STRUCTURAL ANALYSIS OF HANDLES OF HIGHLY CURVED IRANIAN SWORDS

Çok Kavisli İran Kılıçlarının Kabzalarının Yapısal Analizi

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Abstract

The handle of Iranian sword şamşir shows a complicated construction that has not been investigated scientifically so far. The handle consists of handle scales (āj), rivets (mil-e etesāl), adhesive material (zāj-e sepid), crossguard (bolcāq or mohāfez-e daste), pommel cap (kolāhak) and tangbands (āhanak). On some handles, there are two separate steel plates that are attached to the tang via adhesive materials and rivets as well. To analyze the construction, digital scanners, AutoCAD software (Autodesk Inc.) and X-ray radiography will be used. The following article will show that such a construction is not a haphazard one, but in such a construction, the tang of the sword functions like a spring in a spring and dumper system, and the adhesive material also functions as a dumper and the design may significantly prevent propagation of reaction shock waves to the user's hand. The goal of this study is to show how this system of shock absorption works. Further, for the first time, the components of the adhesive material are analyzed using energy-dispersive X-ray spectroscopy (EDS) and secondary electron microscopy (SEM). Another goal of this study is to find out how this material was made in the past. Based on a recipe from a Persian manuscript on precious stones, jewels and metals titled Javāher al-Sanāye' (Jewels of Crafts), this adhesive material is successfully reconstructed. This article shows the close similarity between components of the adhesive material found in Persian şamşir and the mixture of components as prescribed in the recipe of Javāher al-Sanāye'.

Keywords: Sword, Shamshir, Handle, Handle Scales, Crucible Steel.

Öz

İran kılıcı şamşir'in kabzası şimdiye kadar bilimsel olarak araştırılmamış karmaşık bir yapıya sahiptir. Kabzayı oluşturan parçalar; kavrama yan parçaları (āj), miller (mil-e etesāl), yapıştırıcı (zāj-e sepid), balçak (bolcāq veya mohāfez-e daste), kılıç başı (kolāhak) ve pırazvana şeritleri (āhanak). Bazı kabzalarda yapıştırıcılarla ve millerle pırazvanaya iliştirilen iki ayrı çelik plaka vardır. Bu yapıyı incelemek için dijital tarayıcılar, AutoCAD yazılımı (Autodesk Inc.) ve x-ışını radyografisi kullanılmıştır. Aşağıdaki makalede bu yapının gelişigüzel olmadığı, kılıcın pırazvanasının bir yay ve amortisör sistemindeki yay

gibi işlev yaptığı, yapıştırıcının amortisör işlevi yaptığı ve bu tasarımın, reaksiyon şok dalgalarının kullanıcının eline yayılmasını önemli ölçüde engelleyebileceği gösterilecektir. Bunun yanında ilk kez olarak, enerji dağıtımını x-ışınları görüngen gözlemi (EDS) ve ikincil elektron mikroskopisi (SEM) kullanılarak yapıştırıcının bileşenleri incelenmektedir. Ayrıca, değerli taşlar, mücevherler ve metaller hakkındaki Javâher al-Sanâye' (Zanaat Mücevherleri) adlı Farsça bir elyazmasındaki tarife göre bu yapıştırıcı başarılı bir şekilde tekrar üretilmektedir.

