The role of pattern-welding in historical swords – mechanical testing of materials used in their manufacture

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Abstract

The pattern-welding is well known technique that was widely employed in manufacture of swords. While the decorative effect of the genuine pattern-welding (employing phosphoric iron) is indisputable, its reinforcing effect is up to date rather unclear. In order to understand this issue better, wrought iron, phosphoric iron, steel and various pattern-welded samples were prepared, mechanically tested and the results obtained were discussed in detail. Both the mechanical testing and the long-term metallographic investigation of medieval swords suggest that pattern-welding does not have any significant positive effect on the mechanical properties of swords and we should consider it a primarily decorative technique.

Keywords: pattern-welding, sword, blade, phosphoric iron, mechanical testing, Middle Ages.

1. INTRODUCTION

Intensive research has been carried out and a considerable amount of information published about the issue of pattern-welding, but its role in historical objects, especially swords, is still upon discussion among both specialists and enthusiasts involved in the study of historical swords and related issues. It was suggested that pattern-welded composites behaved very much like plywoods, i.e., specimens made this way should be characterized by both better elasticity and toughness in comparison to homogeneous products (e.g., Jones 1997, 5; Wadsworth 2000, 10–15; Williams 1977, 75; 2003, 12, 932; Edge and Williams 2003, 203–204; 2012, 65; Lang, Ager 1989, 107–115; Pelsmaeker 2010, 67–75; Lang 2011). However, this suggestion is highly affected by the fact that "pattern-welding" is nowadays a very broad and – in a historical context – rather misunderstood term (cf. *Pattern-welding*). In the past, the base material for pattern-welding was not steel, as it is often supposed, but phosphoric iron. Unfortunately, although the crucial role of phosphoric iron in these composites was recognized as early as the 1980s (Tylecote, Gilmour 1986, 251–252; cf. Buchwald 2005, 283; Hoyland and Gilmour 2006, 77–79), this fact was not taken into account by any researcher studying the pattern-welding's mechanical behaviour. (Pelsmaeker 2010, 67–75; Lang 2011; Polák 2008). Therefore, the effect of the genuine pattern-welding on mechanical properties of sword blades does not yet seem to be clear. Hence, the question we attempt to answer in this study is: Does pattern-welding have a positive effect on mechanical properties in historical swords?

1.1. Archaeological and archaeometrical background

The pattern-welding technique derives from piled composites dated as early as the La Tène period (Pleiner 1993, 117–118, 125–126, Fig. 12, 17:12; Lang, Ager 1989, 86–87; Jones 1997, 1–2; 2002, 145; Williams 2012, 62). At the time, the deliberate piling of steel and wrought iron together was employed to introduce the more scarce carburized material deeper into the blade's core and/or to reduce the amount of slag inclusions and elongate and fragment the remaining ones, all this to give the weapon better mechanical properties (cf. Buchwald 2005, 283; Anstee and Biek 1961, 86; Jones 1997, 4–5; Williams 1997, 75; Edge and Williams 2003, 203; Lang 2011). Development of the technique of piling introduced the idea of pattern-welding, i.e. the idea to create alternating high-phosphorus iron and low-phosphorus mild steel or wrought iron laminates, which could be further manipulated (full or partial twisting, stock removal, splitting etc.) in order to achieve peculiar decorative surface, revealed through polishing and etching (Anteins 1973, 13–19; Thålin-Bergman 1979, 124; contra Mäder 2001, 282–287, Abb. 47–48, 50–51, 51, 54–57; cf. Anstee and Biek 1961, 88). Hence, when phosphoric iron appeared in these composite materials, the decorative effect presumably began to play the fundamental role in its use. The extraordinary aesthetic value, quickly noticed and keenly sought after, is addressed in written sources, which comment on weapons made using the discussed technique (Davidson 1998, 105–109, 119, 132–136, 142–144; Hoyland and Gilmour 2006, 43, 77–79, 153, 157; Kormákr 1902, 63–64).

In case of swordmaking, the use of twisted pattern-welding was evidenced between the late 2nd and the 10th/11th centuries (Lang, Ager 1989, 89–106, Tab. 7.2; Anteins 1973, 59–63; Hošek et al. 2011; Gilmour 2007; Williams 2012, 62). One laminated rod was usually made of seven strips arranged alternately based on the two alloys' phosphorus content (cf. Jones 1997, 1–2; Thålin-Bergman 1979, 124). After forge welding, the bundle was often twisted (these could have been uniform, interrupted, graduated and came in numerous combinations) and converted back to a rod or a strip.

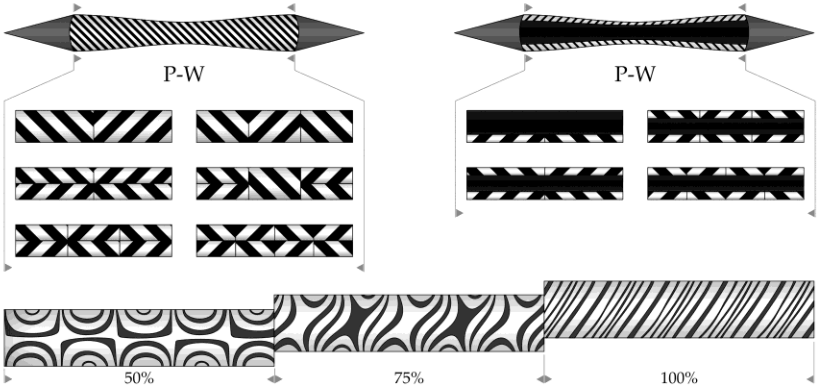

Fig. 1.

