Allan R. Williams
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METHODS OF MANUFACTURE OF SWORDS IN MEDIEVAL EUROPE: ILLUSTRATED BY THE METALLOGRAPHY OF SOME EXAMPLES

BY
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DURING the Dark Ages in Europe, the manufacture of the swords known as «pattern-welded» flourished. This type first appeared in the third century and disappeared by the tenth century A. D. Their characteristic appearance has drawn attention to them and numerous papers have been published describing their manufacture. (1)

They were probably made by the twisting together of half-a-dozen thin strips of iron followed by folding and forging in various ways. This could produce a herring-bone or spiral pattern on the surface of the blade. From the fancied resemblance of this to the «watered-silk» pattern of Damascus steel, pattern-welded blades have often been incorrectly called «damask» or «damascene». In fact the techniques are entirely different. The true Damascus sword was forged by elongating a button or cake of cast high-carbon steel from India. (2)

The advantages of pattern-welding were twofold. First, since a homogeneous bar of controlled carbon content could not be produced (perhaps a consequence of very small hearths), the forging together of small pieces of carburised and uncarburised iron was one way of making a steel-like material of more or less controllable properties. Second, it produced a much sought after decorative effect.

Anstee, in making a sword-blade this way found that the twisting together and forge-welding of two or three strips of the *same* material (wrought iron) could still produce the characteristic herring-bone pattern, since slag trapped in the welds provided the difference in texture.

So many smiths may have been elaborately working pure iron to produce a desirable pattern, without ever realising that this was useless unless the iron had been carburised first. In the course of time, it was appreciated that the carburising treatments preliminary to the pattern-welding were of greater importance and pattern-welded swords began to disappear about the 10th century as it was realised that the same results could be obtained by simpler procedures.

Sword-blades of the 9th-11th centuries were frequently made by «piling» several pieces of iron and steel into a bar and forging them together, without twisting or other elaboration.

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Improvements in hardness could then be obtained by suitable heat-treatment, although the connection between carbon content and hardenability was imperfectly understood. Heterogeneous blades were hopefully quenched to produce hardness in useless places.

In his valuable discussion of forty-one swordblades of Rhenish origin dated from the 6th-12th centuries A. D. Anteins (3) gives analyses of some of thcm. Nine (6th-10th centuries) were made entirely from pattern-welded «steel». Six (9th-11th centuries) had only a thin pattern welded layer welded on to the surface of the blade for decorative purposes. The others, which included Ulfbehrt swords (9th-11th centuries) had «piled» or laminated structures.

One of the swords he analysed consisted of three bands whose carbon content varied from 0.1% to 0.8%. It has been heat-treated to produce what Anteins calls «an incompletely tempered structure», and the steely parts were raised to 250-330 VPH.

Piaskowski (4) has published an analytical study of six knives from Poland (11th-14th centuries) five of which had laminated bodies of alternating strips of low and higt-carbon iron and all with a high-carbon cutting edge. They were heat-treated to give a typical hardness of 400-600 VPH at the edge.

Amongst other microconstituents Piaskowski observed an acicular structure which was «the result of a heat-treatment not precisely identified», and for which he proposed the name «acicular troostite». More will be said about this later.

Surprisingly, compared with the swords of the Dark Ages, very little attention has been paid to sword blades of the High Middle Ages (13th-15th centuries). This paper will discuss eight blades of the 11th-15th centuries studied metallographically by the author.

Five of these were made from a *single* bar (rather than a piled or laminated structure) and case-carburised to give a steel cutting edge which could then be hardened by heat-treatment. The remainder were made by the welding together of several separate pieces of (in two cases) iron and steel or (in one case) steel alone.

The method of case-carburising followed by heat-treatment was known to the Ancient World (5) and even if it was neglected in the Dark Ages, it was understood by the tenth century Viking smith who edge-carburised and quenched an axe (6) and it is clearly described by Theophilus (ca. 1100 A. D.) (7). Such a method was also adopted by the makers of those three medieval swords which have been described elsewhere. (8)

The successful application of this process depends on the appreciation that effective carburisation must *precede* the heat-treatment. The same

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two operations in the reverse order will, of course, prove fruitless. (This might explain the resultant sword described in Panseri's paper).

The overall carbon content of an edge carburised blade may well have been lower than that of one made by piling together several small pieces carburised individually. But, on the other hand, a blade made from a single bar might well be stronger (depending on the skill of the laminating), would certainly be cheaper (Anstee and Biek took forty-three hours to forge a pattern-welded blade) and would probably lend itself more conveniently to heat-treatment. All but one of the swords discussed here had been hardened by some form of heat-treatment. The exception had an exceptionally high carbon content.

The methods of heat-treatment employed in the Middle Ages included:

(i) *Full quenching* (to form an all-martensite structure). If the overall carbon content was low, a full quench without tempering might be employed.

(ii) *Slack-quenching* (not quenching fast enought to produce an all-martensite structure, but a mixture of martensite, and other products; bainite and/or pearlite). The sword could be plunged into oil, boiling water or some other quenching medium less drastic than cold water. The hardness would be less than that of an all-martensite structure, but its brittleness would also be less. Tempering would not be necessary, unless the carbon content was high. An interrupted quench (i. e. plunging into water for a few seconds, withdrawing and then quenching again) might well produce a similar mixture of transformation products.

(iii) *Slack-quenching and tempering.* Reheating a slack-quenched steel would yield a mixture of products, some of which would be difficult to resolve, and many of which would have become aggregates of carbide particles whose origins could not be diagnosed. It is possible that some such process was responsible for forming Piaskowski's «acicular troostite» and Anteins' «incompletely tempered structure». This process was probably employed to harden some of the swords discussed in this paper, but it cannot now be determined by optical metallography.