Anahtar Kelimeler: Kılıç, Şemşir, Kabza, Kavrama Yan Parçaları, Pota Çeliği

1. INTRODUCTION

Sword handle that is also called hilt in English is an important and integral part of any sword. Not only it is responsible for the sword's comfortability in the hand of its user, in many cases such as among European long swords, the sword handle exhibits a relatively heavy pommel to tune the distribution of mass along the sword and optimize its dynamics by reducing the reaction shock force on its user's hand and increasing the applied force on the target (Turner, 2002, pp. 60 -67). In many cases such as rapiers, the handle provides a protection for the user's hand by knuckle guards. Moreover, the handle may bear considerable decoration in the form of carvings, gem cutting and stone setting, or beautiful gold overlaying/inlaying as can be found frequently in Turkish and Indian swords. The handle in a sword was so important that in many Japanese swords it covers the blade tang (*nakago*) that bears the maker's signature (*mei*) or the owner's name. As we know the handle (*tsuka*) of all Japanese sword types such as *tachi*, *katana*, *wakizashi* and *tanto* can be easily removed by removing the peg (*megugi*) (see Moshtagh Khorasani, 2018, pp. 182-185). But some Iranian swords bear also the maker's mark on their tang. The only difference is that it can only be seen when one removes the handle by destroying its adhesive material. Some Iranian swords have a partially broken handle such as a *šamšir* attributed to Shah Soleyman Safavid kept in the Military Museum of Tehran in Sa'd Abad Palace Complex (Moshtagh Khorasani, 2006, pp. 158, 448-449, Cat. 83). This *šamšir* has three gold-inlaid cartouches on its blade: the uppermost has a remarkable inscription, *Ana Man Soleyman wa Ana* (It is from Soloman and it is). It is part of the verse 30 of the sura 27 an-Naml (the Ant) of the *Qur'an*. Soleyman translated as "Soloman" in English rendition of *Qu'ran alludes to Shah Soleyman Safavid*. In other words, related to the sword the translation can be interpreted as "I belong to Soleyman [and Soleyman belongs] to me". Similar to the verse 30 of the sura an-Naml, the afore-mentioned inscription on the sword is followed by the gold-inlaid inscription *Bismellah el Rahman al Rahim* (In the name of Allah, most benevolent, ever-merciful). In the middle, there is a gold-inlaid *bodduh* (magic square) with letters, and at the

bottom is the cartouche, *Amal-e Assadollāh Isfahāni 1092*. The very important feature of this cartouche is that it is dated 1092 hijra (1680-1681 CE) that is within the era of the kingdom of Shah Soleyman (Shah Safi II), who ruled from 1666–1694 CE (1077–1105 hijra). Allan and Gilmour (2000, p. 200) also point out that many Iranian blades are signed on their tang, but since the grips are glued, it is impossible to view the inscriptions without destroying the grip scales. On the above-mentioned example, one can clearly see the chiseled inscription, *Amal-e Assadollāh Isfahāni* (The Work of Assadollāh Isfahāni) on the tang. As one of the grip scales is destroyed.

Even in some languages like Arabic and Persian, swords are counted by their handle (the unit for counting swords in Arabic and Persian is *qabze*, which means handle, see Neshāt, 1989, p. 188). In many swords from different geographical regions and eras, sword handles are precisely designed to increase effectiveness of the weapon, its beauty, and its comfort for its user. Some of these handles are constructed from specific and sometimes rare materials precisely shaped by a labor-intensive method and assembled in a relatively complex and precise manner (see Yoshihara et al. 2012; Evangelista, 1995).

In the present article, we will analyze the most common type of handle in highly-curved Iranian swords based on original swords from 16th to 18th centuries CE (Table 1) and disclose their details using modern scientific equipment. To our knowledge, no scientific investigation and analysis on the construction method of the handle of Iranian *šamšir* has been done so far. Many modern sword makers are not aware of the construction of the handle of Iranian *šamšir* and make a full tang that runs and even curves up in the pommel cap. But this is not the historically correct method of making the handle of a *šamšir*.

Additionally, such a construction does not provide a shock absorption for the sword hand. Antique handles are not constructed this way. They have a narrow tang that is riveted to two separate steel plates. Further, the tang and these plates are glued to each other by a strong adhesive material on left and right sides. Then the handle scales are placed on top of the adhesive material. Further, the handle scales are mostly riveted to the tang. On top and bottom of the handle sides, the tang and the adhesive material are covered by two steel bands that are called tangbands (see Moshtagh Khorasani 2006, p. 187-190).