Pattern-welding applied to historical sword blades. Top left: "true pattern-welding" and its most common combinations. Top right: pattern-welded panels overlapping a homogeneous core and their usual variations. Bottom: patterns intrinsic to the discussed technique revealed through twisting and subsequent grinding (splitting) of an alternately banded laminate. All drawings and photographs by the authors

Pattern-welded elements could have been used in three different ways, either as sole components of the central portion of the blade (which can be referred to as "true pattern-welding"), panels welded to a homogeneous core, or as inlaying material (e.g., Jones 1997, 4–5, Fig. 8; 2002, 146; Williams 2012, 62). Sword-blanks were prepared in a great deal of variants (cf. Tylecote, Gilmour 1986, 146–262, Fig. 103; Jones 2002, 145–146; Lang, Ager 1989, 87–88, Fig. 7.2). Individual parts of the blade, the pattern-welded rods/strips, edge rods (homogeneous or composite, usually sandwiched), homogeneous core piece (if used) were welded together into a bar, from which the blade was forged (Anteins 1973, 13–19; Jones 2002; Maryon 1960, 26–32; cf. Böhne and Dannheimer 1961). It is of utmost importance to underline that no composite sword blade from the discussed period was made entirely of pattern-welded elements. In every case, separate edges were welded to the sides of such a billet.

It is usually claimed that the blade variant with thin patterned panels over a uniform core was of a later chronology and appeared due to the decline of the functional application of the discussed technique, and its sole use was for the visual appeal (cf. Jones 1997, 5; 2002, 146). While such a tendency can be observed (Anteins 1966, 111–116, 123–125; 1973, 28–29), it should be emphasized that this variant was used as early as at least the 4th century, albeit it was surely not predominant at the time (cf. Schürmann 1959; Buchwald 2005, Fig. 277:5; Williams 2012, 70).

Despite the often suggested superior craftsmanship of every sword made in this manner, poor quality pattern-welded specimens (i.e., low carbon content in the edge sections, no or improper heat-treatment, large unelongated slag inclusions and other material impurities, imprecise welds prone to delamination) were not uncommon (cf., e.g., Tylecote, Gilmour 1986, 156–158, 245; Hošek and Košta 2008; 2011). This should not be too puzzling, taking into consideration the fact that in the Migration Era and in the Early Middle Ages (Viking Age), and well into the High Middle Ages, when any use of pattern-welding declined almost entirely, the sword was not solely a fighting tool – it was an important element of the elite culture, ruler's attribute for legitimate power in the Latin civilization as well as a denominator of warrior's status among pagan communities of the Frankish Empire's reaches.

1.2. Mechanical background

Swords, when used in combat, are exposed to impact, bending and buckling load, which they should resist (see Fig. 2). The resistance to these loads depends on the mechanical properties of the material (or combination of materials) and on the geometry (cross section and length) of a sword blade.

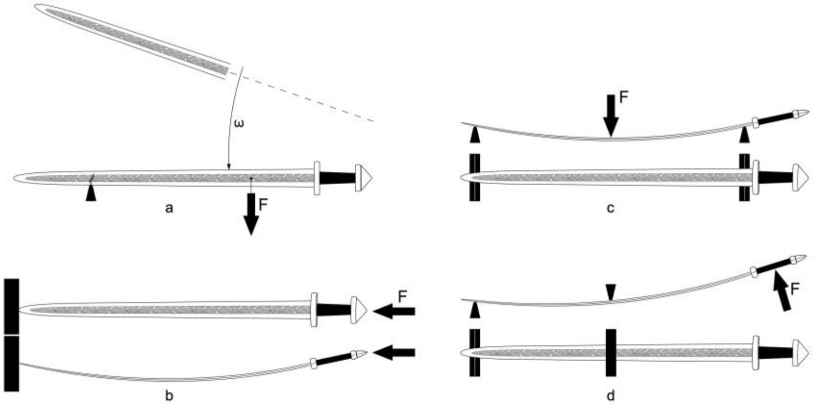

Fig. 2.
Fundamental loads of swords when used; a – impact load; b - buckling load, c, d – bending load

The impact load may cause the fracture of the blade, which has fatal consequences on its usage. Impact load is in relation with the energy with which the sword hits a target. When the target is static, the energy is equal to the sum of the kinetic energy of the sword and the mechanical work of the blow. Resistance to impact load is related to dynamic toughness, which could be characterized by impact energy derived from Charpy impact tests (KV [J]; the higher the better). Impact energy shows the amount of the energy needed to break a notched specimen. Concerning the geometry, the bigger the area of the cross-section of the blade is, the greater the resistance to impact load.

Bending load may cause plastic (or permanent) deformation, which precludes the further use of the sword. In case of low bending load the deformation is elastic but when increasing the bending load the deformation becomes plastic. Resistance to plastic deformation during bending related to strength, which could be characterized by flexural yield strength, derived from three-point bending tests ($R_{pf}^{0,001}$ [MPa]; the higher the better). Flexural Yield Strength is defined as a stress at which the material begins to deform plastically. Concerning the geometry, the shorter and thicker the blade is, the greater the resistance to bending load is.

Under high bending load, the plastic deformation is increasing, which may also cause the fracture of the blade. Resistance to bending fracture related to static toughness which could be characterized by absorbed specific fracture energy derived from tensile tests (W_c [J/cm^3]; the higher the better). This shows the amount of the absorbed energy during the tensile test till fracture. The mechanical background of the mechanical testing is summarized in Table 1.

Table 1.
Mechanical background and terms regarding ~~of~~ the mechanical testing

Load	Result	Material property	Characteristic value	Mechanical testing
impact (dynamic) load	fracture	dynamic toughness	impact energy (KV [J])	Charpy impact test
low bending load	plastic (permanent) deformation	strength	flexural yield strength ($R_{pf}^{0,001}$ [MPa])	three-point bending test
high bending load	fracture	static toughness	absorbed specific fracture energy (W_c [J/cm^3])	tensile test

Under buckling load, a sword blade can buckle and bend, which is disadvantageous if it was also adapted for stabbing, but resistance to bucking load depends only on the geometry and not on material properties, so we apart from discussing this load.

2. METHODS AND RESULTS

Based on the archaeometrical investigations (metallographic and SEM-EDS) we have carried out recently on medieval swords (Thiele, Hošek [in press]), three different types of ferrous alloys used in sword manufacturing could be identified: wrought iron, steel (which is present in sword blades in its natural or hardened state) and phosphoric iron. Authors prefer to use these traditional archaeometallurgical terms in the presented study to make the results more understandable from the perspective of historical crafts. Definitions of these terms can be seen in Table 2.