(iv) *Time-quenching.* A now obsolete process whereby a blade would be plunged into the cooling liquid and then withdrawn after a fixed number of seconds. The transformation structure first formed would be tempered by residual heat. The products would be a mixture of tempered martensite and bainite in bands. (9)

Five of the blades described in this paper were probably hardened by methods (ii) or (iii). Two were probably hardened by method (iv). A Solingen sword described elsewhere (8) was hardened by method (i).

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Methods (i), (iii) and (iv) do not correspond to any modern industrial process, although a form of slack-quenching has been advocated on grounds of cost. (10) The preferred modern method of heat-treatment is a full quench (to produce an all martensite structure) followed by reheating to temper it. This is a difficult operation to control in the absence of any means of measuring temperature or time. The two-stage process of a full-quench followed by a tempering was evidently not used for any of the sword blades discussed in this paper (at least, no microstructure which can be identified solely as tempered martensite was found) but it apparently did come into use in the sixteenth century. This two-stage process was also then applied to the hardening of steel armour. This is the subject of my present research, and I hope to discuss these developments in a future article.

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SWORDS EXAMINED

	Date (cent.)	Museum	Inv. no.	Steel	Method of heat-treatment
1	10th-11th	Stuttgart	—	piled	air-cooled
2	1150-1200	Leiden	Ea92	welded-on	(ii)
3	?13th	Zurich	IN7006	case-carburised	(iii)
4	before 1308	Zurich	LM6369	case-carburised	(iii)
5	early 14th	Geneva	162c	case-carburised	(ii) or (iii)
6	early 14th	Köln	W249	case-carburised	(ii) or (iii)
7	?14th	Frankfurt	X6522	case-carburised	(ii)
8	early 15th	Geneva	163c	welded-on	(iv)

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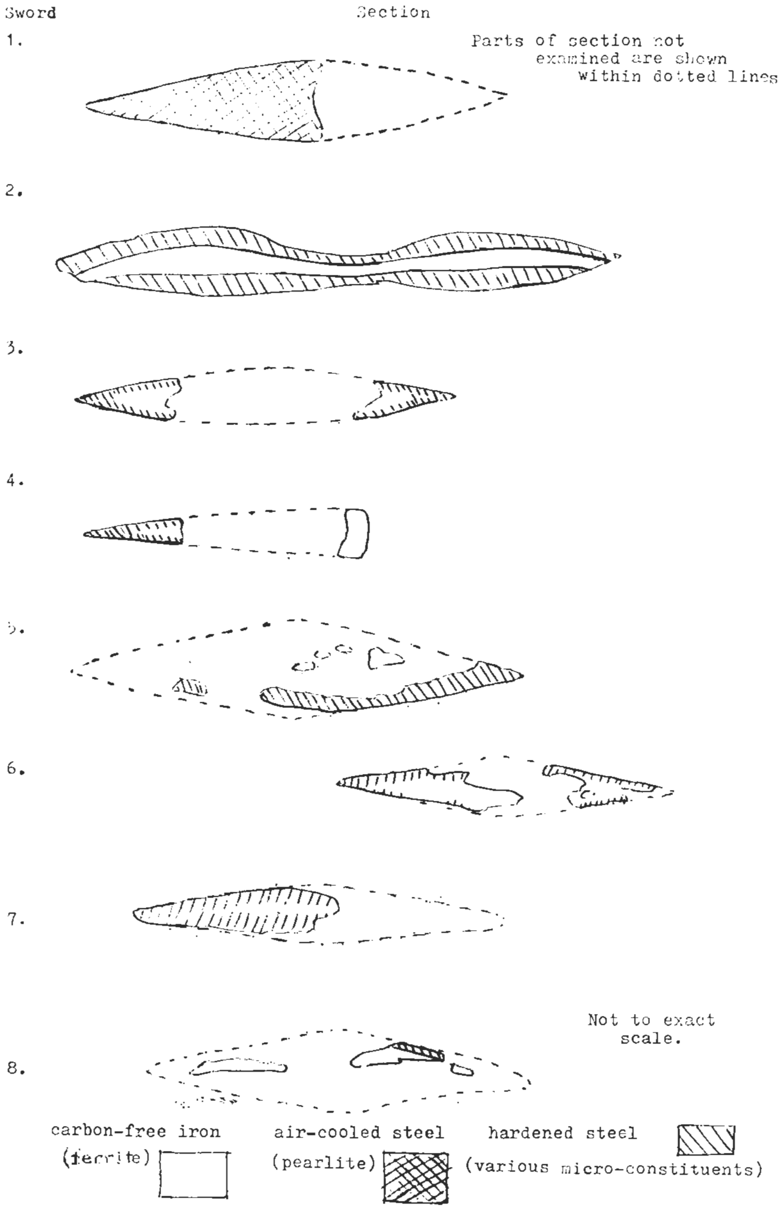

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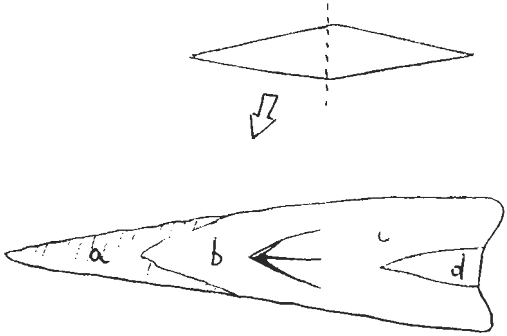
SWORD No. 1

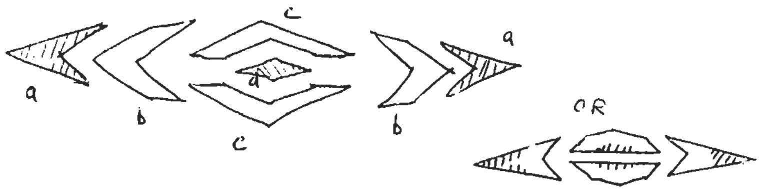
(Württemberg Landesmuseum, Stuttgart)

Sword with the inlaid name VLFBER(CH)T,
10th century? or 11th perhaps from Rhineland

This sword was examined on an already broken section. Half of this cross-section was capable of being polished for photomicrography. It



Possible construction



will be assumed that the other half is the same since the sword is two-edged, and therefore probably symmetrical about a longitudinal axis.

