LABORATORY EVIDENCE OF HOW METAL ARTIFACTS WERE USED

Chemical analyses of metal artifacts recovered by archaeologists are often reported and useful inferences can sometimes be drawn about how or where an object was made from its composition. But this is only a small part of what can be learned about many metal artifacts in the laboratory. Two additional, important sources of information are the microstructure—the interior structure of the metal—and any external markings that may be preserved on the surfaces of the artifact. Study of these features may reveal more about how an object was made than can be deduced from its composition and may show how an artifact was used after it was made.

1. *Use-Wear Analysisi of Metal Artifacts*

The use of microstructural and surficial evidence to deduce the methods by which metal objects were made has been described in several papers by C. S. Smith.[1] He particularly directs our attention to the importance of the decorative arts in influencing the development of metallurgical skills and he places emphasis on objects that were made for decorative or symbolic purposes. These were often then very first uses made of metals in a society but, as metal became more common and began to reach the hands of people outside of the ruling elite, they were turned to utilitarian purposes and become a part of the working lives of a larger proportion of the population. Here I will focus on methods that can be used to discover how metal artifacts were used to accomplish tasks in households and at work.

External Evidence. A set of techniques, usually called « use-wear » analysis, has been developed for the determination of the tasks performed with stone implements.[2] The evidence used comes entirely from the surfaces of the objects studied because the interior structure of a stone tool is not altered by its use. It is only very recently that development of a corresponding set of techniques for the interpretation of surficial markings on metal artifacts has been undertaken.[3] Because metals are plastic rather than brittle, a different set of physical phenomena is involved in the formation of surficial markings on metal artifacts, but metal retains as much, or more, such evidence than do lithic materials. An example of the type of markings indicative of use of a metal artifact is shown in Fig. 1, a magnified view of the edge of a bronze implement from pre-Columbian Peru shaped like a chisel. The surface has been somewhat pitted by corrosion, but a set of parallel striations oriented perpendicularly to the edge are easily seen in the photograph. These striations were formed after the implement was made either in the performance of a task with the artifact or, possibly, in the preparation of the edge of the implement for use. How and why the marks were made is to be determined. (An artifact may have been marked by attempts at cleaning and this may not be known unless it has not been under the care of the investigator since the time of its excavation. The surface damage so produced may be confused with genuine use markings. In the example shown in Fig. 1, the striations were revealed when a covering of adherent soil on the object was removed and were, therefore, present before excavation).

Internal Evidence. A major difference between metal and lithic materials is that artifacts made of metal may contain internal evidence of use. This is because metals are plastic, i.e., they can undergo permanent deformation without breaking. When a metal implement is brought in contact with a resistant material, as in hammering or cutting, the metal in the tool deforms at the same time that the work piece is cut or shaped. The amount of this distortion may be very small, but even very small amounts of interior damage can be detected by the presence of characteristic markings in the structure of the metal.

Metal objects are made up of many small crystals, called *grains*, that are formed when the metal solidified. This array of grains is called the *microstructure* of the metal. When the surface of the metal is polished and lightly etched, the grains are rendered visible because the individual crystals reflect light differently. The technique of revealing the microstructure of metals revealed by polishing and etching was discovered by H. C. Sorby in 1863 and has been used since the late nineteenth century as one of the standard ways of examining the interior constitution of metal obects.[4] Figure 2 is an example of a microstructure consisting only of grains of a single metallic constituent, in this case copper containing dissolved tin (bronze). As a result of the etching, the different grains appear with different colors. When metal such as this is plastically deformed, the individual grains are distorted. This is accomplished by shearing on clusters of planes within the crystals called *slip bands*. When distorted metal is etched, the slip bands are colored more darkly than the surrounding metal and show up as dark lines cutting across grains in the microstructure.