Table 2.
A glossary of terms for the three main ferrous alloys used in the manufacture of pattern-welded swords

Ferrous alloy	Description
Wrought iron	Iron made either by the direct (bloomery) process or resulting from a conversion process such as puddling or finning (Tylecote 1986, 241). It contains some slag and no to little amounts of carbon. The term wrought iron (often abbreviated to iron) is widely used within the field of archaeometallurgy and archaeology for both prehistorical and historical malleable ferrous alloys, which cannot be successfully hardened by heat treatment (Pleiner 1962, 13). Although there is no consensus on the exact maximum carbon content of wrought iron, most archaeometallurgists use this term for ferrous alloys containing less than 0.2 wt%C.
Steel	The term is widely used within the field of archaeometallurgy and archaeology for both prehistorical and historical malleable ferrous alloys, which could be successfully hardened by heat treatment. Most of archaeometallurgists use the term for ferrous alloys whose carbon content exceeds 0.2 wt%.
Phosphoric iron	Within the field of archaeometallurgy this term is commonly used for a specific sort of wrought iron containing more than 0.1 wt% of phosphorus (Vega et al. 2003; Pleiner 2006, 242). Phosphoric iron used deliberately for pattern-welding contained as a rule ca. 0.4 to 1.4 wt%P (Thiele,Hošek [in press]).

Mechanical testing was carried out on all of 3 types of base materials (steel in both natural and hardened state) and also on their combinations (cf. Table 3). The bloomery iron rods of the bracing roof that were replaced during a reconstruction of the 18th century Peter and Paul's church in the Benedictine Abbey of Rajhrad were used for wrought-iron specimens (their metallographic examinations revealed high amounts of fayalitic slag inclusions, which prooves their bloomery process origin). The same wrought iron was re-smelted and carburized in a bloomery furnace and subsequently piled into rods of bloomery steel. Phosphoric iron bloom was produced during a smelting experiment using bog iron ore of high phosphorus content (for further details cf. Thiele 2012).

Rods of these base materials and pattern-welded rods combining them were prepared by internationally recognized swordsmith Patrick Bárta. Prior to the forging, all the base materials were tested by a portable XRF analyser (which can detect light elements, such as P) to judge if their composition is within the acceptable range. Pattern-welded rods were made of 8 and 16 layers and with 1:1 ratio of the base materials. All of the pattern-welded rods were twisted except one, from which the PId8 specimens were produced. The angle between the layers and the longitudinal axis of the rods was around 45°. Heat treatment was carried out only on Sh and PISht8 samples, which were water-quenched from 900°C and tempered in 300°C for 60 minutes. The other specimens were kept in their natural state.

With regards to previously conducted analyses it can be said that all parameters of these materials (which we can consider) lie in acceptable range, i.e., they are neither higher nor lower than those commonly encountered in historical forgings, especially swords. It can be stated that all the tested materials rank among the basic types of material used in the past and all of them are representative from this point of view.

From the forged rods, 3–5 pieces of specimens with a "V" profile notch were cut out and milled for Charpy tests. The Charpy tests were conducted according to the International Standard ISO 148-2:2008(E) (with the exception of the specimen being 10mm longer). The configuration of the Charpy test can be seen in Fig.4a, and the results are summarized in Fig.5a and partially in Table 4. Impact energy depended on the angle measured between the layers and the longitudinal axis of the notch; the higher angle the lower the KV.

After the Charpy test, metallographic examination under optical microscope was carried out on the cross-sections near notches to identify the microstructure and calculate the carbon content (by means of image analysis), cf. Fig. 3. Phosphorus content was measured by Energy Dispersive X-ray Spectroscopy under Scanning Electron Microscope (SEM-EDS) in the cross-sections of samples made of P-iron. The results obtained are summarized in Table 3.

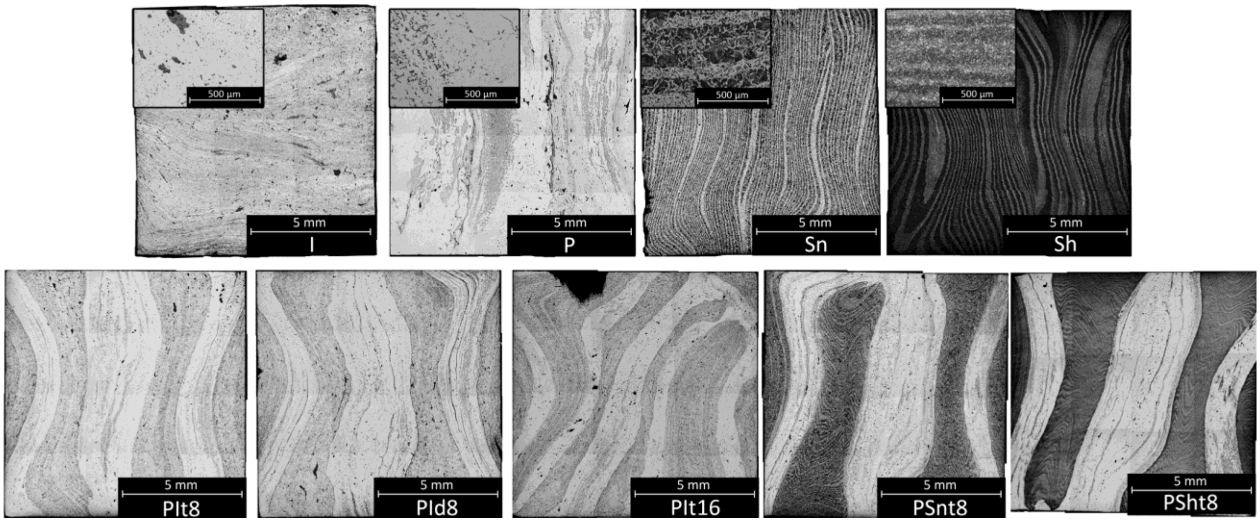

Fig. 3.
Metallographic macro-photographs of cross-sections of representative specimens of each type

