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The development of the screw – an early metallurgy

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A metallurgical analysis of a bronze needle with a screw is presented. This analysis sheds light on the process which led to the invention of the screw. We also present one of the first examples of hardening bronze by mechanical deformation. We offer a simple method for detecting small amounts of some impurities which were present in the original metal ores, which can serve for identification of the ores.

1. Introduction

One of the most important developments of ancient technology is related to the invention of the screw. For technology and for human progress based on technology, the invention of the screw is of the same order of importance as the invention of the wheel. Both the wheel and the screw are natural shapes. The spiral shape of the sea shell is an example. Yet, the small step from the "shape" to the "tool" was a giant leap for mankind.

It might be interesting to know what the significant phases were leading to the development of the screw.

The spiral shape, as in the sea shell, was used for decoration in the chalcolitic period. Some of the bronze canes and staves found [1] in the Judean desert in the cave of the treasure in Nahal Mishmar, have decorations in a spiral shape. An example of such a bronze cane is given in Fig. 1. This bronze cane is 25.5 cm long and 2 cm diameter. The cane, including a spiral decoration, was made by casting. It should be noted that this spiral decoration is one among many other decorations found on canes in the same treasure. Yet, the missing link between the decoration and the tool is required.

A bronze needle recently obtained might shed some light on the question of the missing link. This bronze needle (see Fig. 2), 4.4 cm long and 2.8 mm diameter, was obtained in an antique shop in Madrid, Spain. It has a screw-like point for better penetration, like a drill.

As a result of not finding this needle in an orderly archeological excavation, it is difficult to determine the period in which this tool was made. However, we have some basis to believe that this needle was produced in the Bronze Age. As we will discuss later, this screw was made by twisting the metal. The twisting, however, was done when the metal was at room temperature, which resulted in the hardening of the bronze. Using a deformed metal in the act of production added hardness and increased strength. This twisting process gave birth to a harder kind of bronze. The harder bronze, together with the screw itself, are indications that this needle was intended for work with tough materials, probably leather. For penetrating leather, an iron needle, if available, is much better. Investing so much in a bronze needle might indicate that iron needles were not available, which suggests that this needle was produced during the bronze age.

We further investigated the material content of the bronze and its distribution inside the metal. The bronze has 90.1% copper 9.6% tin and about 0.3% iron impurities. So it is a typical bronze composition. No arsenic was found, which would, therefore, indicate an early bronze. The distribution of the tin inside the metal indicates a rather primitive metallurgical level, which again might indicate an early period.

While investigating the metallurgical aspects of the needle we found inclusions (see the black dots in Fig. 4a as well as in Figs 6 and 7, later). Analysing these inclusions we found that the impurities of the metal concentrated there. Thus, it is simple to detect small amounts of impurities which were in the bronze ore. These impurities can serve as the "finger prints" of the metal which might lead to the location of the mine from which the ore was obtained, if the relevant data are available.

2. Experimental procedure and results

This study was carried out on the bronze needle bought from an antiques dealer in Madrid, Spain. This needle is in the shape of a screw, 4.4 cm long and 2.8 mm diameter, and was prepared for the cross-section examination by conventional metallography. A scanning electron microscope (SEM) with energy dispersive analysis by X-ray (EDAX) equipment was used to determine the composition of the needle. The average chemical composition of the needle is 90.06 Cu, 9.59 Sn, and 0.35 Fe (wt %). The relative distribution of the specific elements in the structure was obtained by a line-scan procedure.

