Does pattern-welding make Anglo-Saxon swords stronger?

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Abstract

The purpose of pattern-welding, used for the construction of some Anglo-Saxon swords, has yet to be fully resolved. One suggestion is that the technique enhanced the mechanical properties of a blade. Another explanation is that pattern-welding created a desired aesthetic appearance. In order to assess whether the technique affects mechanical properties, this experimental study compared pattern-welded and plain forged blanks in a series of material tests. Specimens were subject to tensile, Charpy and Vickers diamond hardness testing. This was to investigate the relative strength, ductility and toughness of pattern-welding. The results were inconclusive, however the study revealed that the fracture performance of pattern-welding may owe to its use. This paper arises from work conducted in 2006-7 as part of an undergraduate dissertation under the supervision of Dr. Catherine Hills (Department of Archaeology, University of Cambridge).

Introduction

Pattern-welding is the practice of forging strips (sheets and rods) of iron, sometimes of different composition, that have often previously undertaken physical distortions such as twisting and welding (Buchwald 2005, 282; Lang and Ager 1989, 85). It was mainly used in the production of swords and spearheads. The purpose of pattern-welding, however, remains debated. This study sought to understand the purpose of pattern-welding through experimental investigation, with particular reference to why it was used to manufacture some Anglo-Saxon swords. In order to establish whether pattern-welding improved the mechanical properties of a sword, a sample was created and compared to a plain forged control sample. The standard material testing methods employed to compare samples investigate strength, toughness and hardness. Before presenting the methods and results of this experimental study, this paper begins with a short review of the archaeological evidence, followed by a background to academic research and discussion, of pattern-welding.

It is not within the scope of this paper to explore aesthetic arguments about pattern-welding and so only one purpose is investigated here, the suggestion of improved mechanical properties. It is important to realise that perceptions of 'strength' may be conceptually different to modern notions, which often pertain to functional and physical properties. For instance, a recent investigation into the distribution of Anglo-Saxon swords has highlighted that perceived strength may be related to origins of manufacture (Birch 2011). The perception of swords as animated objects of strength, as revealed in Anglo-Saxon depictions of swords in art and literature, will be explored in a future paper.

The archaeological evidence for pattern-welding

One of the earliest examples of pattern-welding known from Britain is a blade fragment found in lake Llynn Cerrig Bach (Anglesey, Wales), dated between the 2nd century BC and the mid-1st century AD (McGrath 1968, 79). Other examples have been found in mainland Europe, demonstrating that the technique has its origins in the Late Iron Age. Pattern-welding is more commonly associated with swords and spearheads found in Northern Europe from the 2nd to the 6th century AD, particularly the famous war booty sacrifices found in Southern Scandinavia (Buchwald 2005, 264–291). Fourteen double-edged blades deposited at Vimose (Denmark) were pattern-welded, dating to 210–260 AD and likely to be of Roman manufacture (Davidson 1962, 32; Jensen 2003, 229–230; Maryon 1960a, 27). Ninety pattern-welded blades have also been recovered from Nydam (Denmark). Contemporaneous with the corpus found in Anglo-Saxon Britain, pattern-welded swords have also been found on the continent in Frankish and Alemannic graves, and also in Latvia (Davidson 1962, 33; Tylecote and Gilmour 1986, 253).

The technique of sword manufacture reached its peak during the 6th and 7th centuries AD and is generally accepted to have ‘passed out’ by the end of the Viking period, declining notably during the ninth century (Jones 2002, 145; Thålin-Bergman 1979, 122). It is unclear whether the decline was due to fashion, or availability of better ores and steel (Davidson 1962, 32; Lang 2009, 239; Tylecote and Gilmour 1986, 253). More recently, religion has been cited as another factor in explaining the demise of pattern-welding (Gilmour 2010). Pattern-welding did, however, continue into the 12th century in the manufacture of seaxes, mainly in continental Europe (Tylecote and Gilmour 1986, 253).The technique was also used for constructing samurai blades in Japan, particularly with the Gwassan school during the 16th century, and was also used to produce the Malaysian kris of South-East Asia (Craddock 1995, 272–273; Davidson 1962, 35; Maryon 1960a, 35). Pattern-welding should not be confused with damascening, which is distinctly different (Anstee and Biek 1961, 71; Craddock 1995, 275; Maryon 1960b, 52).

The purpose of pattern-welding: a history of archaeological interpretation and experimentation

It was the experimental work of Maryon (1960a, 1960b) and Anstee and Biek (1961) that has allowed us to understand how pattern-welded swords were made. Despite this achievement, the purpose of the technique still remains to be clarified. Was the technique primarily functional in that it improved the physical qualities of the sword? Or, was it intended to enhance the decorative appearance of the object?

Initial studies by France-Lanord (1980) in 1948 and by Salin (1957) concluded that pattern-welded swords were physically superior to ordinary blades because they were extremely hard, highly flexible and very sharp. In 1961, Anstee and Biek's experiments concluded that the pattern created by twisting the composite iron rods was merely a by-product of its functionality (1961, 85). Tylecote also argued that the technique introduced carbon deeper into the blade and increased its hardness (1962, 250). It seemed, therefore, that pattern-welding was deemed to be a technique to improve the physical properties of an object.

