C. S. SMITH

THE TECHNIQUES OF THE LURISTAN SMITH

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Chapter 2

The Techniques of the Luristan Smith[1]

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From the nomad graves of Luristan in western Iran come many iron or, rather, steel objects that are of considerably greater interest from a technical standpoint than the aesthetically superb and hence more famous bronzes with which they are associated. The bronzes were made by techniques that had been in use for more than a millennium, whereas the iron objects—bracelets, maces, and especially swords—have some unique technical features, for their rugged elaborateness derives directly from the process of manufacture and reveals both high skill and unexpected ignorance.

The Luristan iron and steel objects were made for a people who had not learned to appreciate the shapes that arise naturally under the hammer, and many of the designs emulate more complicated shapes easily possible in a casting. The smith, therefore, who had not yet learned how to hammer-weld, devised a technique for assembling preshaped pieces by mechanical joining.

Although a number of technical studies of the swords have been published in the past (the most important of which are listed in the references at the end of this chapter), they have mainly involved museum objects that could not be damaged in the examination. The objects used in the present study were purchased specifically for the purpose. Moreover, they were heavily corroded, and it was therefore possible to cut out substantial samples for chemical analysis and metallographic studies without aesthetic loss.

Figures 2.1 to 2.5 show the general appearance of eight of the objects used for the present study, some of them both before and after electrolytic cleaning to remove the heavy layers of rust.[2] The provenance of the objects, listed in Table 2.1, is not certainly known. They were purchased as Luristan material from dealers in Tehran in 1961, 1962, and 1967, but only the most interesting sword (No. 105) and the maces uniquely conform stylistically to Luristan.[3] Except for No. 102; which is much later, the other pieces were approximately contemporary with the Luristan irons (ninth to seventh centuries B.C.) and are metallurgically similar although they probably originated in other parts of Iran.

The Steel

Chemical analyses were made at the Applied Research Laboratory of the United States Steel Corporation, through the courtesy of Dr. Max Lightner. The results are reported in Table 2.1. The mace head No. 106 contained nickel, and the dagger No. 102 (of late origin) contained phosphorus, but otherwise the steels are all free from significant amounts of any kind of alloying element except carbon and nitrogen.[4] Sulfur is low in all the samples, as would be expected with charcoal-smelted ores.

The carbon content of the steel is highly variable from place to place within one object, and the average analyses given are locally without meaning. The Luristan smith clearly operated his smelting fire under conditions that were frequently highly carburizing; he made true steel. There are zones with as much as 1 percent carbon (estimated from the amount of iron carbide seen in the microstructure) but carbon-free areas are to be found adjacent to them in the same piece, and everything in between, with no special relationship between location and carbon content. Probably the smith was unaware of these local differences; certainly he did not (as later smiths have done) select and use the harder metal in areas where strength was needed or a softer metal for decorative parts.

The silicon is, presumably, mainly in nonmetallic form in the inclusions, which, as in all ancient iron, are numerous. Figures 2.7 to 2.11 show the appearance under the microscope of four different types of inclusions that have frequently been encountered. The mixed wüstite (FeO), fayalite ($2\,FeO \cdot SiO_2$), and glassy silicate inclusions are perhaps simply residual from the ore, the silica having been fluxed by unreduced oxide. The wüstite content is highly variable from place to place and

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[1] Paper presented at the Fifth International Conference on Iranian Studies, Tehran, April 1968, and the A.C.S. Symposium on Archaeological Chemistry, Atlantic City, September 1968.

[2] Cleaning was done by electrolyzing in 5 percent aqueous sodium hydroxide solution, the specimen being cathodic and the current density about 40 mA per square cm. The action was continued for about 4 days by which time all loose oxide had been reduced or had fallen away without effect on the solid metal. The objects were then removed, washed, scoured with a steel wire brush, warmed, and coated with wax. Such cleaning destroys whatever evidence might lie in the corrosion products and is generally to be discouraged except for objects intended for exhibition or those believed to contain internal chlorides.

[3] The author is grateful to Dr. Peter Carlmeyer, Munich, for help in identification.

[4] The presence of nitrogen was not always shown in the chemical analysis for it was distributed with extreme irregularity. Microscopic examination, however, left no doubt that there were considerable quantities in some areas for it was revealed, especially in low carbon zones, as tiny crystallographically oriented plates (needles in section) characteristic of the nitride Fe_4N, and the more profuse precipitation of Fe_8N. Figure 2.6 shows the richest field that was encountered in any specimen. The structure is comparable to published photomicrographs of iron containing about 0.05 percent nitrogen.

Table 2.1
dentification and
Composition of
Objects Studied*

M.I.T. Designations	Type of Object and Presumed Provenance	Location of Sample for Analysis	Chemical Composition (percent by weight)							
			C	Mn	P	Si	Cu	Ni	Co	N
101	Dagger (Fig. 2.1D, 2.2D). Medean western Iran, seventh century B.C.	Section of blade 4 to 10 cm from hilt	0.57		0.025					0.007
103	Dagger (Fig. 2.1B, 2.2B). Talish or Giyan area, ninth or eighth century B.C.	Section of blade 6 to 10 cm from hilt	0.089	<0.01	0.028	<0.04	0.02	0.05		0.004
104	Dagger (Fig. 2.1A, 2.2A). Talish or Giyan area, ninth or eighth century B.C.	Square portion of handle 2 to 8 cm below "bobbin"	0.23		<0.01					0.003
105	Short sword (Fig. 2.3). Luristan ca. eighth century B.C.	Section of blade 2 to 10 cm below ricasso	0.63	0.02	<0.01	0.02	<0.01	0.01	0.01	0.002
		Section through lion head attached to ricasso	0.39	0.04	<0.01	0.08, 0.17	<0.01	0.01	0.03	0.003
106	Mace (Fig. 2.4B, 2.5B). Luristan ca. eighth century B.C.	Section through square handle 22 to 29 cm from top end of head	0.063	0.02	0.031	0.03, 0.14	0.02	0.48, 0.58	0.25	0.005
107	Mace head (Fig. 2.4A). Luristan, ca. eighth century B.C.	Equatorial section normal to hole	0.23		<0.01					0.006
113	Mace head (Fig. 2.5A). Luristan, ca. eighth century B.C.	Equatorial section normal to hole	0.10	<0.03	0.023					0.006
102	Dagger (Fig. 2.1C, 2.2C). Uncertain, ca. ninth century A.D., perhaps European.	Section of blade 4 to 10 cm from hilt	0.098	<0.01	0.24	<0.01	0.05	0.05	0.03	0.004

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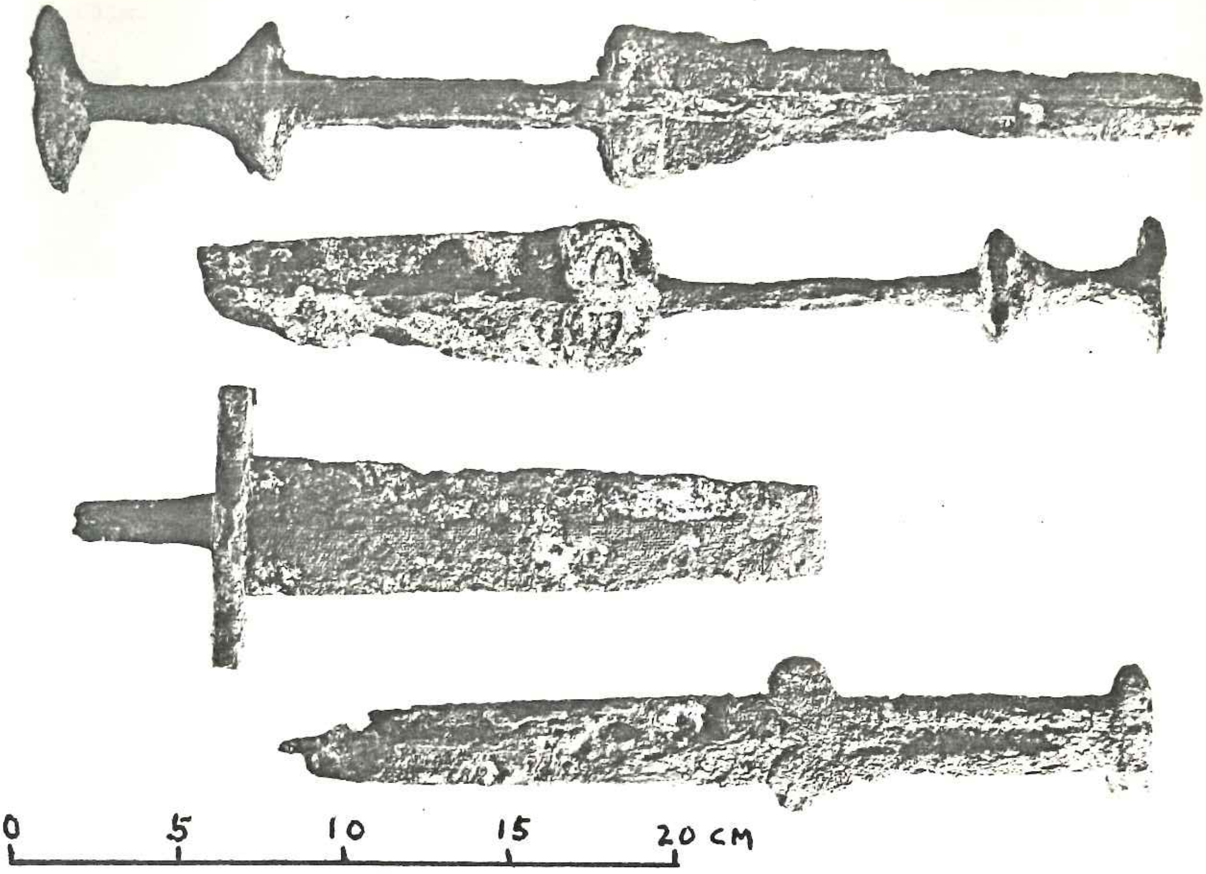
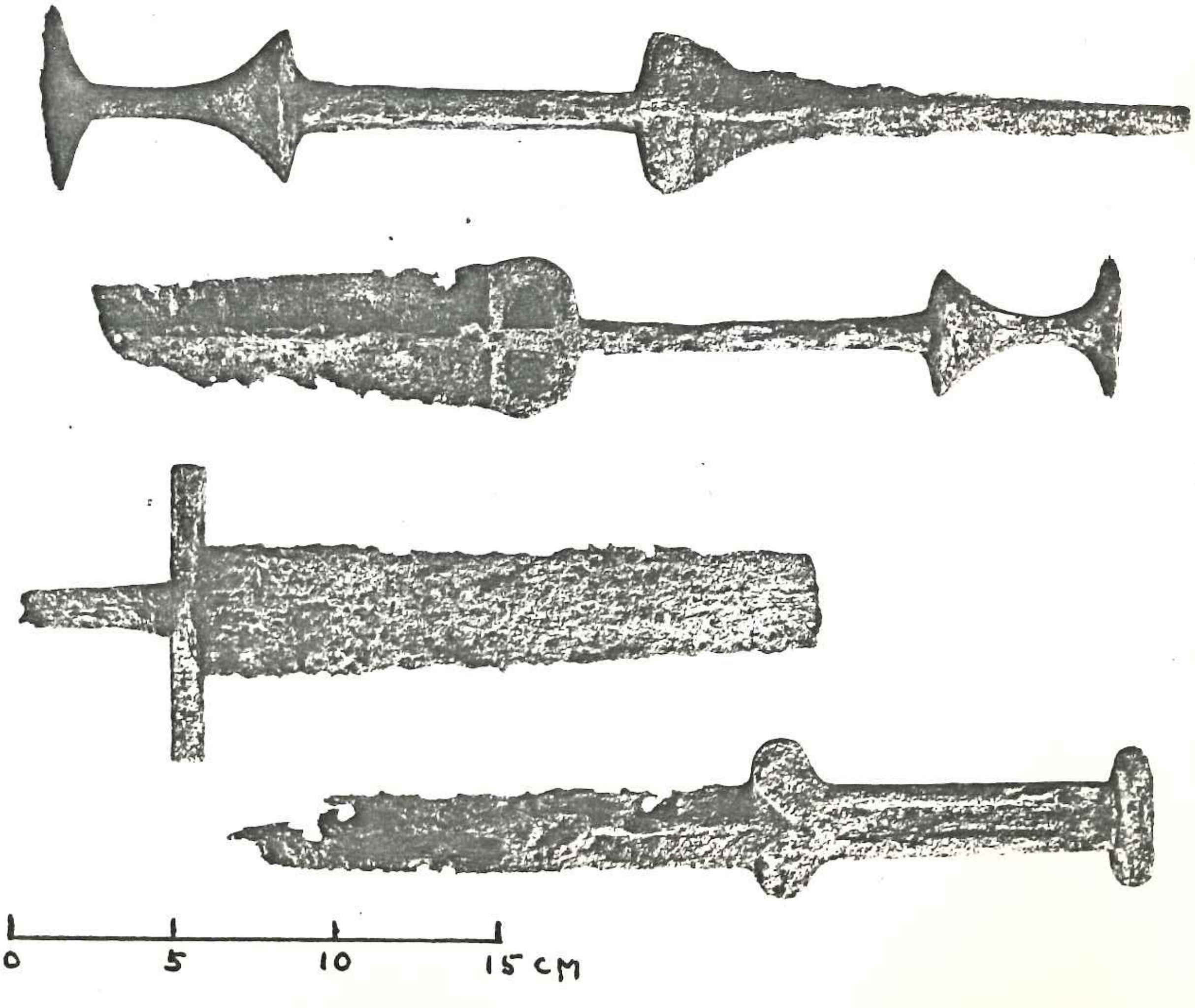
*Note. Additional elements analyzed for, but not detected in any sample, were sulfur in all cases less than 0.01 percent; tin less than 0.002 percent; columbium, molybdenum, titanium and vanadium all less than 0.005 percent. The silicon is present mainly in the form of silicate inclusions.

