A Study in Pattern-Welding*

By J. W. ANSTEE
Museum of English Rural Life, Reading

and

L. BIEK
Ancient Monuments Laboratory, Ministry of Works

DURING the past decade, metallurgists and other research workers have shown an increasing interest in the welding and forging techniques used in the manufacture of certain early European iron sword-blades. A number of detailed papers had been published on 'pattern-welding' by the 1940s, but it was left to H. Maryon(1) to recognize the practical problems involved and put the correct interpretation on the basic method.

The terms *pattern-welded* and *damascened* have sometimes been used as though they were interchangeable. The two techniques are, however, quite distinct. A useful survey, both from the technical and the historical point of view, of *all* the various methods of manufacture which are known to have been used has been made by Smith (2), who also gives the relevant bibliography, and a more specific account by Maryon(3) has more recently appeared. Although there is a superficial family resemblance, the true Oriental *damask* is due essentially to a '*crystallization*' phenomenon in a wrought *steel* (1·2-2·0% of carbon), and far harder to produce. In *pattern-welding* the effects result primarily from the forging, twisting and welding together of strips of *iron*. Alternate strips of carbon-free and low carbon metal have been thought necessary to produce such a pattern, and up to 0·6% of carbon has been reported(4) in some material. As the present work shows, however, patterns are obtained even with strips of the same, virtually carbon-free, iron.

The need for further work was indicated after a ninth-century sword from the then bed of the Thames at Westminster had been cleaned and examined in the Ancient Monuments Laboratory, Ministry of Works, in 1951(5). The results could not be reconciled with the suggestion that certain folding techniques had been used by the makers of pattern-welded swords(6). At the same time full agreement was reached with Maryon's basic conclusion. Furthermore, the herringbone and other patterns observed, either on the surface or (on X-radiographs) within this type of blade, could evidently be produced by (the remains of) composite rods, each pile-forged from thin strips of iron, and adjacent ones twist-welded in opposite directions (5). Some of the difficulties inherent in this natural and apparently simple method of construction were revealed when a

* This article was first submitted in May, 1958. (Ed.)

number of such rods were made in the Laboratory. No welding was then possible; the twisted rods were merely flattened, soft-soldered and ground away to varying levels to reveal the consequent changes in pattern.

THE PALACE OF WESTMINSTER SWORD

(PL. IV, A, B; see also Appendix, no. 1, and Table I)

The examination of pattern-welded ironwork is made difficult, in a comparative sense, by the fact that sound objects cannot be easily X-rayed, and conversely, objects that have corroded so much that an X-ray is useful cannot be metallurgically examined. The Westminster sword represented an intermediate condition where it was possible to do both. Rees Jones(7) had taken both vertical and stereoscopic X-radiographs. He suggested that the central, composite portion had been produced by wires plaited round a laminated central core in a manner somewhat similar to that recently described by Janssens(8), who, however, postulated a twisting process.

This view was not entirely acceptable. Briefly, we felt that the patterns observed on the surface, when the sword was received, were the intermediate patterns of the type produced when a screw thread is sectioned longitudinally near its axis (PL. IV, A). On cleaning (PL. IV, B), these convolute patterns gave way in many places to the herringbone structure, which is normally regarded as the standard appearance, but which, as will be explained, is much less likely to have appeared on a truly finished surface.

As a result of the way in which corrosion had eaten into the surface, and the consequent 'stepwise' revelation of the surface on cleaning, it became clear that both the convolute and herringbone patterns were in fact part of the same basic structure.

This was something that until then had not been generally realized. It clearly showed the way to an interpretation of the pattern in terms of the screw. In addition, metallographic examination (Appendix, no. 1) had shown that adjacent layers in the pattern did not differ in their composition; thus a pattern could obviously be produced without having alternate layers of iron and steel.

EXPERIMENTS

(FIG. 25)

Rudimentary forging equipment was acquired at Reading in 1955 and used without additions throughout a cycle of eight main experiments(9). The hearth, 1 ft. 6 in. (45 cm.) in diameter, had a cast iron tuyère supplied with a continuous air blast from a hand-powered box bellows of Chinese type. A cast iron cheese press weight served as an anvil, while a small vice, 3-pound (1½ kg.) hammer and a pair of tongs completed the outfit. Charcoal was the obvious fuel to use, but it

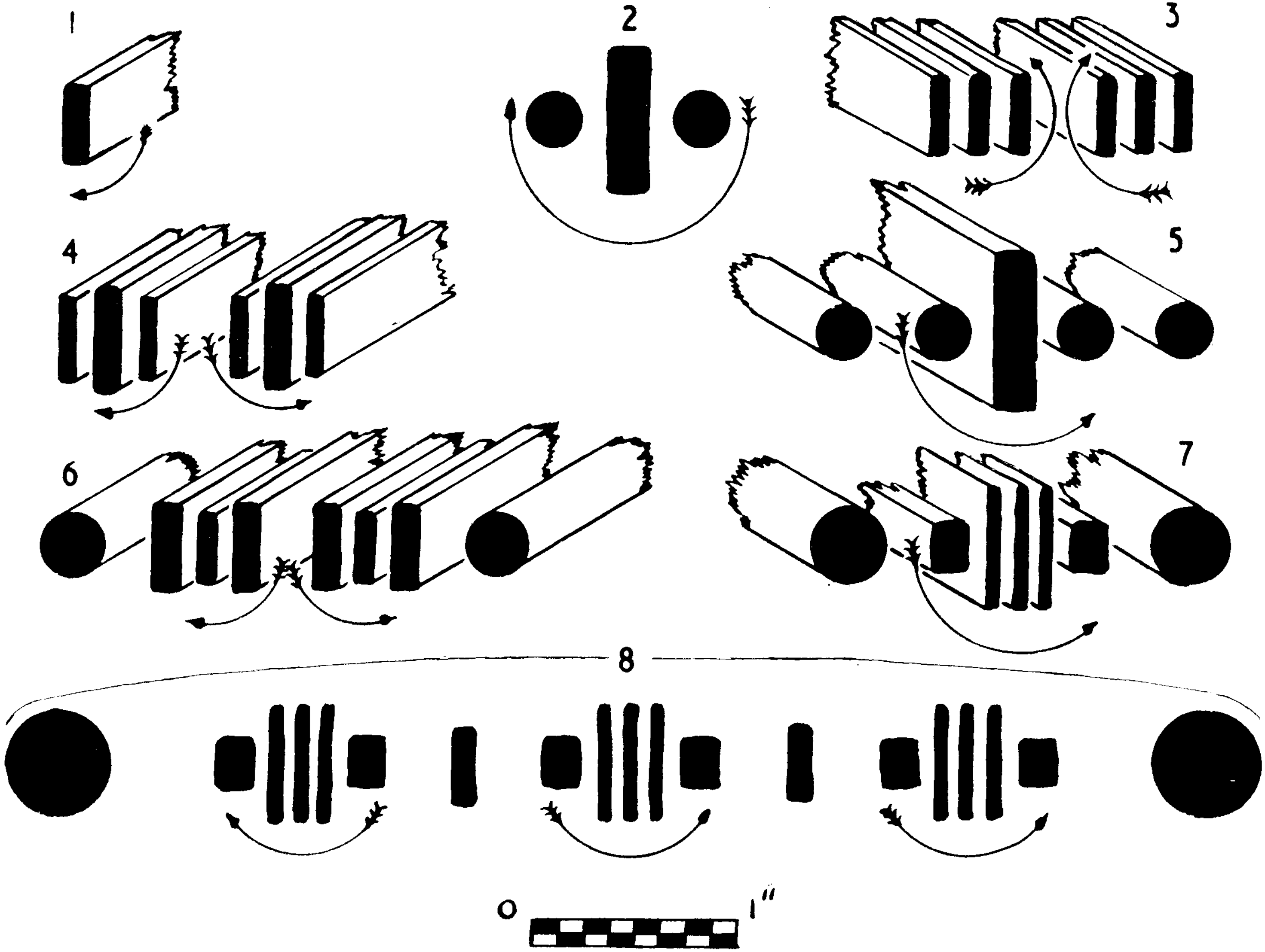


FIG. 25

SCHEMATIC REPRESENTATION, IN SECTION (TO SCALE), OF UNITS PROCESSED IN EXPERIMENTS 1-8 (pp. 72 ff.)

proved much too expensive to buy. Accordingly, some was made from mixed hardwoods, but owing to the difficulty of producing very large quantities its use was later discontinued. The demolition of a nearby Victorian conservatory, built about 1860, provided an ample amount of the high-grade wrought iron needed for the experiments.

THE FIRST EXPERIMENT

When a strip is twisted it forms a double-start thread. Although it was reasonably certain that each twisted unit in a sword had indeed been made from a number of strips, this assumption was not taken for granted. It was just possible that a single strip having a cross-sectional ratio of 3:1 could be twisted into a solid bar. This would mean that the channels of the thread would have to be eliminated, i.e. that each spiral ridge touched its neighbour.