However, Tylecote's opinions changed in later publications, and so did the overall discussion on pattern-welding. He stated that it was unclear whether pattern-welding made weapons appreciably stronger than simple piling (Tylecote 1976, 57), before later arguing that the technique was more concerned with appearance. An investigation into edged weapons by Tylecote and Gilmour concluded that pattern-welded swords were primarily designed as ornamental or prestigious weapons and that the, “complexity of the patterns bore little relation to the overall functional qualities of the blade” (1986, 251). They further argued that phosphoric-iron was utilised to emphasis the patterned appearance of the blade rather than improve its physical properties (1986, 249, 251). Tylecote concluded that pattern-welding was principally employed for its decoration, whilst also acknowledging the technical improvements that resulted from the technique.

Some Viking and Carolingian swords have a composite construction with thin layers of pattern-welding welded to a core, like a veneer. This has led some scholars to believe that the technique was mainly intended to be decorative (Ypey 1983), employed predominantly for its aesthetic and symbolic qualities (Craddock 1995, 271–2; 2010; Leahy 2003, 123). The suggestion that pattern-welding was primarily decorative has often been opposed to the alternative explanation of improved function. More recently it has been suggested that while one purpose was intended, the other may incidentally have been achieved.

As a result of their extensive X-radiographic study, Lang and Ager (1989) concluded that the main purpose of pattern-welding was for its appearance. However, they acknowledged that, “at present there is insufficient evidence to determine whether pattern-welding was primarily for strengthening or decoration, but it is clear that the latter was important” (Lang and Ager 1989, 115). The purpose of pattern-welding remains elusive partly due to the absence of conclusive evidence for either the aesthetic or functional argument.

This study arises from the state of knowledge as of 2006, where experimental research seemed the logical way forward. Experimental work has become the main focus of more recent studies into pattern-welding in a bid to resolve, if possible, the primary purpose of the technique. Comprehensive work by Janet Lang (2007; 2009; 2011), brought to the attention of the author during the preparation of this paper, has provided invaluable insights into the technique. Her experiments into the mechanical properties of pattern-welding have demonstrated that twisting of different irons improved some physical properties of the metal. Practical experiments by Pelsmaeker (2010, 74) concluded that pattern-welding did provide improved weapon performance over 'mono-steel' blades. The subjective nature of Pelsmaeker's (2010) testing methods, however, prevents any objective comparison. The test results presented in this study aim to complement the empirical work achieved so far.

The Anglo-Saxon sword: manufacturing the experimental samples

In order to prepare the samples necessary for testing the physical properties of pattern-welding, careful consideration was taken in the selection of material, construction design, heat treatment and surface treatment. Two samples were made for comparison. A pattern-welded sample (PW) and a non-pattern-welded control sample (NPW). Whilst PW was constructed from multiple units, the control sample NPW was simply forged from a single piece of iron.

The samples were manufactured by blacksmith Hector Cole at his forge in Little Somerford (Wiltshire). Each sample was cut into three equal sized pieces that formed the blanks used for sub-sampling to produce the specimens for mechanical testing. The aim of this experimental approach was to best resemble pattern-welding of an Anglo-Sword construction, for testing, as is evident in the archaeological record.

Material

The metallographic analysis of Anglo-Saxon swords and the Nydam blades has shown that many were piled together from irons of different composition, with varying content of carbon, phosphorous, as well as other alloying elements like nickel and sulphur. The Nydam blades were constructed of high and low-carbon irons, whereas the Anglo-Saxon blades were consistent in their use of low-carbon irons. The Anglo-Saxon swords, however, utilised high and low-phosphorous irons, that may have been exploited to enhance the contrast in appearance of the patterns on the blade. It may also have been utilised for its ability to harden iron (Goodway 1999). Due to the low-carbon content, it may also have strengthened the iron without embrittling it (Goodway and Fisher 1988, 22). It is accepted that the modern materials adopted in this study may not be similar to those available to Anglo-Saxon smiths. However, considering the variability in stock material used to construct pattern-welded swords in antiquity, determining the right material to use becomes a practical impossibility. PW was constructed from a low-carbon iron (0.2% C) and Victorian phosphoric wrought iron. NPW was made from a single piece of low-carbon iron, the same used to make PW. Both PW and NPW were made to the same dimensions.

Design and construction technique

Experimental work by Maryon (1960) and Anstee (1961) provided the final verdict on how pattern-welding was achieved. Not only did they demonstrate a far simpler method than earlier suggestions, but their method is now widely accepted as being correct. It involves the twisting of multiple rods that are forged together into bundles, where several bundles are then forged together to produce the final product. As a result, the earlier proposals for the pattern-welding process were discredited. In 1948 France-Lanord attempted to construct pattern-welded blades via a repeated folding technique. Another proposed construction by Janssens (1958) involved the coiling and welding of a composite strip around a pentagonal core, subsequently removing selected sections. The latter two suggestions were contested due to the great deal of time and effort they required as well as their impracticality. Therefore, the construction technique adopted in this study follows the process outlined by Anstee and Biek (1961).

The design selected for constructing PW is shown in Figure 1, corresponding with pattern 'B1' identified in Lang and Ager's (1989) study of Anglo-Saxon swords. Whilst a variety of different patterns exist for Anglo-Saxon swords, the selected design appears to be one of the earliest and most common patterns from the 5th to 7th century AD. Any original purpose of pattern-welding may relate to the earlier designs, as opposed to the more complex patterns and constructions that appear later.

