GLADIUS
Estudios sobre armas antiguas, armamento, arte militar
y vida cultural en oriente y occidente
XXVII (2007), pp. 149-176
ISSN: 0435-029X

THE METALLURGY OF SOME INDIAN SWORDS
from the Arsenal of Hyderabad and elsewhere

POR

Alan Williams* • David Edge**

RESUMEN - ABSTRACT

La metalurgia de las espadas indias presenta notables diferencias en comparación con la de las europeas. Se explica la distinción entre el 'acero de Damasco' (o wootz) y el acero de crisol. Se ha realizado un análisis microscópico de un conjunto de diez hojas rotas de espada depositadas en la Armería de los Nizams de Hyderabad. Seis de ellas parecen haber sido realizadas a partir de acero de crisol, y son de elevada calidad. En contraste, se examinó también un grupo de seis espadas de colecciones privadas en Inglaterra. Sólo una de ellas estaba fabricada con acero de crisol, y tres de las otras eran de calidad muy mediocre. Esto representa quizá la calidad de las hojas de espada al alcance del soldado medio indio.

The metallurgy of Indian swords shows many differences from that of European swords. The distinction between "Damascus Steel" (or wootz) and crucible steel is explained. Ten broken blades from the Armoury of the Nizams of Hyderabad were made available for microscopic examination. Six of these seem to been made from crucible steels, and are of notably high quality. By contrast, a group of six randomly collected from Private Collections in England were also examined. Only one of these was made of crucible steel, and three of the others were of very mediocre quality. This perhaps represents the quality of blades available to the average Indian soldier.

PALABRAS CLAVE - KEYWORDS

Metalurgia, metalografía, espadas Indias, acero, wootz

Metallurgy, Metallography, Indian swords, crucible steel, wootz

Eastern swords (often misleadingly called "Damascus steel") with a surface pattern said to resemble "watered-silk" are deservedly famous and have been the subject of an extensive literature. However, they are only a small minority among Indian swords, and the metallurgy of less famous, and less valuable, blades is equally interesting.

CRUCIBLE STEEL

In the ancient Middle East a method of making steel developed, entirely different to that of Europe. Crucible steel was made by heating lumps of iron with carbon, or a material con-

* Archaeometallurgist, the Wallace Collection, London
** Armourer and Head of Conservation, the Wallace Collection, London

taining carbon, such as cast iron, in a sealed crucible for many hours, or even days. Eventually enough carbon would have been absorbed for the alloy to melt, and the broken crucible would yield a cake of cast steel, which could be a convenient size for making a sword blade. Since the liquid metal separated from the liquid slag, it was a homogeneous product of high carbon content (1.2 – 1.6%), unequalled in Europe until the 18th century.

The earliest products which were definitely made of crucible steel date from the 6th century, and the earliest descriptions of the process from the 9th century, although there is some, less certain, evidence for its earlier use. The Persians used this steel, and a Sassanian blade of the 6th century in the British Museum, has recently been analysed, and found to be made of a crucible steel[1]. France-Lanord published an analysis of a Luristan blade of uncertain date, but possibly much earlier, and which was also made of a very high-carbon steel[2].

DAMASCUS STEEL

An important subdivision of crucible steel was the steel called *wootz*, in South India, *bulad* in Central Asia, and sometimes, misleadingly, "Damascus steel". This was used to make swords of unique quality and correspondingly high price, recognisable by a characteristic pattern (caused by large crystals of cementite, Fe_3C) on their surfaces, reminiscent of "watered silk". These patterns needed etching with weak acids to make them appear. Al-Biruni describes how they may be worked, and gives a recipe ascribed to one Mayzad ibn Ali, a smith from Damascus, for producing imitation blades from soft iron by etching the patterns with an acidic solution of *zaj,* or ferric sulphate.

Wootz was made, as all crucible steel was, by melting iron with carbonaceous material in a sealed crucible over several days until it wholly or partially melted into a cake of steel, but was then allowed to cool extremely slowly (over days, rather than hours). These cakes were exported to centres of arms manufacture, such as Damascus, where they were carefully forged, with considerable difficulty, into sword blades. Since the melting-point of steel falls with increasing carbon content, a lower temperature than usual has to be employed to forge a blade of higher carbon content than usual, notwithstanding its hardness. This forging broke up the cementite (iron carbide) network left over from the casting, reducing brittleness, and producing the characteristic pattern ("watered silk") visible after etching on the surface of the blade.

The blade so formed needed no further heat treatment to harden it (although attempts were nonetheless sometimes made) nor did any amount of sharpening ever remove its edge.

Articles by Belaiew[3] and Panseri[4] may have been the first to show the microstructure of Damascus steel, and they were followed by France-Lanord and Piaskowski[5] . Extensive efforts by Verhoeven and Pendray[6] to recreate this process have led to a series of very detailed papers on its metallurgy.

---

[1] Lang, J."New evidence for early crucible steel" *Historical Metallurgy*, 32 (London, 1998) 7-14.

[2] France-Lanord, A. "Le fer en Iran au premier millénaire avant J-C" in *Revue d'histoire des mines et la métallurgie*, 1,1, (Nancy, 1969) 75-126.

[3] Belaiew, N.T. "Damascene steel" *Journal of the Iron & Steel Institute*, (London, 1918) 417-439 and (1921) 104, 181-184.

[4] Panseri, C. "Damascus steel in legend and reality" *Gladius* (Caceres, 1965) 4, 5-66.

[5] Piaskowski, J. "Metallographic examination of two Damascene steel blades" *Journal for the History of Arabic Science*, 2, (Aleppo, 1978) 3-30.

[6] Verhoeven, J.D. Pendray, A.H. & Peterson, D. "Studies of Damascus Steel Blades" *Materials Characterisation* (New York, 1992) 29, 335-341 and ibid.(1993) 30, 175 and 187.

However it has become clear, especially after recent archaeological work in the Middle East, that *wootz* was only a small part, albeit a special part, of a crucible steel industry, the extent of which has been rediscovered in recent years[7].

It may be that much of the crucible steel made did not undergo the extremely slow cooling which was to lead to the "watered-silk" pattern visible on the surface of the most highly prized "Damascus" blades, and therefore has not been recognised; so the quantity of crucible steel employed may well have been considerably underestimated in the past.

HYDERABAD SWORDS

The difficulty with analysing swords is that the whole section has to be studied in order to determine how the blade was constructed. However, this is seldom possible unless the blade has already been broken. The metallurgy of a number of such broken European blades has been published[8] but until recently it was difficult to find broken Oriental blades with any provenance.

An opportunity arose through the kindness of the family of the Nizam to examine a number of broken blades from the princely armoury of the Nizams of Hyderabad.

In each case, a sample was taken showing a complete cross-section. This was embedded in polyester resin, polishing down to 1 micron diamond in the usual way for metallography, and then etched with a nital/picral mix. The microstructure is reported below, together with microhardness measurements. A macro to show the overall distribution of microconstituents across the section is also given, where appropriate. In some cases, there seemed to be little or no variation in the microstructure. These blades were evidently those made from crucible steel.

The authors are grateful to Dr. Robert Elgood for assisting with the difficult task of assigning probable dates and terminology to these broken swords.

Hyderabad 1;

A Hyderabadi *khanjar* (a short dagger sometimes called a *jambiya*) of the 18-19th century with a rhino(?) horn hilt and a double-edged curved blade with a medial ridge. Probably locally made and issued in quantity.

The microstructure contains a mixture of ferrite and pearlite (partly divorced into carbides) in varying proportions. The carbon content varies between around 0.2% and 0.4%C. There is also a band, apparently extended by forging, free of carbides, which disappears into the central rib.

Microhardness (Vickers, 100g) range 266-325 : average = 281 VPH.

When etched with Oberhoffer's reagent, this section shows the distinctive banding associated with phosphorus, which encourages carbon to segregate. In other words, the low-carbon (white-etching) area is high in Phosphorus, and the high-carbon band (dark-etching) is low. Some pieces of high P% iron have been used in the manufacture of this sword, which may account for the higher hardness than that to be expected from the microstructure.

(Figs. 1, 2, 3)

---

[7] See, for example, Craddock, P. & Lang, J. 2003 "*Mining & Metal production through the ages*" especially "Cast iron, Fined iron, Crucible steel" 231-257, and "Early Islamic Crucible steel production at Merv" 258-266.

[8] Williams, A. "Methods of manufacture of swords in Medieval Europe" *Gladius* 13 (Caceres, 1977) 75-101.

Hyderabad 2;

Another Hyderabadi *khanjar* (a short dagger sometimes called a *jambiya*) from the 18-19th century.

The microstructure contains mostly ferrite and a very small amount of pearlite with a considerable amount of slag, in the form of circular as well as oval inclusions. The overall carbon content is less than 0.1%C.

Microhardness (Vickers, 100g) range 150-199: average = 171 VPH.