An example of deformation bands in bronze is shown in Figure 3. This is a polished and etched section of an implement from Peru which has been described as a chisel.[5] This implement has been forged to shape while the bronze was hot, producing the elongated grains, and the forging has been continued after the metal cooled down, causing the deformation bands revealed by the etching. The orientation of the bands differs among the different grains because the grains themselves are oriented at random. If the distortion of the metal is sight, the slip bands will be straight lines across the grains but, when deformation becomes greater, the slip bands become more distorted until, with very heavy deformation, they become so dense and so contorted that they can no longer be resolved into individual bands. The illustration is from a section of the blade where the deformation has been relatively light so the bands are well spaced and only slightly distorted. The appearance of deformation bands on a polished and etched surface is a sensitive indicator of plastic deformation and the degree to which the bands are developed shows how severe the deformation has been.

Deformation bands are produced in metals such as bronze or brass (which have face-centered cubic crystal structures) regardless of whether the deformation is slow, as in bending a bar, or fast, as in a hammer blow. Deformation bands are formed in iron (which has a body-centered cubic crystal structure) during slow distortion but a different microstructural feature, the *Neumann band*, appears when the metal is subjected to impacts. Neumann bands are illustrated in Fig. 4, which shows the microstructure of a sample of nineteenth century Swedish iron made by the finery process.[6] The iron grains (bounded by irregular lines) are crossed by parallel, lenticular bands which, unlike the deformation bands illustrated in Fig. 3, have an easily discernible width. They are called twin bands because the metal in each band has been sheared into an orientation related to that of the parent grain by a mirror plane of symmetry, a relation described as « twinning » in mineralogy. (The dark spots in the iron grains in Fig. 4 are a very fine precipitable of iron carbide and are common in Swedish iron). Neumann bands are formed in wrought iron when it is struck with a hammer at room temperature or deformed slowly at a temperature very much below the freezing point of water, an unlikely alternative for archaeological materials. The presence of Neumann bands in an artifact is usually interpreted as evidence that the object has been hammered upon.[7]

2. *Evidence of the Use Made of Metal Edge Tools*

Evidence of use can be expected to be present on almost any utilitarian artifact. For the purposes of illustration, I will discuss one class of metal implement, edge tools, i.e., tools deliberately made with a cutting edge. Edge tools have been used over the years to perform a wide range of tasks. The description of these tasks can be simplified by dividing edge tools into three classes — cutters, fracturers, and splitters — in terms of the physical processes involved in their use. Cutters remove material from a workpiece by separating a small strip of the material worked upon, the chip, as the tool moves over the work. The chip is formed by intense plastic deformation of the material being cut at the edge of the tool and this type of cutting is only possible on materials that are not brittle, such as wood, metal, or bone. It requires a tool with a sharp edge although the actual form of the edge can vary within wide limits.[8] As a tool cuts a chip, its edge wears where it is in contact with the work piece and characteristics marks are formed on its surface. At the same time, another set of characteristic grooves or striations are left on the cut surface of the work piece. Study of the marks left on the tool or the work may give information about how a tool was used or about how a product was finished with a cutting tool.

The marks left by one type of cutter, a scriber used to draw lines on metal, are illustrated in Fig. 5. This is a micrograph of a polished and etched spot on the back of one of the brass parts of an astrolabe made in Nuremberg in 1537. The brass parts were marked out with a scriber before being cut to shape with files.[9] The striations in the groove reproduce the roughness on the end of the scribing point left from the sharpening process; each striation is the trace of the removal of a continuous chip of brass as the scriber passed over the metal. A few deformation bands are visible in the metal adjacent to the groove. The absence of heavy deformation adjacent to the cut shows that the scriber used was sharp and hard and that it cut chips from the brass with a minimum of damage to the surrounding metal. The striations shown in Fig. 1, which are on the end of a bronze tool whose shape suggests it to be a chisel, were formed by the same mechanism, probably by sliding contact with the rough surface of a harder material such as stone. Such markings might arise from sharpening or, as seems more likely in this case, from driving the chisel over a piece of stone that was being worked upon.

A different physical process is required to form chips from a brittle material, since such materials cannot deform by plastic shearing. Contact of a brittle material with a blunt point can cause cracks to form under the point and, when the point is removed, these cracks may unite so as to detach bits of the work piece as chips. The edge of a tool used to make chips by fracture need not be very sharp nor need it be harder than the material worked upon. In fact, if the tool is blunt and tough, it will last longer in service than if it is sharp and hard. The tool may be driven against the work with a hammer, as in chipping rock, or dragged across the surface, usually by a rotary motion, as with a rock drill. An impression of the surface of the material worked upon it left on the edge of the tool if the tool is softer than the work, which will usually be the case when metal tools are used by a stone cutter.