Analyses made in the Applied Research Laboratory, U.S. Steel Corporation, courtesy M. W. Lightner. The analyses for carbon, phosphorous, and nitrogen were made chemically on millings cut transversally from the entire cross section. The other determinations were done by emission spectroscopy on areas ground parallel to the widest surface of the piece, avoiding the areas richest in slag inclusions. A blank means element not determined. The accuracy of the determination (apart from sampling errors) is ±2 on the last digit stated.

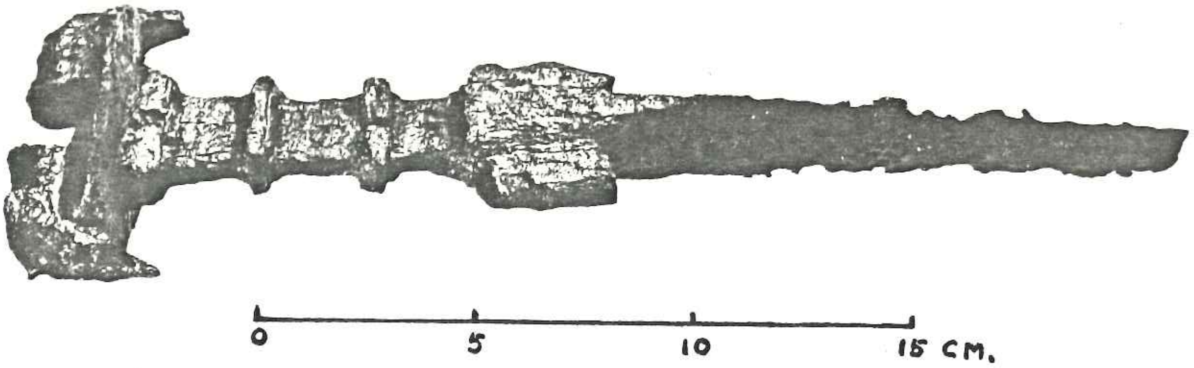


2.1
Daggers in condition as received. (A) No. 104, Talish or Giyan area, ninth or eighth century B.C., (B) No. 103, Same Provenance as a, (C) No. 102, Uncertain provenance, perhaps Abbasid, ninth century A.D., (D) No. 101, Medean, western Iran, seventh century B.C.

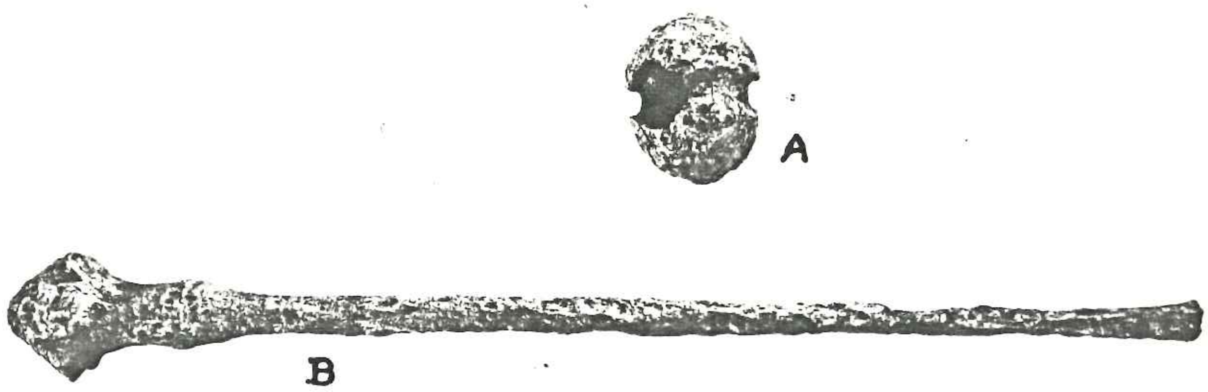


2.2
Daggers 101, 102, 103, and 104 after electrolytic cleaning. See Figure 1 for identification.

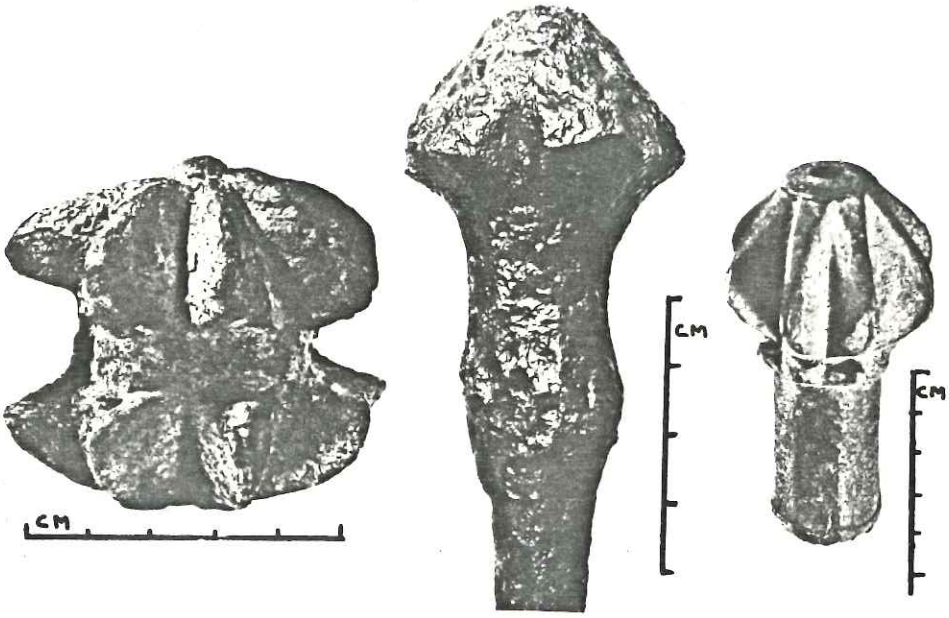
.3
o. 105. Short sword
f classic Luristan type.
a. eighth century B.C.
fter electrolytic cleaning.

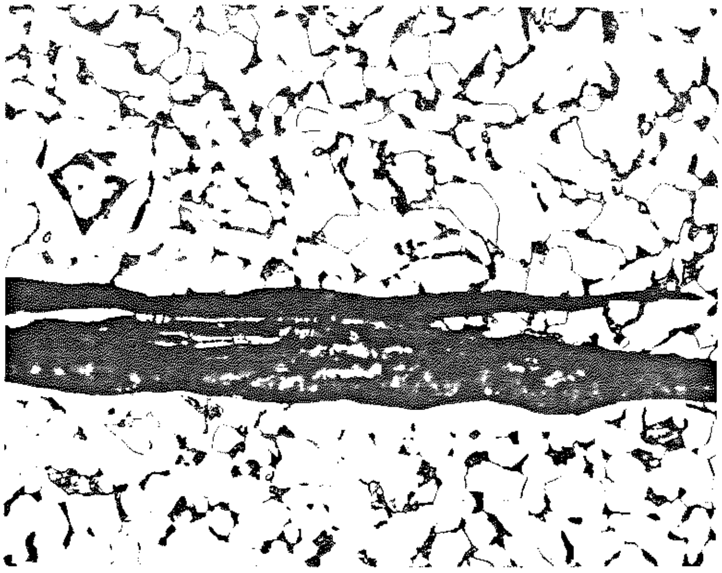


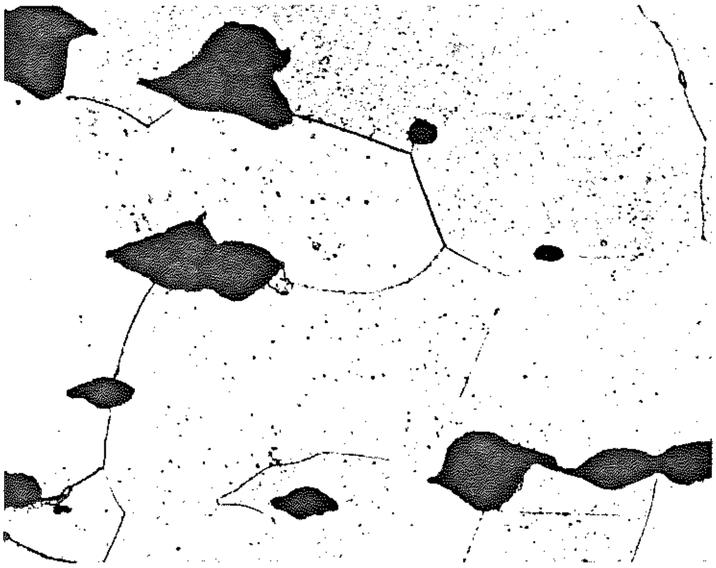
.4
) Mace head, No.
07, and (B) Mace,
o. 106. Luristan, Ca.
ighth century B.C. Elec-
olytically cleaned.

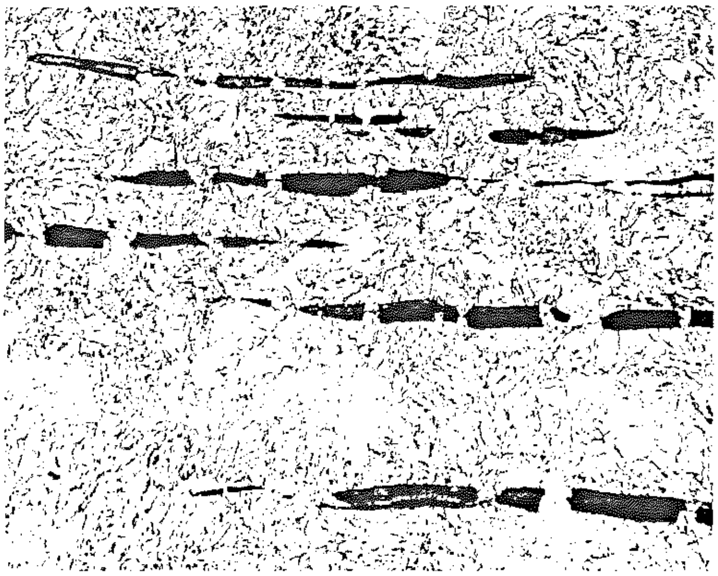


.5
) Mace head, No.
13, (B) Mace head,
o. 106 (Cf. Figure 4),
) Mace head of uncer-
in provenance, proba-
y Luristan, eighth cen-
ry. (A and C, un-
eaned; B after electro-
tic cleaning.)









umn 1
i
rostructure near
er surface of lion at-
hment, No. 105,
wing low-carbon
a with heavy precipi-
on of iron nitrides.
hed, 580X. (Note:
and all subsequent
tomicrographs are
specimens metallog-
hically polished and
hed with a 2 percent
ition of nitric acid in
ohol)

g inclusions in dag-
, No. 103. Spherical
ticles of wüstite
O) partly surrounded
silicate in matrix of
bon-free ferrite grains.
hed, 580X.