(Figs 4, 5, 6)

Hyderabad 3;

A *tulwar* having a blade with two fullers made in the European or "firangi" style. Perhaps an Indian copy, and possibly made in the 18th century.

The microstructure of the specimen contains a mixture of pearlite areas and ferrite grains. The carbon content is around 0.4%C in the core and somewhat more in the outer layers (perhaps 0.7%C) where the ferrite forms a network. There are a small number of oval grey slag inclusions, but no line marking the interface of higher- and lower-carbon areas.

Microhardness (Vickers, 100g) range 184-226 : average = 210 VPH. (core)

(Figs 7, 8, 9)

Hyderabad 4;

Another *tulwar* having a blade (this time with three fullers) made in the European or "firangi" style. This is probably late 17th century, probably of Central Indian make.

The microstructure contains a very uniform mixture of fine carbides, which seems as if it has been formed by tempering martensite, very little slag, and no visible ferrite, lamellar pearlite, or martensite. This is apparently a *crucible steel* which has undergone some heat-treatment to further harden it.

Microhardness (Vickers, 100g) range 483-532: average = 515 VPH.

(Figs 10, 11, 12)

Hyderabad 5;

Another 18th century Deccan or Central Indian *tulwar*, in the "firangi" style (this sword blade being without fullers).

The microstructure contains a very uniform mixture of cementite globules, many of which are still arranged in the form of a network, and a ground mass of pearlite. There are very few slag inclusions. This is apparently a *crucible steel* which has undergone a good deal of hot-working.

Microhardness (Vickers, 100g) range 232-279 : average = 261 VPH.

(Figs 13, 14, 15, 16)

Hyderabad 6;

Another *tulwar* in the "firanghi"style (a broad sword blade with three fullers) made in the early 18th century, although the hilt may not belong .

The microstructure contains very uniform tempered martensite, with very few slag inclusions. This is apparently a *crucible steel* which has undergone some form of heat-treatment to further harden it. This process has been extremely successful, as the hardness demonstrates.

Microhardness (Vickers, 100g) range 457-599 : average = 550 VPH.

(Figs 17, 18, 19, 20)

Hyderabad 7;

A Persian style blade perhaps of the 17th century, with an unusual hilt which is not of typical Indian form, but is perhaps Turkish (maybe due to Turkish influence in the Deccan ?).

The microstructure contains uniform very fine pearlite, with a feathery appearance in places. There are no visible ferrite grains, nor any slag inclusions. This is apparently a *crucible steel* which may have been given a fast air-cool after forging.

Microhardness (Vickers, 100g) range 269-322 : average = 295 VPH.

(Figs 21, 22, 23)

Hyderabad 8;

A *tulwar* (with a broad fuller) probably made in the early 18th century. It bears signs of much use.

The microstructure contains a very uniform mixture of tempered martensite and a network of ferrite grains. There is no visible pearlite, nor any slag inclusions.

This is apparently a *crucible steel* which has been probably been hardened by giving it a slightly delayed quench, and then slightly tempering it. Whatever the exact nature of this heat-treatment, it has been successful in increasing the hardness.

Microhardness (Vickers, 100g) range 379-446 : average = 411 VPH.

(Figs 24, 25, 26, 27)

Hyderabad 9;

A *tulwar* (with a broad back to the blade) probably made in the early 18th century, and probably from the Deccan.

The microstructure contains a mixture of ferrite and slag. Some of the slag inclusions are elongated, and some are circular in section. This is merely a wrought iron.

Microhardness (Vickers, 100g) range 157-185 : average = 170 VPH.

(Figs 28, 29, 30)

Hyderabad 10;

Another *tulwar*, in the "firangi" style (the blade with narrow fullers), probably of the 18th century. It is missing the usual disc pommel.

The microstructure contains very uniform fine pearlite with occasional isolated grains of grain-boundary cementite and no visible slag inclusions. This is apparently a *crucible steel* which has been given a fast air-cool after forging.

Microhardness (Vickers, 100g) range 345-403: average = 371 VPH.

(Figs 31, 32, 33, 34)

OTHER SWORDS

Samples from 6 broken blades of more modest quality from private collections in England were also examined. They were all examined upon their broken cross-sections.

(i) E.100

A 17th /18th century *khanda*

The microstructure contains a mixture of ferrite and carbides (apparently divorced pearlite) in a band where the carbon content approaches 0.3%C .

This also shows distinct banding when etched with Oberhoffer's reagent. The lower carbon band is higher in phosphorus. Surface hardness = 172-208 VPH.

(Figs 35, 36, 37)

(ii) E.101

An Indian copy of a European 17th century blade. It bears a 16th or 17th-century mark attributed to Genoa, but widely copied on both German and Italian blades of this period. In this instance, however, it would appear to be a native Indian copy of the European mark.

The microstructure contains ferrite and slag only. Surface hardness = 158-180 VPH.

(Figs 38, 39, 40)

(iii) E.103

A 17th century southern Indian *pata* with a black surface, and notches on the (broken) blade.

The microstructure contains two outer layers of lower-carbon steel, on either side of a core consisting of a higher-carbon steel (perhaps 0.4%C). The microconstituents are tempered martensite mixed with an acicular material which might be bainite. There is no free ferrite or pearlite visible. Lines of slag inclusions mark the interfaces between these bands. This sword has been made from a billet formed by three pieces of steel, forge-welded together, and the harder part has wound up in the centre. The advantage of this is that the edge would not have been lost on sharpening. After forging to shape, the sword has been hardened by some form of heat-treatment. Surface hardness = 290-620 VPH. (average = 422)

Microhardness (outer band) = 348 VPH.

(Figs 41, 42, 43)

(iv) E.200

A blade from a *pata* of uncertain date.

The microstructure consists of an iron core with a steel layer wrapped around it; the slag line associated with the change in composition suggests that the steel layer was welded on.

The microconstituents are ferrite and spheroidised pearlite, in varying proportions.

(Figs 44, 45, 46) Surface hardness = (centre) 146 VPH (edge) 254 VPH.

(v) E.102.

A blade from the late 17th or 18th century, possibly Persian, with an Indian (Maratha) hilt.

The microstructure consists of a pearlitic matrix with numerous cementite particles, aligned in the direction of forging, but not in rows. This is a crucible steel, and the section shows a fold down the centre. The ingot was evidently folded during forging. The cementite particles are not spheroidised, suggesting that the forging has broken up the dendrites but not been continued long enough to form globules; nor are they microsegregated, and it would not have given a visible wootz pattern. The carbon content is perhaps 1.5%C.

Microhardness range 283-589; average = 355 VPH.

(Figs 47, 48, 49, 50)

(vi) E.105.

A fragment from a *tulwar* blade of the 18th –19th century.

The microstructure consists of ferrite mixed with a little partly divorced pearlite. The carbon content reaches about 0.1%C.

(Figs 51, 52, 53).

TABULATED RESULTS

Sword	Microconstituents	Carbon content (%)	Hardness (VPH)
Hyderabad 1	F + C	0.3-0.6	280
Hyderabad 2	F	<0.1	170
Hyderabad 3	P + F	0.5	210
Hyderabad 4	TM	0.8	515 *
Hyderabad 5	P + C	> 1	260 *
Hyderabad 6	TM	0.8	550 *
Hyderabad 7	vfP	0.8	300 *
Hyderabad 8	TM + F	0.6	410 *
Hyderabad 9	F	0	170
Hyderabad 10	vfP + C	> 0.8	370 *
E100 khanda	F + c	0.3	188
E101 firangi	F	0	165
E103 pata	TM	0.5	350-420
E200 pata	F + P	0.4	146-254
E102	C + P	1.5	355 *
E105 tulwar	F + C	0.2	185

* crucible steels

F = ferrite
P = pearlite
c = carbides (the product of divorced pearlite)
C = cementite
TM = tempered martensite
vfP = very fine pearlite (the product of an accelerated cooling)

VPH is the Vickers Pyramid Hardness scale (the units of which are $kg.mm^{-2}$)

DISCUSSION

Analyses of many more swords will be needed before any sweeping general conclusions can be drawn. However, 6 out of 10 of the swords from the princely Arsenal of Hyderabad seem to have been made of crucible steels (*), although none of them display the segregation of cementite that would have led to a “wootz” pattern.