Figure 1. Swords analyzed in this article. a) Sword 5 in table 1. b) Sword 6 in table 1. c) Sword 7 in table 1. d) Sword 8 in table 1. e) Sword 30 in table 1. f) Sword 37 in table 1.

2. METHODS OF RESEARCH:

The six swords used in this study stem from 16th to 18th centuries. Five swords (a, b, c, e and f) have a typical wedge-shaped blade of a Persian with no fullers and handle with the typical pommel cap standing at 90 degrees to the handle. The sword (d) has a *karabela* hilt with a wide blade (for *karabela* hilt see Toichkin and Khorasani 2016). All blades are made of patterned crucible steel. To shed more light on the construction method of these handles, first, different parts of the handles of these swords and their geometrical dimensions and features are analyzed using digital scanners, AutoCAD software (Autodesk Inc.) and X-ray radiography.

Then, the materials used in the handle are described and analyzed for the first time to our knowledge. The nature and components of the adhesive material of the handle is analyzed using energy-dispersive X-ray spectroscopy (EDS) and secondary electron microscopy (SEM). Then, this material is reproduced using an ancient recipe found in an ancient Persian manuscript titled *Javāher al-Sanāye'* جواهرالصنائع (*Jewels of Crafts*) by an unknown author that is kept in the Library of Iranian Parliament with the number 2849. Finally, our interpretation of mechanical functionality of these handles in an impact is described.

Table 1. Specifications of Swords analyzed in this article.

	Sword-08	Sword-37	Sword-30	Sword-05	Sword-06	Sword-07
Attribution	16 th to 17 th centuries	18 th century CE, King Soltan Hossein	17 th century CE, King Abbās the great, King Fathali	17 th century CE	18 th century CE	16-17 th century CE, King Ismāil I
Inscriptions	Sign of Assadollāh (the master sword maker); An unknown sign; and verses from Qura'n all engraved on the blade	Verses from Quran; Nāde-e Ali (a religious prayer); and year of fabrication all gold overlaid	Work of Asadollah from Isfahan; Abbas, servant of king of the country; Fathali, servant of king of the country; and an unreadable poem all gold inlayed	Floral designs engraved	No inscriptions remained	Word of Assadollāh; A religious phrase; and a poem all gold inlayed
Jawhar pattern	High quality and bold woodgrain	Mohammad's ladder	Mohammad's ladder	Sham	High quality Qum	Mohammad's ladder
Color	Dark tune	Dark tune	Dark tune	Light tune	Light tune	Dark tune
Grip material	Horn	Secondary dendrite of walrus ivory	Elephant ivory	Primary dentine of walrus ivory	Staghorn	Does not exist any more
Blade length	80 cm	85 cm	85 cm	79 cm	78 cm	89 cm
Weight without scabbard	754 g	910 g	814 g	642 g	714 g	741 g
COM¹ distance from shoulder	22 cm	23 cm	25 cm	16.5 cm	16 cm	30 cm ²
COP³ distance from shoulder when rotated around handguard	50 cm	51 cm	50 cm	46 cm	44 cm	52 cm ⁴
Mass of Inertia when rotated around handguard	0.105 m ² .kg	0.135 m ² .kg	0.128 m ² .kg	0.0659 m ² .kg	0.07 m ² .kg	0.134 m ² .kg
Pendulum frequency around handguard	0.677 Hz	0.673 Hz	0.676 Hz	0.704 Hz	0.714 Hz	0.671 Hz
Width near shoulder	36 mm	33 mm	32 mm	34 mm	26 mm	32 mm
Width at the middle	32 mm	28 mm	26 mm	25 mm	25 mm	29 mm
Thickness near shoulder	6.1 mm	6.5 mm	6.2 mm	5.8 mm	5.1 mm	6 mm
Thickness at the middle	5 mm	5 mm	6 mm	5 mm	4.5 mm	5.5 mm
Thickness near tip	2 mm	2.3 mm	3 mm	1 mm	2.5 mm	2 mm
Grip length	90 mm	8 cm	8 cm	10 cm	10 cm	10 cm
Pommel length	39 mm	35 mm	26 mm	30 cm	30 cm	30 cm
Handguard width	120 mm	118 mm	119 mm	115 mm	135 mm	113 mm

1 Center of mass (COM) is the balance point of the sword

2, 4 Destruction of the handle has changed COM and COP of this sword.