The half-section shows four distinct layers which produce different colours on etching and show slag inclusions at their junction. Commencing from the edge (and working towards the centre) there is layer A (a brown-etching material) whose microstructure contains mostly pearlite with needles of cementite within, and a network of cementite around, the pearlitic areas.

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This gives way abruptly to layer B (which etches dark blue-grey) whose microstructure also contains very fine pearlite and cementite.

This gives way to layer C (which is brown-etching) and there is a white band along the frontier of layer B and C. This band also extends some

Ulfbercht sword

Section through one edge.

X 70

way towards the centre of the blade along the median axis. Slag inclusions, of irregular shape, are near to this band but do not coincide exactly with it. It may be the remains of a layer of flux used in welding the layers together. Layer C consists mostly of pearlite. Layer C gives way abruptly to layer D which is mottled in appearance, and consists of pearlite areas with a network of ferrite surrounding them.

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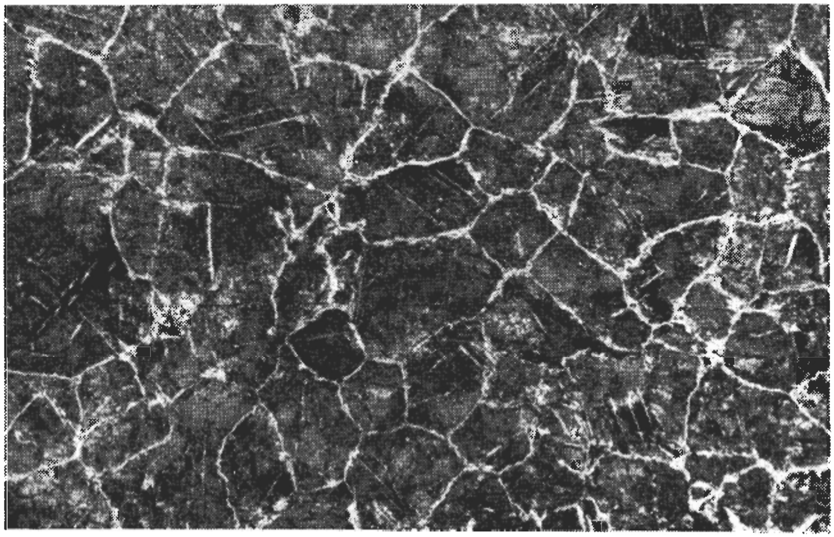
This blade has been made by forging several small pieces of steel together. The different appearance of layers A and B compared with C and D may be due to their having been welded from four separate pieces, or it may be due to differing carbon contents. Since there are no visible

Ulfbercht sword (Württemberg L. M.)



X 320 71.12

Very fine pearlite and cementite from area b.

welds along the frontiers of A with B and C with D, it is not possible to be dogmatic.

So at least four elements have gone into the welding of the blade, i. e. two on each side although these in turn may have been made from several smaller pieces, i. e. four on each side.

The carbon content varies from about 0.7% in the centre to about 1.0% near the edge. The blade has evidently been air-cooled after fabrication, and no ateempt has been made to harden it by heat-treatment. Indeed, in view of the high C%, such treatment would have been very difficult.

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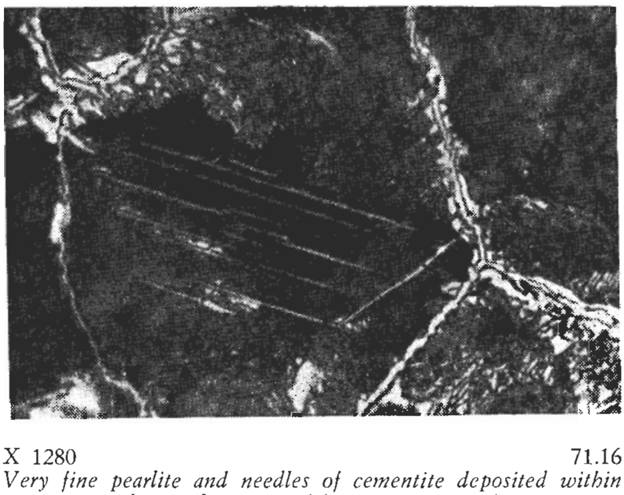
X 320 71.17
At the weld. Note slag inclusion, and light streak perhaps left by flux from welding.

Ulfbercht sword



X 1280 71.16
Very fine pearlite and needles of cementite deposited within the pearlite areas. (Area c on section.)

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SWORD No. 2

(Sword Ea 92. Leiden Wapenmuseum)

Probably made 1150-1200; blade is inscribed
BENEDT DNS DSM

This blade was already broken, so that it was possible to remove a sample from the entire cross-section of the blade. The section was found

Ea 92 X 4

The two outer (dark-etching) layers are of hardened steel. The central layer is of carbon-free iron.