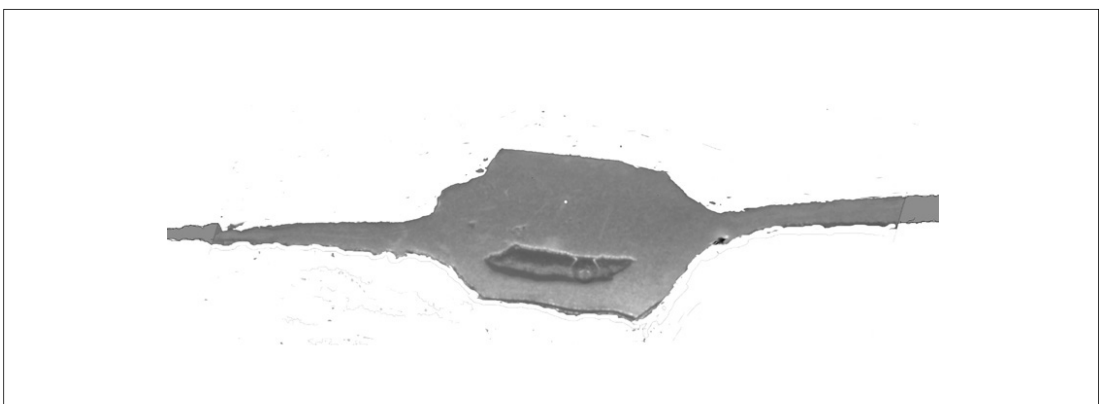
2 out of these 10 are merely wrought irons, and the remaining 2 are steels of low- to medium-carbon content. Even accepting that this sample of swords would probably have been of higher quality than average, it is still remarkable that so many display such excellent metallurgy. Hyderabad may well have been making the best blades in India because of the decline of the Mughal Empire. If these blades were made for the retainers of the Nizam they are indeed of very high quality. Numbers 4, 6, and 10 have all undergone some form of heat-treatment to increase their hardness from its already respectable level to a truly impressive one. They would have been so much superior to any contemporary European blades[9], that it is difficult from a metallurgical point of view to see any motive for importing the latter – except, of course, for the crucial one of cost.

[9] See for example, Williams, A."Seven swords of the Renaissance from an analytical point of view" *Gladius* 14 (Caceres, 1978) 97-127. and Plöckinger, E. “Untersuchung einer Landwehrsäbelklinge” 63-67 in “Die Steirische Landwehr einst und heute” (Graz, 1977).

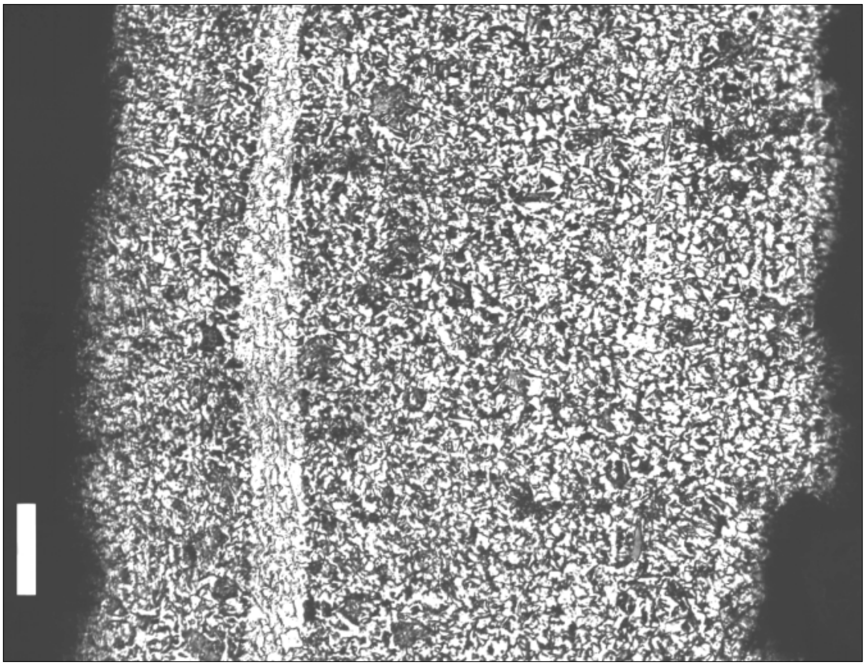
When we contrast these with the randomly assembled private collections of 6 swords, we observe that only 1 of those was made of a crucible steel. This may have been nearer to the general average in proportion, of course. 4 out of the other 5 are of decidedly mediocre quality, but this may well have been representative of the only weapons available to the general mass of the Indian population. The fifth was made of a medium-carbon steel hardened by quenching. Since this procedure would have been capable of producing a sword of similar hardness to one of crucible steel, at much lower cost, it is surprising that more examples were not found in this, admittedly small, sample. Such swords would have been inferior in mechanical properties, of course, since their slag content would have been much higher than those of crucible steels. Crucible steel was capable of producing excellent blades, but at substantial cost, and while many Indian princes may have chosen these for themselves and their retainers, the bulk of the population may have had to make do with markedly inferior weapons. Whether imported blades might have offered an acceptable compromise between cost and quality is a question that will have to await further study.

LIST OF I LLUSTRATIONS:

1. HYDERABAD 1; a *khanjar*

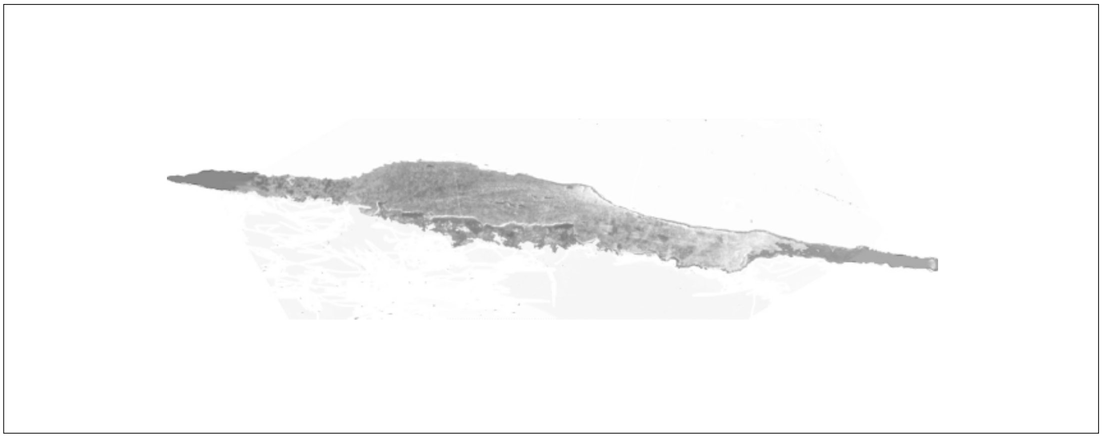


2. cross-section of Hyderabad 1.

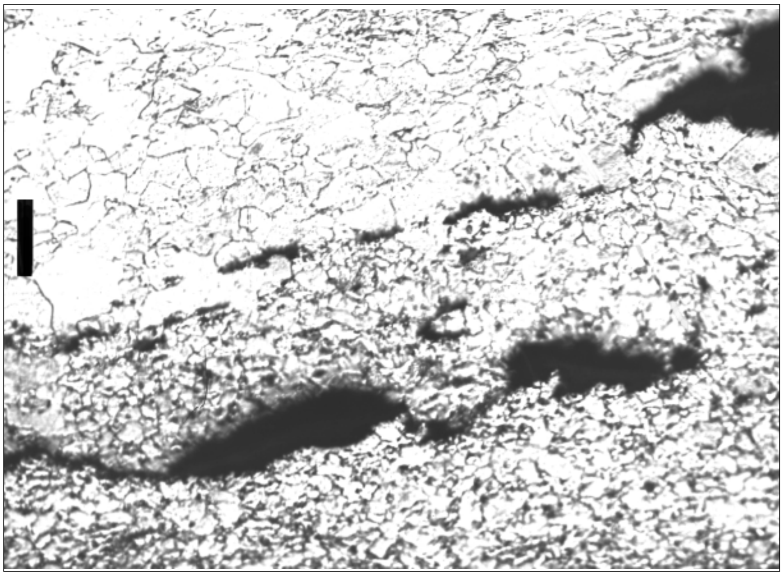


3. microstructure of Hyderabad 1. (scale bar is 50 microns)

4. HYDERABAD 2; a *khanjar*

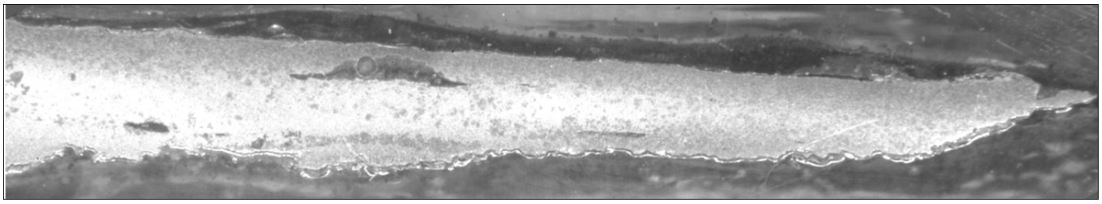


5. cross-section of Hyderabad 2.