A number of rods were forged down to sectional measurements averaging 0·365 × 0·135 in. (9·26 × 3·43 mm.), and attempts were made to twist each one tightly on to itself. Although control of the heat was satisfactory, a great deal of pulling strain was needed on the tongs in every case, to prevent the spiral form from buckling sideways. The best result obtained was a double-start screw about 0·340 in. (8·64 mm.) in diameter, with thread-crests 0·086 in. (0·216 mm.) in thickness, separated from each other by U-shaped grooves 0·150 in. (3·81 mm.) wide and 0·125 in. (3·18 mm.) deep. Any effort to improve on this invariably sheared the screw.

THE SECOND EXPERIMENT (PL. V, A, B)

The next step was to make a composite rod in which a small bar completely filled each of the two channels. It seemed reasonable to expect that the result would weld better after the twisting stage, because the tightly-fitting surfaces would not be so liable to further oxidization. The difficulty seemed to lie in the removal of scale that was formed on the surfaces which met at the end of the twisting work. Clarification of this problem was of great importance. If much oxide was trapped within a composite rod, one would expect this to prevent the welding of adjacent surfaces.

A forged bar of section 0·700 × 0·225 in. (17·8 × 5·72 mm.) had a rod 0·270 in. (6·86 mm.) in diameter placed longitudinally along the middle of each wide flat face. The bundle was welded for a short distance at one end, both to hold it together and to provide a grip for the tongs. Twisting at yellow heat was done in successive and overlapping sections. One end of the bundle was clamped in the vice and the other gripped in the tongs. There was no tendency to buckle, as the bars supported each other. They were easily screwed into a tight rod. A few light taps with the hammer, from time to time, served to keep the rod perfectly straight, besides fulfilling a more important function. The rod, now averaging 0·675 in. (17·1 mm.) in diameter, was brought to a full welding heat in successive short sections and hammer-welded down to a section measuring 1·00 × 0·250 in. (25·4 × 6·35 mm.).

One face of the forging was ground to four stepped levels. These were polished and etched to show the variations in pattern throughout half the thickness of the bar. The other face, left as forged, bore clear marks of indentation made by loose scale lying on the anvil. This emphasized the importance of keeping the anvil clean during any fine work.

The answer to the problem of scale removal was now clear. As during the work the oxide layer became thicker (and duller) it was forced from all surfaces by the twisting stress. The best solution was to allow the scale to form, twist a little, then tap the hot bundle with the hammer. In this manner the strips were finally screwed up on to themselves, the whole length being traversed in short sections altogether four times—twice up and down. Even so, much fine scale was left in the joints; nevertheless, all internal welds there appeared to be perfect, except at one or two points where lumpy particles had been trapped.

The original meagre stock of charcoal was exhausted by this test. About 8 pounds ($3\frac{1}{2}$ kg.) an hour were burnt during all forging work, excluding welding heats. After some time a great deal of ash and fine charcoal remained on the hearth and the fire was difficult to control effectively. At near-welding heats the smallest blast blew showers of sparks all over the place and the oxidizing region of the fire was rapidly consumed. Thus it was not easy to reach a full welding heat, as the fire had a tendency suddenly to burn itself hollow. At such moments the work had to be moved quickly away from the ensuing oxidizing conditions.

THE THIRD EXPERIMENT (PL. VI, A)

The materials for another type of composite rod were prepared. With washed coke breeze as fuel, 6 strips were forged to sections averaging 0·360 × 0·115 in. (9·13 × 2·91 mm.) and made up into two loose bundles. Each of these, consisting of three strips piled flat, one upon the other, was temporarily bound with iron wire and tack-welded at one end. For part of its length each bundle was twisted to a tight screw, one clockwise, one anti-clockwise, without undue concern about the scale in the joints. Any inclusions could not be removed, as the strip surfaces were in continual contact from start to finish of the twisting. On the other hand, much less oxide was likely to have been formed, owing to the rapidly achieved tightness of the joints.

The twisted rods, each 0·530 in. (13·5 mm.) in diameter, showed spirals of shallow surface grooves 0·210 in. (5·32 mm.) wide and 0·05 in. (1·27 mm.) deep, between groups of triple ridges formed by what had been the edges of the strips. At the same moment as the rods were welded together longitudinally, union took place between the strips in each one. After a light forging the bar measured 0·750 in. × 0·180 in. (19·1 × 4·56 mm.) across its section and had a partition weld running along it from end to end. The technique of welding two rods of circular section together, so that the seam lay evenly between them, was not easily mastered owing to a natural tendency for the pair to slip sideways around each other under the hammer-blows.

The quality of the welds was just as high as in the previous experiment—

in view of the included scale this was thought to be somewhat peculiar. Where the six plain strips had not been twisted they met to give the etched, watered-silk pattern so typical of iron weapons built up from flat laminations. The forging appeared to be better in quality than its constituents were originally—a change inferred from a grinding spark test and the higher note it emitted when struck on the anvil. The work had produced a 50% reduction in cross-sectional area.

THE FOURTH EXPERIMENT (PL. V, C-D)

The etching of some pattern-welded swords has shown that many composite rods had nearly half their thickness ground away. Some of the patterns seen on the resulting faces indicate the use of thin filler strips, which appear to have folded on themselves to meet in a short, barely discernible weld(10). It was hoped to simulate this effect by using a tripartite composite bundle whose outer strips were thinner and narrower than its central one. The twisted group was to be consolidated by welding and forged square before folding and welding it to itself although the use of a separate twist-welding technique by swordsmiths was thought to be unlikely.

Three strips were forged, the largest to dimensions of about 0·50 × 0·125 in. (12·7 × 3·18 mm.), the two filler strips 0·410 × 0·095 in. (10·3 × 2·41 mm.) in section. The bundle was screwed up for a length of 5 in. (127 mm.) from both ends, clockwise at one, anti-clockwise at the other. In order to reach one complete twist for every 0·75 in. (19·1 mm.) of length it proved helpful to forge down the ridges of the thread so as to prevent them from tearing across. The twisted end portions of the completed rod, now 0·50 in. (12·7 mm.) in diameter, consisted as before of groups of triple ridges, but this time each ridge was separated from the next by a groove of triangular section, 0·085 in. (2·16 mm.) deep and 0·175 in. (4·45 mm.) across the top.

The rod was welded and forged down along its entire length to a rectangular section measuring 0·340 × 0·225 in. (8·64 × 5·72 mm.). It was folded in the middle, so that the squared twists came to lie together, and welded again, starting from the fold. The forging became the central core of a lance-head, 1 ft. (304·8 mm.) long × 0·612 in. (15·4 mm.) wide and 0·160 in. (4·06 mm.) thick. When etched, its surface showed typical chevron patterns where twisted, but there was no recognizable relation between them and the original tripartite bundle. Its units could only be identified in their untwisted forms or generally in a plane parallel to the surface and half-way through the thickness of the bar. The expected tiny welds in the folded filler strips were discernible.

It is interesting to compare the total sectional area of the original strips with that of the final forging:

original strips × 2 = 0·232 sq. in. (1·5 sq. cm.)
forging = 0·098 sq. in. (0·64 sq. cm.)

A reduction had occurred in the ratio of 7:3. This common phenomenon was very noticeable during all welding, in fact it often seemed doubtful whether any metal was going to be left at all! There appeared to be no great advantage in twist-welding rods individually.

An analysis of the three and a half hours' work spent on this small object turns out to be quite impressive:

	heats used
initial forging of strips	12
twisting work	10
welding and squaring	12
final welding	7
	41

The experiment also proved the danger of hasty speculation about the number and original size of component strips by anyone without a very close knowledge of the practical problems involved.

THE FIFTH EXPERIMENT (PL. VI, B)

The composite rods in some swords have filler rods very deeply embedded in their grooves. The tops of the groove walls then look as if they had been forged down to a dovetail form with a locking effect(11). An experiment was designed to copy this minor feature and at the same time to incorporate the welding of two cutting edges made from a single rod.

The filler rods, 0·27 in. (6·86 mm.) in diameter, were tack-welded, as before (i.e. so as to sandwich it) to one end of a bar 0·75 in. (19·1 mm.) wide and 0·175 in. (4·35 mm.) thick. The bundle, twisted and de-scaled at the same time, ended up with a diameter of 0·65 in. (16·5 mm.). Both thread crests formed by the central strip were forged down so that they tended to spread over the filler rods and hide the small spiral grooves. The rod, 0·600 in. (15·2 mm.) in diameter, was welded and worked down to a bar 0·39 in. (9·91 mm.) square with one sharply tapered end. A length of rod 0·27 in. (6·86 mm.) in diameter was bent nearly double and secured around the tapered core by iron wire. This was to form the cutting edges. It was welded to both sides of the core at the same moment, as this was thought essential if excessive elongation was to be avoided.

Besides showing the expected locking effect on the filler rods, the etched sections also had another interesting feature. The iron immediately on either side of some weld seams had altered considerably in appearance.