Table 3.
Specimens for material testing

Specimen groups	Specimen types in the groups	Symbol	Number of specimens	Microstructure	Chemical composition	
					C (wt%)	P (wt%)
Base materials	Wrought iron	I	5	Ferritic with little pearlite	0.05	0
	Phosphoric iron	P	3	Ferritic with thin ferrite-pearlite layers	max 0.2	0.6 - 1.1
	Steel in nature state	Sn	4	Pearlite with proeutectoid ferrite	cca 0.6	0
	Hardened and tempered steel	Sh	3	Tempered martensite	cca 0.6	0
Reference	Industrial steel	S235	5	n.a.	0.15	0
Pattern welded specimens	Phosphoric iron + wrought iron. twisted. 8 layers	PIt8	5	Same as in the base materials		
	Phosphoric iron + wrought iron. not twisted. 8 layers	PId8	4			
	Phosphoric iron + wrought iron. twisted. 16 layers	PIt16	4			
	Phosphoric iron + steel in nature state. twisted. 8 layers	PSnt8	4			
	Phosphoric iron + hardened and tempered steel. twisted. 8 layers	PSht8	4			

Both halves from the specimens broken in Charpy tests were heated up to 1250°C embedded in cast iron swarf (to prevent the oxidation of the surfaces) in a heat-treating furnace equipped with silicon-carbide rods and subsequently rolled by a rolling mill into flat specimens of 3 mm thickness. The angle between the layers and the longitudinal axis of the specimens decreased to around 30° after rolling.

Three-point bending tests were conducted according to the International Standard ISO 7838:2005(E), (with the exception of specimens' dimensions). The configuration of the three-point bending test and the dimensions of the specimens can be seen in Fig. 4b. The force-deflection curve was registered during each test. Force-deflection curves of three-point bending tests were transformed to flexural strength (σ_f [MPa]) – flexural strain (ε_f [-]) curves using equations defined in International Standard ISO 7838:2005(E). We have defined the flexural yield strength as the amount of flexural stress that will result in a plastic flexural strain of 0.001. Flexural yield strength was calculated from the flexural strength – flexural strain curves using the definition. The flexural yield strength results are summarized in Fig. 5b and partially in Table 4. It could be established that in case of all pattern-welded specimens the flexural yield strength was nearly equal to the average of the flexural yield strength of the base materials. During the bending test all the P specimens broke in their tensile side (underside) and the outer layers of some Sh, PId8 and PIt8 specimens were also fractured (cf. Fig. 10), due to the low toughness. The bending-modulus, which is the tangent of the linear beginning section of the three-point bending curve, was nearly the same.

Specimens for the tensile tests were milled out of the flat-rolled specimens. Tensile tests were conducted according to the International Standard ISO 6892-1:2009(E) (except for the specimens' dimensions). The configuration of the three-point bending test and the dimensions of the specimens can be seen in Fig. 4c. During each test, a force-elongation curve was registered. Absorbed specific fracture energy was calculated from the force – elongation curves and from the measured cross-sectional area before and after testing (for method cf. Gillemot 1961). The absorbed specific fracture energy results are summarized in Fig. 5c and partially in Table 4.

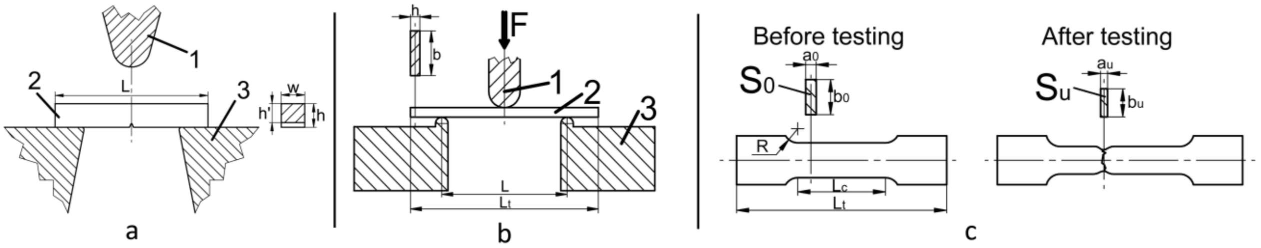

Fig. 4.
a) Configuration of the Charpy test and the dimensions of the specimens: 1 – Striker, 2 – Specimen, 3 – Anvil, L – Length L = 65 mm, h – Height h = 10 mm, w – Width w = 10 mm, h' – Height below notch 6 = 8 mm;
b) Configuration of the three-point bending test and the dimensions of the specimens: 1 – Crosshead, 2 – Specimen, 3 – Supports, L – Support distance L = 40 mm, L_t – Length of test piece L_t = 60 mm, b – Width of test piece b = 14mm, h – Thickness of test piece h = 3mm, Crosshead speed was 20 mm/min;
c) The dimensions of the flat tensile specimens: L_t – Total length of test piece L_t = 60 mm, L_c – Parallel length L_c = 28 mm, R – Radius R = 4 mm, a_0 – Original thickness of test piece a_0 = 3 mm, b_0 – Original width of the parallel length b_0 = 10 mm, S_0 – Original cross-sectional area of the parallel length, a_u – Final thickness of test piece, b_u – Final width of the parallel length, S_u – Final cross-sectional area of the parallel length, Crosshead speed was 20 mm/min.