Finally, an edge tool may be used for splitting, the division of the work into two nearly equal pieces. The wedge is the most comon tool used for this purpose. It it is driven into hard material such as stone, striations will to be cut on its sides; if driven into softer material such as wood, its sides will be worn and perhaps polished. Some of the softer material may adhere to the surface of the wedge where it may be retained and detected at a later time.

3. *Example*: *Peruvian Bronze Tools*

These principles of working with edge tools can be applied to a great variety of implements, including tools used for felling wood, working stone, or carving bone, as well as to weapons with sharp or blunt edges. To illustrate how analysis of the use of such tools may be carried out, I will describe one example as a case study. This is a set of bronze implements found at the Inca city of Machu Picchu, Peru, by Hiram Bingham in 1912. These were probably made in immediately pre-Columbian times, the late fifteenth or early sixteenth century. The metallurgy of some of the artifacts from Machu Picchu has been described by Mathewson.[10] Most of them can be recognized as intended to be use in personal adornment or decoration but others could have been used for tasks done by workmen.[11] Indications that they were so used can be found in both the external markings that they carry and in their internal structure.

An example of one of the most common bronze artifacts from pre-Columbian times in the central Andes is shown in Fig. 6. It consists of a flat blade with a cross bar on one end. Because the cross bar could be used to help bind the implement to a haft, these objects are usually described as « axes ». There are several of them among the specimens brought back by the Bingham expedition and these examples carry both internal and external evidence suggesting their use in heavy work.

Some of the « axes » in the collection have sharpened points and others are blunt. On some, the edges appear unmarked and undeformed while on others the edges are damages or even broken. Each has probably been used in a different way. A side view of the working edge of one of the « axes » is shown in Fig. 7. It has clearly seen some hard service; the edge, which is blunt has been turned over and, as can be seen in the photograph, the damaged portion is grooved. Closer examinations shows that these grooves contain fine striations such as would be made by the removal of metal chips. The most likely way that this could come about is from contact with a rough, hard surface. Since the edge is flattened, split, and indented, it appears that this particular tool has seen heavy use in working against resistant material, probably one of the igneous or metamorphic rocks common in the area near Machu Picchu.

Chisels used for stone work today do not have a cross bar such as that on the implement shown in Fig. 6. This form of « axe » with cross bar is often shown in drawing of the ceremonial activities of the pre-Columbian peoples of the central Andes. Some of the artifacts having this shape are carefully decorated and were certainly not intended to be used in heavy work. Was the cross bar present because this was a style that had developed over a long period of time during which these objects served decorative or ceremonial purposes, or was the bar placed there to serve some utilitarian function? Since only a small number of these implements have been studied closely, we cannot give a definite answer to this question, but it is possible to show that the cross bars of the « axes » recovered from the site of Machu Picchu were used in the performance of work. The end surfaces of these bars are covered with shallow depressions that might be simply reproductions of rough surfaces in the molds in which the imprements were cast, or might be the result of using the cross bar as a hammer. Metallographic examination shows that these markings are acually due to hammering. Figure 8 is a micrograph of the metal in the interior of the cross bar of one of the bronze « axes ». It consists of underformed grains of bronze containing cavities. (The cavities are pores formed by gas released by the metal as it solidified in the mold in which the implement was cast). The structure of the metal near the surface of the end of the cross bar is shown in Fig. 9. The picture is taken at one of the indentations, which is responsible for the concavity of the surface visible in the photograph. Beneath this indentation the metal has been heavily deformed. This is shown by the abundant deformation bands and the distortion of the grains. This evidence shows that the indentation visible in the photograph was made by a heavy blow. The structure of the metal adjacent to the other identations is similar and we may infer that the cross bar has been used as a hammer head by someone holding on to the blade of the « axe » as a handle. Although this form of implement may not have originated with the idea that the cross bar both protects the hand of a person hammering on it and serves as a convenient hammer itself, these practical uses were evidently discovere when such « axes » became available to workers.