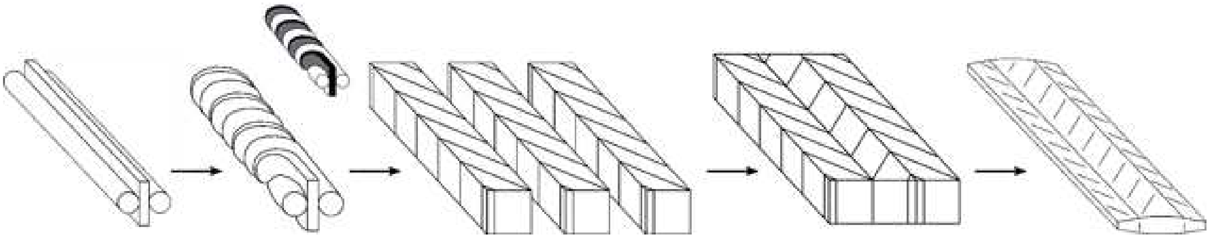

Fig 1. A diagram showing the stage by stage process for the pattern-welded construction of PW. The flat strip that is twisted with two rods (used to make a bundle) is highlighted in grey in the smaller image accompanying the second stage. Three bundles are finally welded and forged together.

Having examined the X-radiographs of the swords at the British Museum of the B1 design, it was observed that the width of the bundles and the interval between twists varied greatly within and between swords. The width of the bundles of the Hurbuck (Durham) sword varied between 8–10mm, with some areas reaching a minimum width of 4mm. The interval between twists varied between 4–7mm. The Faversham blade was much more consistent, where intervals between twists were consistently 2–3mm. The thinner the flat strips, the closer together they can be twisted, and thus the greater angle they make with the axis of the rod during twisting (Maryon 1960a, 29). Due to the variability presented in the archaeological record, no specifications were made for the interval measurements between twists, nor the angle of the twists for constructing PW.

The construction of PW (Figure 1) was achieved by forging together three bundles, each containing three rods (two round and one flat). The flat rod (strip) in combination with the two round rods creates the tightest twist (compared to three round rods) and minimises the gutters or grooves created during twisting, trapping less slag and reducing the likelihood of unwelded seams. The bundles were twisted to their full tightness. The angle of the flat strips to the rod was 45–46º. The three finished bundles (composite rods) were then welded and forged together. The central bundle remained a consistent width of 7mm. The two outer bundles reached a maximum of 10mm, due to their slight widening during hammering. As already stated, PW and NPW were forged to the same dimensions. The purpose of this study was to focus on the properties of pattern-welding and so this variable was isolated for investigation. No edge material was adopted in constructing PW as this would qualify as another variable and technical feature worthy of investigation in its own right. Any investigations into replica pattern-welded swords with cutting edges will overall reflect sword performance and not necessarily the properties of pattern-welding.

Heat treatment

The affect of heat treatment on the blade depends very much on the carbon content, whereby increased amounts of carbon means the blade is more likely to be affected. The pattern-welding technique introduces more carbon into the blade than simple case-hardening, whereby the rods and strips are being carburised on their surfaces when introduced to the oxidising part of the hearth. These carburised surfaces are subsequently twisted and interned into the blade. Any heat treatment is more likely to affect PW due to the likelihood of its increased carbon content.

Anstee and Biek (1961) compared the outer bundles in experiment number 8 before and after being tempered and annealed. They demonstrated increased tensile strength and hardness values after heat treatment. The archaeological evidence for heat treatment in Anglo-Saxon swords, however, shows chronological variation as well as different types. Tylecote and Gilmour's (1986) study revealed that most of the early Anglo-Saxon pattern-welded swords were not quenched. Of the eighteen early Anglo-Saxon swords examined, only six show evidence of heat treatment in the form of quenched cutting edges to achieve a greater edge-hardness (Tylecote and Gimour 1986, 245). Two middle Anglo-Saxon swords examined were quenched, most likely in water. Of the eleven swords dating from the ninth to the eleventh century AD, five were heat treated. One was possibly quenched in oil, two in water, and another two were tempered and annealed (ibid, 248). Due to the evidence for heat treatment in some Anglo-Saxon swords, both PW and NPW were quenched in water upon being finished at red heat (about 800–900ºC). They were not annealed.

Surface treatment

Most Anglo-Saxon pattern-welded swords do not show signs of being ground away and few had fullers. It appears there were differences in surface treatment between the British swords and continental types that go beyond the scope of this paper. No surface modification in the form of grinding, polishing or etching took place on the samples. Test specimens were prepared from PW and NPW in their as-finished condition.

Examination of the samples: X-radiography and metallography

Prior to the sub-sampling for the preparation of test specimens, PW and NPW blanks were examined for any internal faults. This was achieved through X-radiography and an assessment of the microstructure. Standard radiographic exposures of the samples (2–3mm mean thickness) were obtained with a Pantak 160kV CP Unit using fine-grained Fuji 80/50 film, with an accelerating current of 20mA and a 60s exposure time. The source dimension was 3mm with a focus film distance of 80cm and a 90º beam angle. The X-radiographs were viewed on a light-box with a tube current of 90kV. Macro-section from PW and NPW were etched using nital and examined to assess the microstructure using a metallographic microscope in reflected light mode.

Fig 2. Photograph (top) and corresponding X-radiograph (bottom) of the six blanks used in this study: first three blanks are from sample NPW and the last three blanks are from sample PW. The design of PW can be seen in the accompanying close-up image of the surface of one of the blanks (right).

The X-radiograph (Figure 2) showed that the weld seams in PW were successful throughout the sample until the remaining *c*. 15mm of one end, where the weld terminates unsuccessfully (cavities observed). A macro-section extracted from this area showed that the two weld interfaces between the three composite rods were successful in the central portion of the blade section, but that they became more partial and eventually incomplete towards both surfaces of the sample (Figure 3).