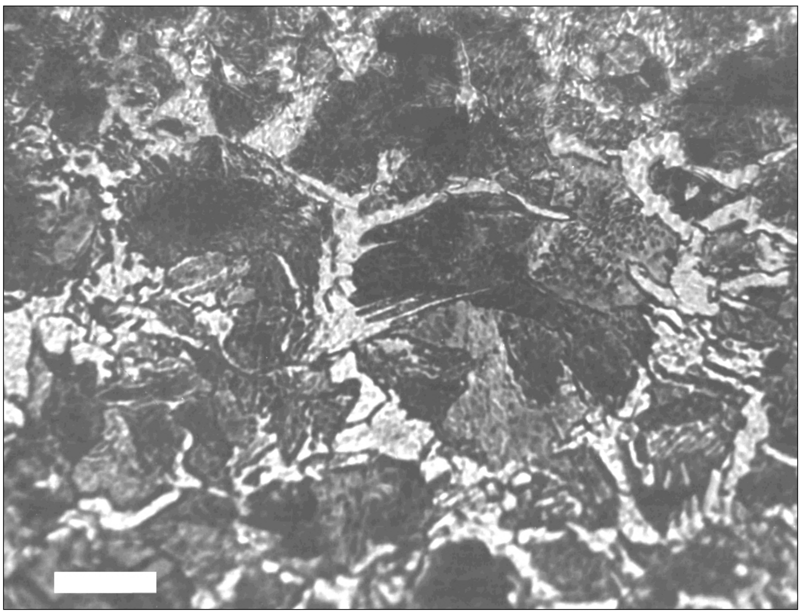


6. microstructure of Hyderabad 2. (scale bar is 100 microns)

7. HYDERABAD 3; a *tulwar*

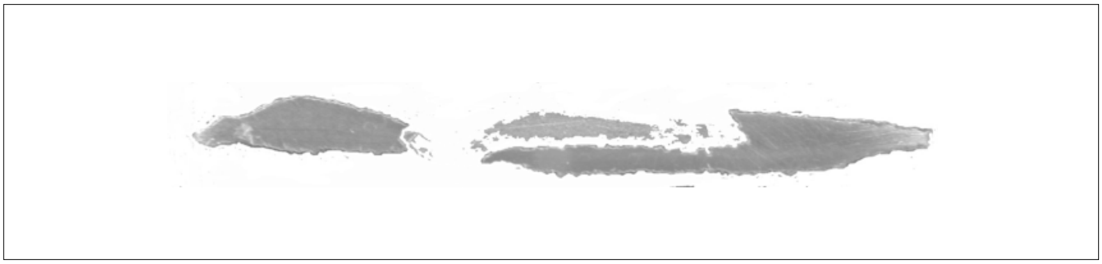


8. cross-section of Hyderabad 3; the darker areas are pearlite

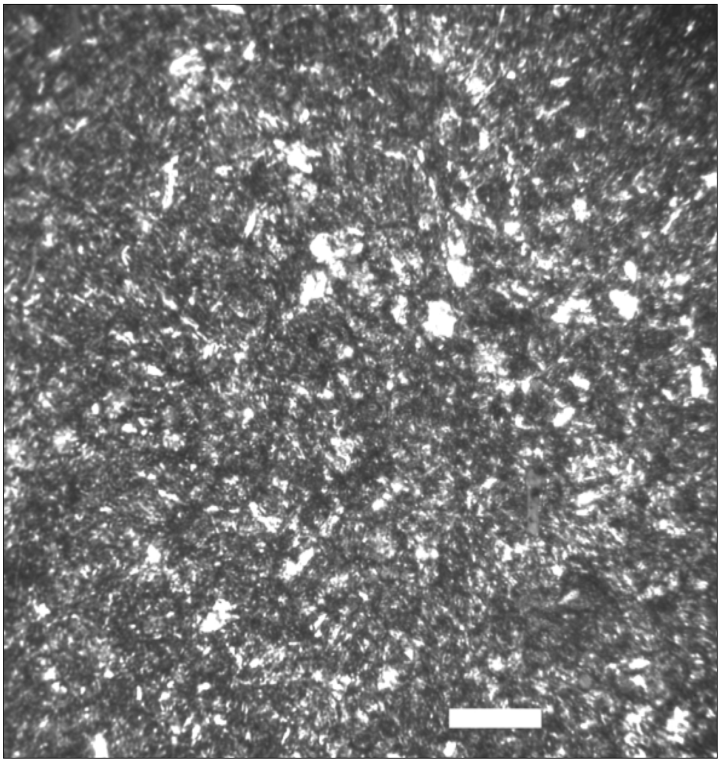


9. microstructure of Hyderabad 3. Pearlite and ferrite (scale bar is 50 microns).

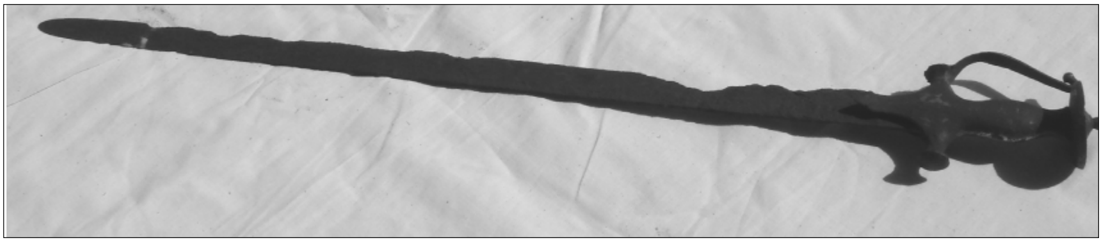
10. HYDERABAD 4; a *tulwar*



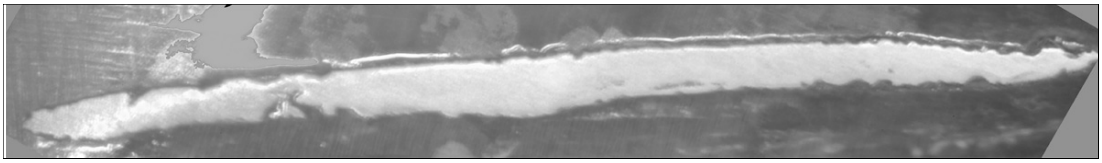
11. cross-section of Hyderabad 4; (isolated area is corrosion products)



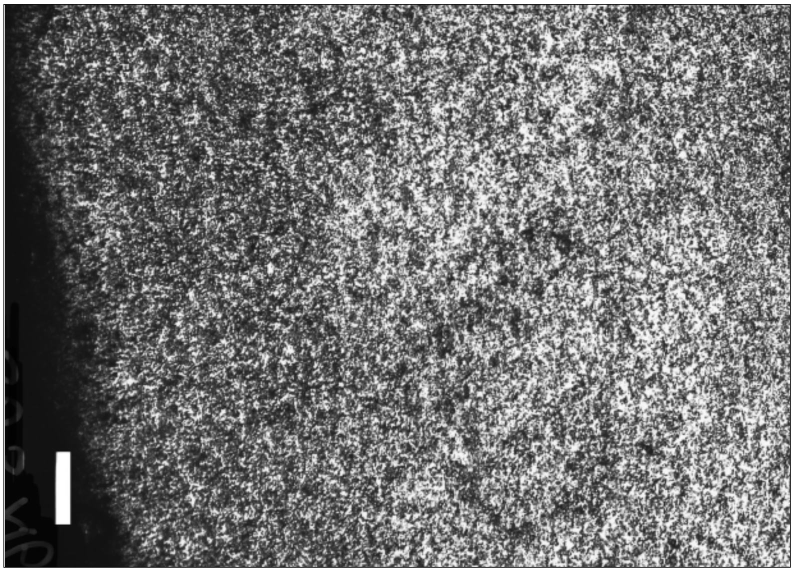
12. microstructure of Hyderabad 4. (scale bar is 10 microns).