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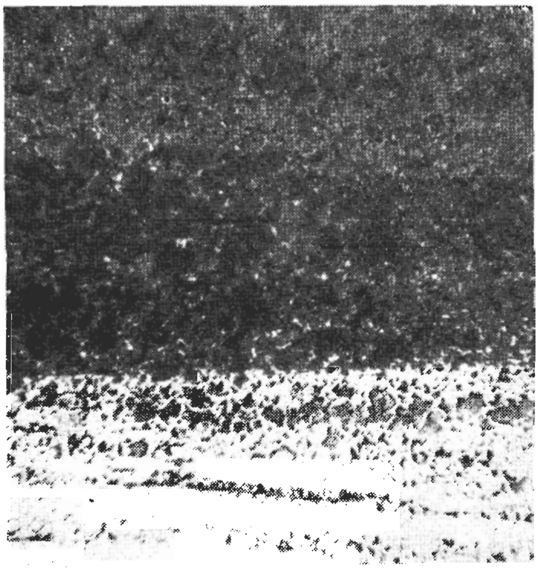
to show three distinct layers. The central layer consists mostly of ferrite with a large corrosion crack running down the middle. The two outer layers (and these are shaped so that they also form the cutting edges) consist principally of a dark-etching material whose boundary with the ferritic centre is sharply defined.

There are also numerous slag inclusions which are largely to be found at these boundaries.

This sword has evidently been made by welding together a bar of almost carbon-free iron and two bars of medium-carbon steel, and then,



Ea 92 X 64

The centre is nearly all ferrite.

after shaping, heat-treating the result to harden it. Neither the carbon content nor the method of heat-treatment can now be deduced with any certainty.

The microstructure of the outer layers consists principally of a dark-etching irresolvable material which is probably bainite. This is associated with proeutectoid ferrite, some of which is in a spiny form. There is also some martensite visible.

The sword has been slack-quenched, perhaps cooled in oil or some other mild quenchant. There has been time for ferrite to form at the

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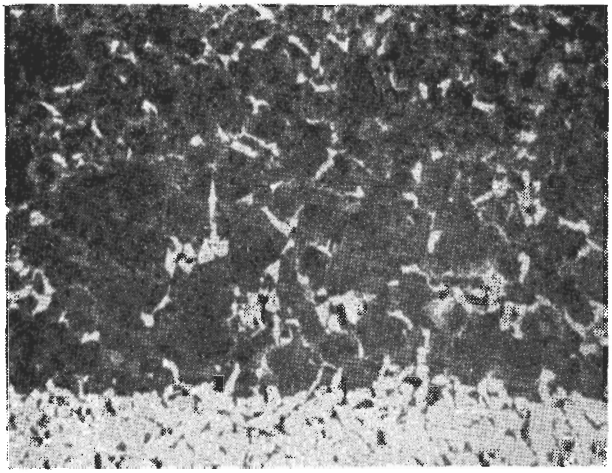
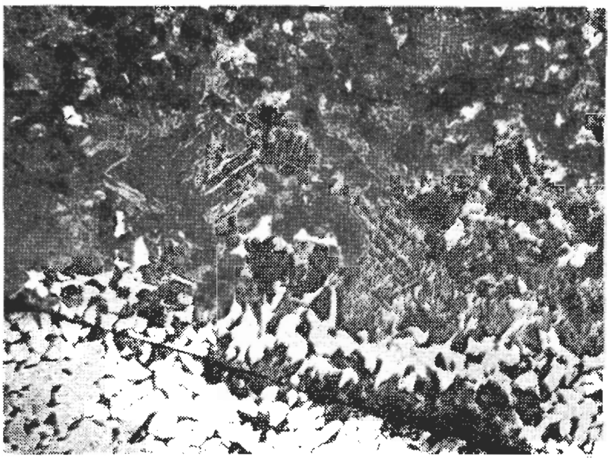


Ea 92 X 192
The border between the high-carbon and low-carbon areas is very sharp.



Ea 92 X 240
The hardened zone contains martensite, a dark-etching material, and (near the centre) spiny ferrite. Note the long slag inclusion.

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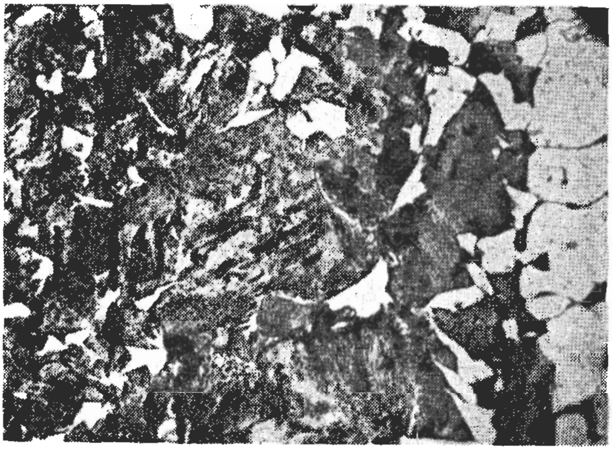
austenite grain boundaries before the austenite has started to transform, initially into bainite (or perhaps very fine pearlite) and subsequently the remainder into martensite.

Average Hardness = (centre) 200 VPH (30 g. load) (hardened zone) 650 VPH.



Ea 92 X 160

Martensite, dark-etching material (probably bainite) and spiny ferrite.

SWORD No. 3

(Swiss National Museum, Zürich IN. 7006)

Sword Blade, perhaps of 13th century

This sword was examined on a section already broken. It was heavily corroded, but areas around both cutting edges were intact (see sketch).

The microstructures of both these areas contain ferrite near the centre which gives way *gradually* to hardened zones. These contain an irresolvable constituent as well as areas of a granular material which preserves an acicular outline.