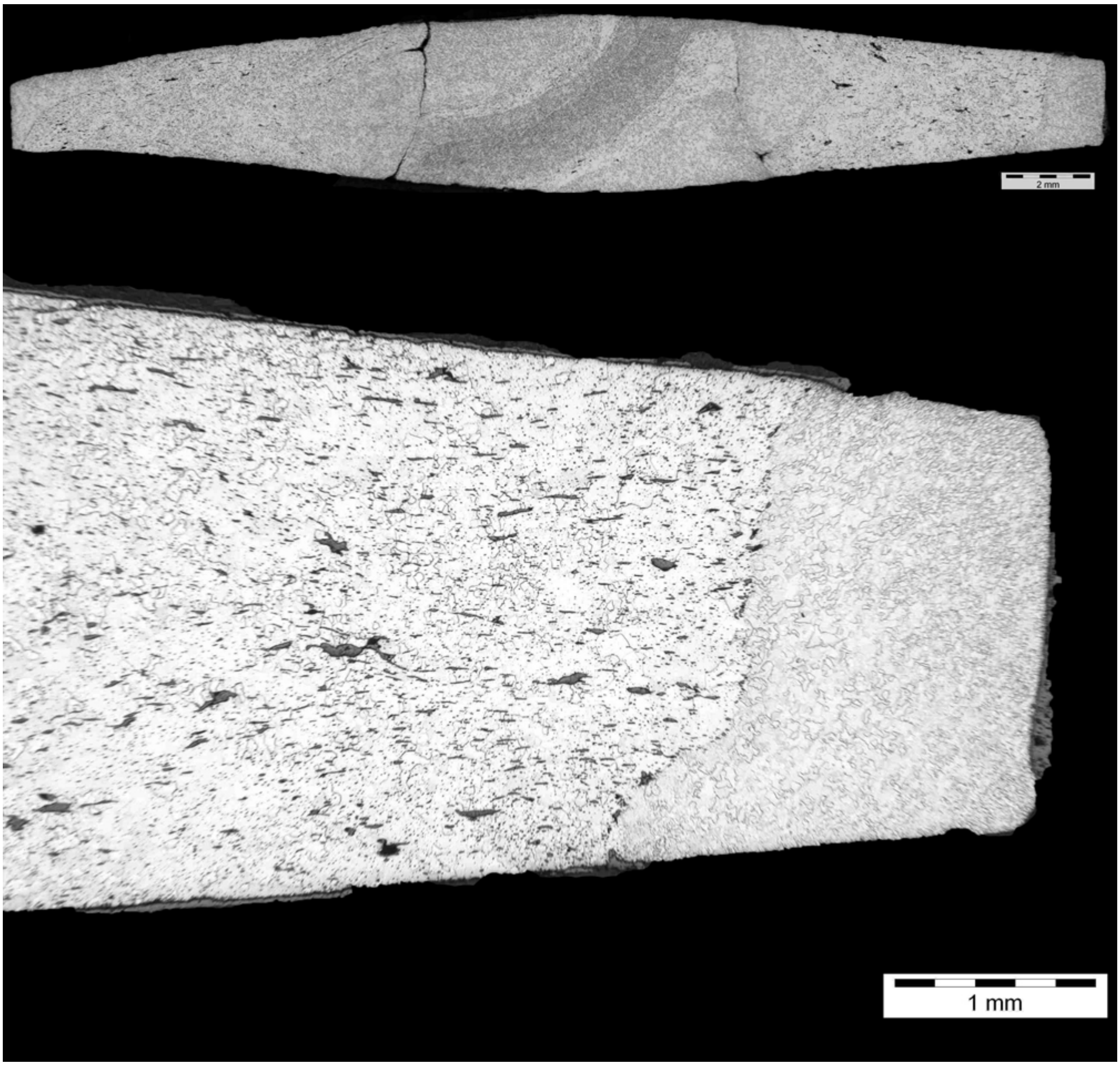

Fig 3. The macro-section of sample PW (top), highlighting the localised failed weld seam with its cavities identified through X-radiography; two distinct zones (bottom) defined by the presence and absence of slag inclusions, with uniform recrystallised ferrite grains and an uneven distribution of carbon (pearlitic structures) due to the different irons used in the manufacturing process.

Varying grain sizes were observed in PW owing to the different irons used to manufacture the sample. The macro-section of PW, seen in the montage of Figure 3, revealed that the sample had one well defined region of unevenly distributed slag inclusions and a few areas of oxidation along weld-line interfaces (Brick and Phillips 1949, 41; Nutting and Baker 1965, 121).

No faults were observed in NPW. The montage of NPW, seen in Figure 4, shows a uniform structure of recrystallised ferrite grains with no pearlite observed. Some spherodised carbides were observed. The recrystallisation of the ferrite grains, usually indicative of annealing, shows here that the sample was not cooled rapidly. Oxides were observed in places along the surface of the sample, indicating some oxidation took place as part of the forging and/or quenching process.

