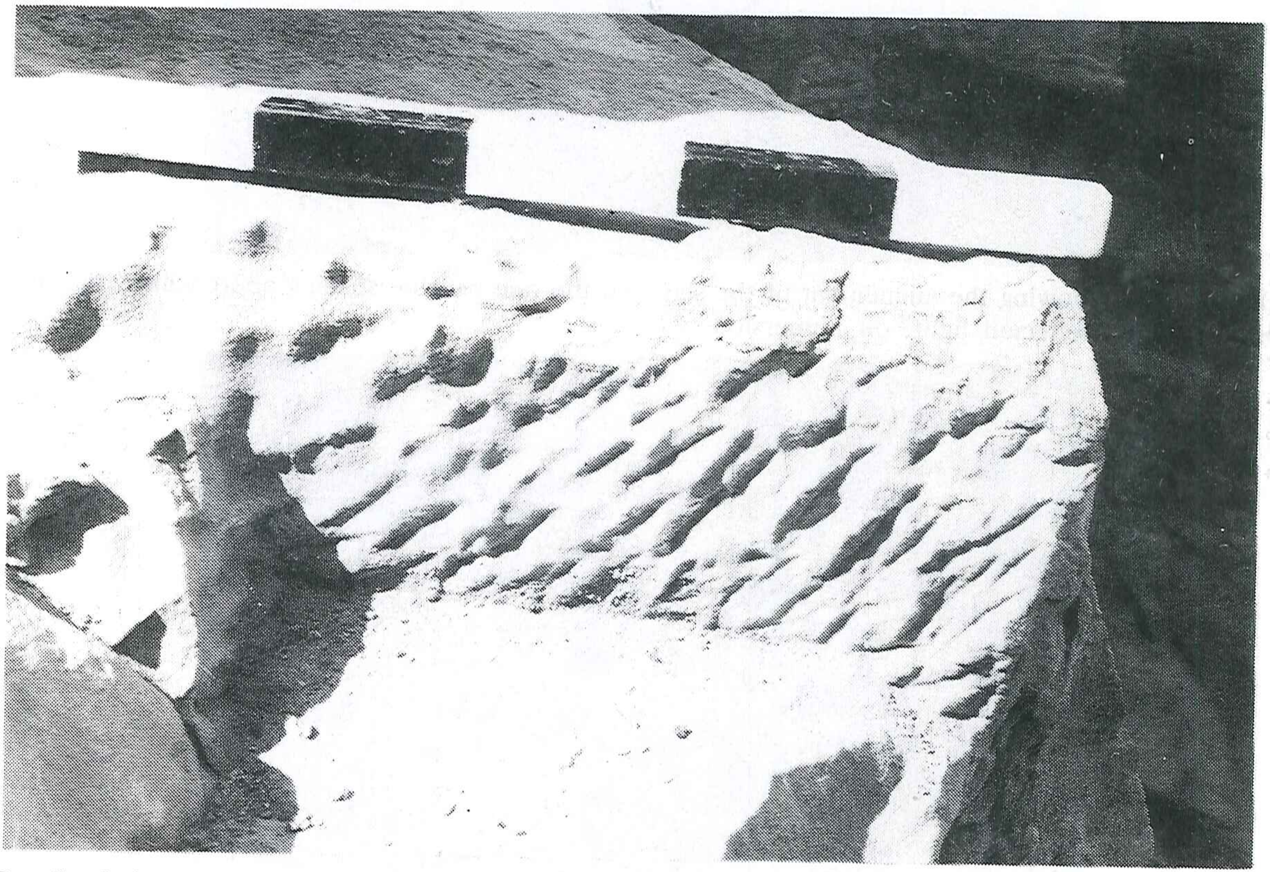
1. The "triple-shaft" in Wadi Khalid/Feinan is a unique technical monument in the history of mining. Two shafts have been constructed during the Iron Age II, the third one (x) was opened from the platform in Roman times. The two iron objects have been found in the waste dump heaped up by the Romans.



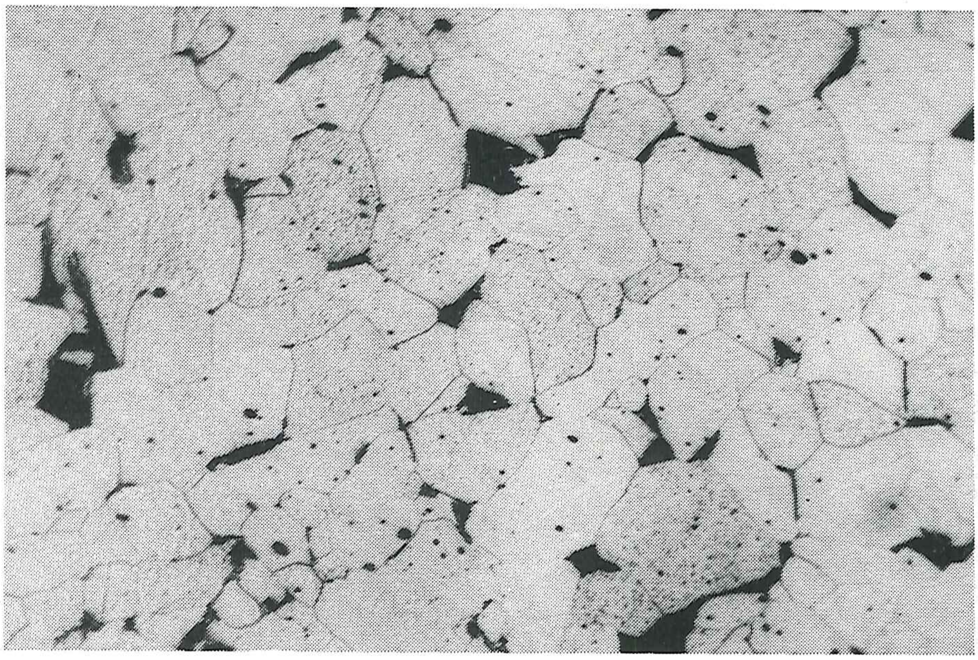
2. Detail of the "triple-shaft" construction showing chisel marks in the sandstone.

1. Microstructure of the "working" end of the chisel 20/1. Note the alignement of slag inclusions in a matrix of eutectoid steel consisting of pearlite. 220x, reflected light.

2. Detail from 1 showing the alignement of the slag and the fine pearlite spacing approaching that of a bainite. 500x, reflected light, oil immersion.

3. Blunt end of chisel 20/1. The composition of the eutectoid steel is similar to the working end of this tool showing slag alignement in a pearlite matrix. Note the fine spacing of pearlite and the grains of proeutectic ferrite. 500x, reflected light, oil immersion.

1. Microstructure of the mildly carburized bloomery iron of tool 20/2. This structure is the same for the whole tool. Note the ferritic grains with some pearlite spacing. 220x, reflected light.



2. Detail from 1 at a higher magnification. 500x, reflected light, oil immersion.