B
g inclusions in a high-
bon area in No.
5. The silicate slag
d been first elongated
en plastic (perhaps
uid) and subsequently
oken by deformation
a lower temperature.
ched, 230X.

lumn 2
9
ringer of transparent
assy slag in center of
mmel, No. 104. Lon-
udinal section. Etched,
0X.

10
rge slag inclusion in
. 104, showing well
rmed dendrites of
üstite in glassy silicate
atrix. Etched, 580X.

11
mplex crystalline slag
clusion in No. 102.
ote, this dagger is
er and the steel less
re than the Luristan
aterial.) Etched,
0X.

is roughly in inverse amount to the carbon content, as would be expected since wüstite cannot exist under highly reducing conditions. Compare Figure 2.7, showing mainly wüstite (perhaps residual particles of partly reduced unmelted oxide from the ore) surrounded with a little glassy slag in a carbon-free area, with Figure 2.8 which shows a wüstite-free silicate slag in a zone having high carbon content. Most of the inclusions had been deformed in a plastic (probably liquid) state, but quite frequently well-elongated stringers of slag had been later broken up mechanically when solid, with the fragments unchanged in shape by either spheroidization or deformation and separated by metal forced between them (Figures 2.8 and 2.9). The metal, therefore, must have been first worked at a high temperature and subsequently extensively deformed when much colder. The two stages probably correspond to the initial reduction and consolidation of the iron sponge and to the final shaping operations, respectively.

Many of the slag inclusions have the glassy transparent character that denotes high silica content. Figure 2.9 shows such slag in No. 104. In Figure 2.8, the smallest stringers are glassy while the larger ones have partially crystallized—more likely as a result of nucleation than of differences in composition. Many ancient irons contain minute spherical particles (about 1 to 10μ diameter) of a clear glassy material, seemingly different from the larger inclusions. Their origin is obscure—they may represent small isolated silica inclusions in the ore that were fluxed and later reduced while entirely surrounded by metal, or they may be residual ash from charcoal fragments that became incorporated in the metal and were subsequently deprived of carbon by diffusion.

It is more common for the slag to have one or more phases in a dendritic or crystalline shape that could only form from the liquid state. (See Figures 2.10 and 2.11 and also Figures 47 to 51 in Smith, Reference 12.) Figure 2.11 is of the dagger No. 102, of a much later date than the others, and shows in the slag three distinctly different crystalline phases which have not yet been identified positively.

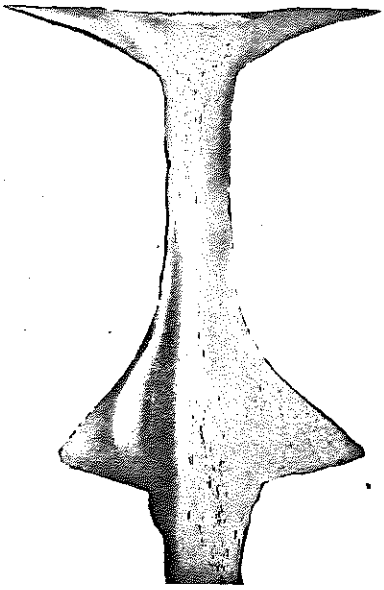
Slag inclusions carry with them much evidence regarding the details of metallurgical processing and their analysis is to be the next stage of this research. But whatever the composition and structure of the slag, its distribution, like that of the carbon, provides an index of local metal flow and gives clues to the deformational history of the metal which, in turn, reveals much about the smith's practice in making the objects (see Figures 2.12 to 2.17, 2.32, and *passim*). Though one cannot rule out the possibility that several different pieces of sponge iron were combined together to give a big enough bloom to forge these objects, or even the possibility that scrap from previous operations was faggoted into the new metal at this stage, there has been no later welding. Except for mechanical attachments each of the objects, with its blade, handle, pommel, and decoration, is a single piece, metallurgically intact. Although the long seams of high and low carbon metal do rather suggest the welding together of pieces of different but more or less uniform composition, the stringers of slag are not related to the boundaries between areas of different carbon contents. The general heterogeneity is entirely of the type that could have originated in the original spongy bloom of iron as it left the reduction hearth or furnace, modified with the subsequent shaping of the entire piece and some diffusion of carbon. In the Luristan sword examined by Maxwell-Hyslop and Bird in collaboration with Hodges (References 7 and 1), the hilt had been composed by hammering a stack of irregular flat strips into a compact mass; this had obviously been done hot but at a forging heat not at the much higher temperature needed for welding.

The carbon content in the swords is not related to the position in the weapon, that is, the cutting edges vary just as much in carbon content as do the decorative parts. There is no evidence whatever of superficial or local carburization of the finished piece, and, surprisingly, very little evidence of surface decarburization during forging.

General Shaping Techniques

The objects examined were so heavily corroded that no fine surface detail was visible. The decorative heads on the Luristan short swords illustrated by Lefferts (Reference 5) and Ternbach (Reference 13) seem to have been finished by both chiseling and chasing and perhaps by some use of abrasive, but in general the objects owe their shape entirely to the simple percussive tools of the smith. The general symmetry and surface characteristics of the Luristan steel objects make it almost certain that some kind of round or flat swages were used rather than free hammer work, and perhaps large shaped sets. Sections through the length of the blades (Figures 2.12 to 2.15) show the metal flow, and the cross sections of the blades (Figure 2.16) show—excepting again No. 102—an irregularity of structure that comes from simple forging without any major laminations or welds.

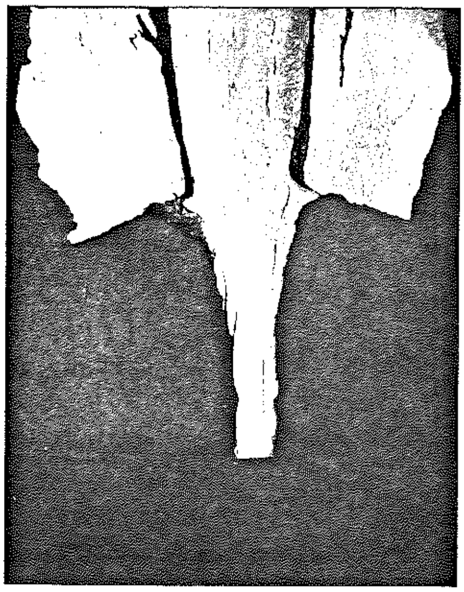
The ends of several of the pieces had been transversely cut to shape by the use of a saw or, more likely, by grinding, not with the blacksmith's cold chisel. This is easily seen particularly in Figure 2.17, the head of the short sword No. 105. Both the main handle itself, which is integral with the blade, and the decorative heads have slag lines terminating abruptly at the



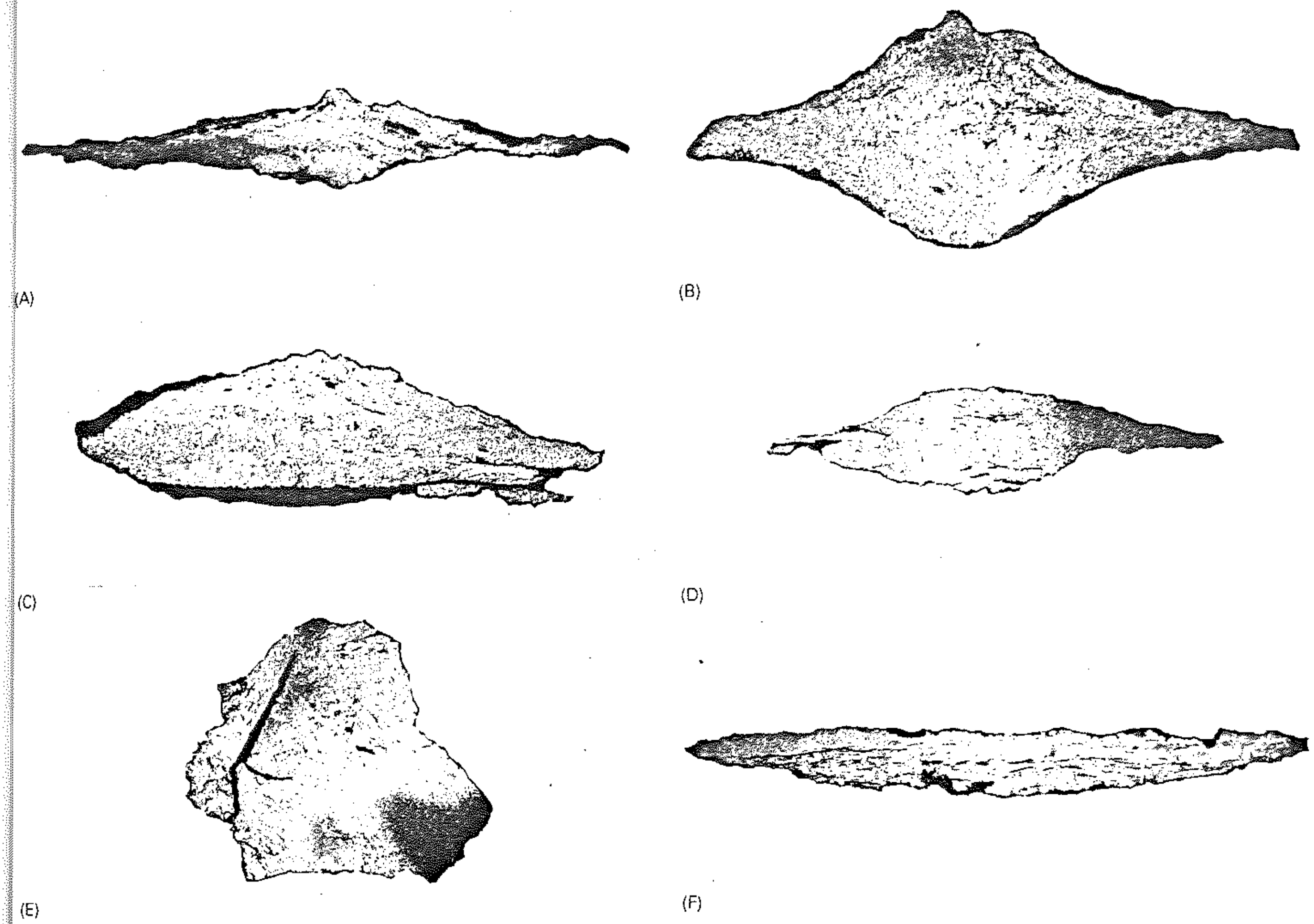
2.12
Axial section through handle in No. 104. The flow of the metal during forging is revealed by the distribution of the slag streaks and zones of higher carbon (dark etching) metal. Etched, 90% of actual size.