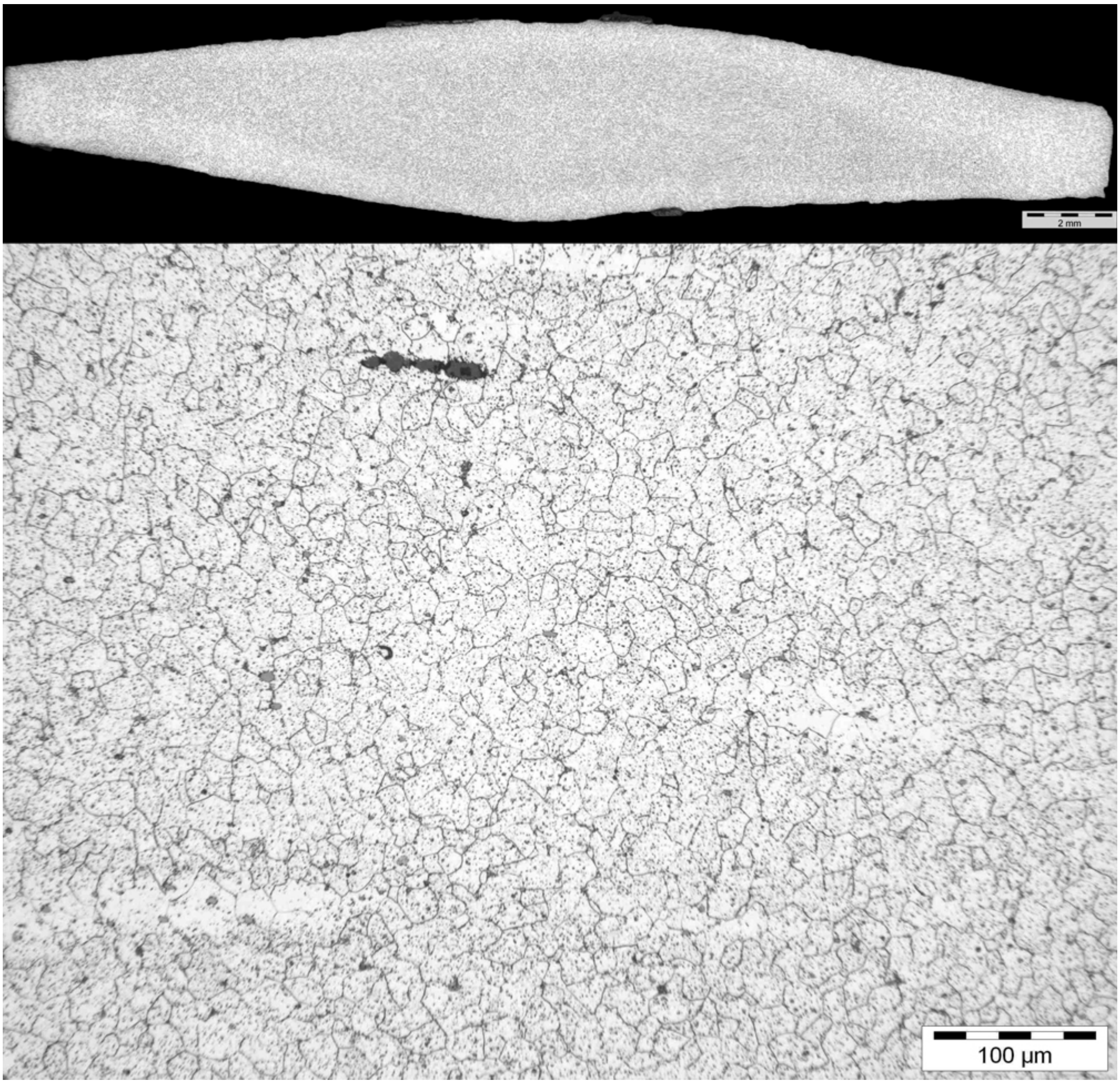

Fig 4. The macro-section of sample NPW (top), showing uniform recrystallised ferrite grains containing spherodised carbides (bottom).

Mechanical testing for the properties of pattern-welding

This section describes the three tests that were performed on PW and NPW to test for strength and ductility, resistance to fracture and hardness. PW and NPW were cut into three equal sized blanks that were sub-sampled to produce the necessary test specimens for tensile, Charpy and Vickers micro-hardness testing. The examination of PW and NPW outlined in the previous section proved invaluable in deciding the locations from which to extract test specimens. A schematic diagram of the sub-samples removed for testing can be seen in Figure 5.