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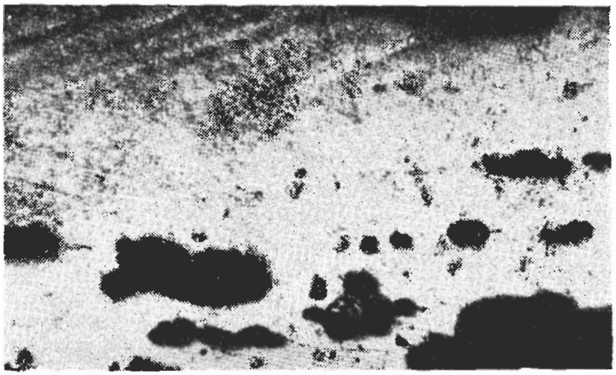
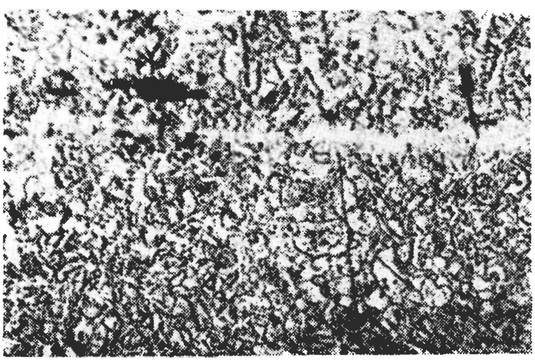
This sword has evidently been made by carburising its edges after fabrication from wrought iron, and then heat-treated to harden it.

The precise nature of this heat-treatment cannot now be determined,



IN. 7006 X 100 64.17

Surface of blade is at top of photograph. Note gradual carburisation.



IN. 7006 X 400 64.21

since the carbon content is unknown. But the acicularity suggests that the steel was originally quenched from above the uper critical temperature but cooled only at a rate fast enough to produce mostly bainite rather than martensite.

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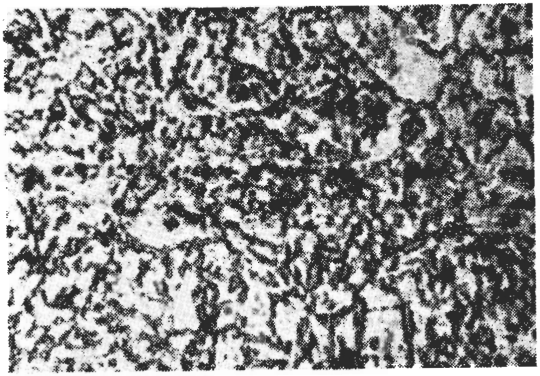
The irresolvable areas may be of a different carbon content which has led to a different transformation product being formed.

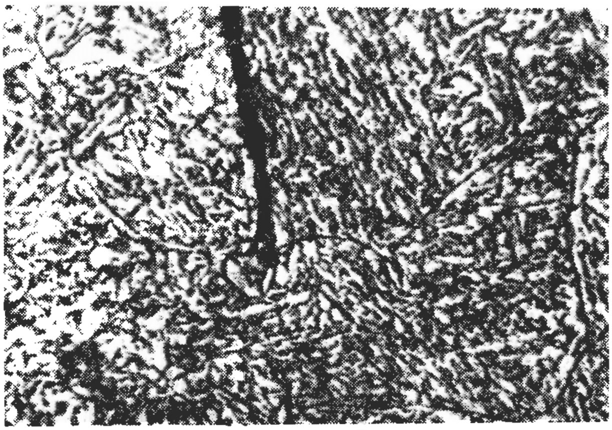
The blade has then been reheated to temper it, and the bainite (?) has



IN. 7006 X 1600 63.37

A network of carbide particles.

formed fine carbide granules. These occur in some places as a network, and in others as an acicular aggregate.



IN. 7006 X 1600 64.16

A tempered structure which shows the original acicular structure outlined by the austenite grain boundaries. Note slag inclusion.

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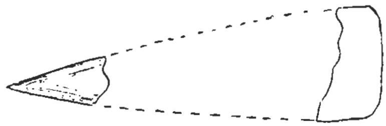
SWORD No. 4

(Zürich)

Fragment of a single-edged dagger excavated from Schnabelburg (destroyed 1308); LM. 6369; studied by examining its section where it had been broken.

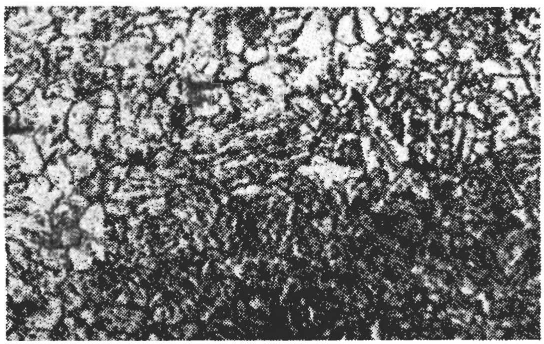
Because of the irregular corrosion that this blade had undergone only isolated parts of the section yielded metallic surfaces for examination.



However, the two areas visible were at the sharp edge and the back of the blade (see sketch) so that the nature of the corroded parts can be deduced.

The sharp edge

At low magnification, two zones can be distinguished. That next to the surfaces of the blade consists of dark-etching material with a fine mi-



Both LM. 6369 X 400
63.15,18

Reheated bainite (or martensite).

crostructure. The inner portion of the blade is white-etching ferrite. At higher magnification, the hardened zone may be seen to contain a

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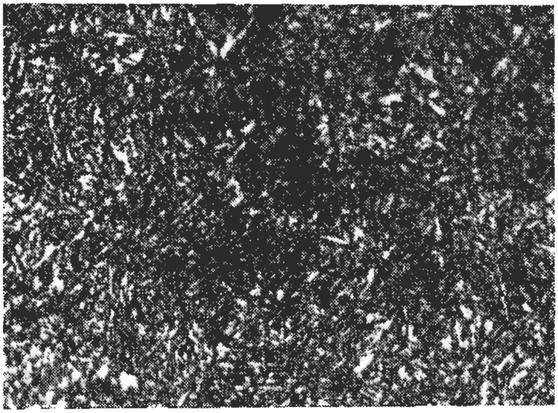
granular structure which is probably tempered martensite, and an irresolvable material which is probably bainite. Very little ferrite is visible in this zone, but it becomes more plentiful as the centre is approached.