Although bronze such as was used in pre-Columbian Peru is harder than wrought iron, it is not as hard as steel and bronze implements used in heavy work in contact with tough or hard materials will suffer considerable damage. If a reasonably sharp or well formed edge were required on the implement, it would have to be resharpened from time to time. Again, the metallographic method provides evidence that this was done to some of the implements from Machu Picchu. The edge of one of the examples studied showed no evidence of use—it is free of distortion and indentations. Does this mean that it is a new tool never put in service, or that it was never intended for use as a tool and was never so used? A micrograph of a section of the tool, Fig. 10, shows that the metal of the edge is heavily distorted. Deformation bands become more intense and the grains become flattened as the edge is approached. Another indicator of heavy deformation is the elongation of the non-metallic inclusions that are present in all of the bronze from Machu Picchu and are particularly abundant in this sample. These inclusions, which consist of copper sulfide, are roughly circular in the interior of the object but near the tip they can be seen to be elongated transversely to the axis of the blade. This is perpendicular to the direction of the elongation that would result if the blade had been forge to shape, i.e., forging would elongate the inclusions parallel to the long axis of the blade. We can conclude from the lack of distortion of the sulfide inclusions in the interior of the blade that the implement was cast and was not further shaped by forging. But, it was subsequently used in tasks that caused the working edge to be flattened and deformed. When the resulting damage became more than the artificer using the implement could tolerate, it was resharpened, probably by removing the distorted metal by rubbing it against a stone so as to reform the blade. This sharpening did not remove all of the deformed metal, however, and the evidence of previous hard use has been preserved in the interior structure of the blade even though the external evidence of distortion has been removed by the resharpening.

It remains to identify what kind of work these tools were actually used to perform. This will require field studies of the tasks that were being undertaken at Machu Picchu in which the use of metal tools might have been helpful. A search for this kind of evidence is just getting under way. It is laboratory results such as those just described which, in this case, suggest what to look for in the field.

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1 See, for example, C. S. Smith, « The interpretation of microstructures of metallic artifacts », in *Application of Science in Examination of Works of Art,* W. J. Young, ed., Boston, 1967, pp. 20-52.

2 *Lithic Use-Wear Analysis,* Brian Hayden, ed., New York: Academic Press, 1979.

3 For example, R. B. Gordon, « Laboratory evidence of the use of metal tools at Machu Picchu (Peru) and environs », *Journal of Archaeological Science,* 12 (1985): 311-327.

4 C. S. Smith, *A History of Metallography,* Chicago: University of Chicago Press, 1960. See Ch. 13.

5 C. H. Mathewson, « A metallographic description of some ancient bronzes from Machu Picchu », *American Journal of Science,* 40 (1915), 525-616.

6 The importance of Swedish iron, such as that illustrated, in making steel is explained by K. C. Barroclough in *Steelmaking Before Bessmer,* 2 vols., London: The Metals Society, 1984.

7 An example is shown by J. D. Light and H. Unglik in *A Frontier Fur Trade Blacksmith Shop,* Ottawa: Parks Canada, 1984, p. 119.

8 See Gordon, note 3 above.

9 R. B. Gordon, « Sixteenth century metalworking technology used in the manufacture of two German astrolabe », in *Annals of Science,* 44 (1987): 71-84.

10 See Mathewson, note 5 above.

11 J. W. Rutledge, *The Metal Artifacts from the Yale Peruvian Expedition of 1912, Catalog and Commentary,* M. A. thesis, Yale University, 1984.