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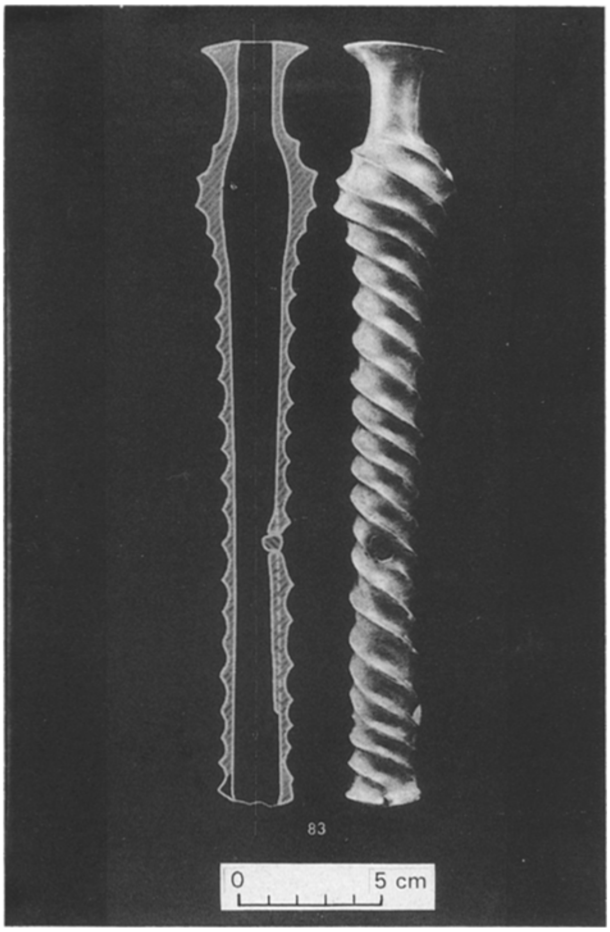

Figure 1 A chalolitic bronze cane from Nahal Mishmar.

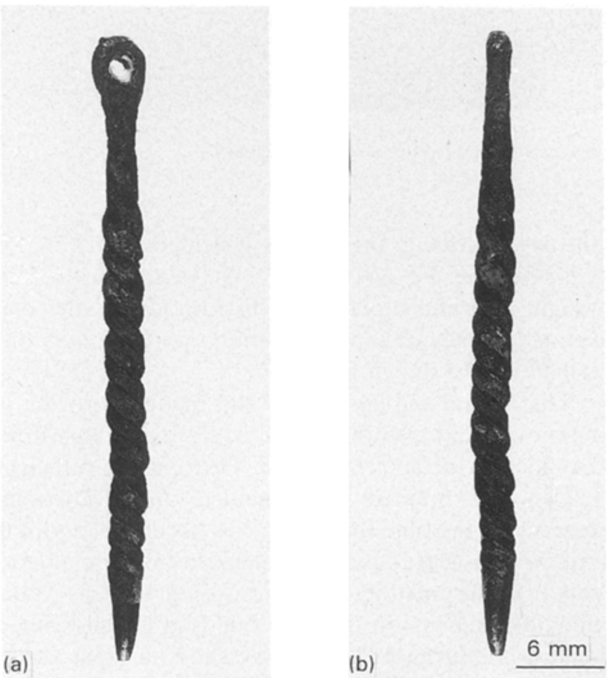

Figure 2 The bronze needle: (a) face; (b) side.

This bronze needle has a special shape. Its sharp tip with the twisted structure in the middle can be seen in Fig. 2a and b and a small hole of 1.7 mm in the centre of its upper part. This needle was treated by using

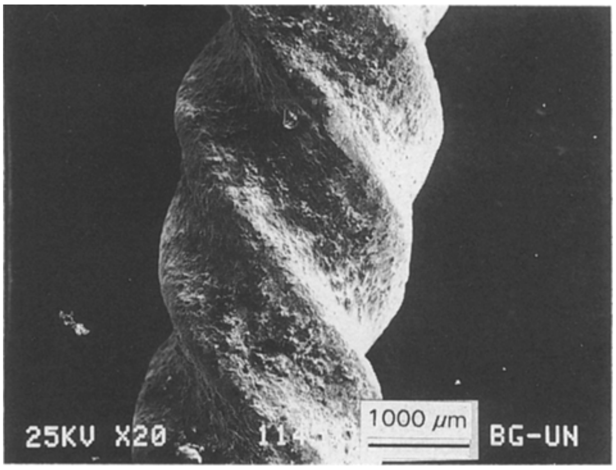

Figure 3 The thread of the bronze needle.

external stresses making angles between 45° and 55° between the threads and the needle axis. The dimensions of the threads depend on their locations on the needle (Fig. 3).