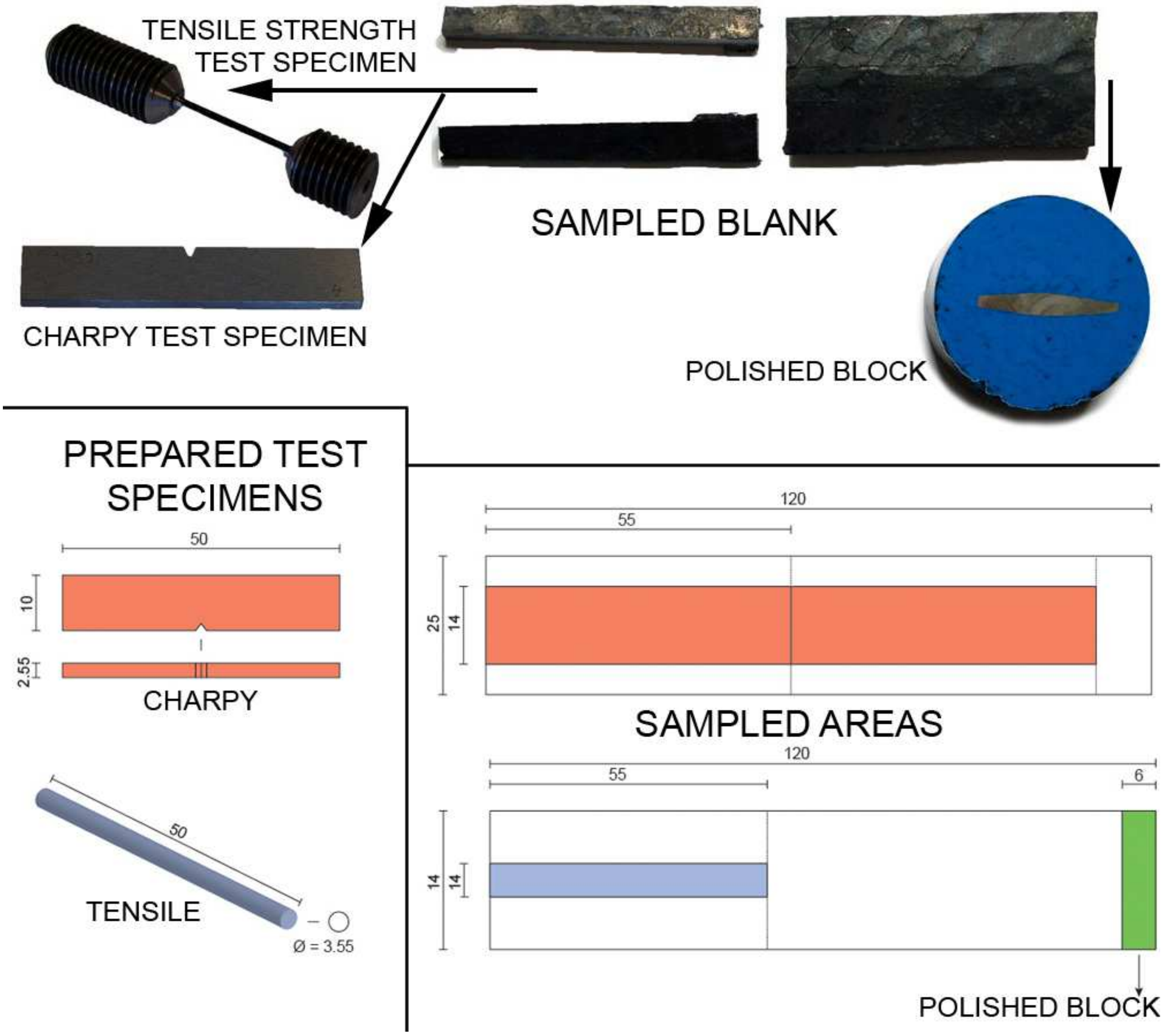

Fig 5. Schematic diagram illustrating the sub-sampled locations to produce the test specimens. The three blanks for both PW and NPW were sampled as follows: one blank to produce two Charpy specimens (red), two blanks to produce tensile specimens (blue), one blank of which also produced the macro-section (green). Measurements are provided in

millimetres. An example of a sampled PW blank with accompanying images of prepared test specimens can be seen in the top image.

Ultimate tensile strength testing

Two cylindrical tensile test specimens (Ø=3.55mm) were prepared from both PW (avoiding the identified faults) and from NPW blanks in accordance with standard requirements. These were subjected to standard ultimate tensile strength testing using an Extensometer number 100S/135 which was calibrated to BS EN ISO 9513:2002 class 1.0 requirements. The test for ultimate tensile strength provides information about the strength and ductility of the material being tested.

The test reveals the elastic limit of the material, whereby the strain (caused by the load) is elastic. When the strain no longer returns to zero (as the load is increased) the specimen is being plastically deformed permanently. A point is reached where the material continues to plastically deform without an increase in the load. This is known as the yield point. The tensile testing in this study will not measure the yield point, but instead will measure the proof stress (the stress value for a small amount of permanent plastic strain). This is because some steels do not exhibit a yield stress. The test will also determine the ultimate stress reached (the maximum stress the material reaches), providing a measure of the ultimate tensile strength.

The behaviour of a specimen during testing is also informative about the materials ductility. A brittle material will usually break and fail at the ultimate strength. A ductile material will continue to stretch as the load is increased, plastically deforming in order to reduce the stress. The elongation of the specimen (how much it has stretched) and its reduction in area (minimum cross-sectional area) are measures of ductility. A ductile specimen will not only stretch uniformly, but it will exhibit a trait known as 'necking'. Necking describes the non-uniform deformation that occurs at a localised area in the specimen as the load is further increased. It is also the point where the specimen will fail.

The Charpy test

Two test specimens (55mm x 10mm x 2.55mm, with 2mm V-shaped Charpy notch) were prepared from both PW and NPW blanks in accordance with standard requirements. Two

Charpy tests were conducted at different temperatures; the first test at room temperature (23ºC) and the second test at 5ºC. This was to assess whether differences in temperature may affect the toughness of the specimens. The test specimens were subjected to 300 Joules nominal striking energy and the machine calibrated to BS EN 10045-2:1993.The Charpy test measures the amount of energy that can be absorbed by a test specimen on impact until it fractures. A pendulum is swung to fracture the specimen on the side opposing the V-shaped notch. The amount of energy required to fracture the specimen is measured (in Joules), thus measuring impact toughness. It measures a material's impact resistance to fracturing.

The sub-sampling for one PW specimen included the unsuccessful weld-seam area previously identified, as priority for specimen preparation was given to tensile specimens. Despite the constraints of the study the affected sample was still deemed worthy of investigation.

Vickers diamond pyramid test

One macro-section was removed from both PW and NPW to produce a standard metallographic polished block. Each section was prepared in a hot-setting Bakelite phenolic resin using dialylphthalate glass fibre as a backing material to promote good edge retention, and then flatly polished. A 10kg load was applied using a Vickers diamond pyramid indentor that was calibrated to test specification BS EN ISO 6507-1:2005. Seven hardness values were obtained for each macro-section (measuring the square-based diamond pyramid indentation along the traverse of the specimen). The resistance to indentation provides a measurement of the specimen's hardness and resistance to the load being applied.