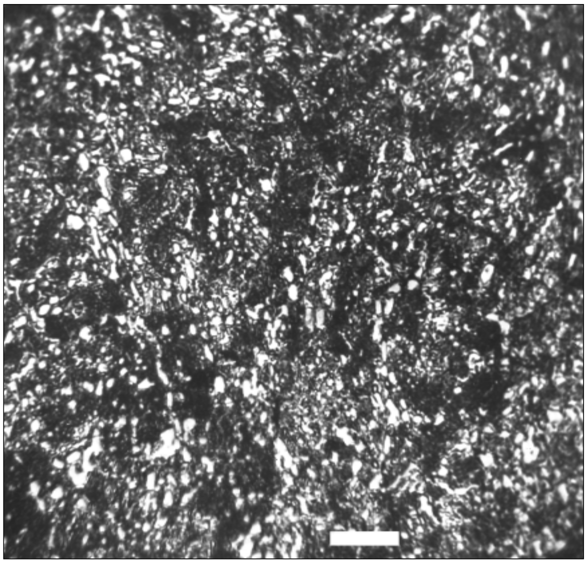
13. HYDERABAD 5; a *tulwar*



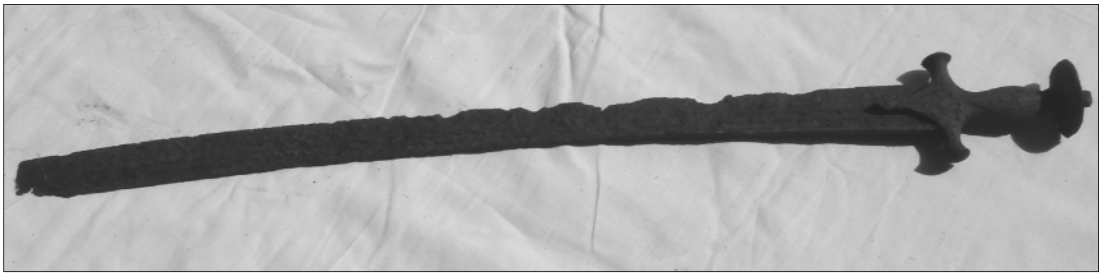
14. cross-section of Hyderabad 5 (note uniformity)



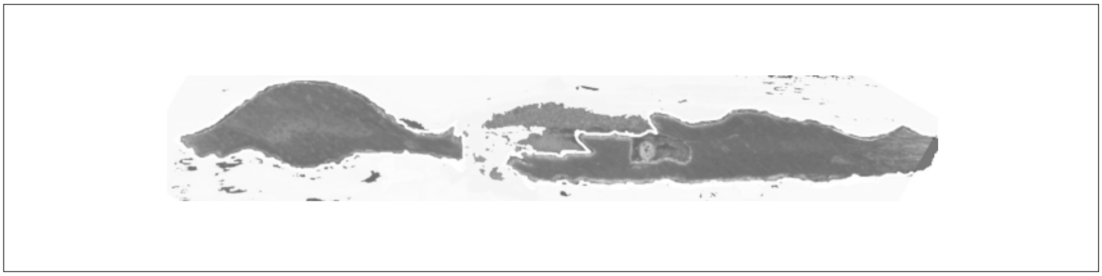
15. microstructure of Hyderabad 5 . (scale bar is 50 microns)



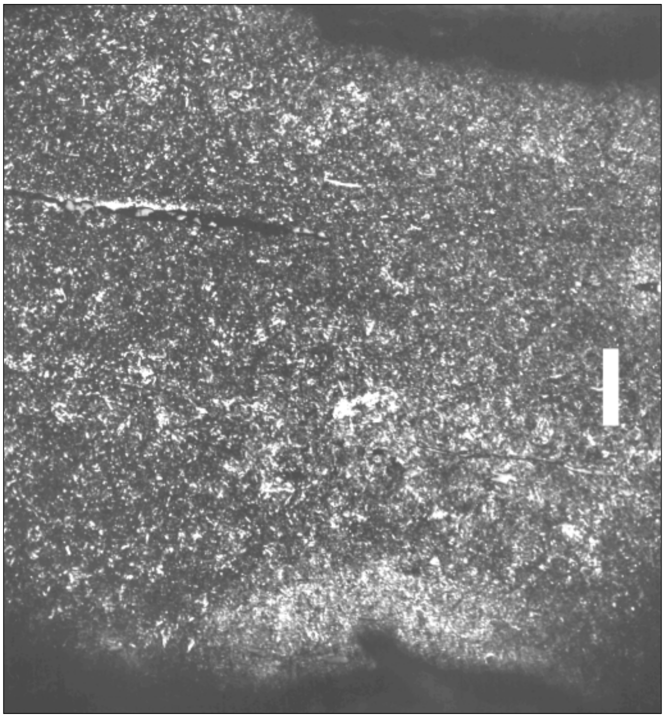
16. microstructure of Hyderabad 5 . cementite and pearlite (scale bar is 10 microns)



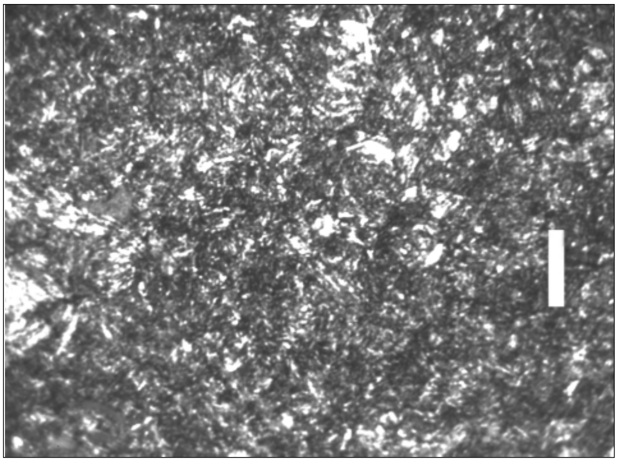
17. HYDERABAD 6; a *tulwar*



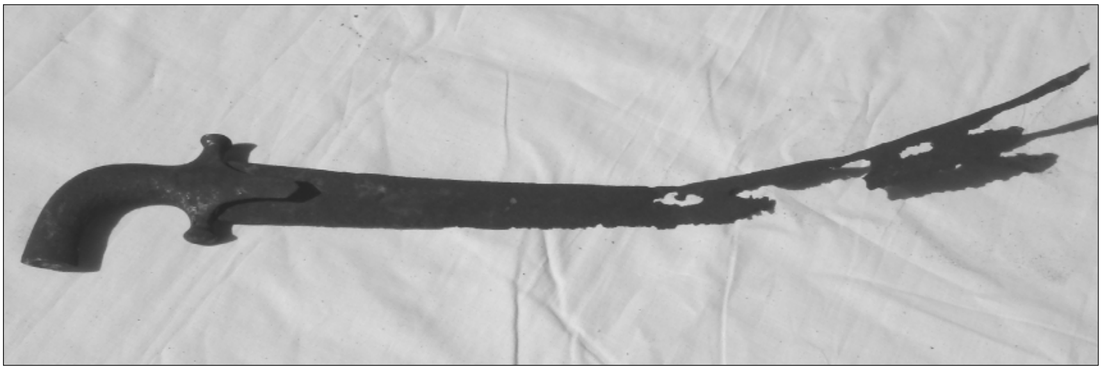
18. cross-section of Hyderabad 6 (note uniformity)



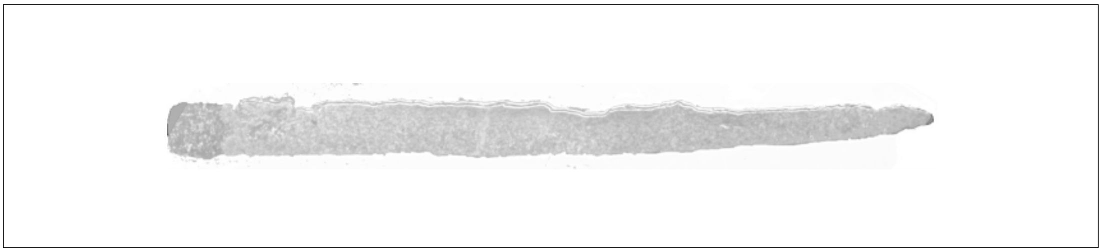
19. microstructure of Hyderabad 6 . (scale bar is 50 microns)



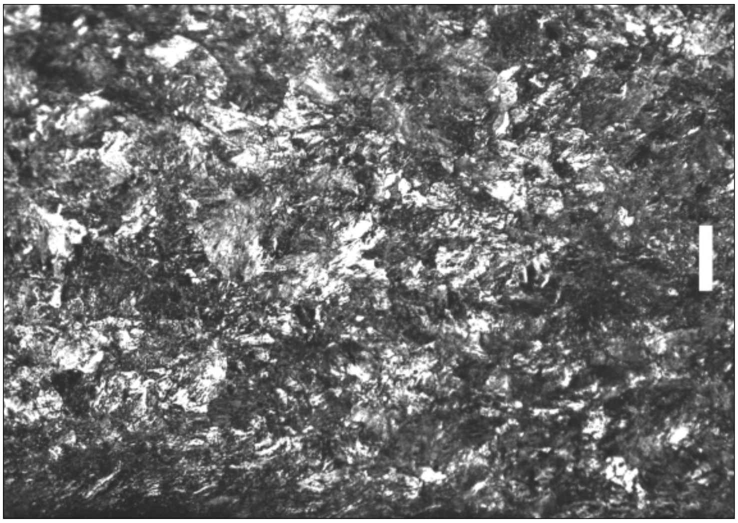
20. microstructure of Hyderabad 6 . (scale bar is 10 microns)