It was found that the "screw shape" was obtained by twisting the metal at room temperature. Because it is much easier to produce the screw while the metal is hot, there must be some particular reason to do it at room temperature. Mechanical deformation at room temperature creates hardening in the bronze.

The use of mechanical deformation for the hardening of bronze is not common, even nowadays. Crystal structure rotation during the tensile and compressive deformation can be obtained. When the single crystal is deformed in either tension or compression, the crystal lattice usually rotates and this tends to align the slip plane and the active slip direction parallel to the tensile stress axis. The active slip plane should be the $\{1\,1\,1\}$ plane in face-centred cubic (F C C) materials when the slip direction is $\langle 1\,0\,1 \rangle$ in mainly α bronze structure. In polycrystals the same mechanism of deformation occurs, but every grain has different active planes and active slip directions. However, the grains can only be of the same families. During straining, the number of dislocation defects in the lattice structure of the metal increases. This increase in the number of retained dislocations results in a strengthening of the metal [2]. In other words, the increase in hardness of strength of a metal with deformation, is closely associated with an increase in the concentration of the dislocations. Fig. 4a presents a representative structure of the cross-section of the needle. At high magnifications of the microstructure it is evident that the needle structure is typical of a highly deformed structure, as can be seen by the high-density slip planes which occur in grains of the microstructure (Fig. 4b).

The effect of dislocations and stress on the corrosion of alloys has long been recognized and studied [3]. Materials after plastic deformation are sensitive to general corrosion, caused by the corrosive agents in the environment which penetrate through crevices, pores, or cracks in the surface of the needle and reach the metallic particles trapped within the needle. The

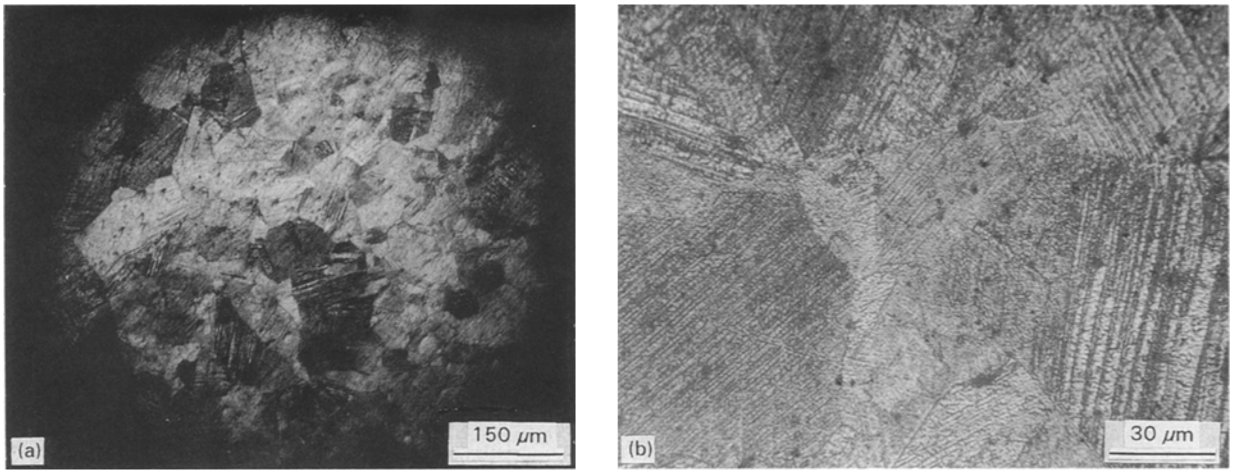

Figure 4 Optical micrographs showing the microstructure of the upper cross-section of the bronze needle: (a) low magnification; (b) high magnification.