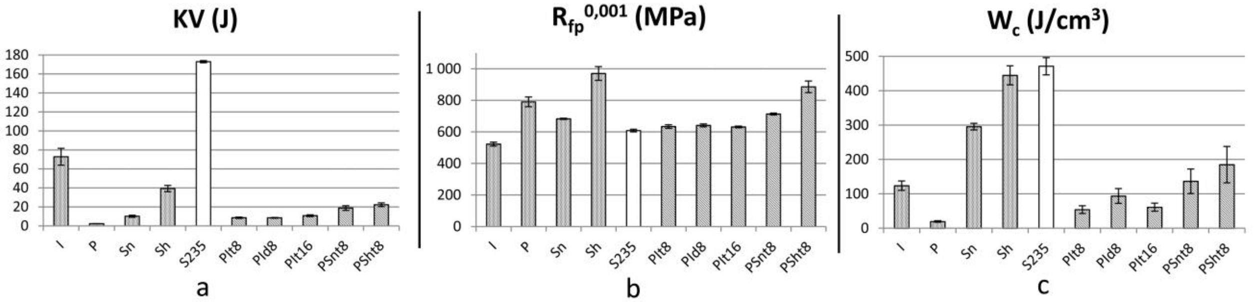

Fig. 5.
Characteristic values of samples tested: a) Impact energy (KV [J]), b) Flexural yield strength ($R_{pf}^{0,001}$ [MPa]), c) Absorbed specific fracture energy (W_c, [J/cm^3])

3. DISCUSSION

While medieval sword makers and their customers could check the quality of real swords in real situations, we must rely on the results of the conducted mechanical tests, on our knowledge of historical weapons and on statistical methods. Basic data collected from mechanical tests seem to be well understandable on their own; however, in order to insight their possible latent structure and facilitate their interpretation, factor and multi-criteria analysis was performed.

3.1. Factor analysis

With the purpose of better understanding how the tested materials and pattern-welding affect the mechanical properties, factor analysis was used to describe the covariance among our data by only a few factors that are easy to interpret.

First, all the data were arranged in Table 4, which includes a list of specimens and corresponding variables such as materials used individually in the past (I... iron, S... steel in natural state, Sh... hardened steel), application of pattern-welding (PW) and selected mechanical properties (KV [J] – impact energy, $R_{pf}^{0,001}$ [MPa] – flexural yield strength, W_c [J/cm^3] – absorbed specific fracture energy). For materials, the values indicate a portion of material within a sample (i.e., 1 for mono-steel, etc., and 0.5 for pattern-welded samples). Because performed analysis of variance suggested that the distinct material arrangement of pattern-welded samples (employing wrought iron) did not have a significant effect on the results we obtained, we did not consider it in the further data processing.

Table 4. Overview of the results obtained (1st, 6th, 7th and 8th column) and the variables (2nd to 8th column) used in the principal component and factor analysis

Specimen	I	Sn	Sh	PW	KV [J]	$R_{pf}^{0.001}$ [MPa]	W_c [J/cm^3]
I_1	1	0	0	0	86.5	532.2	121.5
I_2	1	0	0	0	65.0	502.2	77.2
I_3	1	0	0	0	96.5	533.6	136.9
I_4	1	0	0	0	60.0	491.3	137.4
I_5	1	0	0	0	56.0	554.7	145.2
Sn_1	0	1	0	0	8.5	672.1	289.3
Sn_2	0	1	0	0	8.5	687.6	289.0
Sn_3	0	1	0	0	10.5	690.8	280.1
Sn_4	0	1	0	0	13.0	682.1	323.5
Sh_1	0	0	1	0	36.0	890.8	508.4
Sh_3	0	0	1	0	35.0	1064.2	408.9
Sh_4	0	0	1	0	47.0	956.7	416.6
PIt8_1	0.5	0	0	1	11.0	644.7	50.2
PIt8_2	0.5	0	0	1	8.0	656.2	16.9
PIt8_3	0.5	0	0	1	7.5	642.2	71.5
PIt8_4	0.5	0	0	1	8.5	628.6	65.4
PIt8_5	0.5	0	0	1	8.0	598.5	66.3
PId8_1	0.5	0	0	1	8.0	630.0	59.2
PId8_2	0.5	0	0	1	9.5	665.4	53.7
PId8_3	0.5	0	0	1	8.0	646.8	132.6
PId8_4	0.5	0	0	1	8.5	622.9	129.1
PIt16_1	0.5	0	0	1	9.5	642.6	67.0
PIt16_2	0.5	0	0	1	12.5	625.2	91.5
PIt16_3	0.5	0	0	1	12.0	638.3	47.0
PIt16_4	0.5	0	0	1	9.0	619.6	39.2
PSnt8_1	0	0.5	0	1	12.5	702.4	162.2
PSnt8_2	0	0.5	0	1	19.0	722.9	96.1
PSnt8_3	0	0.5	0	1	19.0	704.3	63.3
PSnt8_4	0	0.5	0	1	24.5	724.8	224.5
PSht8_1	0	0	0.5	1	23.0	887.6	60.6
PSht8_2	0	0	0.5	1	26.5	870.9	168.0
PSht8_3	0	0	0.5	1	22.5	981.6	317.9
PSht8_4	0	0	0.5	1	17.0	804.2	192.9

Prior to the factor analysis, a principal component analysis (PCA) had been performed in order to find a number of principal components (factors), which can sufficiently explain our data. The number of principal components was determined by eigenanalysis of the correlation matrix. Regarding the size of eigenvalues and using the Kaiser criterion, there are three major principal components that cumulatively explain 94.8% of the variance in our data. However, in order to keep a space for random variations, two major principal components (cumulatively explaining 73.5% of the variance) were retained.

The next step was the factor analysis. According to results of the PCA, two factors were extracted. The obtained results were arranged into Table 5.

Table 5.
Sorted Rotated Factor Loadings and Communalities (Varimax rotation)

Variable	Factor1	Factor2	Communality
$R_{pf}^{0,001}$ [MPa]	0.919	-0.020	0.846
I	-0.892	0.369	0.931
W_c [J/cm^3]	0.804	0.489	0.886
Sh	0.776	0.363	0.735
Sn	0.322	-0.108	0.115
KV[J]	-0.257	0.889	0.856
PW	-0.143	-0.870	0.777

As one can see (from the Table 5) $R_{pf}^{0,001}$, W_c and Sh have large positive, and I large negative loadings on the factor 1; we can label this factor as *Distinct strength of iron and hardened steel*. Pattern-welding has large negative, while impact resistance large positive loadings on the second factor. We can label it as *Brittleness of pattern-welded rods*. These two factors (*Distinct strength of wrought iron and hardened steel* and *Brittleness of pattern-welded rods*) are those which significantly affected our data.