Reheated martensite (?). The carbide particles outline the orignal structure vaguely.

There are a number of slag inclusions but they do not correspond to the borders of the hardened zone.

The back

The surviving part of the back of the blade consists entirely of ferrite.

Conclusions

This blade has been fabricated in (carbon-free) wrought iron, and the cutting edge case-carburised to form a steel edge. Either the back was not packed in the carbonaceous material, or else it was subsequently decarburised. The former seems more probable.

The edge was not welded on, for the change in carbon content is *not abrupt,* nor is there a line of slag inclusions corresponding to a weld. The blade was then hardened by heat-treatment.

It was probably fully-quenched (i. e. cooled rapidly from above the Upper Critical Temperature) since no proeutectoid ferrite seems to have separated, and formed a mixture of martensite, and other products such

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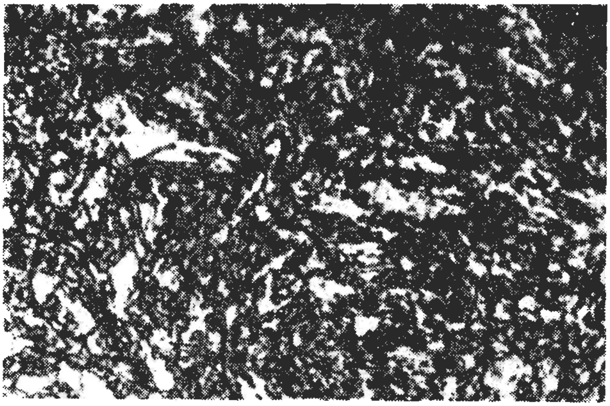
as bainite, depending on the local carbon content. It was then probably reheated to temper it, but the precise nature of the operations performed cannot be deduced with certainty.

Hardness *approx.* 320 VPH.



LM. 6369 X 1600 63.21

Carbide particles probably formed by heating bainite or martensite.

SWORD No. 5

(Musée d'Art et d'Histoire, Geneva. 162c)

Sword Blade of the early fourteen century

This broken blade was examined on the section already visible. This surface was very corroded, but areas of unattached metal were still visible (see sketch). Those areas nearer the centre of the blade were found to have microstructures consisting entirely of ferrite. Those near the surface had a dark-etching, fine structure. This appears, at high magnifications, to consist of numerous irregular granules. This might be tempered martensite or bainite or nodular pearlite.

This sword has probably been made by case-carburising a wrought iron blade, and then heat treated to harden it. This heat-treatment may

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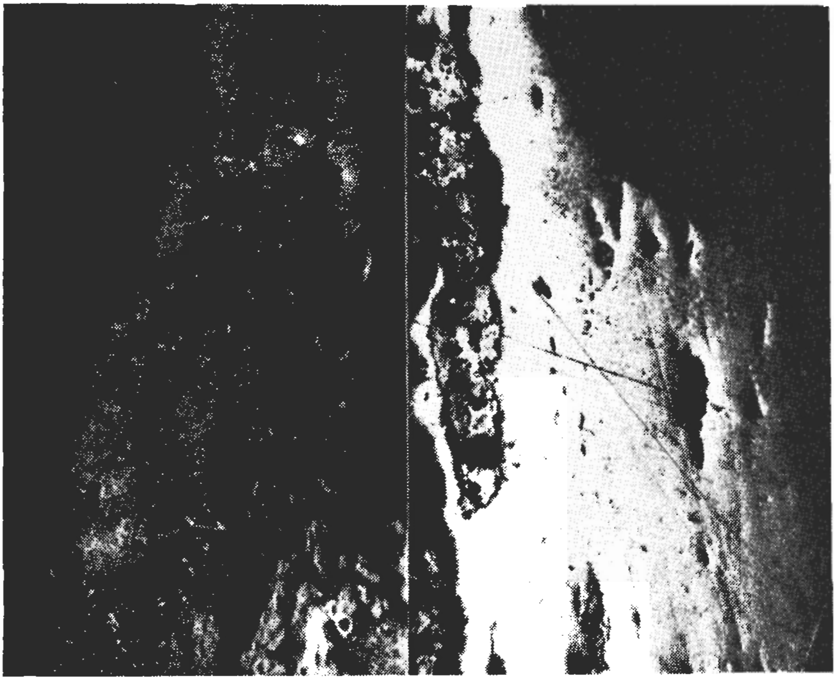
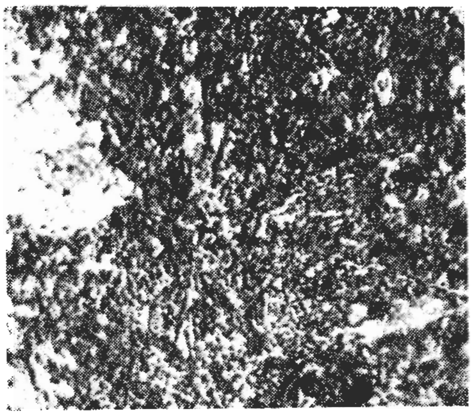


Sword 162c (Geneva) X 70 51.1,1a

Uncorroded iron (light) and steel (dark) in the centre.



Sword 162c X 1280 54.36

A granular structure is visible.

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well have been a slack quench i. e. a cooling from the upper critical temperature insufficiently fast to give an all-martensite structure but fast enough to yield a mixture of martensite, bainite, and perhaps pearlite. It has probably then been reheated.