2.13
Section through shoulder of blade, No. 104. Etched, 3.9X.

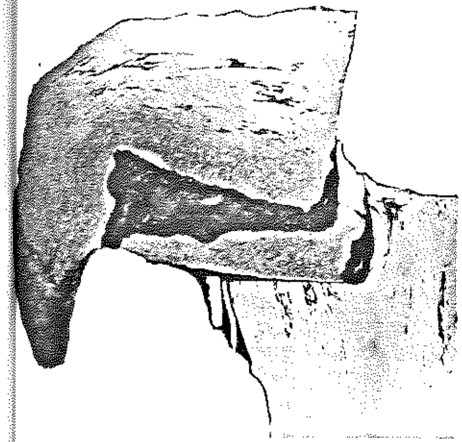
2.14
Microstructure showing surface deformation and partial recrystallization beneath ridge in No. 104 (Cf. Figure 2:13). Etched, 190X.

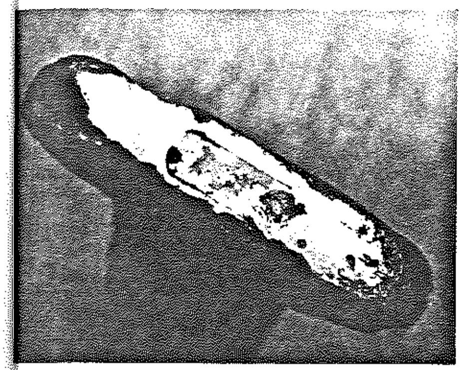


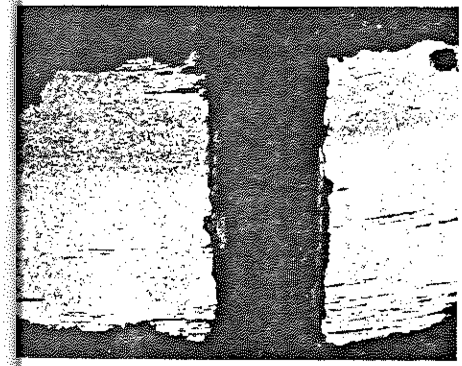
2.15
Transverse section through ricasso of short sword, No. 105, showing manner of attachement of the decorative lions. Etched, 1.4X.



2.16
Etched transverse sections of dagger blades showing distribution of carbon and slag content
(A)
No. 101, 4X;
(B)
No. 103, 4X;
(C)
No. 104, 8X;
(D)
No. 105, 4X;
(E)
No. 106 (Mace handle), 4X;
(F)
No. 102, 3.25X.



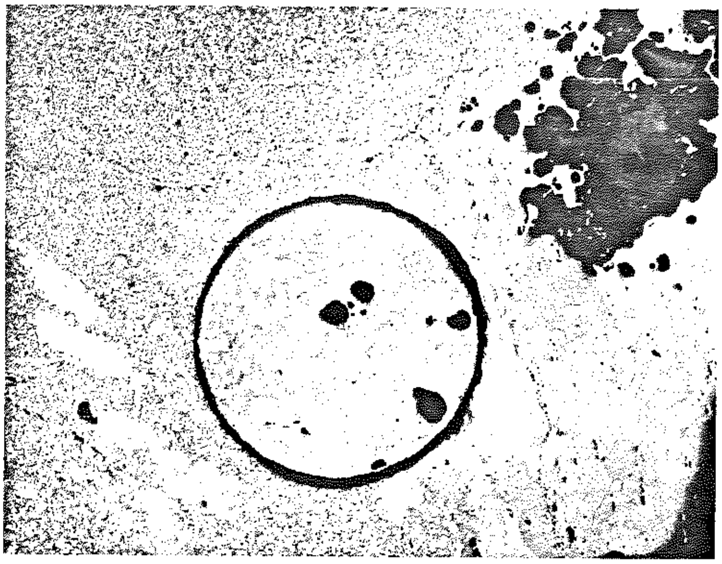


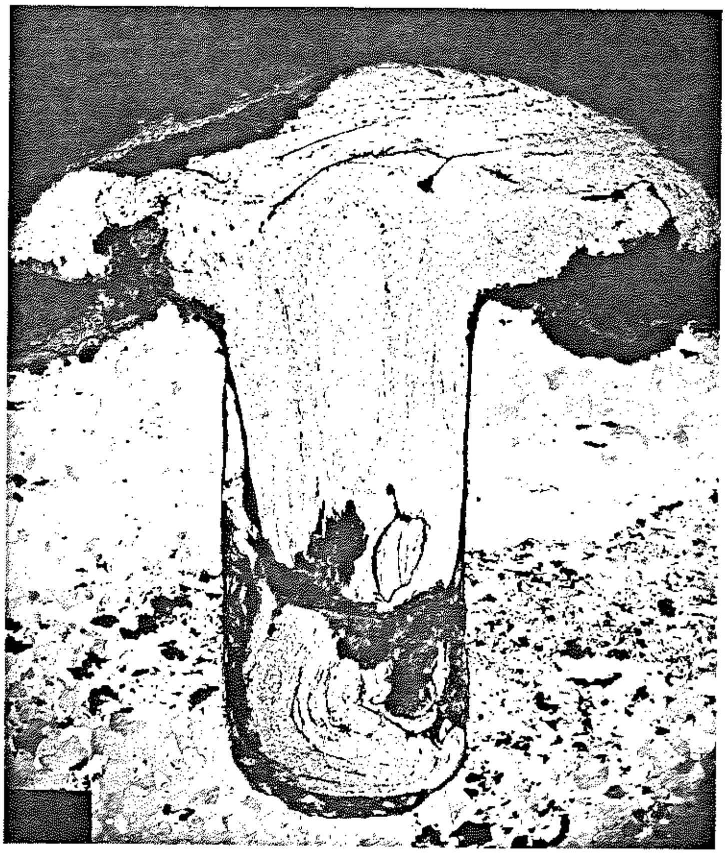


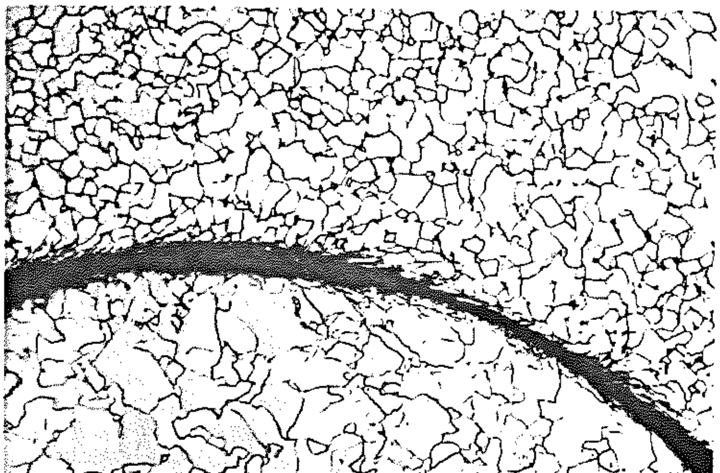
2.17
Section through end of hilt, pommel and attached heads, No. 105. (See Figure 2.34 for section normal to this). Etched, 1.4X.

2.18
End of handle, No. 101. Shows tang fitting into accurately cut hole. Lightly polished and etched, 1.4X.

2.19
Longitudinal section through handle of mace, No. 106, showing transverse drilled hole. Etched, 3.5X.







2.20
End of mace head No. 107, ground flat and polished. Shows section through decorative pin fitted in drilled hole. Note large variation in grain size. Etched, 11X.

2.21
Axial section through decorative pin in mace head, No. 113. Etched, 9X.

2.22
Edge of pin shown in Figure 2.20 at higher magnification. Etched, 55X.

end with almost no deformation as they approach the surface (Figure 2.17). Even more remarkable is the ability of the smith to make well-shaped holes. A rectangular hole with slightly rounded ends was cut in the pommel of No. 101 (Figure 2.18) and No. 105 (seen in cross section in Figures 2.17 and 2.32). A round hole tapering from about 4 to 4.5 mm diameter had been drilled neatly through the handle of the mace, No. 106 (Figure 2.19), with little distortion of the adjacent metal. Such a hole could have been made by using a soft metal tool loaded with abrasive and rotated by means of a bow drill.

Particularly interesting are the holes in the mace heads, Nos. 107 and 113, that were made to accommodate little decorative pins (Figures 2.20 to 2.22). Both of these are 3.2 mm in diameter and were drilled into a depth of about 7.0 mm. The surface metal is locally displaced and the structure distorted (Figure 2.22) but not in the same direction of rotation everywhere, which suggests an oscillating drive for the drill. The distortion, which is reflected in locally increased hardness (Figure 2.48), may also have arisen when the pin was driven. The shape of the bottom of the hole in No. 113 (Figure 2.23) shows that the drill had a narrow rounded protrusion on its head or that the hole was drilled in two stages. The head of the pin had clearly been formed by upsetting the protruding end of a length of wire of a diameter to fit into the hole. Both the structure and the hardness of the body of the pins show a gradient from the center to the outside, and it is probable that the final shaping of the pin had been done cold. The pin body is accurately circular in section, but it is unlikely that it could have been made by drawing, for neither enough power nor suitable die materials would have been available. The iron used for the pins was very malleable, for it had withstood with only slight cracking the further extension to about 9 mm diameter during the flattening of the head. These pins marked the only significantly cold-worked metal found in any of the objects.

The microstructure of the body of the pin in No. 107 (Figure 2.20) shows a larger grain size and less obvious deformation than that in No. 113. Only the surface of this pin showed any distortion, actually to about the same extent as the matching surface of the inside of the hole (Figure 2.48). The pin in No. 113 (Figure 2.23) was slightly tapered, and the end was irregular and broken. There are some irregular metal fragments wedged into the hole, which had been intensely cold-worked but have recrystallized to an extremely small grain size (Figure 2.24). These may have been formed by abrasion when the pin was driven in, but possibly they are chips from engraving or filing operations that had been put into the hole to wedge the pin. The other mace head, No. 107 (Figure 2.21), contained no such material but had intact, well-fitting pins.

The pommel on No. 101 was attached by peening over of a projecting tang in an accurately fitted hole. Both tang and hole are flat rectangular shapes, the short sides heavily rounded (Figure 2.18). Because the semicircular ends partially overlap the parallel slot in between, the holes were clearly *not* shaped by drilling two holes and cutting out the metal in between, but both half-round and flat files seem to have been used.

The Mace Heads

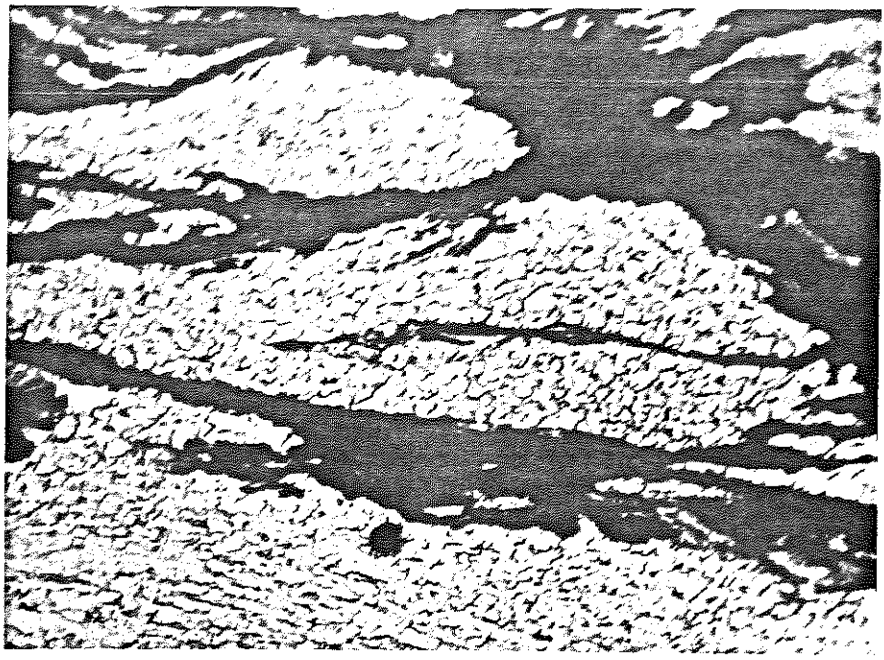
The mace heads are of three types. No. 106 (Figures 2.4B, 2.5B) was forged integrally with its iron haft; No. 266 (Figure 2.5C) was forged with an internal conical hole evidently to fit on the end of a pointed rod; and the third type, of which there are two examples, Nos. 107 and 113 (Figures 2.4A and 2.5A), had a cylindrical haft-hole passing transversely through its center. All had deep flutes except No. 107, which had been heavily damaged by corrosion. These flutes seem rather definitely to have been formed by a fuller or other special tool, for they are beautifully shaped and well finished.