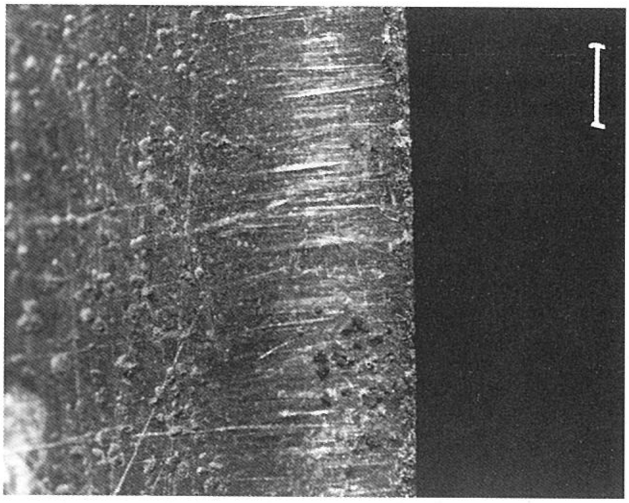

Figure 1. - An example of « use-wear » markings on a metal artifact. This is the edge of a bronze object described as a chisel from immediately pre-Columbian times in central Peru. The striations perpendicular to the edge were made by the removal chips from the metal by sliding contact with the rough surface of a hard material, probably stone. Length of the scale bar is 1 mm.

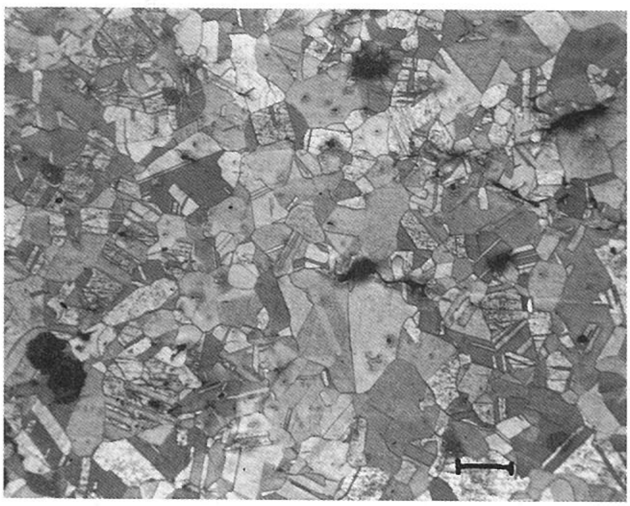

Figure 2. - An example of the microstructure of a metal artifact. Polished and etched section of pre-Columbian bronze from Peru showing individual metal grains in the different colors produced to etching. The dark areas are pores in the metal. Length of the scale bar is 0.1 mm.

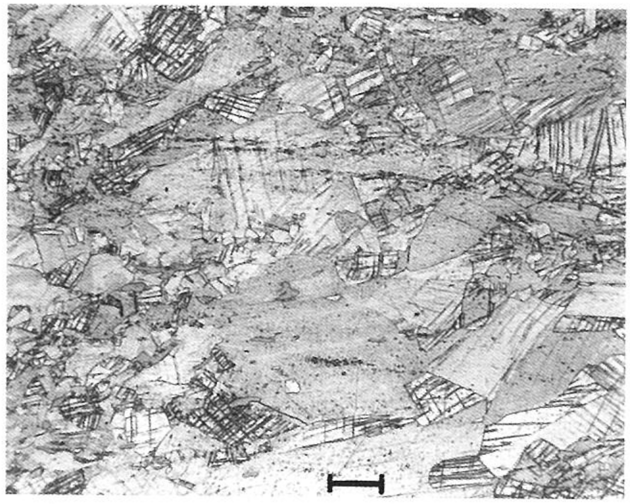

Figure 3. - Deformation markings illustrated in a polished and etched section of a bronze artifact from pre-Columbian times in Peru. The artifact has been described as a chisel and the blade was formed by forging the metal as it cooled from red heat. Grains distorted by the forging as the metal became cool retain evidence of the deformation they suffered. When the metal is etched, dark bands appear within these grains. These bands are called « deformation markings » or « slip bands ». Length of the scale bar is 0.1 mm.