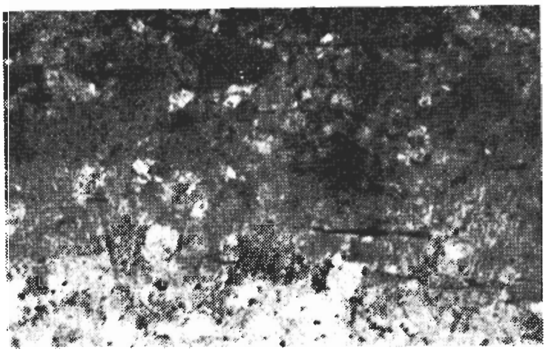
Average hardness approximately = 600 VPH.

SWORD No. 6

(City Museum, Köln)

Dagger W. 249. Early 14th century

This fragment was examined on an already broken section. Corrosion has left only part of the cross-section intact, but enough metal remains to show the overall structure. The central parts have a microstructure



W. 249 X 240 79.61

In this case, the hardened zone is at the top of the photo. Note the large number of slag inclusions.

consisting mainly of ferrite, which gives way gradually to hardened areas near the surfaces. There is a *distinct gradient* in the transition from the core to the hardened outer zones. The microstructure of the latter contains spiny ferrite, bainite and martensite.

This dagger has been case-carburised after fabrication and then hardened by rapidly cooling from above the upper critical temperature.

The higher-carbon areas have been transformed by the quench into martensite. The areas of lower carbon content have transformed to bai-

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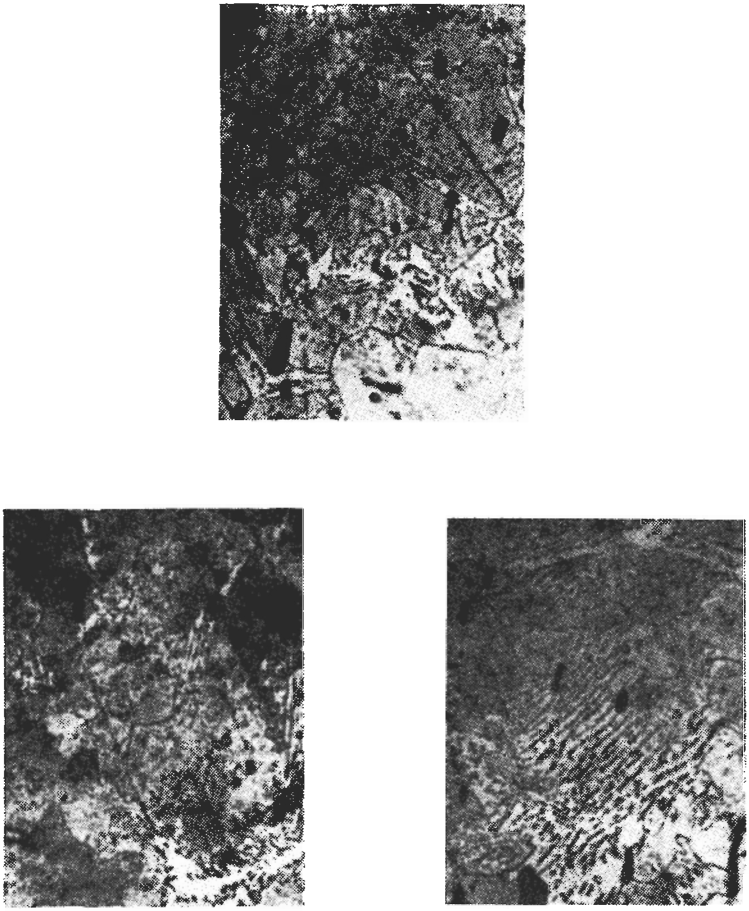
nite, and other products. It may then have been rehea ted, but it is not now possible to say definitely.



All Dagger W. 249 X 960 79.41,49,57

From a lower-carbon area: spiny ferrite and an irresolvable material that might be bainite.

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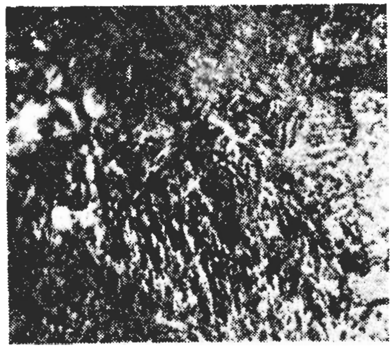
Hardness varies (from centre out to edge) from about 250 to 660 VPH.

Average (hardened zone) = 470 VPH.



79.37

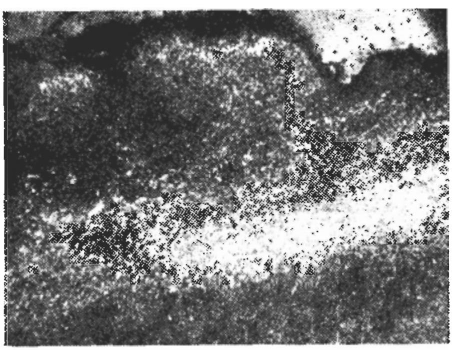
From a higher-carbon area; a granular material that might be tempered bainite. Note the smaller number of slag inclusions.

SWORD No. 7

(Historical Museum, Frankfurt)

Sword X6522/ON29 of perhaps 14th century

This sword was examined on an already broken section. It proved possible to detach half the section (from the centre to one edge) for exam-



Frankfurt sword X6522

X 60 74.20

The light band in the centre of the section consists of grains of ferrite.