The slag distribution in the sections of Nos. 113 (Figure 2.24) and 107 revealed a complicated pattern of metal flow, suggesting a sequence of forging operations somewhat as follows: A lump of sponge iron was forged into a cylindrical rod about 4 cm diameter and 7 cm long. A hole was then made with a cold drifting iron, and the piece swaged cylindrical again. The ends were then enlarged by upsetting (with the center of the shank in a hole or split ring) to give a dumbbell shape. Finally, the flutes were shaped by the use of a special curved V-shaped swage struck at an angle roughly 45° to the original axis, perhaps also finishing in a concave die. The surfaces do not show individual hammer marks. The lower faces (normally invisible) of some of the flutes revealed unwelded cavities, and the sections of both 113 and 107 disclosed some internal unconsolidated metal.

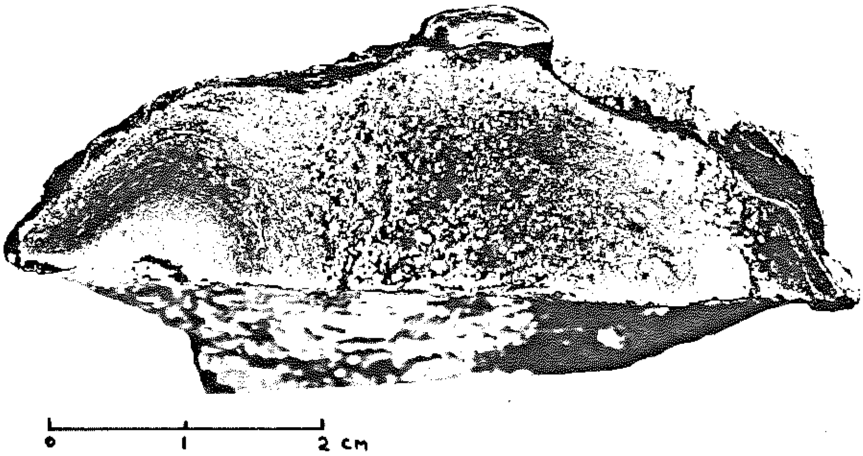
The pins inserted in laboriously drilled holes in the mace head (discussed in the previous section) served a purely decorative function and disguised the fact that all the grooves and flutes did not meet exactly at the common center; a forged projection at this place would have interfered with the finishing of the fluted surfaces.

In the mace head No. 266 (Figure 2.5C), of uncertain provenance, there is a smooth conical axial hole extending the full length, 9.2 cm, tapering uniformly from 2.2 cm diameter at the bottom to 0.80 cm at the top, leaving the metal thickness, except for the flutes, tapering from about 2.5 mm to about 8.0 mm.

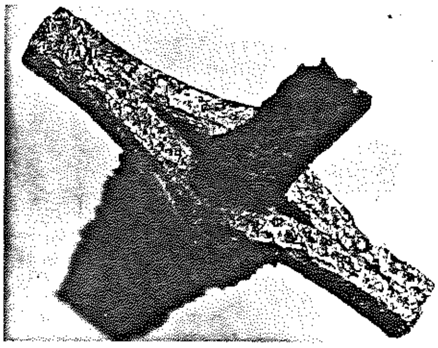
2.23
Metal chip between pin and body of mace head, No. 113 (Cf. Figure 2.21), shows recrystallized metal of extremely small grain size. Etched, 1350X.



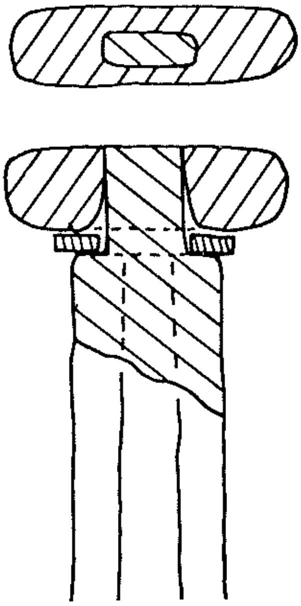
2.24
Midsection through mace head No. 113, in place of fluting slightly above the pin shown in Figure 2.21.



2.25
Attachment of guard to hilt of dagger, No. 102. 75% of natural size.



2.26
Sketch showing construction of handle of dagger No. 101. Traced from a radiograph.



The collar of small projections is matched by a slight depression on the inside, but the forging of the longitudinal flutes left no internal marks.

he Daggers

The decoration of most of the daggers is of a type that would come naturally to a smith using a hammer and a few sturdy tools such as fullers and swages. A common form of dagger (not here investigated) consisted of a simple, nearly flat, forged blade of steel with a tang onto which was cast a decorative hilt in bronze. Birmingham et al. (Reference 8) have described Luristan sword blades of wrought bronze with cast-on hilts, also bronze. Our late dagger, No. 102 (Figure 2.2C), has an effective guard in the form of a cross piece of rectangular section with an elongated slit fitting over the tang. Despite its appearance (Figure 2.25) this guard was not welded, but is a single piece of solid metal in which a hole was apparently drifted and subsequently flattened on the tang.

In the dagger No. 101 (Figure 2.2D) the entire blade and handle with its decoration was forged from a single piece of steel, except for the small cross piece at the end which is perforated to fit a small tenon (Figure 2.18). In view of the intricacy of the surfaces forged at the other end of the handle (Figure 2.26), this joint seems almost unnecessary, but it was perhaps used to allow the tool used in forging the longitudinal grooves in the handle to have full run, for much the same reason as the pins in the mace heads. The bobbin-shaped handles of daggers 103 and 104 (Figures 2.2A and 2.2B) seem to have required special dies or swage blocks for their shaping. No. 104 was sectioned and shows (Figures 2.13 and 2.14) that the detail at the shoulder of the blade was achieved mainly by deformation (forging), not cutting, though the metal at the extreme surface is distorted in places, and there was probably some abrasive finishing.

he Short Sword: echanical Joints

The most interesting object was the complicated short sword No. 105 (Figure 2.3), of the type unique to Luristan. In the less corroded examples that have been published, the lumps flanking the ricasso are seen to represent crouching lions, and those bent over the edge of the pommel are compound human and animal heads. As Naumann (Reference 9) and others have shown, these swords are composed of many pieces separately forged and mechanically joined together by a kind of crimping operation. The process is curiously unblacksmithlike in nature, but it called for considerable skill in shaping the parts with sufficient accuracy. Our sword was sacrificed completely in order to obtain cross sections for study from all significant places, thereby gaining more information about its construction than was possible with the museum-owned objects studied by earlier investigators.

Figure 2.27 is a radiograph of the entire hilt, showing the spaces between many of the parts. There was no visible hint of these joints on the sword as received, but most of them became visible to some degree after electrolytic cleaning had removed the rust. Figure 2.28, which is based on the radiographs but incorporates the information provided by later sectioning, shows the manner of construction. Six pieces (which served more of a decorative than a functional purpose) were attached directly to the integrally forged blade and handle,[5] and two pieces to the pommel. All the joints are purely mechanical, the matching male and female parts being carefully shaped and held in place by a final local plastic deformation of the metal. Because of the fine tool work needed on the decorative heads, it is easy to see why the smith might choose to make these separately and attach them in much the same manner as an inlaid carved gemstone, but the use of a similar technique on the pommel itself and the plain bands encircling the hilt indicates a curious unwillingness to forge details that could more easily have been shaped integrally with the hilt.

The simplest joints to describe are the two bands surrounding the hilt transversely. These are pieces of rectangular iron bar about 6.5 mm square, cut to length and bent—bent hot, for the metal at the bends is not significantly cold-worked. These bands fit closely into accurately shaped grooves that had been precut all around the handle and provided with raised flanges at the side that had been finally hammered back to grip the ring tightly. This can be seen in the cross section, Figure 2.29, and in the general view of a groove after its ring has been removed, Figure 2.30.[6] Figure 2.31 shows the microstructure of the joint at higher magnification. It should be noted that there is no flow of metal except in the immediate vicinity of the flanges near the surface. The flanges seem to have been raised with a chisel-like tool driven almost parallel to the surface of the handle, stopping before the raised-up chip broke away, yet there are no visible chisel marks even in the uncorroded area. The bottom of the groove is slightly convex and is remarkably uniform in shape all the way round the hilt (Figure 2.30).

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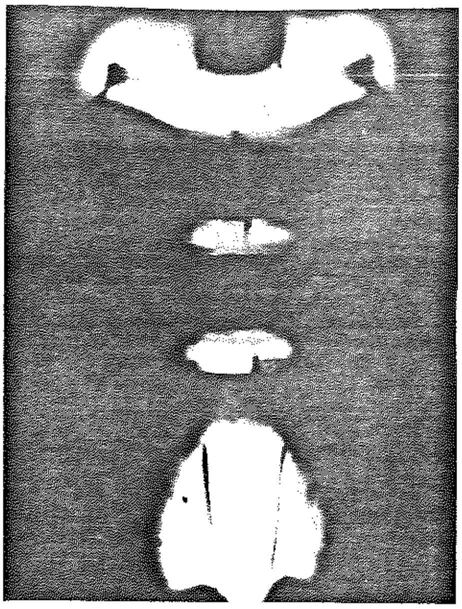
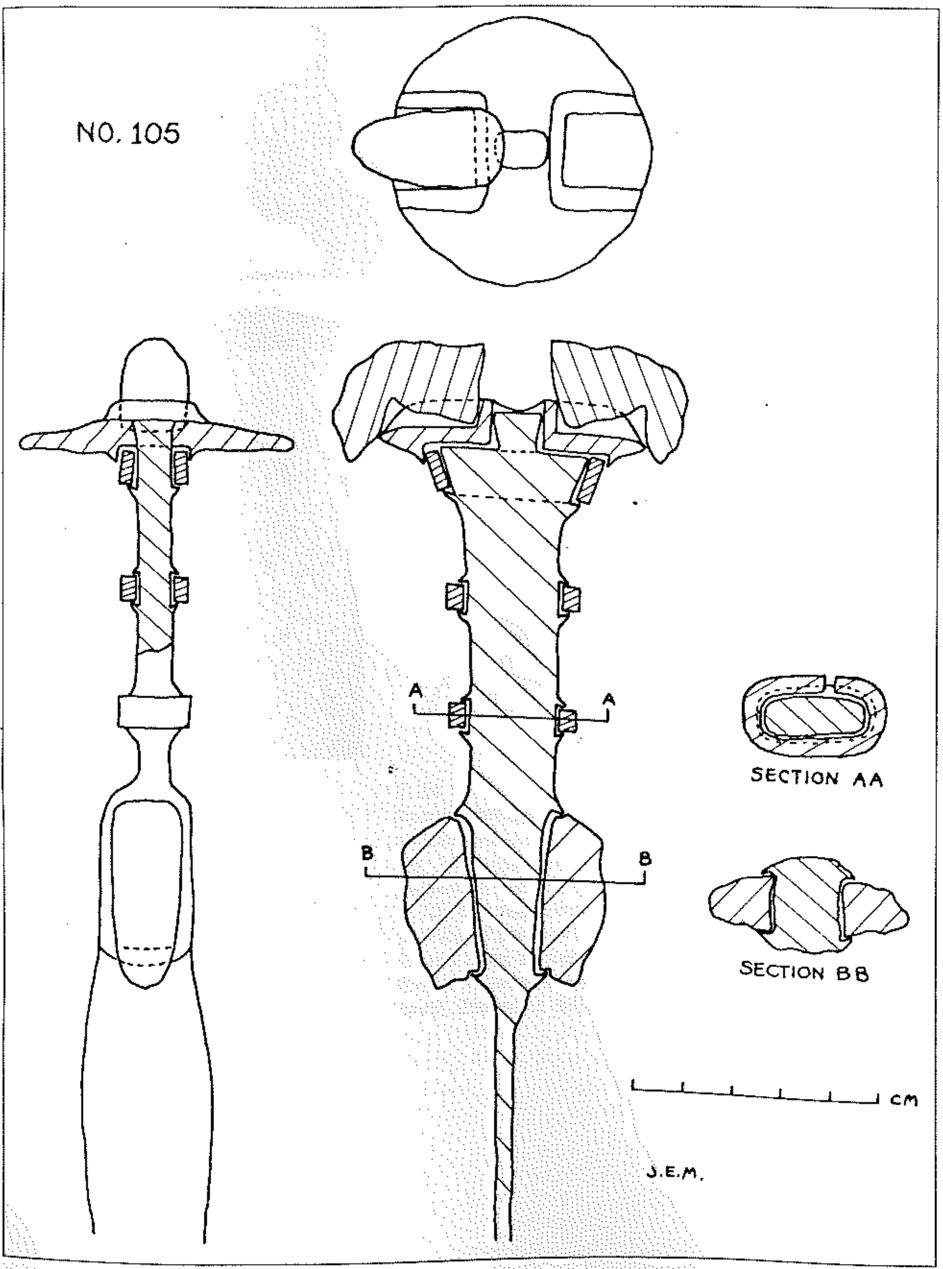
[5] In the majority of the swords described by other writers, the blades are separate pieces, inserted into a slot in the hilt. The single-piece integrally forged construction of the present weapon is both simpler and mechanically better.