THE SIXTH EXPERIMENT (PL. VI, C)

Although it seemed unlikely that the central strip of a composite rod was ever narrower than its outer ones, it was decided to carry out a somewhat illogical experiment to check this.

A strip 0·350 × 0·110 in. (8·88 × 2·78 mm.) in section was sandwiched between two larger ones measuring 0·390 × 0·135 in. (9·91 × 3·43 mm.). The bundle was twisted for some of its length at both ends, as before, and the resulting multi-start screwed portions were forged to tight round rods. This was done by rotating them under spirally directed, drawing blows of the hammer. The rod was doubled back in the plane of its untwisted central portion, welded to itself and dressed to a section measuring 0·625 × 0·310 in. (15·9 × 7·86 mm.). Another rod, 0·300 in. (7·62 mm.) in diameter, was doubled and welded to the core as before, to form a cutting edge. The forging was now 1·00 in. (25·4 mm.) wide × 0·190 in. (4·81 mm.) thick.

It transpired that an interesting variety of pattern had been made—one so characteristic that if a similar type occurred elsewhere its origins could be confidently explained. During the twisting work, the small central strip was forced sideways in one direction between the pair of outer ones. This uncontrollable phenomenon eventually formed alternate groups of double and triple strip edges, which became single and double weld seams, respectively, on the surface of the welded forging. On a lower plane, where the surface was ground away, one edge of the central strip was seen to be completely enclosed by the folded edges of the two outer strips, meeting over it at the single weld.

A side-slipping tendency had previously been noticed when rods of circular section were being welded together. This was partly brought under control by holding them in the tongs by their unwelded ends:

	heats used
primary forging	10
twisting	30
twist welding	24
edge welding	15
A total of	79 heats in 8 hours' work.

THE SEVENTH EXPERIMENT (PLS. VII; VIII, A; XIV, B; XV and XVI; see also Appendix, no. 2)

France-Lanord points out that some patterns are due to the use of partially carburized component strips (12). Many of his published examples indicate that the central layers of some composite rods consist of three such treated strips. The apparent absence of folded welds in a number of filler rods shows that the latter must have had circular or square sections before twisting.

The previous experiments had tended to prove that the best sectional measurements for a *single* central strip were in the ratio of 1 : 3 or 1 : 4. If such a strip was to be made from *three* components, each of these would originally have to have a sectional ratio of 1 : 9. The making of a composite rod from five strips was to include an attempt at superficial carburization in the forge.

Three lengths of rod cut from the same piece were forged to sections measuring 0·065 × 0·567 in. (1·64 × 14·3 mm.) (i.e. about 1 : 9). When cool they were wire-brushed and tapped with a chisel edge to remove patches of fine black scale. The three strips were allowed to lie on edge for ten minutes in a reducing fire made by shutting off the air blast. It was hoped that they might in this way acquire a very fine carburized skin. After they had cooled down in the dying fire, the strips were wire-brushed again, and made into a bundle which was flanked on either side by a filler rod of squared-off section, 0·260 × 0·160 in. (6·50 × 4·05 mm.).

Starting with a tack weld at one end, five heats were used in moving along the bundle as before to give an initial slow twist. This was followed by five more heats on the way back, for the combined operation of twisting, de-scaling and circumferential forging. Two more multi-purpose runs were needed before the bundle was reduced to a tight rod with only a faintly spiralled surface. It measured 0·485 in. (12·2 mm.) in diameter and had undergone one complete twist for every 0·75 in. (19·1 mm.) of length. On its surface, groups of triple strip edges formed alternate spirals with single ones produced by the filler rods.

A rod 0·350 in. (8·88 mm.) in diameter, for the cutting edges, was doubled on itself and welded to the core in the usual manner. A natural tapering effect, appearing to start as a result of the heavy initial welding at the point, diminished in extent as welding progressed, and ceased after a length of 7 in. (178 mm.) had been completed. The experiment also proved that a mirror-like polished finish was sometimes sufficient to reveal the patterned structure when the apparently homogeneous surface was tilted against the light.

The etched blade showed varying types of pattern merging into one another—a feature caused by the sloping face, which had been deliberately cut at a low angle through half the thickness of the forging in the manner of a taper section. All the patterns appeared to duplicate original forms, as intended, both in size and shape, while the usual light and dark zones were remarkably clear. At the tip of the core there was a change of pattern, as on most swords. It consisted of the tapered bundle of strips which had remained untwisted where gripped within the jaws of the tongs.

The report produced by the National Physical Laboratory (Appendix, no. 2) after their examination of this specimen suggested, in effect, that the patterns were due entirely to the normal body-slag incorporated within the iron, and not to carburization, there having been no significant increase in carbon content:

	heats used
strip forging	14
filler rod forging	4
twisting	20
edge welding	13
final forging	3
Total	54

THE EIGHTH EXPERIMENT (PLS. VIII, B; IX; X, A; FIG. 26)

The experience gained by this time was considered a good basis for an attempt at making a complete sword blade. The process was to include a special heat treatment with certain substances, apparently used by some early armourers.

Fifteen wrought iron rods, 0·22 in. (5·59 mm.) in diameter, were forged to form the components of three composite rods similar to the one used in the previous experiment. Two other rods were worked into strips measuring 0·370 × 0·125 in. (9·40 × 3·18 mm.) in section, to serve as 'packing' strips.

Of the 15, one group, consisting of three strips and two squared filler rods, was twisted and forged in the normal manner. The ten remaining strips and rods were piled into a loose bundle, together with interleaved and enclosing layers of a home-made compound(13). This mixture was made by thoroughly mashing the following into a stiff paste:

	% by weight
pigeon droppings	39½
plain flour	21½
honey	14½
olive oil	2
milk	22½
	100—3 lb. 8 oz. (1·6 kg.)

The bundle was wrapped in cloth and tied with string. It was pressed into a sand-bed filling a length of cast iron gutter-channel. The addition of more sand and another inverted gutter-trough sealed the unit. This was laid across iron stakes driven crosswise into the ground to form a support. The whole assembly was surrounded by a loose brick retaining wall. With wood as fuel, the iron package reached a red-orange heat in half an hour. It was maintained in that condition for another ninety minutes and then allowed to cool.

The pliability of the treated strips appeared to be unchanged, but when test pieces had been heated to redness and plunged into water they fractured after being bent only once, and exhibited a cased section. A greater effort was needed to twist these treated strips, and, as their thin edges tended to tear, both composite rods had to be heavily forged during the process.

The three composite rods, separated from each other by the two straight 'packing' strips, were laid flat, side by side, the two 'carburized' rods on the outside. The assembly was fastened together near one end by a thick slidable iron clip. Welding began at this end and proceeded along the bundle in the usual inch-length stages.

As this work moved forward the binding clip had to be driven well ahead of each newly welded area and kept relatively cool so that it might retain its stabilizing effect on the unwieldy core mass. The raw cutting edges, made from a doubled rod 0·5 in. (12·7 mm.) in diameter, were welded on in the same manner. This operation met with increased difficulty, owing to the distance [1·4 in. (35·6 mm.)] between seams that had to weld at the same moment. The solution lay in the exact siting of the forging at the critical part of the fire, and in a slow increase in temperature up to all welding heats.

Earlier experience had shown that there was no second chance if seams failed to weld the first time. Such an accident did in fact occur with this sword blade. Another attempt to weld at the same place thinned the core so much that a length of 7 in. (178 mm.) from the point had to be cut off and new cutting edges welded on. The forging of a square-shouldered tang also failed, but a fresh one was cut from the top of the blade.