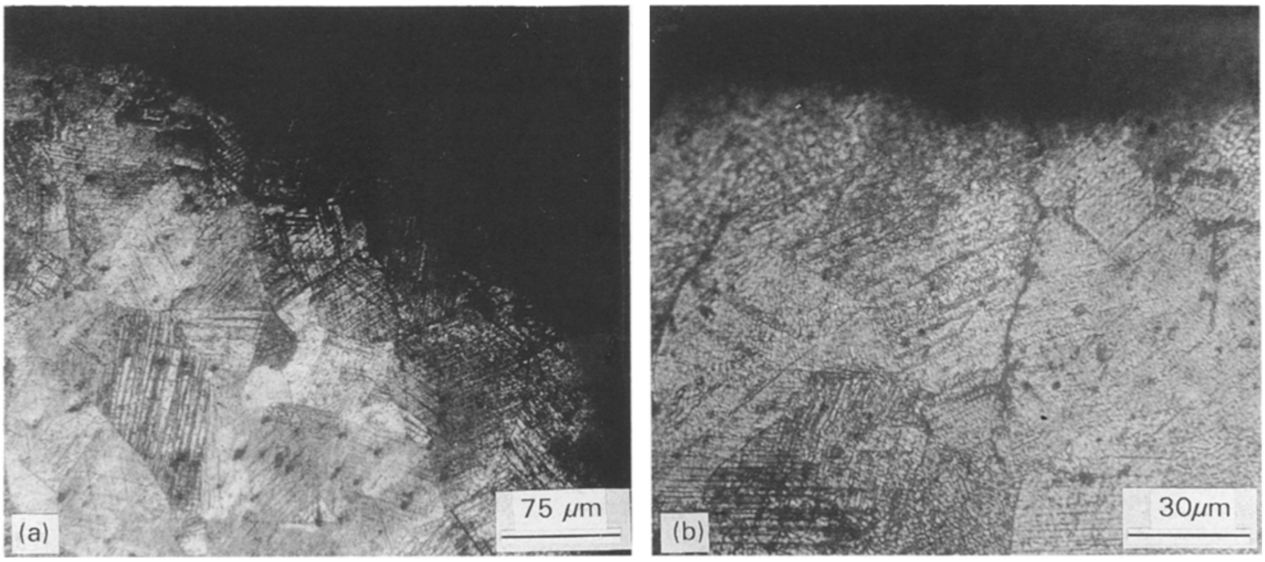

Figure 5 Optical micrographs showing: (a) general corrosion in the bronze needle, and (b) stress corrosion cracks.

near-surface regions (100 μm) of the needle show general corrosion (Fig. 5a). On the other hand, in states of stress or strain a material in a corrosive environment has increased susceptibility to stress-corrosion cracking. Stress-corrosion cracking refers to cracking caused by the simultaneous presence of tensile stress on a specific corrosion medium. Typical stress-corrosion cracks with a transgranular mode, which initiated on the surface and propagated to the centre, are shown in Fig. 5b.

The distribution of the major elements (copper and tin) in the bronze is demonstrated in Fig. 6a. The line profiles of both elements obtained by EDAX on line-scan SEM, show inhomogeneous concentrations of these elements on the line, as would be expected from the mixed materials (after plastic deformation) which were originally solidified in the casting process.

The bronze microstructure includes a high density of small inclusions (Fig. 4a). Sulphur was detected by SEM (Fig. 6b) as already indicated (arrowed). Chemical analysis obtained by EDAX from the particle shown in Fig. 7 indicates that these small inclusions in the needle contain the following elements: S 11.56, Pb 3.07, Se 2.66, Fe 1.01 with Cu 81.35 and Sn 0.35 in weight concentrations. The distribution of the elements (profiles of copper, selenium and sulphur) obtained is also shown in Fig. 7.

The origin and history of the melting process is unknown, and also the needle could have come from any locality or ancient period. There is not sufficient evidence to indicate that chemical analysis was in practice at the time the needle was produced, and it is improbable that the ancient blacksmiths were able to separate the melting stock according to its various alloying elements in order to build-up a well-defined melt in the furnace. The bronze shows a great variation in composition. In the present study the needle was found to consist of large amounts of inclusions which contained sulphur, lead, selenium and iron; however, arsenic was not traced. The composition of these inclusions indicate the source of the copper ore, because they do not melt during the melting process. Thus, the specific composition of the inclusions, might indicate the place in which the copper ore was found.