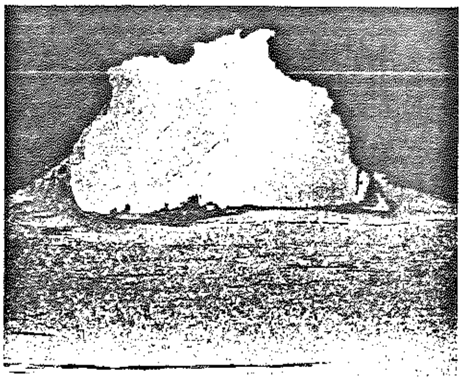
[6] The flange is similar to that on the sword illustrated by Maxwell-Hyslop (References 7 and 1). The heavier squarer flanges on the Philadelphia and New York hilts involve more substantial displacement of metal.

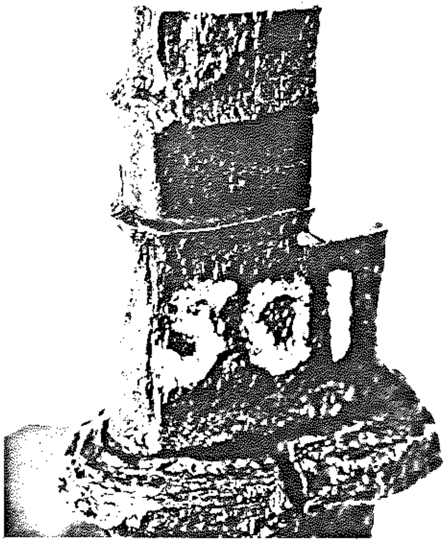
2.27
Radiograph of handle of short sword No. 105.

2.28
Sketch showing construction of short sword No. 105. Traced from a radiograph, with details supplied by examination of the sections cut for metallographic examination.





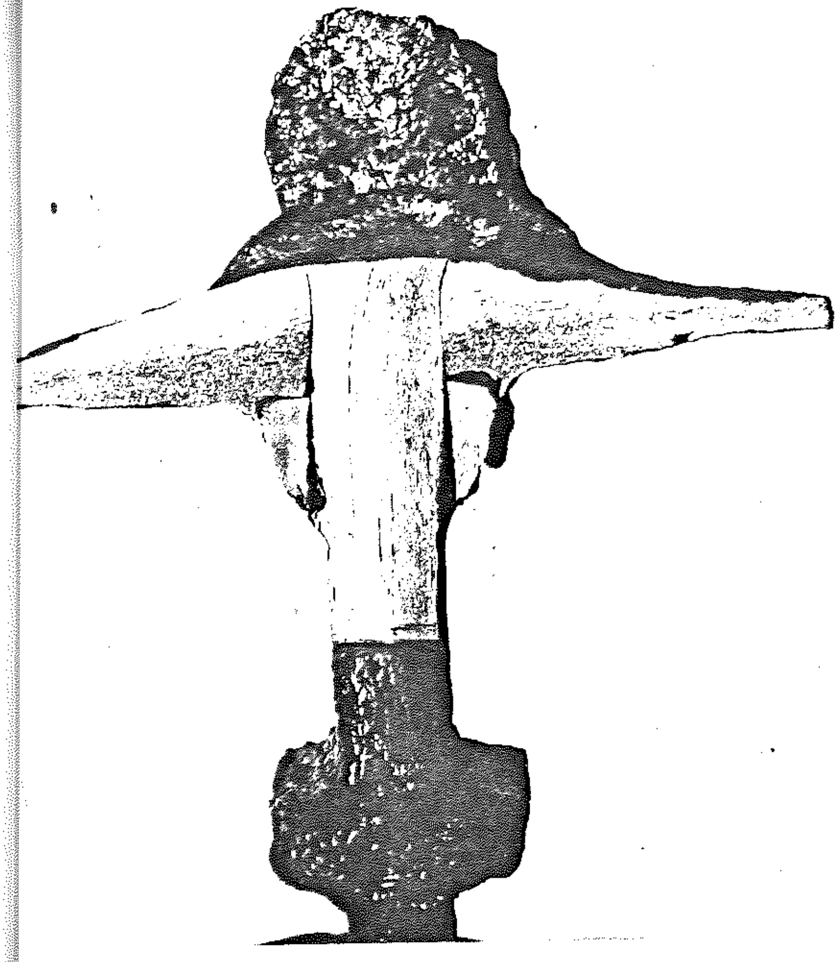


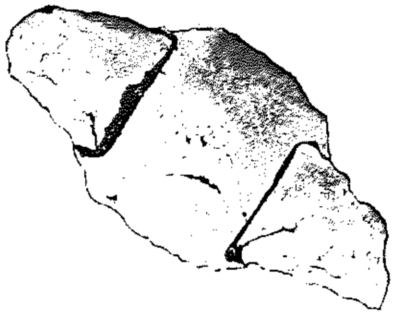


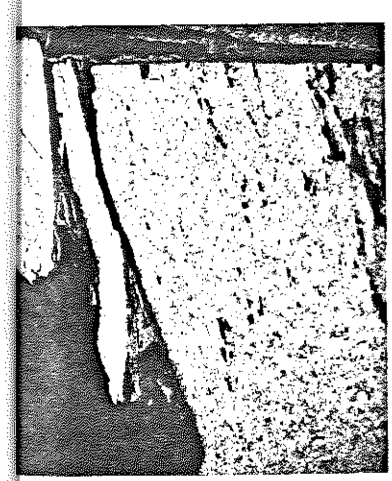
2.29
Transverse section of hilt, No. 105, showing attachment of encircling band. Etched, 6X.

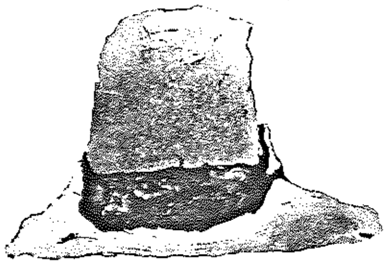
2.30
Appearance of hilt after removal of decorative band, showing groove cut to receive it. Etched, 2X.

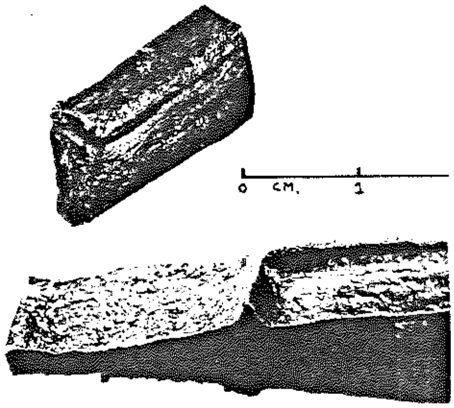
2.31
Same specimen as Figure 2.29 at higher magnification. Shows detail of metal flow in cleat. Etched, 48X.











through pommel
in No. 105,
o smallest di-
of hilt, at right
o section
n Figure 2.17.
natural size.

of hilt and
in No. 105.
ection as Figure
t higher magnifi-
Etched, 7X.

2.34
Section through head attachment and pommel, No. 105. (Section cut parallel to that in Figure 2.32, but near circumference of pommel.) Shows deep socket forged to receive the head. Etched, 1.5X.

2.35
Transverse section through ricasso of short sword, No. 105, showing manner of attachment of the lions to the main forging of the hilt. 1.5X.

2.36
Detail of section shown in Figure 2.35, showing clinching of flange into groove of attachment. 9X.

2.37
The socket on the hilt (partly sectioned) with the lion boss removed, and (above) the boss, inverted, showing the groove in the matching surface

At high magnification, it can be seen that the flat bottom of the groove had been heavily cold-worked, but only superficially so—to a depth of about 0.2 mm. Though the flange is highly distorted (Figure 2.31) and seems to have been accumulated by lateral displacement of metal, the depth from which it had come was shallow, for the slag stringers beneath the cut are almost undistorted.

The manner of attachment of the disk-shaped pommel to the hilt will be clear from the transverse section through it, Figures 2.17 and 2.34 and the sketch, Figure 2.28. A tang the full thickness of the hilt (7.9 mm) but only a third as wide projects through a rectangular hole piercing the pommel and is slightly peened over at the top end. For added security or for decoration it rests not only on the shoulder of the hilt but also on a ring, very similar to those in the middle of the hilt, which abuts a flange cut on the hilt and nests within a similar flange raised on the underside of the pommel. Both flanges had been produced in the same way as those discussed in the last paragraph, and they had the same heavily distorted surface microstructure. Figure 2.33, of a section (Cf. Figure 2.17) through the junction between hilt and pommel normal to Figure 2.32, shows the shoulder of the hilt—which the slag streaks prove to have been cut, not forged—and the ring fitting against a flange, now corroded away. Because of the strong taper of the hilt in this plane, a thin wedge had been driven inside the ring to secure it.

The pommel is much more elaborate than appears in the section Figure 2.32, for at the right angle to this on top, it has raised flanges or sockets to carry the decorative heads. The inserts do not fit snugly, but the flanges allow for this by their height—they extend to a distance of 9 mm above the bottom of the groove. Unlike the smaller flanges on the hilt, these flanges were shaped by gross forging, for slag inclusions (Figure 2.34) show metal to flow up into them for a distance and there is no superficially cold-worked layer. Some die or punch was almost certainly used. It could not have been an easy operation.

The crouched lions mounted on the ricasso were set into complete rectangular cells that were made by forging over a shaped punch in the same way as the three-sided cavities for the heads on the pommel. Figure 2.35 shows a cross section entirely through the ricasso, and Figure 2.36 a detail of the joint. Figure 2.15 is a longitudinal section, normal to Figure 2.35, and reveals a poorer fit. Breaking open the joint after the sections had been made revealed the true shape of the two matching surfaces (Figure 2.37). Note the rounded corners of the insert and the rather deep groove punched around it to provide good anchorage for the matching flange.