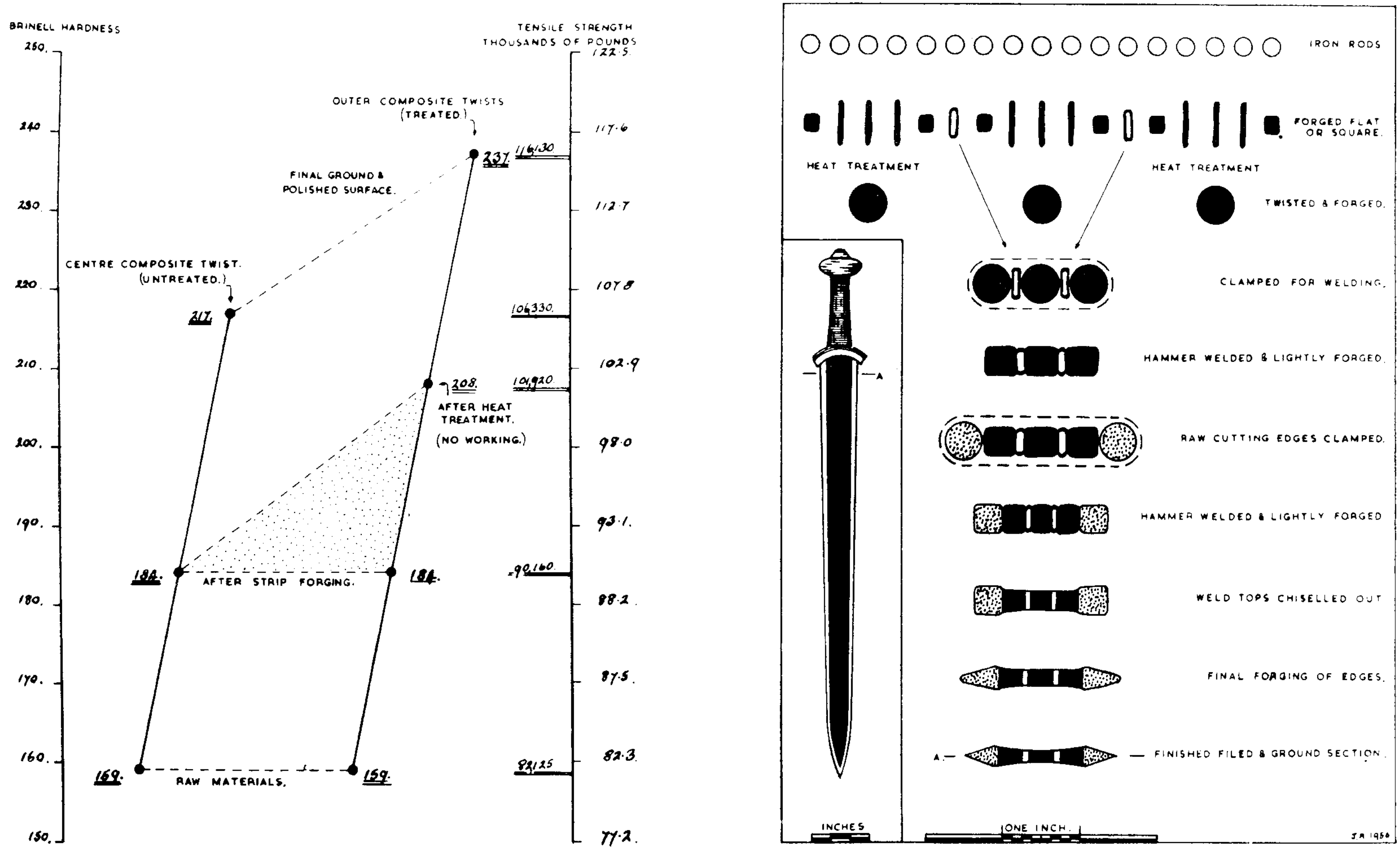
Both exposed faces of the composite core assembly were cut away with a cold chisel, down to a plane where the composite rods had met completely. Final forging bouts were needed to thin out the edges and straighten the blade.

The chiselled grooves were roughed out into fullers, using a wet sandstone wheel. This stage was simplified as the grooves provided their own guiding boundaries when the blade was moved from side to side across the curved surface of the rotating wheel. A modern, fine carborundum wheel was used to cut the fullers down to their final sunken arcs. For this operation, tapering guide lines had to be scribed on the blade through a coating of copper deposited by swabbing with a copper sulphate solution. After the cutting edges had been filed, universal polishing completed the work on the blade. A hilt and pommel were made to finish the weapon, to which were added a scabbard and belt.

During the manufacture of the blade, stretching and grinding-away had reduced the total cross-sectional area of the original strips by 70%. A weight of 1 lb. 3 oz. (0·54 kg.) of metal had been removed by abrasive action, leaving a final weight of 1 lb. 10 oz. (0·73 kg.) for the blade. The grinding of fullers was an obvious course to follow removal of the outer surfaces of the core assembly. Its longitudinal weld seams had not compacted sufficiently on their two surfaces (in the raw blade) because the final forge welding had reduced the composite rods to a square section with rounded corners.

If, as was first assumed, the heat treatment was a straightforward but incomplete carburizing process, about eight hours of continuous firing would have been sufficient for the complete penetration of the strips by carbon. Although a layered structure could be seen in the strips, and both of the ensuing composite rods were harder to twist than the untreated one, no significant carburization could be detected under the microscope (Appendix, no. 2, p. 91; PL. XV, e.g. C, D). However, something must have happened, because application of copper sulphate solution showed up the differences between the rods. On the untreated surfaces the deposited copper remained loose and soft, but it plated cleanly and firmly on to the treated ones.

The treatment was certainly responsible for a small but significant increase in hardness. Tests carried out on samples taken from all the components at various stages gave progressively higher hardness values which were directly related to, and superimposed on, the additive stages of forging the blade.



a *b*

FIG. 26

THE EIGHTH EXPERIMENT (p. 80)

a. Comparison of increases in hardness and tensile strength caused by forging, as between heat-treated and untreated strips.
b. Schematic representation in section (to scale) of the stages of manufacture. Note the heavy reduction in sectional measurements.

Two interesting facts were noticed a short while after completion of the weapon. Although only the best seasoned pitch pine had been used for the scabbard, a bloom of rust formed on the upper surface of the enclosed blade when it was lying flat. This was undoubtedly due to the water vapour expelled by the wood when adjusting itself to an indoor atmosphere. In the light of this evidence it is highly probable that the remnants of fur or hair so often found embedded in the surfaces of ancient swords represent a scabbard lining intended to act as a reservoir for preservative oils.

The necessity for some sort of binding or clip, to keep the sword firmly in its sheath, was shown clearly by the unfortunate results of its handling by people unaccustomed to doing so. The decoration on the pommel was always smashed when the sword fell out of its upturned scabbard. At such moments one can understand both the reluctance of Saga heroes to part with their favourite weapons and the frequency with which they used them!

All the stages of manufacture had been timed, and a record kept of the number of forging and welding heats used. During heats marked with an asterisk more than one strip or rod was in the fire at the same moment.

Stage	Description	Number of heats	Time (hours)
1.	Forging 5 strips	12*	2
2.	Twisting 5 strips for central composite rod	24	3
3.	Forging 10 strips for outer rods	12*	2½
4.	Mixing and packing compound for heat treatment		2
5.	Preparing open hearth and fuel		2
6.	Heat treatment of 10 strips	1	2
7.	Twisting outer composite rods	28*	3½
8.	Forging 2 'packing' strips	5*	¼
9.	Welding the core	15	2¾
10.	Welding the edges	16	3
11.	Chiselling out surfaces of core assembly		2
12.	Forming the tang		½
13.	Rough forging of edges	15	1½
14.	Rough filing of edges		1
15.	Grinding the fullers		6
16.	Fine filing of edges		2
17.	Rough polishing of blade		6
18.	Final polishing of blade		2
	Total for blade:	128	43
19.	Brass quillons made		3
20.	Door-knob pommel trimmed and weighted		1½
21.	Boxwood grips		2½
22.	Grip binding		½
23.	Stone setting made		2
24.	Wooden scabbard in two halves		3½
25.	Canvas cover sewn on		1½

26.	Chape made	$3\frac{1}{2}$
27.	Top scabbard mount	$3\frac{1}{2}$
28.	Rough cutting of flint pebble	$2\frac{1}{2}$
29.	Polishing and setting flint pebble *en cabochon*	2
30.	Finishing the scabbard seam	$\frac{1}{2}$
31.	Belt and buckle fittings	4
	Total time:	$74\frac{1}{2}$ hours.

All the specimens described have been given to the Science Museum.

DISCUSSION

Very little progress could be made with the interpretation of experimental results until it was realized that a vital clue lay in the unavoidable presence of some scale within all twisted composite rods. A number of methods had been devised to reduce the quantity trapped, but none was totally successful. It was then noticed that where fair amounts had been included the welds showed up in a remarkable manner. Contrary to expectation, the weld would be represented by a fine, very bright streak flanked on either side by zones corresponding to those which etched to a lighter colour than the rather dark central parts of each strip.

A brief experiment was carried out during the compilation of this report. After a tightly twisted composite rod had been made, and pulled to pieces again with some difficulty, it was quite clear that strongly reducing conditions had existed within the unwelded seams throughout the twisting process. A related reaction has been commented on by Gordon in his description of the 'shingling' or multi-fold forging process(14). This was used until quite recently to refine the slag-filled structure of the wrought iron balls produced in puddling furnaces. A rough comparison of both these observations was made in a ninth experiment by twist-forging a lance-head core out of a square bar which had originally been made by shingling and rolling from four pilings (PL. IV, E; PL. X, B). No difference could be detected between this and some of our earlier experiments, using loose strips, as far as the relationship between the different components in the joints was concerned. It seemed reasonable to infer that a similar cause was responsible for the observed effect in both cases. Work carried out by the British Welding Research Association on the rod has, however, shown no actual decarburization at the joints, possibly because of the low overall carbon content (PL. XI, A, B).

The experiments have shown that it is possible to produce any chevron or allied and derived patterns by twisting and grinding normal wrought iron. The surface chevrons may be approximately copied by twisting any round or square sectioned piece of pile-forged iron, but more accurate reproduction of any pattern sequences can be made by twisting a number of loose and graded strips made up into a bundle.