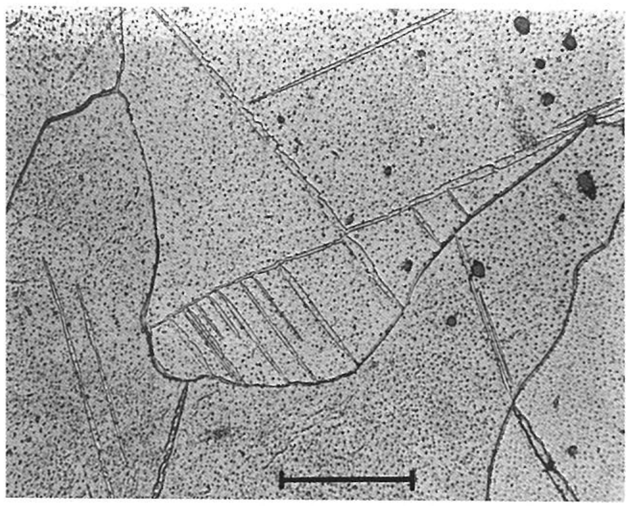

Figure 4. - Neumann bands (lenticular bands cutting across individual grains) in a sample of nineteenth century Swedish iron. They are evidence of deformation by impact, as from hammer blows. Dark spots within the grains are a fine precipitate of carbide particles. Length of the scale bar is 0.05 mm. (Photograph by Dan G. Rosenthal).

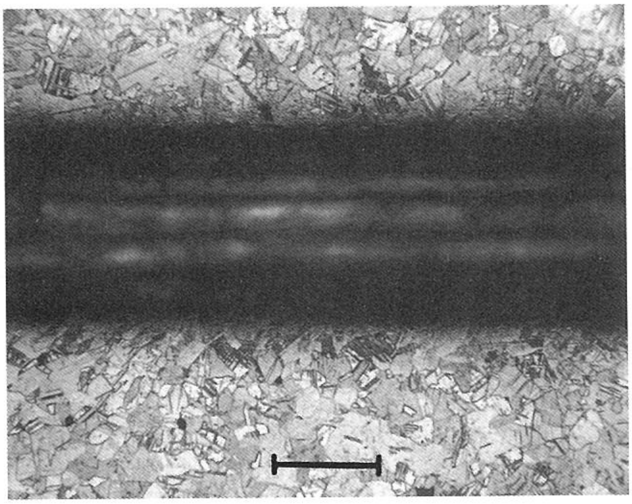

Figure 5. - Groove cut in the brass rule of an astrolabe made in Nuremberg in 1537. The small amount of deformation in the metal surrounding the scribed line (shown by the absence of deformation markings) proves that the tool used was sharp and well hardened. The striations in the groove (which are slightly out of focus in this picture) were formed as the scriber cut a chip out of the brass and reproduce the roughness of the tip of the tool. Length of the scale bar is 0.1 mm.

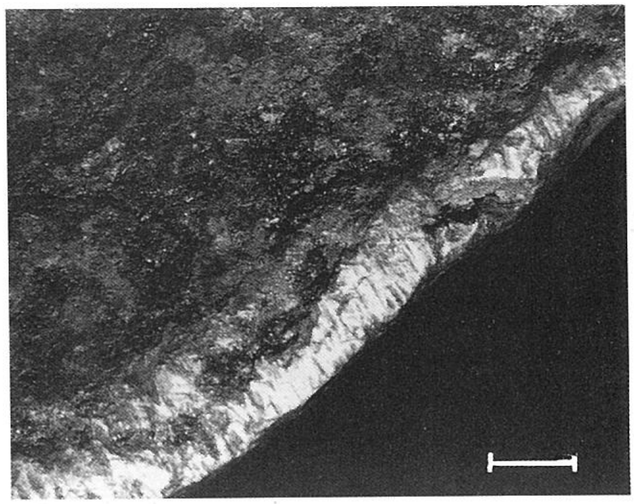

Figure 7. - Side view of the edge of an « axe » from pre-Columbian times in central Peru showing evidence of use in work on a hard substance, probably stone. The edge has been turned over and striations have been cut into it. Length of the scale bar is 1 mm.

Fig. 6. - A bronze implement found in the Inca city of Machu Picchu, Peru, by Hiram Bingham in 1912. The length of the implement is 130 mm. Implements of this type were common in pre-Columbian Peru and are now usually called « axes ». Markings and microstructural evidence show that this implement was probably not used as an axe but as a chisel.