Altogether these swords are astonishing. I cannot accept the statement of Maxwell-Hyslop (Reference 9) that the smiths were not competent; I regard them as having been extremely adept in complicated shaping, but since they were unable to weld they developed elaborate methods of mechanical joining. The maces indicate that the gross convex form of the decoration on the short sword could have been forged, and there even exist some swords (for example Maxwell-Hyslop, Reference 7, Plate L, No. 5, and Ternbach, Reference 13, Plate XIII, No. 3) in which some decorative detail was forged as an integral part of the pommel. The decoration resembles in part a jeweler's inlay, in which a separately carved piece made by a different worker was inserted. This would indeed be preferable to the performing of elaborate finishing work on a forged sword.

Heat Treatment

The microstructure and hardness of iron carbon alloys are both very sensitive indices to the heat treatment that the metal has received. Although the objects examined present a number of different structures, none of them corresponds to intentional hardening by quenching or other rapid cooling. At most, cooling was accelerated by waving around in the air. The hardness numbers given in Table 2.2 confirm this.[7]

As mentioned before, the carbon content varies almost randomly through the steel. Typical microstructures of low carbon areas are shown in Figures 2.38 to 2.40 and ones of higher carbon content in Figures 2.41 to 2.43. The former (omitting the slag discussed in an earlier section) consist of more-or-less well formed grains of ferrite (alpha iron). The straight-line Neumann bands (mechanical twins), which are shown in the large grains in Figure 2.39, could be found in the low carbon areas of most samples. They are

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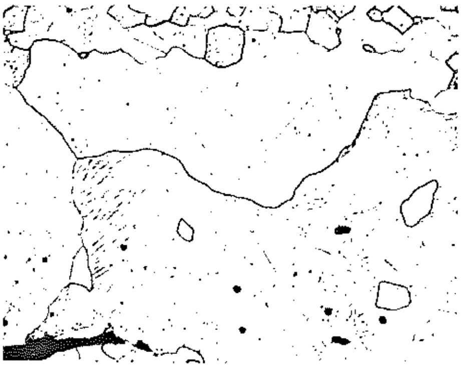
[7] For comparison with the hardness values given in Table 2.2, it might be noted that pure iron-carbon alloys with 0.1 to 0.8 percent carbon have hardnesses in the annealed condition between about 80 to 200 VHN, while if rapidly quenched in water they range about 350 to 950 VHN. Poor quenching or partial reheating (tempering) would give intermediate values. Like bronze, iron can also be hardened by cold-working. See also the next subsection.

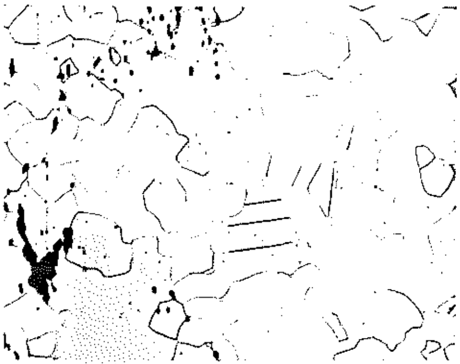
A tiny fragment ostensibly from a Luristan axe that came from a well-known museum had a well-laminated texture and the microstructure (reproduced in Figure 43 of Reference 11) corresponding to quenched steel. It was hard (400 VHN, in places). Since all the other samples examined were unhardened and not laminated, it is safer to question the origin of this sample than to suppose that Luristan smiths did sometimes quench their steel. It would, in fact, be a rather frustrating operation to quench-harden steel as variable in carbon content as typical Luristan material.

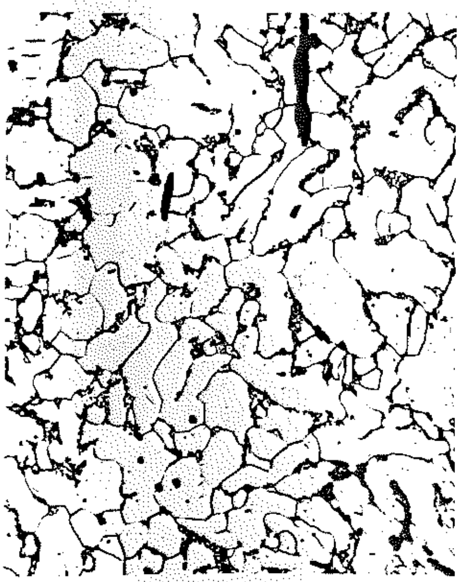
rse section of
No. 102. Shows
r grain size and
osts of previ-
xisting alpha-
structure
by phosphorous
tion. Etched.

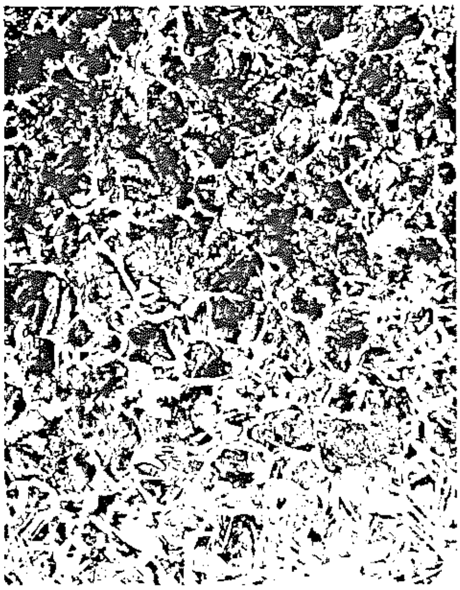
structure in hilt
103 (Cf. Figure
The straight lines
larger grains are
ical twins (Neu-
bands). Etched.

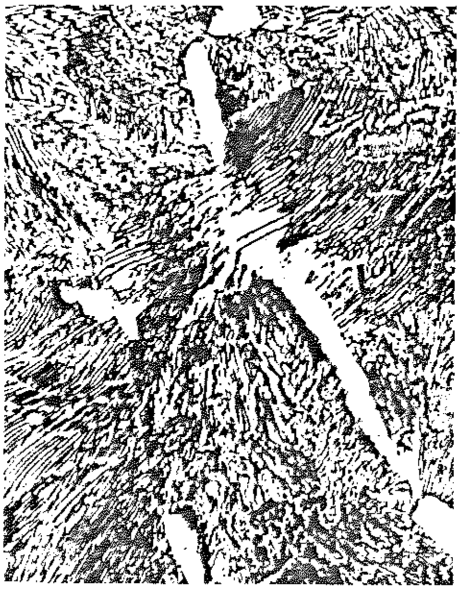
teel'' structure
verse section of
f No. 105.
190X.











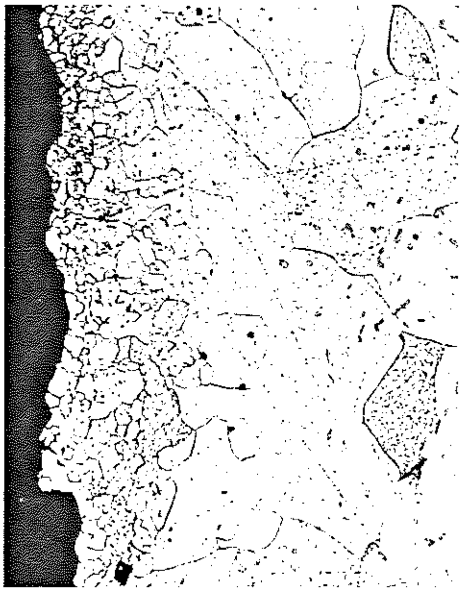
2.41
Transition between high and medium carbon area in handle, immediately below pommel of No. 104 (Cf. Figure 2.16C). Etched, 96X.

2.42
Gradient in structure of high carbon area in No. 106. Etched, 96X.

2.43
Typical well-formed pearlite in handle of dagger No. 104. Etched, 960X.

2.44
Slightly spheroidized pearlite in hilt of No. 105. Shows also fragmented slag (Cf. Figure 2.8). Etched, 480X.

2.45
Spheroidized carbide and precipitated nitrides in hilt of No. 105. Etched, 480X.



2.46
Finely recrystallized structure at the surface of the cavity for decorative insert in the ricasso, No. 105. Etched, 190X.

2.47
Surface of hilt in vicinity of band beneath pommel No. 105 (see Figure 2.17). Shows well-formed pearlite well below surface and spheroidized carbide near the surface, which had presumably been worked before the last low-temperature annealing. Etched, 480X.

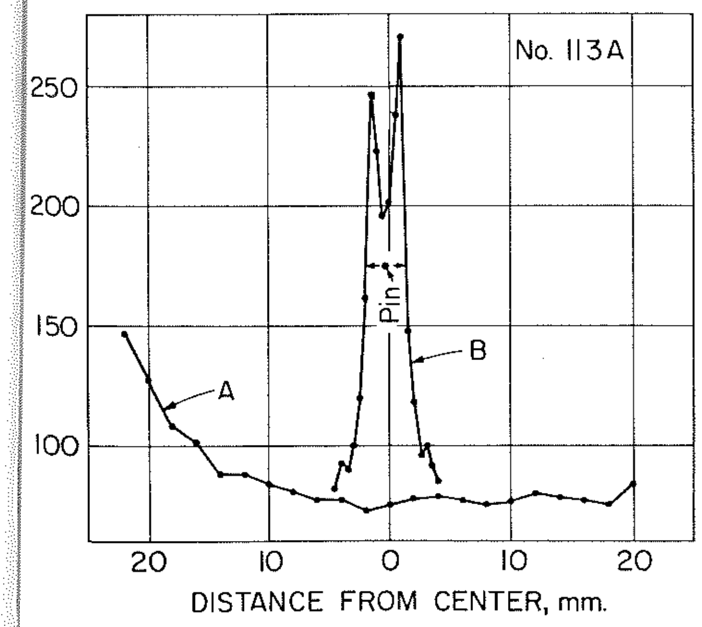
2.48
Local variation of microhardness in Mace head, No. 113. Lower traverse A is in the thickest part, parallel to the axial hole, about 1 cm from it (Cf. Figure 2.25). Upper curve B is across the body of the pin, Figure 2.21.

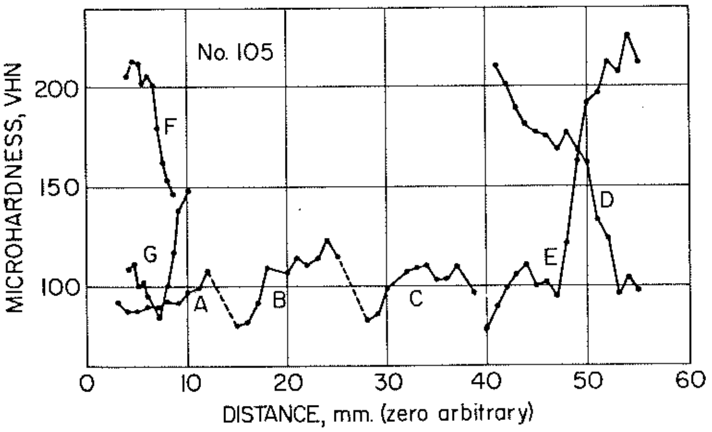
2.49
Microhardness in various regions of the short sword, No. 105. Curves A, B, and C represent a continuous traverse across the three parts of the ricasso, Figure 2.14. A and C are the lion inserts; B is the central portion of the hilt. D represents the diagonal traverse across the head attachment to the pommel, Figure 2.36. E the vertical traverse across the center of ricasso, Figure 2.37 center, F the vertical traverse through section of pommel, directly above right edge of ring insert, Figure 2.34, and Curve G is the transverse section through handle, 1.5 cm below top, Figure 2.34.