An interpretation of the number of strips used in a composite rod is best attempted by etching a longitudinal polished taper section, ending in a plane about half-way through the thickness of the bar. As many swords were originally ground down to a considerable depth below their surfaces, they automatically give the best level for examination. But the patterns observed can only be copied by a process of trial and error involving many experiments with strips varying in number, size, sectional ratio, material and treatment. Even the intimate knowledge gained by making a composite rod does not always help when the operator subsequently tries to analyse the result.

Even where the patterns are not produced, as they were in these experiments, by slag inclusions, the light and dark bands do not necessarily correspond to alternate iron and steel strips used deliberately. This is quite apart from the fact that the relative colour values may be completely reversed with different etching reagents, nor is it always possible to characterize an intentional, partial carburization of individual strips, although there can be little doubt now that this technique was well known in all its complexity. It is highly probable that an unintentional decarburizing process may be involved in many cases.

Under the peculiar conditions which exist in the seams of a twisted composite rod, when it is being slowly brought up to a welding heat, it is thought that a strong reducing action can affect trapped oxide scale and, equally, the carbon content in the surfaces of all strips where they are not exposed to the air. This may result in the oxide scale being, in effect, reduced to the metal, at the same time as decarburization of the strip surfaces produces ferrite bands of appreciable depth.

Some of the constituents of the slag inclusions in the same area are probably also modified. As some decarburization can occur everywhere in such areas, irrespective of the actual quantity of carbon present initially, the same relative tones will show on the etched surfaces afterwards, no matter whether the specimens were made from low, medium or high carbon material.

The patterned surface of a sword, whether emphasized by polishing, etching or rust bloom, did provide the customer with a guarantee of quality. But it must not be assumed that the twisting method which produced the pattern was devised merely for that purpose. Indeed it seems more likely that the pattern is just a by-product.

The reason for the method adopted must be sought ultimately in the metallurgy of iron. Its peculiar properties while in the process of extraction from the ore make it natural for it to appear, in the end, as a rather small and heterogeneous unit of material. This is in complete contrast to copper, where relatively large and easily fusible ingots may be obtained far more simply. The weaponsmith was thus forced to depart radically from normal practice as the use of iron weapons became more general, and the requirements more particular.

If one accepts France-Lanord's conception of the method of building up a blade by forging out small billets, the simplest way of getting thin strips, which would burn if heated singly, into a condition suitable for welding is precisely the type of operation which produces a composite rod. Small strips are ideal for rapid carburization but, again, that was most probably not the main reason for making them. It is as well to remember that in the Westminster sword the carbon content was uniformly low, lower in the cutting edge than in the core, with the result that the latter was harder than the edge. It is quite clear that the production of steel was well known and extensively used, but that it was not an essential in pattern welding.

It has also been suggested that the pattern-welded sword was superior to a straight forged blade because it would contain appreciable quantities of steel and be less easily bent in battle, both for that reason and by virtue of its complex internal structure. Judging by the Westminster sword, again, this also was not always true. The metallographic evidence shows clearly that the Westminster sword was slowly cooled in air from a temperature of about 900° C. (1650° F.). This can be taken to have been the last metallurgical operation performed on the weapon. It occurred before the hilt was decorated, because the melting point of the metal which decorates the hilt (a zinc-tin bronze) is in the region of 800° C. (1470° F.), and there were no signs of softening or fusion on it. It may, therefore, be inferred with some confidence that the cooling in air was deliberate, and not the result of a fire subsequent to the weapon's manufacture.

But if a weapon of such construction is heated to 900° C. (1650° F.) after manufacture, the effect of this is to homogenize its composition in the sense that any orientation of 'grain' within the body loses its metallurgical effect. There is thus in this sense no difference, simply as the result of construction, between pattern-welded and other swords.

There is, however, a most important difference in another respect. Improvement in quality follows directly on the reduction and distribution of slag content to a condition where the alignment, size and shape of the inclusions have no transverse weakening effect on the forging. Repeated forging work also has a considerable hardening effect on the strips, apart from drawing them out to the required size.

The existence of strips as primary units must be regarded, therefore, as the result of an extremely thorough refining process, carried out by forging and drawing-out the roughly made iron bloom into units progressively smaller in cross-sectional area. The quality of a sword core will plainly improve with the number of thin strips and small composite rods used in its construction. A workable limit is reached when the small rods become difficult to weld into a regular mass that extends right through the thickness of the blade. They must then be used as facings, applied to both surfaces of a core which extends from edge to edge of the blade.

It has been argued that composite rods were split longitudinally, and welded on to such a core with their cut faces outwards(15). This idea was evidently put forward to explain the presence on the surfaces of finished blades of patterns which can only exist near the diametrical section through a composite rod. It could not have been realized that large amounts of metal have to be ground away from the roughly-forged blade in order to reach sound welded junctions between the rods. Besides being rather pointless, such slitting of small, individually welded, composite rods is very difficult to do efficiently even with a modern fine hacksaw. It must, therefore, remain a highly improbable operation at a time when hot or cold chisels and thick-bladed hacksaws were the only available tools.

Such a process has, nevertheless, been again postulated recently by Janssens(8). The method of twisting round a mandril was first suggested scientifically in modern times by Faraday(16), who carried out some experiments. In the case described by Janssens it evidently produces the results shown. While there must have been many variations, however, the basic ancient process probably never departed far from the principle of the simple solid screw. Almost always where visual examination of the metallic surface is possible in detail, small areas may be found where selective corrosion has exposed this screw structure in depth (PL. IV, C).

In all the specimens examined, all the details of structure discussed by Janssens can be explained in terms of the general method here outlined. In particular, the shape of the transverse section (his fig. 10) is a by-product of the welding, forging and grinding operations and does not require a rod of pentagonal section (his fig. 1) as a starting material, nor any of the subsequent cutting and reassembly. This is felt to be true even for a sword with a solid, continuous core such as Janssens postulates for his specimen, although no such construction was attempted in the series here described.

On the other hand, Janssens' method does not explain the change in pattern with depth. Nor does it permit the production of blades with more than two adjacent lengths of pattern. Yet of the specimens examined, only about a quarter have two, the others showing three or four lengths side by side.

Rees Jones's interpretation of the X-radiographs of the Westminster sword (p. 72) can probably be accounted for as follows. Only two of the original four superimposed herringbone patterns would have been left on the sword as received in the laboratory, or indeed (almost certainly) as finished. Sufficient 'turn' had clearly remained in places to indicate a helical construction.

For any one of the visual helical units, the X-radiographic pattern could indeed have been produced by a single composite rod, going right through the thickness of the blade. It was, however, in this case manifestly the result of two separate, superimposed half-rods. If, at the heart of the blade, there were a solid, unpatterned core, lying between the two half-rods, the X-radiographic picture would be very similar to that produced by a single spiral wound round a central plain strip.

Visual examination of the surface of the blade shows clearly that only such half-rods have remained. Rees Jones's impression thus tends to confirm the existence of a single thin, plain core the width of the patterned central part and (probably) integral with the cutting edges. There are other direct visual indications of a core. This kind of X-radiographic evidence has in fact been used, in general, to suggest the existence of such cores (see Table I).

So much forging, elongation and grinding work takes place during manufacture that a 70% loss in sectional area must be allowed for when calculating the number of bars and strips necessary for a blade of specific size. The removal of an undesirable post-welding feature is thought to be the prime reason behind the characteristic large concave 'fullers' on European sword-blades.

If any general pack-carburizing treatment is considered, the best time to apply it is when the blade has been finished except for fine abrasive and polishing work. Cutting edges can then be honed up after the hardening and tempering stages.

It is clear that a really fine quality sword with modestly decorated fittings might have taken at least 200 hours to make, i.e. approximately one month. About 2-3 cwt. of charcoal would be needed for the forging of the blade. If the selling price of the weapon was directly related to the time spent on it by the craftsmen, it could have cost between £60-£100 in terms of present-day values.

In contrast to the methods described in this paper, the welding of the folds in a small laminated bundle, sharply corrugated in concertina-fashion(6), is impossible without clamping it in a vice or jig immediately after removal from the fire. By the time the bundle has been secured in this way, the metal has cooled too much. It should be stressed that welding must be complete within seconds of removal from the fire.

No evidence was found during the series of experiments to support the time-honoured suggestion that iron was, and can be, heavily carburized by working it hot in the presence of carbon dust on the anvil.

No work has been done or seen by us on the specific mechanisms of (a) the visual development of pattern on etching a freshly polished blade, or (b) its intensification by preferential corrosion, in the circumstances here considered. Remarkable effects have been obtained simply by revealing the distribution of phosphorus(17). A variety of specialized etching reactions is known(18). Clearly the disposition of slag particles, both those that exist in the original wrought iron and those that are caused by the subsequent piled structure, must contribute a major share. Another factor is the grain size of the ferrite, coarser grain appearing brighter. The copper-adhesion effects indicate the existence of cathodic areas. Finally, the 'very resistant' zones postulated by Chilton and Evans (19) might be expected, at least along the weld seams which appear to be harder and sometimes even show in X-rays.