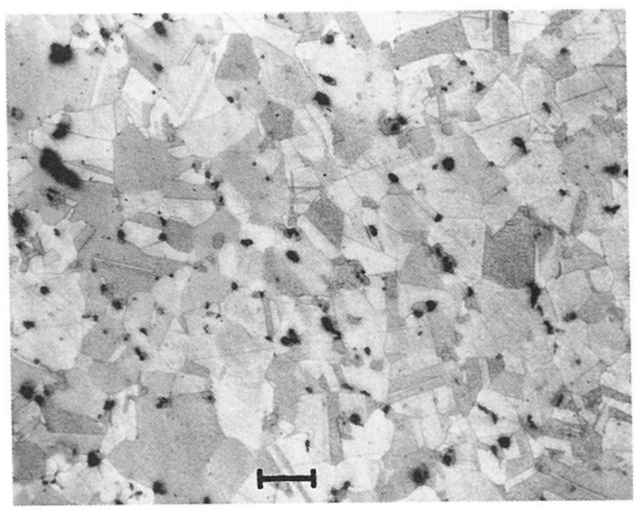

Figure 8. - Microstructure of metal in the interior of the cross bar of a bronze « axe » from pre-Columbian times in central Peru. Undeformed grains of bronze and porosity are visible. Length of the scale bar is 0.1 mm.

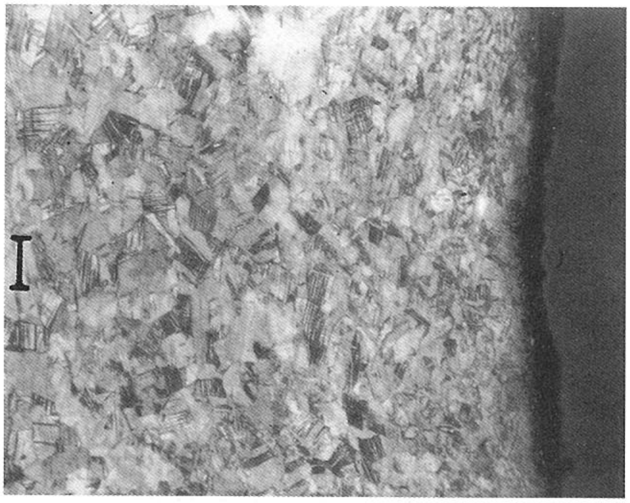

Figure 9. - Microstructure of metal at the end of the cross bar of the bronze « axe » illustrated in Fig. 8. The photograph is taken at an indentation visible on the surface of the end of the cross bar. Deformation markings present within the grains show that the indentation was formed by distortion of the implement and was not part of the original casting. This is taken as evidence that the cross bar was used to hammer with. Length of the scale bar is 0.1 mm.

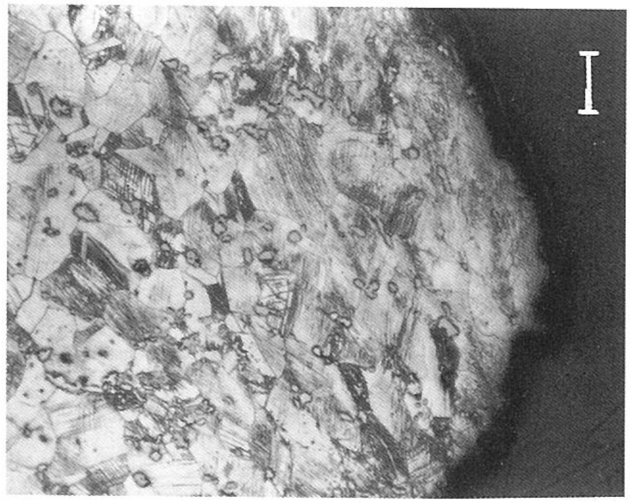

Fig. 10. - Micrograph of a section of the edge of a bronze « axe » from pre-Columbian times in central Peru. No surficial evidence of use remains on this artifact but the deformation of the metal grains near the edge shows that the implement has had heavy use and was subsequently reformed and resharpened, treatment that removed the external evidence of the distortion of the metal. Length of the scale bar is 0.1 mm.