At the same time, it can be deduced that the use of hardened steel has a strong positive effect on increasing the strength (represented by $R_{pf}^{0,001}$) and on the static toughness (represented by W_c) of blades, while the use of iron leads to the reduction of strength and static toughness (the effect of the materials does not seem to be highly affected by pattern-welding). The use of pattern-welding has a strong negative effect on impact resistance (represented here by KV). On the contrary, resistance to impact increases when wrought iron is used, though the positive effect of iron seems to be only relative because pattern-welded rods containing wrought iron were not so good (pattern-welding has a strong negative effect in this case). The discussed results also reveal that hardened steel has certain positive effects on each of the mechanical properties, mainly ($R_{pf}^{0,001}$ and W_c), but strong positive effect of pattern-welding on any of these mechanical properties was not recognized.

Multi-criteria Analysis

The multi-criteria analysis can be employed in order to compare preferences obtained for pattern-welded composites with preferences for wrought iron and steel, whose mechanical properties should be the best for sword making. Following from the introduction, we can define three criteria that satisfactorily describe the essential demands placed on sword blades or their materials respectively:

1) Resistance to impact load (RIS), related to dynamic toughness, which could be characterized by impact energy derived from Charpy impact tests (KV [J])
2) Resistance to plastic deformation during bending (RPD), related to strength, which could be characterized by flexural yield strength derived from 3-point bending tests ($R_{pf}^{0,001}$ [MPa])
3) Resistance to bending fracture (RBF), related to static toughness, which could be characterized by absorbed specific fracture energy derived from tensile tests (W_c [J/cm^3])

Since RIS, RPD and RBF are related to mechanical properties, we can express these criteria in numerical terms for each of the tested sample (material). Subsequently, we can use them in multi-criteria analysis to find preferences for materials (out of the ones we have tested) for making sword blades.

The multi-criteria analysis consists, among others, of two steps: 1) determining the values of individual criteria and 2) determining the importance (relative weights) of each criterion. The determination of the values of criteria is an easy step; a matrix of measured KV, $R_{pf}^{0,001}$ and W_c average values is simply transformed into a normalized matrix (see Table 6).

Table 6.
Criteria matrix with measured values of mechanical properties and calculated normalized matrix

Sample	Criteria matrix with values of related mechanical properties			Normalized matrix for the criteria		
	RIS	RPD	RBF	RIS	RPD	RBF
I	72.8	522.8	123.7	1	0.54	0.28
P	2.3	790.6	19.6	0.03	0.81	0.04
Sn	10.1	683.1	295.4	0.14	0.7	0.66
Sh	39.3	970.5	444.6	0.54	1	1
PIt8	8.6	634	54	0.12	0.65	0.12
PId8	8.5	641.2	93.6	0.12	0.66	0.21
PIt16	10.8	631.4	61.2	0.15	0.65	0.14
PSnt8	18.8	713.6	136.5	0.26	0.74	0.31
PSht8	22.3	886.1	184.8	0.31	0.91	0.42

For determining the importance (relative weights) of each criterion we use the analytic hierarchy process (AHP) by Saaty (1980). In the analytic hierarchy process, criteria are scored against each other via pairwise comparison (using a 1–9 scale) and their importance is calculated.

Prior to this step, however, we have to take into consideration the geometry and the use of swords in battle and the possibility of damage. In battle, swords are in general exposed to two main possible sources of energy, which can cause their damage: the kinetic energy delivered from blows and the kinetic energy of moving warriors. The kinetic energy of a swinging sword lies roughly between 60 and 140 J (Williams 2003, 918; Turner [n/d]), the kinetic energy of a 70–80 kg man running with the speed of 3.6–4.7 m/s is ca. 450–890 J (cf. with results of our tests). Although most of the energy is absorbed by human body movements and by cutting into or through a target, there is still some energy that is absorbed by the blade, which it should withstand without being bent or broken. Both these types of damage are possible. For example, the low strength of Celtic swords recorded (claimed) by Polybius is well known (Pleiner 1993, 157–158). The risk of a fragile fracture of long-bladed weapons is well documented by some archaeologically excavated solitary fragments of blades without traces of plastic deformation (e.g., Žákovský et al. 2013a,b). Earlier medieval swords were rather robust in comparison to those from the 9th or 10th century (when the use of pattern-welding in sword manufacture was clearly abating) and adapted for cutting. A warrior could strike his opponent with a powerful blow, and it seems that materials with high resistance to impact load were slightly more preferred for the reliability of these blades than materials with good resistance to plastic deformation (sufficient toughness of blades could be achieved by their enhanced thickness). On the contrary, during the course of the 9th–10th centuries, swords turned to become more slender and were adapted for easier manoeuvrability. These specimens were not primarily destined for simple cutting, though this time they met harder targets; they were designed for both cutting and stabbing and their blades, especially on the pointed side, were noticeably more graceful than blades of the earlier period. One can easily verify that a 5 mm reduction in width and 1 mm in thickness nearly halves a blade's section modulus (S [mm^3]), which expresses its ability to resist bending load. Therefore, it seems that materials' resistance to permanent deflection should be preferred as much as materials' resistance to impact. Resistance to bending fracture plays this role as well, but sword-blades of good quality had to be made in dimensions allowing the avoidance of plastic deformation. Consequently, this characteristic is less important than the previous two. Taking this into consideration, the pairwise comparison by Saaty's method can be done in the following way (cf. Tables 7 and 8).

Table 7.
Matrix for pairwise comparison of determined criteria and their importance calculated for swords from the 6th–8th centuries

Criteria	RIS	RPD	RBF	Importance
				(relative weight)
RIS	1	2	3	0.54
RPD	1/2	1	2	0.3
RBF	1/3	1/2	1	0.16

Table 8.
Matrix for pairwise comparison of determined criteria and their importance calculated for swords from the 9th–10th centuries

Criteria	RIS	RPD	RBF	Importance
				(relative weight)
RIS	1	1	3	0.43
RPD	1	1	3	0.43
RBF	1/3	1/3	1	0.14

Consistency ratio is in both cases below 0.1, which means that our judgements are acceptably consistent and the calculated importance reliable. Now, the importance is added to the criteria-normalized matrix and preferences for the tested materials are calculated, see Tables 9 and 10.