Some of these factors, at least, are very likely to have determined the course of corrosion, as far as it is controlled by the nature of the basic metal. One would expect corrosion to proceed most rapidly along the convoluted planes of junction between materials that differ, however slightly. But more refined interpretations will be needed to account for the effects observed, for instance, at X in PL. XII, A.

X-RADIOGRAPHIC AND VISUAL EXAMINATION OF PATTERN-WELDED IRONWORK

The results of an examination carried out in the light of these experiments on swords and other objects are given in Table I (between pp. 88-9). The technical terms used have been evolved on the basis of the present work. The number of composite rods refers to what would be visible on either surface of the object in its pristine condition, and in the case of a single pattern this would go right through, the same composite rods showing on both sides. A double pattern indi-

TABLE I

Reference	Type of object	X-Ray	No. of composite rods	Type of pattern-welding			Remarks	Present location	Provenience	Publication	Date assigned by excavator	By courtesy of
				Single or Double,	and ? Core	Standard or Alternate						
Canterbury, A.M.5345	Sword	672-5	2	D	C	St.		Royal Museum, Canterbury (1957/1)	Bekesbourne	Unpublished	Mid-6th c.	Frank Jenkins and Royal Museum, Canterbury
Finglesham, A.M.5287	,,	665-6	3	D		A		Ospringe, Maison Dieu	Finglesham, Grave G 2	Chadwick, S., *Med. Archaeol.*, II, 1-71.	?5th-6th c.	Ministry of Works
Holborough, 13	,,	697-9	4	D		A		Maidstone Museum	Holborough, Grave No. 7	Evison, V. I., *Arch. Cantiana*, LXX, 84-141		The excavator and Ministry of Works.
Holborough, U/S	,,	695-6 699	3	D		A		,,	,, Grave No. 2	,,		,,
Westminster, 1948	,,	see ref. 7	2	D	C	St.	(*V*)	Palace of Westminster	Westminster	Dunning, G. C., and Evison, V. I., *Archaeologia*, XCVIII, 123-158.	9th c.	Ministry of Works
Kennet (mouth of), Reading, 90:61	,,	Q, R	3	D	C	St.		Borough Museum, Reading	Kennet Mouth, Reading, dredged from river	Unpublished	10th c.	Reading Corporation
Reading, 16.36	,,	P	2	D		St.		,,	Tilehurst, nr. Station from burial	*Berks. Archaeol. J.*, XLI, 39.	10th-11th c.	,,
Southend, 17	,,	C	3	D		A		Prittlewell Priory Museum, Southend	Prittlewell	*Trans. Southend Antiq. Soc.*, I (pt. 2), 119-121	?550-650	Libraries, Art Gallery and Museum Committee, Southend
Southend, 11	,,	D	3	D		A		,,	,,	,,	,,	,,
Southend, 425/1	,,	E	4	D		A		,,	,,	Unpublished	,,	,,
Southend, 18	,,	F, G	3	D		St.		,,	,,	*Trns. Southend A.S.*, as above	,,	,,
Southend, 25	,,	H, I	2	D	C	St.		,,	,,	,,	,,	,,
Richborough, 1375	,,	—	2	D		St.	(*V*)	Richborough Museum	Richborough	*Richborough*, V (Soc. Ant. Res. Rept.), forthcoming.		Society of Antiquaries and Ministry of Works
Dartford, Riseley	,,	AK	4	D	C	St.		Dartford Museum	Riseley, Horton Kirby	*Trans. Dartford Antiq. Soc.*, No. 8, 70-1; also *B.M. Quart.*, XII (pt. 2), 57	Late 6th -early 7th c.	Dartford Borough Museum
Dartford, Riseley, Grave LXXV	,,	AL, AM	4	D	C	St.		,,	,,	,,	,,	,,
Brentford, O.2114	,,	AP	3	D		St.		London Museum	Thames at Brentford	Unpublished	Undated	Trustees of London Museum and Layton Trustees
Brentford, O.2110	,,	AQ	3	D		St.		,,	,,	,,	,,	,,
Brentford, O.2112	,,	AR	4	S	(C)	St.	Plain core deeply fullered blade	,,	,,	,,	,,	,,
Brentford, O.2111	,,	D. Napier & Son, Ltd.	3	D	(?C?)	St. (A in small portions)	Short lengths of straight 'grain' on one side, in central rod only	,,	,,	,,	,,	,,
Sheffield, Brushfield, J. 93.1161	,,	Industrial Radiography, Ltd.	3	D		A	Splitter strips between composite rods; superimposition badly out of alignment in places	Sheffield City Museum	Brushfield, nr. Ashford, Derbyshire	Howarth, E., *Cat. Bateman Coll.*, Sheffield Mus., 1899	7th c.	Sheffield City Museum
Sheffield, Witham, J. 1954.3	,,	Hadfields, Ltd.	3	D		St.	Wavy strips independent of, and superimposed on, pattern-welding nr. hilt, probably similar to 'maker's mark' of France-Lanord (see ref. 18)	,,	Witham	*Sheffield Mus. Ann. Rept.*, 1954		,,
Northolt, A.M. 2391	,,	439	2	D		St.	Narrower (and probably shorter) than 'normal' swords	Gunnersbury Park Museum	Northolt Manor	Hurst, J. G., below, p. 288, PL. XXXII, A, 2	Context 13th c. but possibly from disturbed Saxon grave	The excavator and Ealing Borough Council
Brentford, O.2100	Scramasax	AN	3 (+?)	D	(?C?)	St.	Some additional features as yet unexplained	London Museum	Thames at Brentford			Trustees of London Museum and Layton Trustees
Brentford, O.2101	,,	AN	3 (+?)	D	(?C?)	St.	,,	,,	,,	Below, PL. XII, A		,,
Brentford, O.2102	,,	AN	3 (+?)	D	(?C?)	St.	,,	,,	,,			,,
Walthamstow (R. Lea)	,,	677-80	3	D		St.	(*V*)	Walthamstow Museum	River Lea, Maynard Reservoirs	Unpublished		Walthamstow Museum
Magna Carta, Reading, 283.47	,,	—	1	S		St.	(*V*) Deep fullering in pattern-welding	Borough Museum, Reading	Thames, near Magna Carta Island, Runnymede	,,	8th c.	Reading Museum and Thames Conservancy Board
Thames, Kingston, 288.47 (A.M. 9593)	Lance-head	—	2	S		St.	(*V*)	,,	Thames, Kingston	Below, PL. IV, C	10th-11th c.	,,
Surbiton, Reading, 291.47	,,	—	4	D	C	St.	(*V*) Same twist on all rods (anti-clockwise)	,,	Thames, Surbiton, Raven's Ait	Unpublished	,,	,,
T. C. Board, Reading, 287.47	,,	—	2 thin, with separate rod all round	D	C	St.	(*V*)	,,	Thames, backwater of, below Cookham	,,	,,	,,
Kennet (Gasworks), 95.61	,,	S	2 near tip 3 at heart 5 at shoulder	D	C	St.		,,	Dredged from Kennet, near gasworks, Reading	,,	,,	,,
Reading, 286.47	,,	—	4	D	C	St.	(*V*) Central splitter	,,	Sunbury Weir Stream	,,	,,	,,
Finglesham, A.M.5286	Weaving sword	666	4	D		St.		Ospringe, Maison Dieu	Finglesham, Grave D 3	*Med. Archaeol.*, II as above	?5th-6th c.	Ministry of Works
Seacourt, A.M. 8207	Dagger	829	2	D		St.	Ceremonial weapon? Exceptionally narrow rods	Ashmolean Museum, Oxford	Seacourt	Biddle, M., *Oxoniensia* XXVI-XXVII, 70 ff.	mid-13th c.	The excavator and Ministry of Works.

(*V*): Visual examination of the (cleaned) metallic surface was possible in these cases.

cates that two separate assemblies are involved, each of which would be visible from one side only. In such a case, these assemblies could either be welded back to back and thus form the whole of the central core, round which the cutting edges would then be welded; or each assembly could be mounted separately on either side of a simple, flat, wrought core that would be integral with the tang and cutting edges. The individual composite rods can run in the standard twisted manner, or the twisted portions may alternate with straight, longitudinal ones.

All evidence obtained only from X-rays must remain conjectural because the super-imposition in double patterns may produce effects that might (even from stereo-radiographs) be interpreted in various ways. None of these could be conclusively proved without metallographic examination of transverse sections. This would involve destruction of part of the object, with consequent loss of exhibition and other values, and is in any case not likely to be feasible for many of the objects owing to the state of preservation.

APPENDIX

The following results of metallographic examination are here given by kind permission of the Director, National Physical Laboratory, Department of Scientific and Industrial Research.