21. HYDERABAD 7; a blade of Persian style with a Turkish (?) hilt

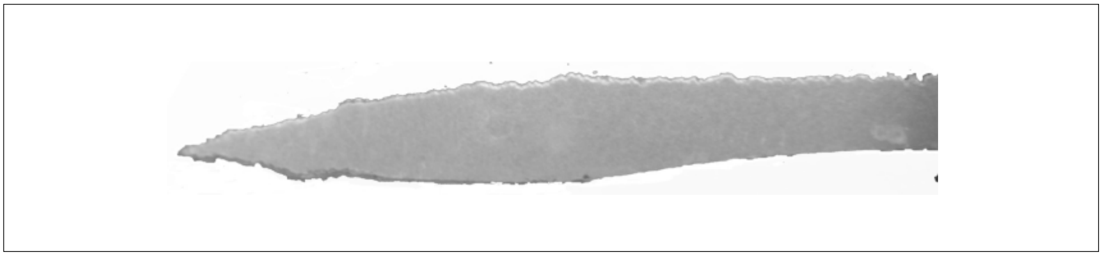


22. cross-section of Hyderabad 7

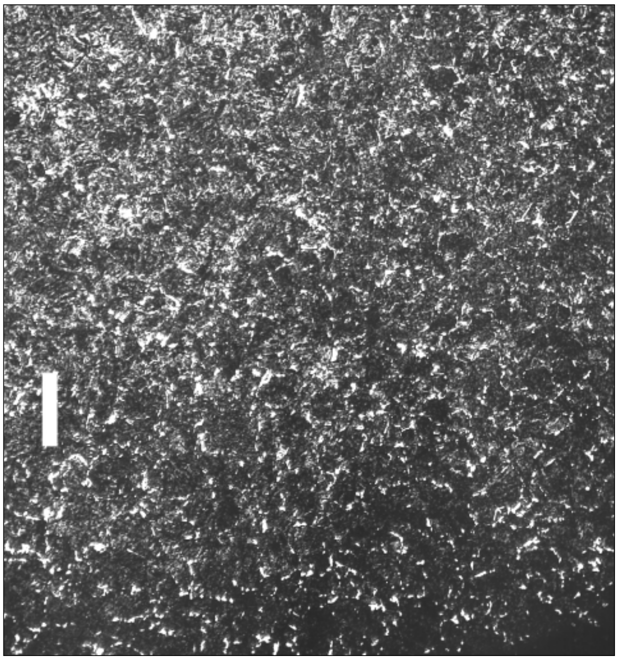


23. microstructure of Hyderabad 7;
very fine pearlite, irresolvable in places (scale bar is 50 microns)

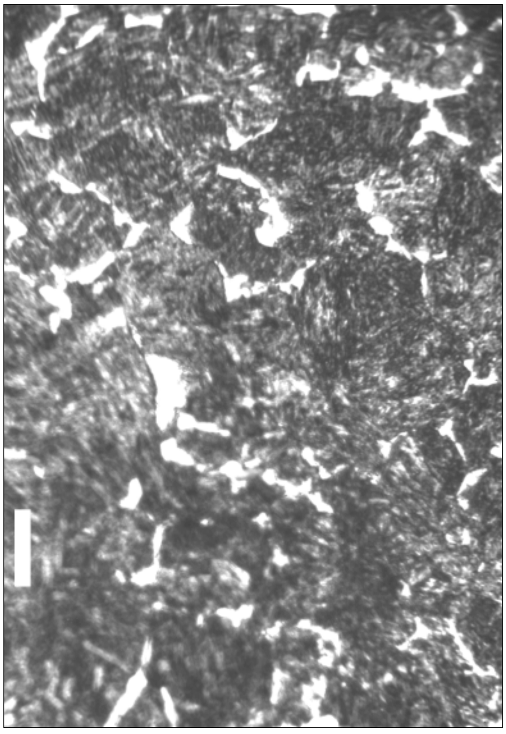
24. HYDERABAD 8; a *tulwar*



25. cross-section of Hyderabad 8

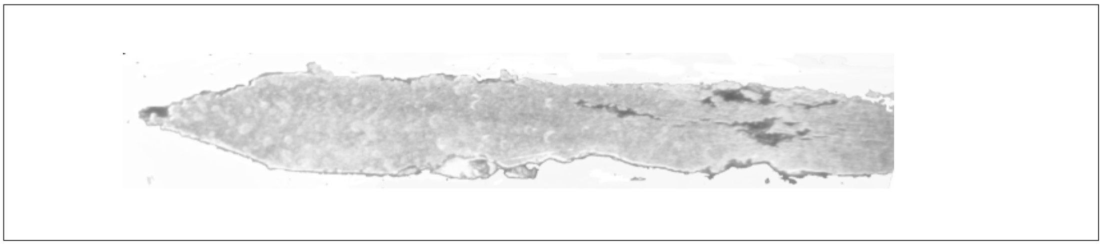


26. microstructure of Hyderabad 8 (scale bar is 50 microns)

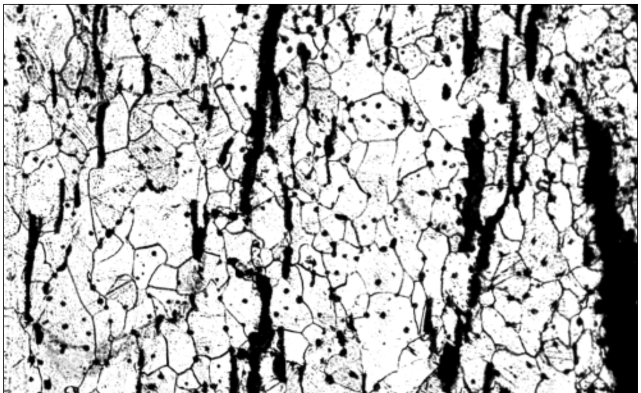


27. microstructure of Hyderabad 8; tempered martensite and ferrite
(scale bar is 10 microns)

28. HYDERABAD 9; a *tulwar*

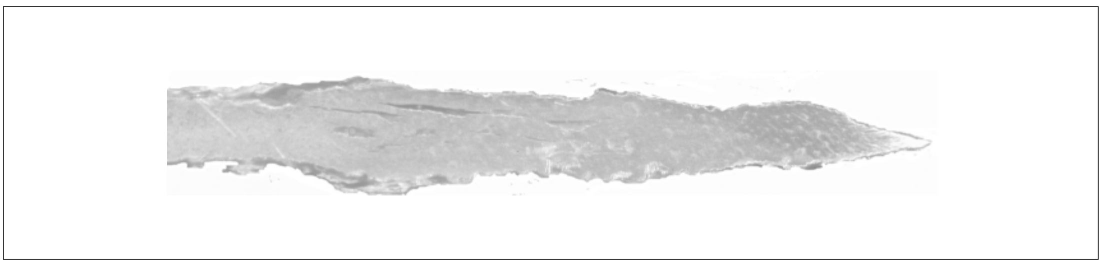


29. cross-section of Hyderabad 9 (edge)

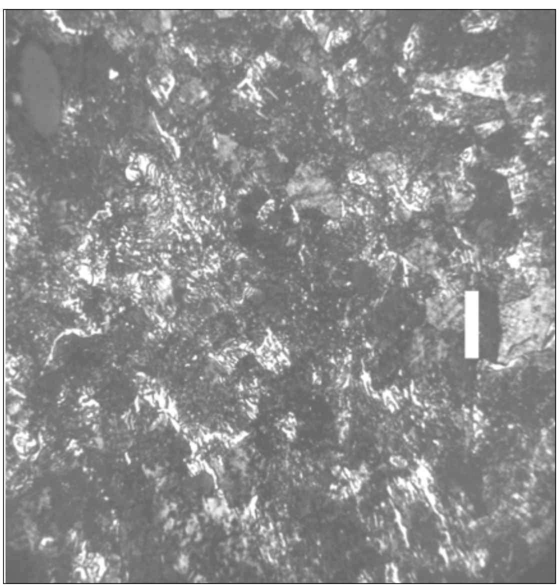


30. microstructure of Hyderabad 9; ferrite and slag (scale bar is 50 microns)

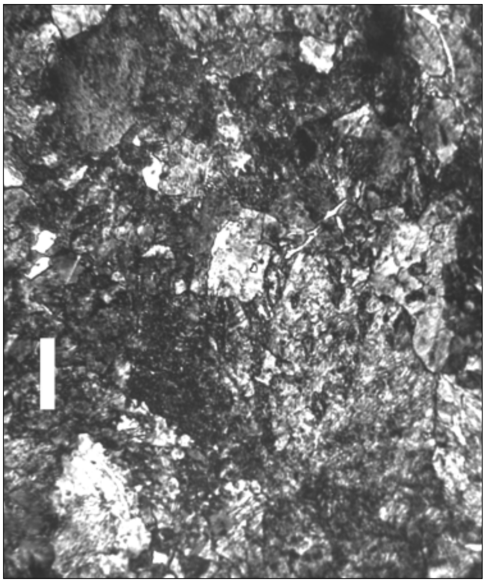
31. HYDERABAD 10; a *tulwar*



32. cross-section of Hyderabad 10 (edge)

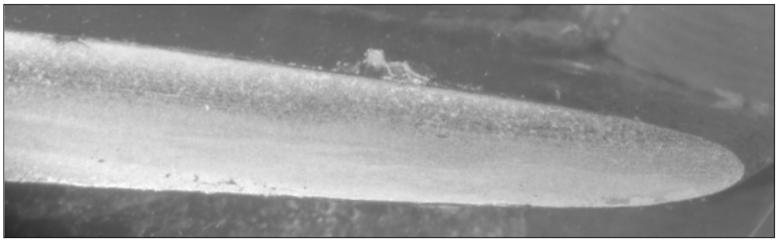


33. microstructure of Hyderabad 10 (scale bar is 50 microns).
Fine pearlite an cementite, with no visible slag.