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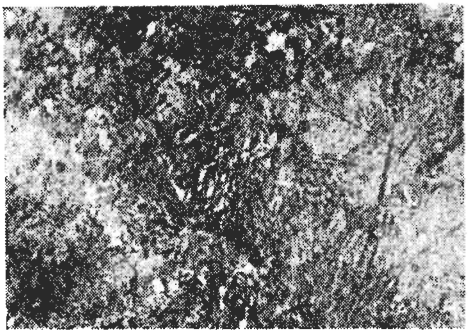
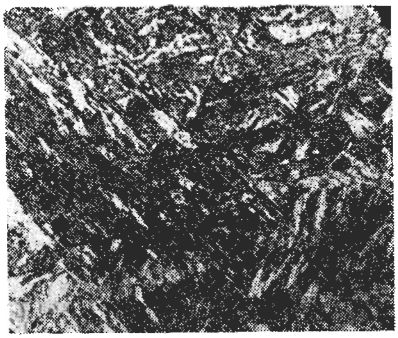
ination. The microstructure showed a central layer consisting of ferrite and another structure which may be bainite. This central layer is surrounded by a dark-etching area which extends to the surface on both sides. This microstructure is not clearly resolvable everywhere; but does, in places, contain tempered martensite and an acicular material which might



X 240 74.9

Large, elongated slag inclusions with grains of ferrite, an irresolvable material, and nearer the surface, tempered martensite.

be bainite. Spiny ferrite is also visible. There are numerous slag inclusions in lines parallel to the outer surfaces. They are concentrated in the middle of the dark-etching area and do not coincide with the division between this area and the ferritic centre.



X 1200 74.38

Tempered martensite.

If this sword was made by wrapping a piece of high-carbon steel around a piece of low-carbon steel and forging them together, then the result must have been heated above (the upper critical temperature) for

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some considerable time to allow the carbon dissolved in the austenite time to diffuse away from the line of slag inclusions.

More probably, the blade was fabricated and then case-carburised.

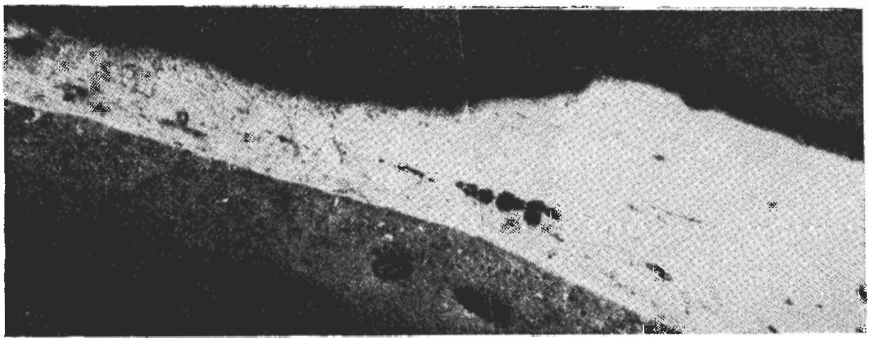
It has then been hardened by heat-treatment. This method cannot now be deduced with certainty but it probably consisted of a quenching (i. e. rapid cooling from A_3 temperature) which transformed the higher-carbon austenite areas into martensite and the lower-carbon areas into bainite. It may then have been slightly reheated to temper it (perhaps by residual heat).

SWORD No. 8

(Musée d'Art et d'Histoire, Geneva. 163c)

Sword blade of the early fifteenth century

This broken blade was examined on the section already visible. The surface was very corroded, but areas of unattached metal were still visible (see sketch). A large area near the centre has a microstructure consisting



Sword 163c X 60 53.24,27

The dark area is the hardened outer zone.

entirely of ferrite, but a smaller area near the surface shows a hardened zone. On closer examination, this latter area is found to consist of three different layers. On the inner side there is an area of ferrite. This gives way gradually to an increasing proportion of light-brown-etching

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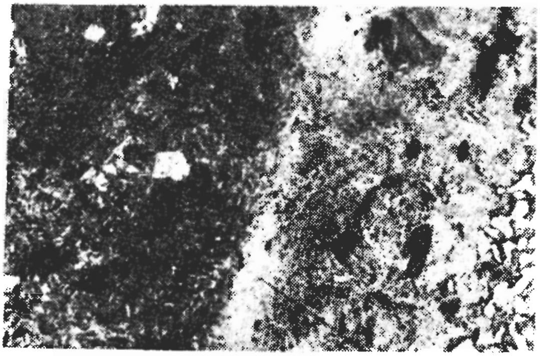
Sword 163c (early 15th cent.) found at Geneva



X 360 53.22

Division between light- and dark-etching areas of the hardened zone.

areas of a material which is probably bainite. This layer gives way abruptly to a dark-brown-etching and fairly uniform layer. There is a very distinct frontier between this zone and the rest of the section.

X 960 53.17

Probably tempered martensite.

At high magnification, tempered martensite mixed with an irresolvable material (perhaps tempered bainite) can be seen in this dark layer. There are numerous slag inclusions visible throughout the section. This sword has been made by case-carburising a wrought blade, and then heat-treated to harden it. This may have been a «time-quench» i. e. the sword has been cooled rapidly from above the upper critical temperature (probably by plunging into water). The outermost layer of the steel has

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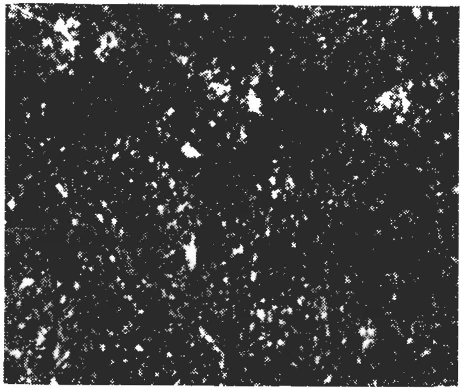
cooled most rapidly, being in contrast with water, and the austenite has transformed to (principally) martensite. The sword has then been withdrawn from the water. The heat left in the centre of the blade has been sufficient to temper the martensite formed in the outside as the blade



X 1280 54.31,32

Probably tempered bainite. Both structures from the hardened zone.

has cooled down. The inner (and also lower-carbon) areas have been cooled less drastically and formed bainite.

Approximate hardness (ferrite/bainite): 275 VPH; (tempered martensite): 650 VPH.

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