1. THE PALACE OF WESTMINSTER SWORD (p. 72)

Report M.2154

Preparation for Microscopic Examination

Two areas on one face of the shorter part of the blade in the positions marked at *a* and *b* in PL. XIV, A were selected for examination. These two areas were rubbed down with successively finer grades of emery paper, and were then polished on a rotating felt pad, using first free cutting alumina and then gamma alumina as abrasives. The two areas were then etched by swabbing with cotton wool dipped in 3% nitric acid in alcohol for 15 seconds. The etching liquid was washed off with a jet of alcohol and then dried in warm air.

Microstructure

The areas polished included both the fibrous edge and the herringbone centre. The structures observed were of three types:

1. Coarse grained slag-free iron (ferrite).
2. Fine grained iron with small globules of slag particles.
3. Fine grained mild steel containing ferrite and pearlite together with a few slag particles.

Both areas examined were similar in microstructure; the photomicrographs, PL. XIII, A-D inclusive, are all of area *a*. Structure types 1 and 2 are shown in A and B at magnifications of 50 and 150 diameters respectively. Type 3 is shown in C and D at magnifications of 500 and 1,500 diameters respectively.

In general types 1 and 2 occurred mainly in the centre of the blade but not in great quantity. Type 3 was found both at the cutting edge and in the centre.

Discussion and Conclusions

The general microstructure was consistent with the theory that the blade had been made up from strips of material of different compositions, but the difference was not great, and may not have been intentional.

The welding, i.e. the junction between the strips, was excellent. There were no voids and only in one or two places were lines of slag particles detected.

In the centre of the blade the general grain of the material was such that it was apparent that the strips of material used in making the blade had not been placed parallel to the long axis but had been folded or plaited over one another. This can be seen in PL. XIII, A; the bands of coarse grained iron here run across the long axis of the blade. The composition of the edge, i.e. the band with a fibrous structure in PL. XIV, A, was not radically different from that of the centre.

The slag present in the areas of ferrite (structure types 1 and 2, PL. XIII, A-B) was not typical of wrought iron; the amount was much less than is usual in wrought iron, and the character of the slag was different. (The long triangular shaped area of non-metallic inclusion shown in PL. XIII, A may be a corrosion product. It is not the normal type of slag inclusion.)

The carbon content of the steel (type 3, PL. XIII, C) corresponds to a 0·2% carbon steel, and is low enough to indicate that the blade was not intentionally hardened by any carburizing process. The dark patches seen in PL. XIII, C are pearlite and contain iron carbide (Fe_3C). PL. XIII, D, shows an area containing pearlite at a magnification of 1,500 diameters. The presence of pearlite shows that the blade has not been hardened by quenching from a high temperature.

Five Diamond Pyramid hardness impressions were made on the polished areas. The hardness values found were for the edge 136 and 145 and for the centre 186, 186 and 188. These values are approximately those of a plain carbon steel (0·20% C.) which has been cooled in air from a temperature of about 900° C.

Summary

The centre of the sword blade had been made by welding together plaited strips of carbon-containing iron of similar composition, and afterwards cooling in air. The carbon content of the iron was about 0·2% although in some areas the material was similar to a clean wrought iron.

There was little difference, except that of texture, between the edge of the blade and the centre. The welding technique was good.

2. THE SEVENTH EXPERIMENT (p. 78)

Report M.2576

An area of the reverse side of the blade about 9 in. from the point was rubbed down, polished and examined under the microscope. A hardness survey was made across the polished surface. Small sections of the pieces of material used to make up the composite blade were cut and polished and their hardness determined.

Material of the component parts of the blade

These were *a*, cutting edge, round rod about $\frac{3}{8}$ in. diameter, *b*, filler rod which was round rod forged from about $\frac{7}{32}$ in. to square section, and *c*, material which had been flattened from $\frac{7}{32}$ in. round rod to strip $\frac{1}{2} \times \frac{1}{16}$ in., and then twisted into a screw.

Material *a* was thought to be mild steel: *b* and *c* were stated to be wrought iron from a Victorian summerhouse, date about 1860-1870.

a. Cutting edge material

The microstructure of a longitudinal section of the original material is shown in PL. XV, A-B. This shows heterogeneous grains of ferrite with small amounts of grain boundary carbide and some pearlite. There seemed to be rather more pearlite near the edges of the longitudinal section than in the centre. The amount present corresponded to a carbon content of about 0·03 or 0·04%. Both longitudinal and transverse sections showed a few particles of rounded slag; one is visible in the lower centre of PL. XV, B. The cutting edge material was thus not mild steel containing appreciable amounts of carbon but might better be described as a soft iron produced by a steel melting process.

b and *c*. Filler rod and twisted strip material

Both *b* and *c* had a banded microstructure of ferrite grains and slag streaks, with a small amount of pearlite or grain boundary carbide usually associated with bands of finely grained ferrite. PL. XV, C shows a typical area in the longitudinal section of the twisted strip material (*c*) at × 150, and PL. XV, D shows the form of the carbide in the longitudinal section of the filler rod *b*. The pearlite in material *c* was present mainly in the centre of the section. The material was thus wrought iron.

Microstructure of sword blade

In the unetched state bands of rounded and globular slag were visible throughout the wrought iron centre of the blade as shown in PL. XVI, B. The cutting edge was clean. Although about 0·03 in. of metal had been removed the welding between the surfaces of the centre strips was not perfect, slag filled gaps being present. On one side of the blade the welding of the centre portion to the cutting edge metal was also not continuous. In the areas where the welding was good in the centre of the blade at powers of × 50 and upwards, there was no sharp difference in structure between the filler rod and the centre screwed strip. Some bands of pearlite were observed, as shown in PL. XVI, C, but there was no evidence of any major carburization. The amount of pearlite present was similar to that present in the wrought iron before pattern welding.

The weld between cutting edge and wrought iron centre is shown in PL. XIV, B. The structure of the cutting edge metal at the join varied. Occasionally lumps of slag were present. Often a layer of fine grains ran along the join, sometimes a band containing pearlite was encountered.

The structure of the cutting edge metal was mainly polygonal grains of ferrite with a small amount of grain boundary carbide and occasional areas containing pearlite. Again no evidence for appreciable carburization was found.

In some areas distorted or elongated ferrite grains were present as shown in PL. XIV, B. The amount of pearlite shown is typical of the amount present where it occurred, but does not indicate the overall average quantity in the cutting edge metal.

Hardness determination on the sword blade and its component parts

Vickers Diamond hardness impressions under a load of 20 kg. at about 1½ mm. intervals along a straight line at right angles to the long axis of the blade were made. The values are given below:

Hardness of sword blade

		Centre of blade			
Cutting edge	Weld	Filler rod	Edges of screw strip	Weld	Cutting edge
173 182 175 178 174 Mean 176	185 164	152 153	140 147 155 153 Mean 149	193	189 189 192 180 Mean 187

Hardness of material before welding

	Cutting edge	Wrought iron	Filler rod
Transverse section	150 137 149 (Mean 145)	135 116 113 (Mean 121)	
Longitudinal section	136 120 125 125 (Mean 126)	147 146 151 135 169 (Mean 149)	199 166 143 (Mean 169)

It can thus be seen that fabrication has resulted in an increase in the hardness of the cutting edge material by about 30% whereas the hardness of the wrought iron centre of the blade has not been much altered.

Conclusions

No evidence of significant carburization during the welding process was found.

Some discontinuities in the pattern welding and in the join between cutting edge and centre were found.

The patterning in the centre of the blade was due to the characteristic structure of a series of welded pieces of wrought iron and not to carburization effects.

The cutting edge metal was harder after fabrication than before; the hardness of the wrought iron was not substantially different.