Table 9.
Results of the multi-criteria analysis for swords from the 6th–8th centuries (based on the AHP method)

Criteria	RIS	RPD	RBF	In total	Material preference
Weight	0.54	0.3	0.16		(1st is the best)
I	0.54	0.16	0.05	0.75	1
Sn	0.08	0.21	0.11	0.39	4
Sh	0.29	0.3	0.16	0.75	1
PW-PIt8	0.06	0.19	0.02	0.28	7
PW-PId8	0.06	0.2	0.03	0.29	6
PW-PIt16	0.08	0.19	0.02	0.3	5
PW-PSnt8	0.14	0.22	0.05	0.41	3
PW-PSht8	0.16	0.27	0.07	0.5	2

Table 10.
Results of the multi-criteria analysis for swords dated to the 9th–10th century (based on the AHP method)

Criteria	RIS	RPD	RBF	In total	Material preference
Weight	0.43	0.43	0.14		(1st is the best)
I	0.43	0.23	0.04	0.7	2
Sn	0.06	0.3	0.09	0.46	5
Sh	0.23	0.43	0.14	0.8	1
PW – PIt8	0.05	0.28	0.02	0.35	7
PW – PId8	0.05	0.28	0.03	0.36	6
PW – PIt16	0.06	0.28	0.02	0.36	6
PW – PSnt8	0.11	0.32	0.04	0.47	4
PW – PSht8	0.13	0.39	0.06	0.58	3

As expected, the results show that hardened steel together with wrought iron would be the materials of best mechanical properties to form a good quality blade. But only hardened steel meets all the criteria more or less uniformly and can be used individually with success. Wrought iron itself has excellent resistance to impact, but it is easy to plastically deform mono-iron blades (because of their low strength). For that reason, when wrought iron prevails in a sword, blade thickness should be enhanced to a sufficient extent and reinforcements by steel or (with much less success) by pattern-welded composites are appreciated. In fact, sophisticate combination of well hardened steel and wrought iron would provide blade with the highest resistance to whatever damage.

3.2. Comparison of the results

We should verify the results we achieved by comparing calculated preferences of wrought iron vs. steel with ratios of these materials encountered in archaeometric studies. First, it is generally accepted that in the course of the 9th–10th centuries a new type of swords appeared, differing from its predecessor in improved manoeuvrability and a greatly enhanced portion of well heat-treated steel in blades, which, with decreasing exceptions, lacked pattern-welding that was limited to inlaid inscriptions and marks (Oakeshott 2002, 7; Haupton 2011, 42; Lang 2009, 239). The emergence of these "steel" blades was widely evidenced metallographically by Williams (1977; 2003, 13–14; 2007; 2009; 2012, 116–183), Hošek (Hošek and Košta 2007; Košta and Hošek 2009; Hošek et al. 2012; Hošek et al. 2013) and others (in greater numbers: Biborski et al. 2011; Thålin-Bergman and Arrhenius 2005; Edge and Williams 2003; Anteins 1966; 1973, 20–63; for earlier, Merovingian examples see: France-Lanord 1949; Salin 1957, 57–69; La Salvia 1998, 49–63). Sword blades typical of the 6th–8th/9th centuries have, as a rule, pattern-welding visible in fuller sections, their blades are more robust without expressive narrowing and tapering, contrary to examples of later types; metallographic investigations in general suggest the frequent use of wrought iron in these blades (cf. Tylecote, Gilmour 1986, 251; Hošek and Košta 2008). We can, therefore, consider that the preferences calculated in both Tables (9 and 10) follow the contemporary trend.

A significant study indicating this trend was carried out by Tylecote and Gilmour (1986), who analysed sword blades from the British Isles. Most of pattern-welded examples dated to the 5th–7th centuries they examined (18 specimens) were made using iron alloys of poor carbon content. The authors note that its presence was much too low to be subjected to successful quenching, and, in most part, no such attempts had been made (ibidem, Table N, 167–209, 244–245; cf. France-Lanord 1949, 37). Two later (dated to the 7th–9th centuries) examples show a certain change in the techniques of manufacture in comparison to the earlier ones, with sandwitched blades made using – in both cases – strips of medium- and high-carbon steel for the cutting edges, which were subsequently quenched. One had a steel spine with pattern-welded panels butt-welded onto its flat surfaces (Tylecote, Gilmour 1986, Table N, 209–213, 246). Five pattern-welded examples dated to the 9th–11th centuries were forged in varying ways, with steel constituting the cutting-edges, all of which were heat treated. Two examples had a wrought iron core welded between pattern-welded panels (ibidem, Table N, 213–217, 222–225, 227–229, 229–232, 232–234, 248). Despite the clear shift in quality of these weapons, mostly during the 7th–8th centuries, the pattern-welding didn't change significantly, at least in terms of materials used, with their carbon content varying between 0.1 and 0.3%, but usually below 0.1% (cf. ibidem, 251). This was also evidenced in a more recent study (Hoyland and Gilmour 2006, Fig. 20). It needs to be underlined that in most cases the layers of pattern-welded sections clearly alternated in phosphorus content, thereupon allowing a sharp visibility of pattern after etching.

Now, let us compare the preferences calculated for pattern-welded composites with those calculated for iron and hardened steel. If pattern-welding was not used solely for a decorative effect, the preferences for composites should be significantly higher than for the input materials. However, preferences for pattern-welding are lower overall. Pattern-welding, which combines phosphoric iron with wrought iron, has apparently the poorest mechanical properties, but a combination of phosphoric iron and hardened steel can result in a relatively good composite material. Still, this composite would be preferred fairly less than a set of wrought iron and hardened steel or their combination respectively, and examples of such composites are scarce. Presented results illustrate that pattern-welded composites could not be successfully utilized on a larger scale in the manufacture of swords in order to ameliorate the mechanical properties of blades. It can be suggested that low mechanical properties of pattern-welding, which were registered, could be an important reason for the demise of use of said techniques (cf. Kucypera 2009), with pattern-welding being gradually replaced by iron (or steel) in blade cores.