Results

The results of the tensile, Charpy and Vickers diamond hardness testing of PW and NPW are presented here. A discussion of the results follows this section with special attention paid to fracture performance. The empirical data presented here should be regarded as informative and complimentary to previously published studies.

Strength and ductility

The tensile testing results are presented in Table 1. Both NPW specimens fractured outside the central third, as did one PW specimen, not in meeting with standard requirements (inside the central third) for a satisfactory test. Fractures outside the central third usually give values lower than those that would be obtained from within the central third. Therefore, the results for the three unsatisfactory tests are likely to be lower than they should be. Despite only one specimen fracturing successfully inside the central third, the results show differences between PW and NPW specimens.

	Specimen	Proof stress (N/mm^2)	Maximum stress (N/mm^2)	Elongation (%)	Reduction in area (%)
NPW	1	331	422*	33.0	55.0
	2	343	430*	33.0	64.0
PW	1	290	409	31.5	43.0
	2	302	413*	25.5	24.0

Table 1. The tensile strength test results for two specimens extracted from NPW and the two from PW. The asterisked results mark specimens that fractured outside the central third.

NPW specimens exhibited greater proof-stress and ultimate strength values than PW, and it is likely that these values should be higher than those obtained. The maximum difference of 21 N/mm^2 between NPW and PW should be considered marginal. Although NPW specimens are consistent at 33% elongation, there is no immediate clear difference to the elongation values obtained for PW specimens. The greatest difference recorded between NPW and PW specimens is the reduction in area, where the maximum difference is up to 30%. The tensile test results would indicate that NPW specimens are more ductile than PW, which is likely due to the uniformity of the material, compared to the heterogeneity imposed by PW's composite construction. One PW specimen displayed interesting features in the fracture surfaces, which is addressed in more detail later on.

Impact toughness

The Charpy test results showed that both NPW specimens required more energy to fracture than PW specimens (Table 2). At both room temperature and 5ºC, NPW specimens required around 5 Joules more than their PW counterparts to fracture on impact testing. More energy was required to fracture NPW and PW specimens at 5ºC than at room temperature, indicating that they increased, if not maintained, their toughness at lower temperature conditions. NPW specimens exhibited greater lateral expansion compared to PW. Lateral expansion increases with toughness, and so the difference confirms the Charpy test results that the NPW specimens were somewhat tougher than the PW specimens.

	Toughness (Joules)		Lateral expansion (mm)	
	23ºC	5ºC	23ºC	5ºC
NPW	19	20	1.29	1.40
PW	14	16	1.18	1.14

Table 2. The Charpy test results of NPW and PW specimens being impacted at room temperature (23ºC) and at 5ºC.

The fracture performance of the Charpy test specimens is worthy of note. Both NPW specimens fractured completely with smoother surface planes compared to the ragged tears observed in the two PW specimens. One PW specimen (5ºC) failed to fracture completely and remained partially intact. A more detailed discussion of the differences in fracture performance will follow later.

Hardness

There is no significant difference between the mean Vickers hardness values obtained for PW and NPW (Table 3), which can be confirmed by a two-sample T-test. The more interesting observation is the variation in hardness values. Greater variation in hardness values can be seen in PW with a maximum of 156 and a minimum of 108, reflecting the uneven carbon distribution. The values across the macro-section of NPW are more consistent, confirming the uniformity of the microstructure and absence of pearlitic structures. The reader may wish to compare the hardness values of PW and NPW to other reconstructed pattern-welded samples provided by Hector Cole that were also tested as part of this study (see Appendix 1).

	Hardness (Vickers)							Mean
NPW	136	142	138	133	133	121	128	133.00
PW	138	138	108	139	124	136	156	134.14

Table 3. The seven Vickers hardness values obtained traversing along the macro-sections of PW and NPW samples, provided with the mean value.

Evaluation of the mechanical tests

There are many variables to consider when discussing these results. Before discussing the qualitative results, a comment should be made on the test values obtained by tensile and Charpy testing. In evaluating the experiment, two uncontrolled variables exist in the form of grain size and inclusions. These were unintended and future experiments should seek to promote material comparability.

Non-metallic inclusions often serve to reduce fatigue strength, and so the slag inclusions present in PW (compared to the near absence of inclusions in NPW) is a likely explanation for the difference in the values obtained. Similarly, the predominance of a smaller grain size in NPW is also likely to have contributed to its greater performance. The influence of grain size and slag inclusions may be inferred from the PW tensile specimen test results. Although one PW specimen appears to have failed along a weld-line interface (Figure 6), it is unlikely that this is the cause for the low tensile value (413 N/mm^2) because the second PW specimen (clean fracture) value is similar (409 N/mm^2), pointing towards other causes (grain size and inclusions).

The economic constraints of this study only allowed for a small sample size. Future experimental investigations should employ a relevant sample size in order to subject results to more rigorous statistical methods, lending greater weight to any conclusions being drawn. It is fair to state that the information generated in this study is inconclusive. However, that does not mean to say it is not informative, as will now be highlighted.

Discussion: the fracture performance of pattern-welding

The nominal values obtained by tensile and Charpy tests should be considered in conjunction with the qualitative results. Differences observed in the fracture surfaces between specimens may also lead to conclusions about fatigue behaviour.