N. P. Allen,
Superintendent.

REFERENCES

1. Maryon, H. (1948) 'A sword of the Nydam type from Ely Fields Farm, near Ely,' *Proc. Camb. Antiq. Soc.*, XLI (1948), 73-76.
2. Smith, C. S. (1957) 'Decorative etching and the science of metals,' *Endeavour*, XVI (1957), 199. Although this is not mentioned by Smith, pattern-welding must have been in use in the far east—*cf.* the 19th-century 'Malayan' sword illustrated in Maryon (1960), fig. 5.
3. Maryon, H. (1960) 'Pattern-welding and damascening of swordblades,' *Studies in Conservation*, V (1960), 25-37; 52-60.
4. Neumann, B. (1927) 'Römischer Damaststahl,' *Arch. f.d. Eisenhüttenw.*, I (1927), pt. 3, 241-243. See Beck quoted on p. 242.
5. Biek, L., Anstee, J. W., and Cripps, E. S. (1952) Unpublished report on the 'Westminster sword'—Ancient Monuments Laboratory, Ministry of Works, 1952.
6. France-Lanord, A. (1949) 'La fabrication des épées damassées aux époques mérovingienne et carolingienne,' *Pays gaumais*, X (nos. 1-3, 1949), 11, figs. 5-7.
7. Rees Jones, S. (1949) Communication to Ministry of Works.
8. Janssens, M. (1958) 'Essai de reconstitution d'un procédé de fabrication des lames d'épées damassées,' *Studies in Conservation*, III (no. 3, 1958), 93-105.
9. Biek, L. (1956) 'Technology of ancient glass and metal,' *Nature*, 178 (1956), p. 1430-1434. Report of symposium held at the Sheffield Meeting of the British Association for the Advancement of Science. Includes first, brief account of experimental work at Reading.
10. France-Lanord, A. (1949) *Op. cit.* in no. 6, p. 9, fig. 4; p. 10; pl. v, no. 2, upper composite rod, right of centre.
11. *Id.*, *op. cit.* in no. 6, p. 12; pl. vi, no. 2, lower right.
12. *Id.*, *op. cit.* in no. 6, p. 7; p. 14; pl. viii, no. 3.
13. Thidrik Saga. Description of the forging of the sword Mimming by Velent. See H. R. Ellis Davidson, *The Sword in Anglo-Saxon England* (Oxford, 1962), pp. 159-160.
14. Gordon, G. F. C. (1936) *Elementary metallurgy for engineers* (2 ed., London, 1936), p. 55.
15. Liestøl, A. (1951) 'Blodrefill og Mål,' *Viking*, XV (1951), 71-98. See also France-Lanord, *op. cit.* in no. 6; but Maryon (*op. cit.* in no. 3) rejects this interpretation, and that of Janssens (*op. cit.* in no. 8).
16. Hadfield, Sir Robert (1931) *Faraday and his metallurgical researches* (London, 1931), pp. 76-7. Account of work carried out by J. Stodart included in a letter to W. Nicholson published in 1804 but describing a paper 'some ten years earlier'.
17. Brearley, H. (1910) 'Use of microscopic methods in relation to industrial problems,' *Sheffield Soc. Engrs. and Metallgsts.*, 1910, figs. 74, 76.
18. E.g., Polushkin, E. P. (1956) *Defects and failures of metals* (London, 1956), p. 30. The reagents listed for 'developing' phosphorus segregation all contain copper, which is in some cases deposited firmly on steel but not iron.
19. Chilton, J. P., and Evans, U. R. (1955) 'The corrosion resistance of wrought iron,' *J. Iron & Steel Inst.*, 181 (Oct., 1955), pp. 112-122.
20. France-Lanord, A. (1952) *Revue de Métallurgie*, XLIX (no. 6, 1952), 417, pl. vi, 1, centre of blade.

ACKNOWLEDGEMENTS

We are much indebted to many friends and colleagues for help of all kinds, and particularly to the following:

Mr. K. J. Barton, Mr. E. S. Cripps and Mr. W. E. Lee, for some of the X-radiography and help in assembling the paper; Mr. W. E. Carrington for most of the metallographic work and helpful discussion; Mr. P. Cornwall for some of the hardness testing; Mr. J. B. Wade for some of the metallographic work and helpful discussion; to Mons. A. France-Lanord for permission to reproduce the illustration shown in PL. IV, D; to the Director, British Welding Research Association, for permission to publish PL. XI, A and B; to Professor H. O'Neil, Dr. D. E. Davies, Mr. A. P. Greenough, Mr. S. Rees Jones, Mr. H. Maryon, Mr. D. W. Brown, Mr. C. S. Smith and Mr. H. H. Coghlan for valuable technical discussion; to Mrs. H. R. Ellis Davidson for providing documentary evidence and much helpful discussion and encouragement; to Mr. G. C. Boon, Mr. F. Jenkins, Mr. S. S. Frere, Mr. T. L. Gwatkin, Mr. L. Helliwell, Mr. S. Atkins, Mr. J. E. Bartlett, Mr. S. E. Overal, Mr. H. V. Radcliffe, Mr. J. Wymer and Mr. J. T. Wilson for assistance in obtaining access to specimens and permission to publish results of examination; and to the Principals and Staff of Institutions specifically mentioned in the text for work done and for permission to publish.

EXPLANATION OF PLATES

IV A. Portion of blade of Palace of Westminster sword (pp. 72, 85) half-cleaned to existing metal surface.
B. The same, cleaning completed: note change in pattern at X.
C. Reading, 288.47 (Table I): detail of pattern in depth 'revealed' by corrosion and removal of corrosion products.
D. Musée Lorrain (see reference 20, pl. vi, no. 5): section of blade with multiple core showing pattern due to two composite rods, at the present surface.
E. Ninth experiment (p. 84): portion of blade with about half the thickness removed: polished and etched. Note basic striation in untwisted cutting edge (characteristic of 'piled' metal) and remarkable similarity to D.

V A. Second experiment (p. 74): twisted components and step-grinding of welded bar, showing steps in edge.
B. The same, showing progressive change in surface pattern with decreasing thickness (right): note variation in texture of individual units.
C. Fourth experiment (p. 76). (*a*), finished product with small amount of surface removed, showing primary chevron pattern: note recurrence of slight variants; (*b*), composite rod before assembly into core: note overtwisted portion (similar phenomena have been observed on a number of swords).
D. Reverse of C, *a*. Surface at three levels: end portions, as for C, *a*; right centre, plane parallel to surface after *c.* $\frac{1}{4}$ of the thickness has been removed; left centre, ditto, after $\frac{1}{2}$ of the thickness removed. Only in left-centre portion can individual strips be positively identified.

VI A. Third experiment (p. 75). Finished product and specimens representing various stages of manufacture: note 'watering' similar to 'true damascene' effect.
B. Fifth experiment (p. 77). Triple composite rod showing (l.) beginning of twist, with two cutting edges at tip (left unfinished), forged from one rod, as shown. Central portion taper-ground in shallow arc from l. to r., with minimum thickness (*c.* $\frac{1}{2}$ removed) at centre, showing typical whorled patterns.
C. Sixth experiment (p. 77). Finished product with (r.) an original rod, flattened at one end, and (l.) specimens of raw cutting-edge rod (above) and composite rod (below). Note recurrent groups of pattern in blade (as in PL. V, C, *a*).

VII A. Seventh experiment (p. 78). Assembly of a single core (one composite rod) from (*a*), three flattened rods, and (*b*), two square filler rods, into (*c*) an unwelded composite rod very lightly twisted; (*d*), attachment of cutting edges; (*e*) view of edge of complete blade section.
B. The same. Roughly forged, completed blade before grinding.
C. The same. Surface taper-ground (to r.), polished and etched, showing change in pattern (from diagonals to whorls) as thickness decreases.

VIII A. Enlargement of PL. VII, C at approximately natural size showing detail of pattern. Weld seams, running along centres of light-coloured areas, are not visible until magnified at least 50 times.
B. Eighth experiment (p. 80). (*a*), typical strip; (*b*), three strips and two filler rods assembled into composite rod; (*c*), polished and etched tip of sword core (discarded) consisting of three composite rods and two splitter strips, with cutting edge welded round point.

IX A. Reverse of PL. VIII, B, *c*, showing surface as forged, with cutting edge.
B. Two views of final core before attachment of cutting edges. Note that seams show need for fullering; also, reduction of core on attachment of cutting edge. Sc. for B, I, as A.

X A. Eighth experiment (p. 80). Completed sword and scabbard.
B. Ninth experiment (p. 84). Twin core twisted from shingled, piled bar, with cutting edge of same material untwisted; roughly forged completed blade (see PL. IV, E).

XI A. Unwelded composite rod (p. 84), cross-section, × 4, showing construction, with slag in joints.
B. The same, × 100; portion of central strip (complete width), showing microstructure uniform throughout.
C. Eighth experiment (p. 80). Portion of core: finished surface, × 3, showing pattern.

XII Radiographs of blades listed in Table I: A=AN (no. O. 2101); B=AP; C=D; D=H.

XIII Photomicrographs of the Palace of Westminster sword (pp. 72, 89). A. Area in centre of blade, near hilt. B. Field in A, above large inclusion. C. Area in centre of blade. D. Field near C.
Etch: 3% nitric acid in alcohol swabbed on for 15 seconds.
Note: The photographs were taken with the hilt always at the bottom of the photograph and the long axis of the blade parallel to the longer edge of the print.

XIV A. Hilt end of Palace of Westminster sword (Sc. *c.* $\frac{1}{2}$).
B. Seventh experiment (p. 91). Structure at weld between cutting-edge metal and patterned centre portion of sword blade; etched 15 seconds in 2% nitric acid in alcohol.
Note: In PLS. XIV-XVI all photomicrographs of the sword are mounted so that the short side of the print is parallel to the long axis of the sword.

XV Seventh experiment (p. 90). A, B. Longitudinal section of cutting edge material (*a*); etched 12 seconds in 2% nitric acid in alcohol. C. Longitudinal section of screw material (*c*). D. Filler rod (*b*). Both C and D etched 10 seconds in 2% nitric acid in alcohol.

XVI The same. A, B, C. Centre of sword blade. D. Weld between cutting edge and patterned centre portion of sword blade. A, C, D etched 15 seconds in 2% nitric acid in alcohol. B, unetched.