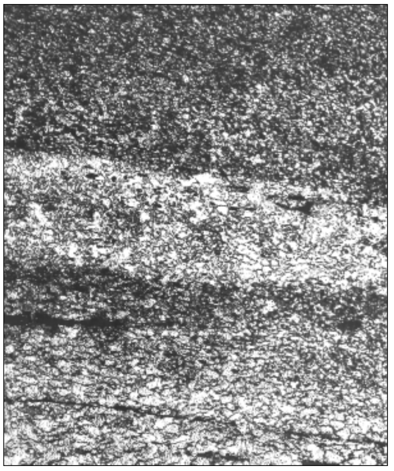


34. microstructure of Hyderabad 10 ; fine pearlite and isolated cementite grains (scale bar is 10 microns)

35. E.100. a 17^{th} /18^{th} century *khanda*; the blade has been removed from the hilt

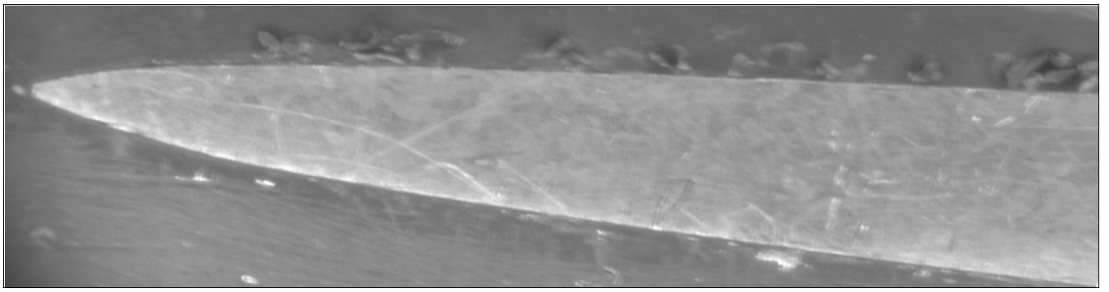


36. cross-section of E.100



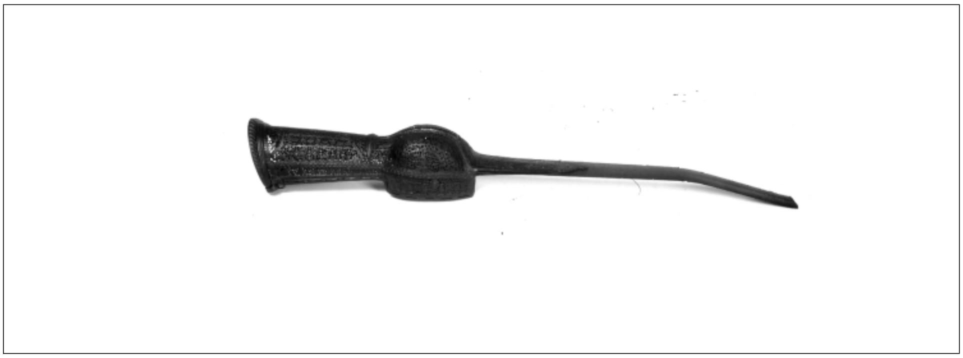
37. microstructure of E.100; ferrite and carbides after etching with Oberhoffer's reagent (scale bar is 100 microns)

38. E.101. a *firangi* blade bearing a 16th or 17th-century mark attributed to Genoa

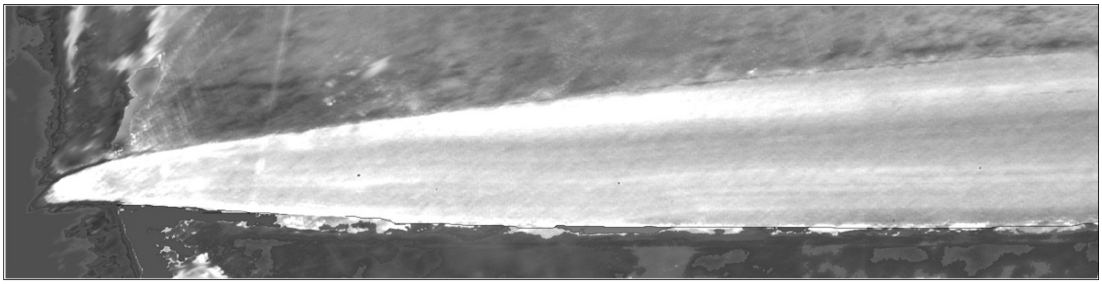


39. cross-section of E.101.

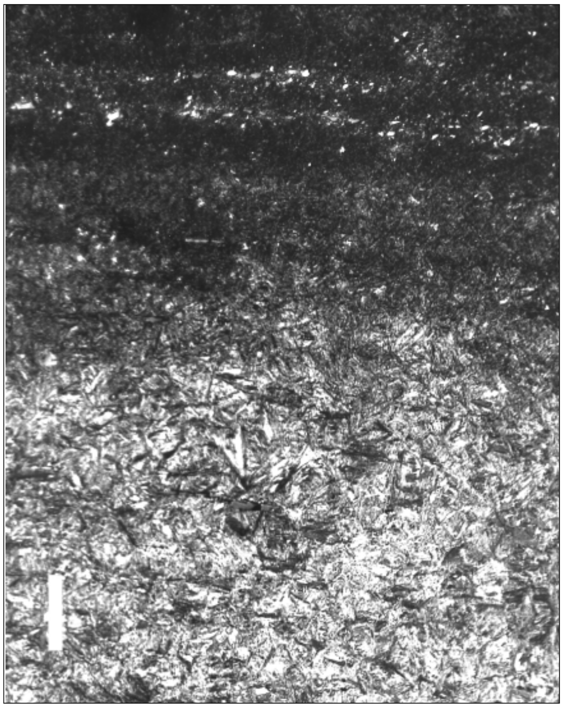
40. microstructure of E.101; very coarse ferrite and slag only (scale bar is 50 microns)



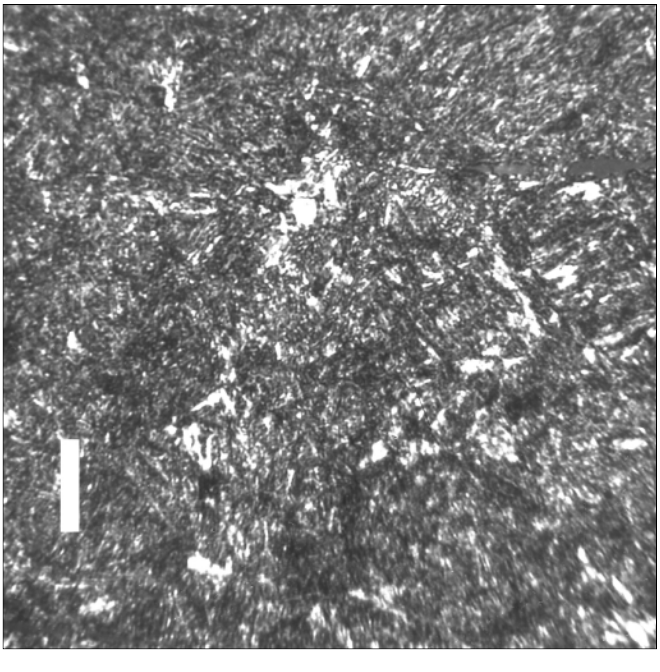
41. E.103. a 17th century *pata* with a black surface



42. cross-section of E.103. Note the differently-etching layer in the centre of the blade

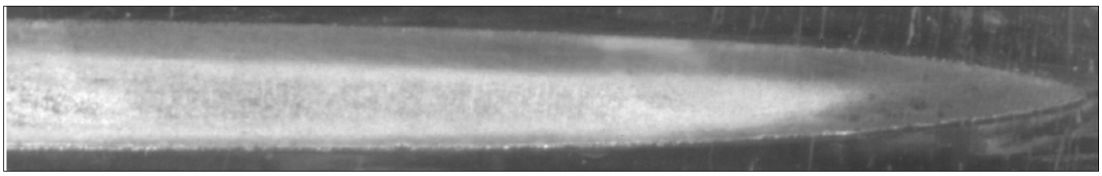


43. microstructure of E.103; martensitic layers (scale bar is 50 microns)