A macroscopic examination of the fracture planes of the Charpy specimens revealed differences between PW and NPW (Figure 6). In short, NPW specimens produced largely smooth flat planes, a fracture characteristic of brittle materials. By comparison, however, PW specimens produced rough undulating fracture plans more often associated with ductile materials. As already described, one of the PW Charpy specimens failed to completely fracture (Figure 6). This Charpy specimen remained partially intact, bridged by an unbroken rod in the central bundle.

The composite construction of PW may affect the behaviour of crack propagation. The 'fibrous' nature of PW inhibits crack propagation because the rods, which can be considered as 'fibres', act behind the propagating crack. This is an extrinsic fracture toughening mechanism known as contact shielding, where the rods absorb energy and encourage crack closure. As observed in the aforementioned Charpy specimen, the crack terminated at the single unbroken rod, along which the specimen remained intact. The shear lips on the second PW specimen also infer this ductile quality.

Conclusion

NPW values for proof-stress and ultimate tensile strength (maximum stress) were marginally greater than PW, indicating that NPW specimens were slightly stronger. The clearest difference between NPW and PW in tensile testing was the reduction in area, where NPW was deemed to be more ductile. Although both exhibited increased toughness at 5ºC, Charpy testing confirmed NPW to have a greater toughness than PW specimens. The differences in quantitative results are best explained by the observations made in the microstructures of NPW and PW, owing mainly to differences in grain size and inclusions.

The qualitative differences observed in fracture performance between PW and NPW may indicate one of the favourable properties of pattern-welding, and indeed its use in Anglo-Saxon swords. The composite construction of a pattern-welded sword means it is more likely to remain intact along one of its core rods than a uniform blade made from a single body of iron. The fibrous quality promotes crack closure. The rods utilized to form a pattern-welded construction may be likened to the thin veneer sheets used to form 'plywood'. Fracturing plywood against the grain will not succeed in a clean, or necessarily complete, fracture. The analogy between the composite rod construction of pattern-welding and 'plywood' (or 'fibres'), helps to highlight one of the potentially important properties of pattern-welding. Pattern-welding may have deliberately intended to achieve this type of fatigue behaviour, compared to the clean and complete fracture that is achieved from a uniform microstructure. Keeping a sword together under physical stresses no doubt would have been a desirable physical property.

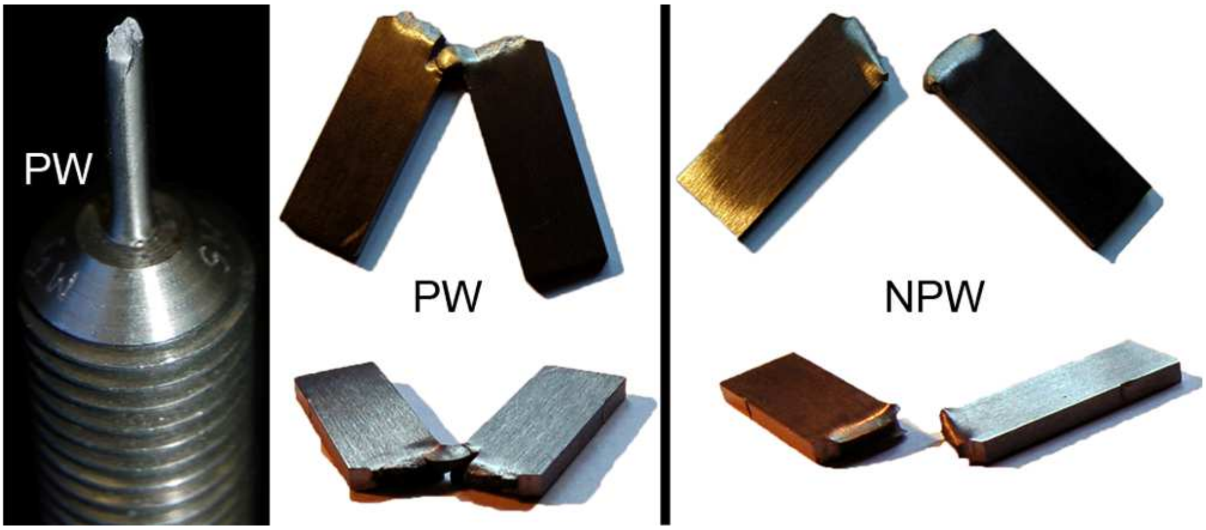

Fig 6. Images of specimens after mechanical testing: PW tensile specimen that fractured along a weld-line interface (left); aerial and oblique views of the PW specimen that remained intact along an unbroken rod (middle), and aerial and oblique views of the NPW specimen (right).

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Appendix 1

Below are the Vickers hardness values obtained from other pattern-welded sword replicas that were tested as part of this study, manufactured and supplied by Hector Cole.

	Hardness (Vickers)									Mean
Brimble Hill Sword	centre	170	157	159	176	174				167.2
	edges	657	642	627	620					636.5
Saxon Sword Number 7	centre	113	143	142	138	151				137.4
	edges	193	230	210	203					209.0
Sutton Hoo Mound 17 Sword	centre	119	131	148	151	145				138.8
	edges	224	232	230	224					227.5
Roman *Gladius*	centre	115	133	141	141	117				129.4
	edges	185	199	192	178					188.5
Damascus Steel	centre	209	194	197	203	188	186	183	185	193.1

Table showing the Vickers hardness values traversing along blade macro-sections, provided with the mean hardness. All values were obtained from the mid-thickness. Edges examined were always higher-carbon regions. Montages and micrographs of these sections are available from the author.

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