e 2.2
ness
surements

ct	Location	No. of Readings Taken	Microhardness (VHN)*		
			Minimum	Maximum	Average
	Transverse section of blade, Figure 2.16A	24	111	260	161
	Transverse section of blade, Figure 2.16F	13	158	187	163
	Transverse section of blade, Figure 2.16B	28	100	185	140
	Transverse section of blade, Figure 2.16C	13	103	158	129
	Cross section of blade near top, Figure 2.16D	14	102	189	141
	Section of blade 15 mm below ricasso, Figure 2.14	10	89	124	108
	Section of hilt, 1.5 cm below top, Figure 2.34	10	85	148	110
	Section of pommel, traversed parallel to hilt of both ring insert, Figure 2.34	10	147	212	189
	Pommel sectioned near periphery, Cf. Figure 2.36	25	91	172	131
	Transverse section through base of decorative head attached to pommel, Cf. Figure 2.36	16	97	210	160
	Transverse section through center of ricasso, Figures 2.37 and 2.52E	16	78	226	145
	Lower part of hilt, beneath attached lions, Figures 2.14 and 2.52B	10	81	123	105
	Section of right lion, Figures 2.14 and 2.52A	10	83	113	103
	Section of left lion, Figures 2.14 and 2.52C	10	88	108	94
	Traverse through left lion attachment, Figure 2.37	12	81	113	98
	Section through lower band surrounding hilt	26	101	136	118
	Transverse section of handle, 2 cm from end, Figure 2.16E	20	99	169	117
	Transverse section through thickest part, normal to hole	16	79	127	97
	Axial section through decorative pin, A	10	135	173	153
	Axial section through decorative pin, B	8	144	173	158
	Transverse section through thickest part, parallel to axis of the hole, Figures 2.25 and 2.51	22	75	147	87
	Cold-worked head of inserted decorative pin, Figure 2.23	19	212	271	235
	Shank of inserted pin	19	153	271	207

e microhardness numbers, in kilograms per square millimeter, were measured with the Vicker's indenter using a 200 g load. Indentations were spaced tervals of 0.25 to 2.0 mm, usually in two traverses at right angles to each other representing the entire section at the place noted.





presumably due to shock in manufacture or in use, for they are easily produced by a hammer blow. They are found to some extent in most ancient irons of low carbon content and large grain size.

The grain size varies considerably. Some of the grains large enough to be seen by the naked eye as in Figures 2.15 and 2.21 are almost certainly a result of exaggerated grain growth occurring during the annealing of a purely ferritic sample at a temperature below the critical point (910°C in pure iron), but most of the ferrite grains had the slight irregularity associated with their production by transformation of austenite. The structures in Figures 2.41 to 2.43 are typical of air-cooled samples of steels of medium carbon content. Light-etching areas of ferrite have formed around the grain boundaries of austenite, and there is further growth of ferrite into the body of the grains in a more geometric form. The dark areas represent eutectoid pearlite (fine alternating lamellae of iron carbide and ferrite resulting from transformation just below the critical point at 723°C).

Several photomicrographs of Luristan steel that have been published—for example, Brick (cited by Maryon, Reference 4) Naumann (Reference 2) and Smith (Reference 11)—have shown the carbide to be spheroidized to a greater or less degree. This could have resulted only from heating below the transformation temperature, though the degree to which spheroidization occurs is very sensitive to deformation and the structure therefore differs considerably in different parts of the objects. Much of the carbide in short sword No. 105 was in well-shaped pearlitic form (Figure 2.43), but in other areas it was somewhat spheroidized (Figure 2.44). It seems probable that the spheroidized structures resulted simply from forging at a slightly lower temperature than usual, for the smith could hardly have been aware of the abrupt critical point.

Spheroidized carbide mixed with nitride was encountered in one part of No. 105 (Figure 2.45) but it is usually difficult to recognize the nitride when much carbon is present. In the dagger No. 102 there were many areas in which the ferrite in the microstructure revealed ghost markings (Figure 2.38) obviously related to segregation occurring in a preexisting alpha-gamma microstructure that has disappeared during cooling. This is the only one of the objects studied to contain a significant amount of phosphorous, which diffuses slowly and is distributed in quite different amounts in the alpha and gamma phases.

Although most of the pieces examined had, both internally and on the greater part of their surfaces, structures associated with simple air-cooling from temperatures well above the critical point (725° to 910°C depending on carbon content) without any further treatment, there is evidence of later heating to a lower temperature.

It was mentioned earlier that the steel in the grooves cut to receive the bands on the hilt and pommel of No. 105 had been superficially cold-worked in a manner that suggested working with a chisel. Actually the ferrite in the most heavily cold-worked areas has recrystallized to an extremely small grain size (Figure 2.46) and in similar areas that are pearlitic the carbide has become spheroidized (Figure 2.47). This indicates that the mechanically finished dagger had been heated for a short time to a temperature perhaps as high as 650°C. A similar effect was encountered on the surface of the shaped shoulder of No. 104 (Figure 2.14). The recrystallization of the heavily distorted chips alongside the pin (itself unaffected) in the mace head No. 113 (Figure 2.23) suggests a similar if less intense thermal history. The objects had been forged mainly at the usual supercritical temperatures, and the fine recrystallization occurred only in regions that had been subjected to severe and highly localized surface deformation. Was the final fitting together of the parts perhaps done just below a red heat? The fact that the effect occurs on several of the objects makes it unlikely that it resulted from heating in a cremation or an accidental fire; perhaps it marks the use of bluing or some other low-temperature chemical treatment carried out to produce an attractive corrosion-resisting surface on the finished objects. There are no records describing the surface appearance of iron objects in the period under discussion, but it seems somewhat unlikely that they would have been bright.

Hardness

Table 2.2 summarizes microhardness measurements on the objects. The average hardness numbers are misleading, for there is considerable variation from place to place. Figure 2.48 presents a number of measurements across various sections of the short sword No. 105. The hardness in local regions is roughly what would be expected for metal of carbon content revealed by the local microstructure after air-cooling from temperatures somewhere in the range 750 to 900°C.

Locally enhanced hardness caused by cold-working is clearly shown in Figure 2.49, which summarizes measurements on the mace head No. 113: Curve A is a traverse across the head in an area that is mainly recrystallized low-carbon iron, and Curve B traverses the stem of the cold-worked pin. The latter shows the high, local hardness in both the body of the pin and the sides of the hole drilled to receive it. Although this metal is of low-carbon content, it is harder than any other metal encountered in the investigation. The

Luristan smith (in common with most other iron workers at any time) did not exploit the superior mechanical properties of cold-worked steel in sword blades or other objects.

A cold-worked bronze containing 10 percent tin could easily surpass the hardness of any of the present steels, and even a cast bronze (with a hardness of about 110 VHN) would be superior to most of them. The advantage of iron over cold-worked bronze must have been mainly an economic one. The ores of iron are far more widespread than are those of copper and especially those of tin, though when making complicated shapes this advantage would have been partly offset by the greater labor needed in forging iron than when casting bronze.

ary and sions

Iranian smiths in the period 800 (±200) B.C. were highly skilled, although they were unacquainted with some of the basic methods of ironworking. Their forging, which involved the use of special swages, is magnificent, but there is no evidence of welding, and the smith assembled shapes as complicated as those of bronze castings by using elaborately fitted mechanical joints, locked by peening or crimping. Holes were drilled and surfaces were accurately cut by a technique, supposedly using abrasives, that only superficially distorted the adjacent metal.

Chemical analysis showed the steel to be unusually free from impurities, though one sample contained nickel, and iron oxides and silicates were generally present as slag inclusions. The carbon content, as estimated from the microstructure, varied between 0 and 1.0 percent in different parts of the objects, reflecting uncontrolled local variations of carburization in the reduced iron sponge as it came from the smelting hearth. No significant carburization or decarburization had occurred either during forging or after. The microstructure showed the pieces to have been air-cooled after forging, not quenched for hardening. The hardness, averaging about 130 VHN, varied locally between 80 and 270 VHN, the highest values being only in a few regions that had been locally cold-worked. There was some evidence of a final low-temperature heat treatment, perhaps to confer corrosion resistance by surface oxidation.

Until many more studies of a comparable kind have been made on material from other cultures, it is premature to draw general conclusions. Nevertheless, the Luristan smith's curious combination of skill in forging and ignorance of either welding or quench hardening seems rather clearly to denote a transitional period in the knowledge of iron. Furthermore, the iron objects whether swords, daggers, maces, or bracelets are all of a decorative design that is more appropriate to the mold of the foundryman and the chaser's chisel than to the hammer of the smith. It seems that the economic advantage that lies in the greater abundance of the ores of iron compared with those of copper and tin was offset to a considerable extent by the greater labor involved in the forging operation and by the apparent inability to use scrap. Homer's legend of the blinding of Polyphemus proves that the quench-hardening of steel was known at the time (at least in Greece), but the Luristan smith either did not know it or preferred not to use it because of the extreme difficulty of consistently producing steel of a suitable quality and of properly controlling the quenching operation. In the unquenched state, steel is little better than bronze: indeed, it is inferior to cold-worked bronze, and it would probably not have been used had not economics accelerated its introduction. Some bronze swords at the time were cold-worked; had the iron been so treated, its mechanical properties would have been considerably enhanced. The absence of such processing except in trivial parts suggests that sufficiently powerful hammers and sufficiently resistant anvils for cold-working large objects had yet to be developed. (When these did become available later, comparable properties were more easily obtained by heat treatment.)

Acknowledgments

The photomicrographs in this paper are mainly the work of Mrs. Betty Nielsen of the University of Chicago, Mrs. Katharine Ruhl and Mrs. Judith Moore of M.I.T. Their careful work is gratefully acknowledged. The United States Steel Corporation through the courtesy of Dr. M. W. Lightner performed the chemical analyses. Support for this study was provided by the Sloan Fund for Basic Research, M.I.T., and by the U.S. National Endowment for the Humanities.

Addendum

By far the most important paper on Luristan steel yet to appear was published after the present paper was written (early in 1958). This is Albert France-Lanord, "Le fer en Iran au premier millénaire avant Jésus-Christ," *Revue d'Histoire des mines et de la métallurgie, 1*, 1969, pp. 75–127. France-Lanord includes photographs of two typical short-swords in unusually fine condition showing fine traced decoration and many photographs of metallographic sections of similar swords. All were assembled without welding, but the number of parts and the details of their attachment differ. In one of the short swords, rivets were used to secure the decorative heads on both pomel and ricasso, and also to fix the blade to the handle. France-Lanord notes the lack of welding and points out that the forging, shaping, and riveting techniques were essentially those of the bronze worker. He concludes that there was a complete separation between those men who smelted iron as an article of commerce and those who shaped objects from it, using old methods on a newly introduced material.

France-Lanord also describes daggers with cast-on bronze hilts, axes, spears, horse bits, and several sword and knife blades. Most of the objects are irregularly carburized, although France-Lanord observed that harder metal was generally selected for blades and softer iron for decorative parts. One blade (No. 10, of unspecified origin) seems to have been carburized locally on its cutting edge, though a fortuitous fluctuation of carbon content is not excluded. Another (No. 14, of the seventh to sixth century B.C.) has a laminated composite structure somewhat reminiscent of later Damascus swords. France-Lanord believes that the structure could not have resulted from the simple forging of an unmelted sponge and suggests possible origin either in a Wootz-like material (high-carbon steel, melted, and slowly cooled to give a coarse crystalline segregation) or in stacks of iron plates impregnated with molten cast iron as in Needham's co-fusion process used in the Far East some centuries later. However, it seems to the writer that the making of "natural" steel by operating the refiner's hearth under highly reducing conditions must at least occasionally involve the transitory production of some liquid cast iron, and structures like that of France-Lanord's No. 14 could easily result from the irregular distribution of liquid metal within a poorly consolidated sponge. Even large gradients of carbon content in hyper-eutectoid steel would not be eliminated by diffusion as long as working was done at a temperature low enough to retain some carbide everywhere. I have seen Iranian iron in which heavy carburization locally follows deep seams and cracks in a distribution that could not possibly occur by gas transfer but would easily result from eutectic material being carried by capillarity into these regions. Though the chemistry is identical with co-fusion it does not require the prefabrication of plates of iron and their immersion into separately-made cast iron, but is simply a result of differing degrees of carburization at different locations within a single, somewhat porous, lump of metal.

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