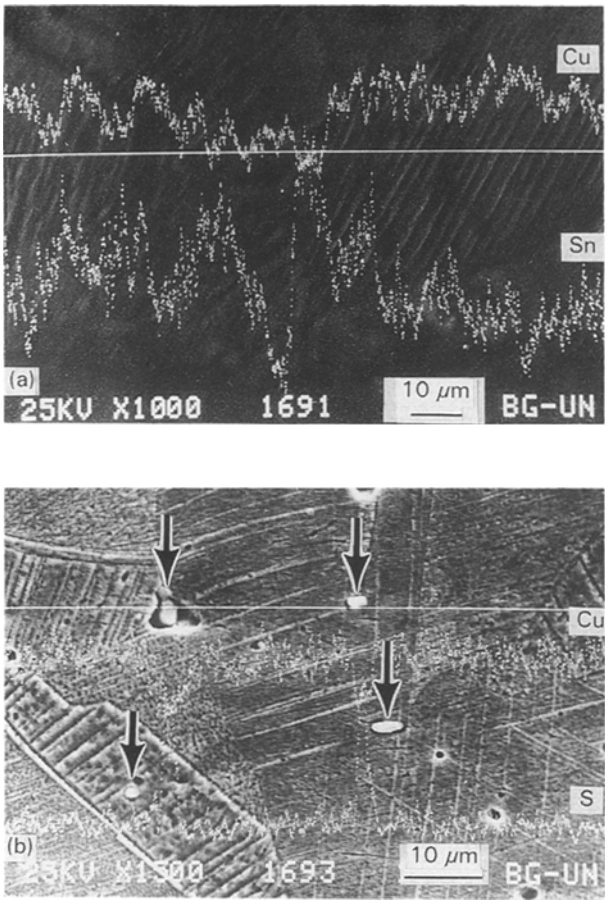

Figure 6 EDAX line profiles of the elements (a) copper and tin, (b) copper and sulphur.

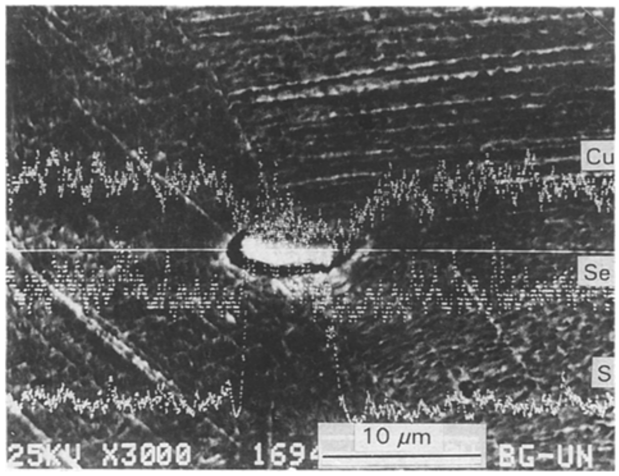

Figure 7 EDAX line profiles of the elements copper, selenium and sulphur.

3. Discussion

A metallurgical analysis of a bronze needle with a screw is presented. We believe that this analysis sheds light on the important and interesting question of "how was the screw invented?", that the necessity to use bronze tools for penetration in hard materials initiated the invention of the screw.

By metallurgical analysis we have found that it was not only the screw itself which helped make better bronze tools. We noted that this bronze screw was produced by twisting the metal at room temperature, a process which added hardness and increased the strength of the bronze. So this is, probably, a very early example of hardening bronze by mechanical deformation. We have also probably discovered one of the first examples of stress corrosion.

During this analysis we also found that the impurities in the metal (such as sulphur, lead and surprisingly selenium) tend to concentrate in the bronze microstructure as a small inclusion. These inclusions can be quite easily detected and analysed using SEM, which can provide information about the small amount of impurities which were originally in the bronze ore. Thus, these impurities can serve as "finger prints" for identification of the source of the copper and tin ores. However, more information about impurities in copper and tin ores is needed before this method can be used for identification purposes.

The major drawback of our investigation is our inability to date the needle accurately. As we have already discussed, the efforts invested in producing this bronze-screw needle indicate that better tools (e.g. iron tools) were not available. Furthermore, the inhomogeneity of the bronze itself indicates a rather primitive metallurgical level. However, these indications are not proof of the period of the production of this needle. We are not aware of any similar bronze needles found in an orderly archeological excavation. If there are such, they would be of importance to the current study.

Acknowledgement

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