The comparison of our findings with results of earlier studies devoted to mechanical properties of pattern-welded swords is unfortunately difficult. The problem lies mainly in the lack of published details about the conducted tests and in using modern steels in the composites that, for this reason, significantly differ from those used in the past. Despite that, the previous research into the mechanical properties of pattern-welding should be mentioned and discussed. Pattern-welded specimens were already mechanically tested by France-Lanord (1949, 37) as mentioned by Salin (1957, 60–62; 1965). France-Lanord found them to be approximately three times more resistant to bending than ordinary blades. However, there are no further details stated, therefore we cannot consider the conclusions reliable for our needs (cf. Williams 2012, 74). Recently, Pelsmaeker (2010) performed mechanical tests on two sword blades, one pattern-welded, the other made of steel. The blades were gradually bent and both their elasticity and resistance to ongoing plastic deformation was measured. The mono-steel blade appeared to be more elastic, but at the same time more easily deflected permanently. This result corresponds with France-Lanord's conclusions, but Pelsmaeker used modern steel (S235) subjected to carburisation for the tested blades and his results are affected by a slightly increased blade thickness in favour of the patterned blade (cf. ibidem, 57, 62). Although Pelsmaeker's research is valuable, it was not accurate enough to reliably assess the role of pattern-welding in historical swords. Experiments conducted by D. Sim reportedly show that pattern-welded blades were always likely to be less strong than one-piece blades (Williams 2003, 12, footnote 4). Research of a great value was conducted by Lang (2009; 2011). But her samples were also made of modern steels without phosphoric iron in pattern-welded samples. Her research was focused on pre-medieval sword manufacture and she avoided deeper discussion on pattern-welded swords, keeping in mind that pattern-welding in her samples was not comparable with those she encountered in genuine pattern-welded weapons. Unfortunately, Lang had at her disposal only a limited number of samples for testing and her results, therefore, lack statistical significance. Nonetheless, they suggest that impact resistance of some composites might have been higher than in case of base materials employed. At the same time, it appears that impact resistance highly depends on the direction in which cracks propagate across layers. When a crack forms parallel to layers, the impact resistance can be as much as twice higher than in case of a transverse propagation. This effect was observed by others as well (Černý and Čechlovský [n/d]), and it was also recorded in our tests. However, in our case only samples with steel clearly proved this tendency and only composites with steel in a natural state had better impact resistance than the base materials used. The interesting fact is that, statistically, the results of the impact resistance of PSnt8 and PSht8 samples do not significantly differ from each other, while in case of Sn and Sh they clearly do. To conclude, with regard to the results of our tests, we are not in general capable to predict impact resistance of pattern-welded samples reliably, but the overall effect of pattern-welding (using phosphoric iron) is evidently negative. Although Tylecote and Gilmour (1986, 254) pondered that mixing structures of high phosphorus iron (large grain size) and low phosphorus low carbon iron (small grain size) in alternate bands could produce a combination of high corrosion resistance of high phosphorus bands and crack-arresting characteristics of the fine-grained wrought iron, our tests suggest that wrought iron can have a very limited effect on the improvement of the impact resistance of these composites.

Finally, the conducted research proved that the characteristic values of ductility and toughness of medieval bloomery iron materials are much lower than those of modern steels. Modern S235 steel has about three times higher impact energy and absorbed more specific fracture energy than bloomery wrought iron (cf. Fig 5. a and c), however, it has both the same chemical composition and ferritic microstructure. The difference is that bloomery wrought iron contains slag inclusions. These cause notching and stress concentration effect in the metallic phase, and provide a point of departure for cracks. The effect of slag inclusions is a hard function of their size, shape and amount, but the study of crack propagating in bloomery iron alloys requires further investigations on the basis of fracture mechanics. The technique of multiple forge welding during pattern-welding has probably a positive effect on ductility and toughness by elongating and wracking of slag inclusions, despite additional slag and hammer scale introduction into the welds.

4. CONCLUSION

Based on the results of the conducted mechanical tests and the knowledge of pattern-welding utilization in historical swords, it can be concluded that genuine pattern-welding does not have any important positive effect on the mechanical properties of sword blades. The main reason for this is that phosphoric iron, and, hence, pattern-welded composites themselves, irrespective of the pattern (twisted or straight pattern, number of layers), have very low dynamic and static toughness – a mechanical characteristic highly valued in the manufacture and the usage of swords. In case of blades that consist mostly of wrought iron, the only positive effect of pattern-welding might have been associated with a somewhat enhanced resistance to plastic deformation, but steel, as a material of choice for the same purpose, would grant the same or even, if sophisticatedly hardened, superior effect. Although pattern-welded composites comprising phosphoric iron and tempered steel have relatively good mechanical properties, they are, as a rule, encountered only in blades characterized by a fair amount of tempered steel in their cutting edges and, sometimes, in the blade's core. Thereupon, there was no reason to use pattern-welded elements to achieve a quality-wise shift in mechanical characteristics. All this furthers the alleged assumption, formulated already by Tylecote and Gilmour (1986, 251), that the discussed technique was applied almost distinctly for aesthetic purposes and could not provide or secure mechanical properties greater than a simple set comprising robust steel edges welded onto a ferrous core.

The conducted research also proved that the notching and stress concentration effect of slag inclusions strongly decreases all the characteristic values of ductility and toughness of medieval bloomery iron materials compared to modern steels Therefore, any use of modern steels in a research focused on mechanical properties of historical swords (weapons, tools, etc.) should be attempted highly judiciously, so as to avoid misinterpretations of yielded test results, be they rather deprived of the human factor, or associated with solely subjective observations.

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