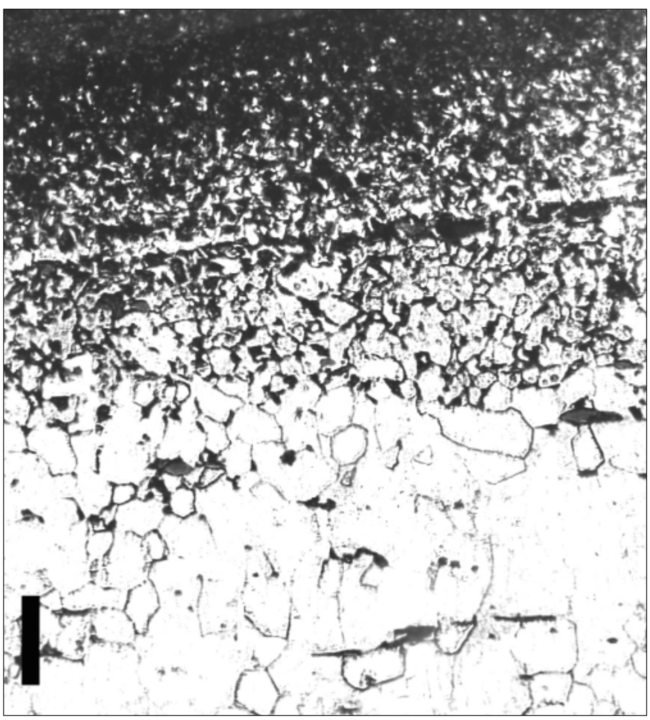


44. microstructure of E.103; martensite and slag inclusions (scale bar is 10 microns)

45. E.200. the tip of a *pata* blade (40cm long), probably of European origin

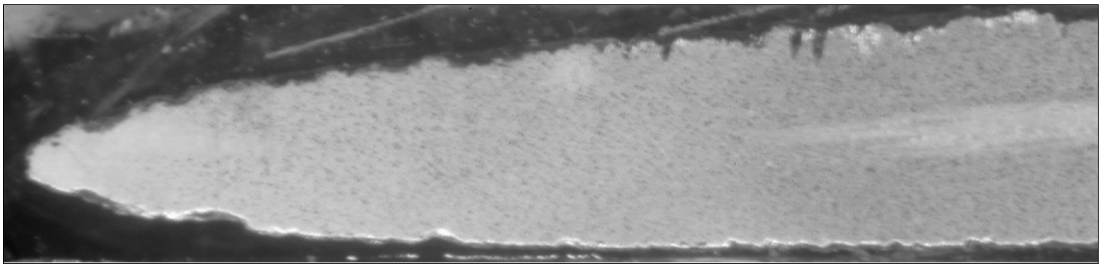


46. cross-section of E.200. Note the higher-carbon layer wrapped around the iron core

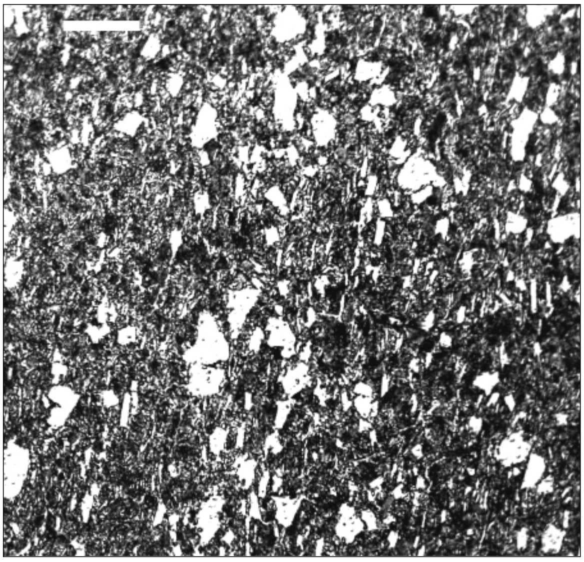


47. microstructure of E.200. Ferrite and carbides. Note line of slag inclusions.
(scale bar is 50 microns)

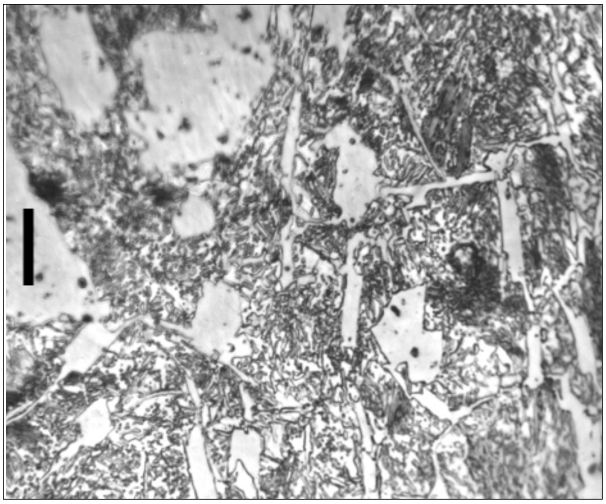
48. E.102. a *tulwar* with a (probably) Persian blade, with a Maratha hilt



49. cross-section of E.102. Note the fold line, but otherwise a very uniform section

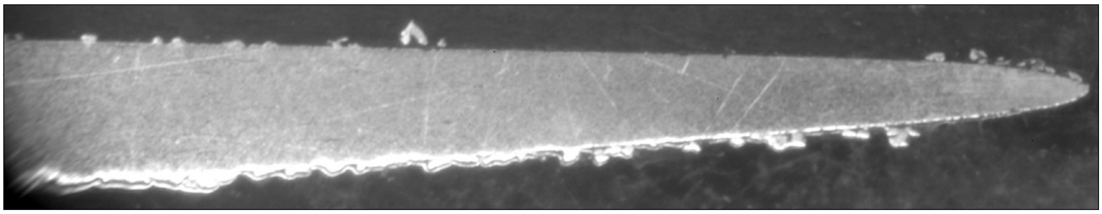


50. microstructure of E.102. Pearlite and cementite particles (scale bar is 50 microns)

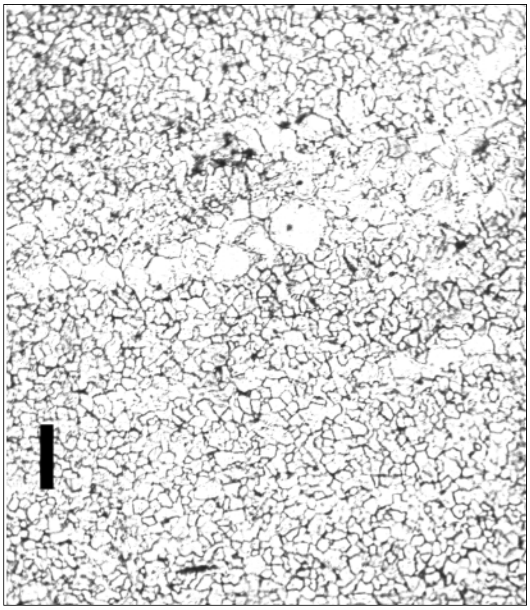


51. microstructure of E.102. Pearlite and massive cementite particles (scale bar is 10 microns)

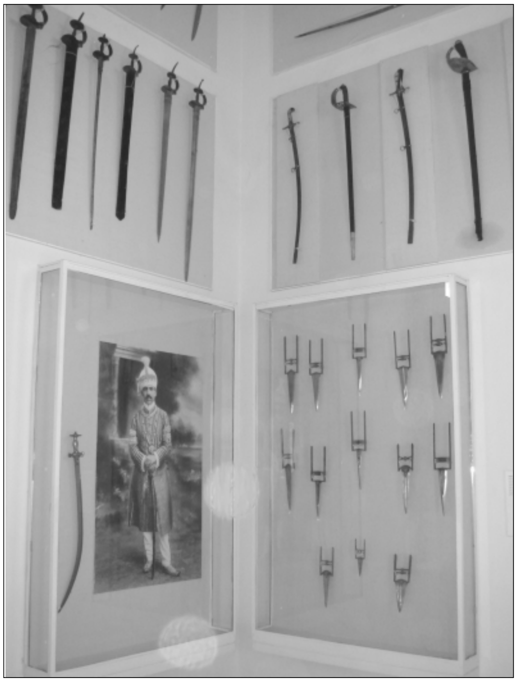
52. E.105. Hilt from a *tulwar* (though probably not original to the blade)



53. cross-section of E.105



54. microstructure of E.105. Ferrite and pearlite (scale bar is 50 microns)



55. The Hyderabad Arsenal

56. The Hyderabad Arsenal – general view

ACKNOWLEDGEMENTS

The authors are enormously grateful to Princess Shehkar Jah for making the scientific study of these blades possible.

Recibido: 26/06/2007
Aceptado: 12/09/2007