3 Center of percussion (COP) is the location on a sword at which an impact will produce no reaction force the user's hand. This location of point is found by the pendulum method (Turner 2002).

3. GEOMETRICAL ANALYSIS

The handles of highly curved swords from 14th to 19th centuries CE that are found through the whole Middle East are mostly one-handed with a handguard and a pommel cap located generally at about 90° angle. Ottoman Turkish swords of this era usually have a cross guard and their pommel is circular and a continuation of the grip (figure 2.a). In these swords, usually the grip and pommel are made in one piece. In rare cases the so called *Karabela* hilt (figure 1-d) is made and used in Iran and Turkey as well (Toichkin and Moshtagh Khorasani, 2016, pp. 181-197). Indian swords of this era, usually have a disk-shaped metallic pommel where its center is attached to the end of the sword's tang and in some cases, they have a knuckle guard (figure 2.b). Using precious or semi-precious stones in Ottoman Turkish and Indian handles are more common. Many Turkish and Indian swords of this era are enameled as well and gold overlay is very common in them. In less common cases, lion head or horse head shapes are used in highly curved Indian swords, too. In Arabic swords of this era having a cross guard and a relatively longer conical pommel located at an angle slightly smaller than 90° to their grip and silver wire decorations are more common (figure 2.c). In later centuries some European handles are copied and used through the middle east as well. However, these European like handles are mostly mounted on European style blades which are not highly curved.

Figure 2. a) A typical Ottoman sword's handle. b) A typical Indian sword's handle. c) A typical Arabic sword's handle.

Iranian swords of this era are usually equipped with a cross guard and a cylindrical metallic pommel cap located generally at a right angle to

the grip (figure 3.a). Although many high-quality Iranian swords of this era bear gold inlay or carvings, generally the high-quality patterned crucible steel that is used in these swords is considered a jewelry on its own right and its beautiful woodgrain patterns are considered the best decoration and sign of quality in Iranian swords. This is a feature that Iranian swords share with Japanese Nihonto swords. Simplicity is the key element of design. Thus, in general, the Iranian smiths maintained their tradition of simplicity as well when decorating the handle. The crossguard and the scabbard mounts normally have the same decoration and material. They often have a smooth steel surface, and some of them have gold inlays and overlays (Zeller and Rohrer, 1955, p. 101).

Although the aforementioned features can be used as a hint to distinguish geographical origin of different Middle Eastern highly curved swords, readers should be very conscious about the fact that due to the huge cultural, economic, political and military relations and exchanges between nations in this region, all of the aforementioned handles could have been produced in limited quantities in all of the Turkish, Arabic, Indian and Iranian regions during that era.

Figure 3. A typical handle of a high quality highly curved Iranian sword (sword 37 in table 1). a) Viewed from the back side. b) Viewed from the edge side. Since the tang is covered by the whitish adhesive, tangbands and handle scales, it is not visible.

Handles of Iranian highly curved swords are composed of a cross-shaped handguard (*bolčāq* or *mohāfez-e daste* in Persian), a pommel cap (*kolāhak* in Persian), a tang (*um-e* or *zabāne* in Persian), handle scales (*āj* in Persian), a whitish and extremely strong glue (*zāj-e sepid* in Persian), and two steel bands covering the edge-side and back-side of the tang (*āhanak* in Persian) (figure 3.a) (see Moshtagh Khorasani, 2010). In some cases, two thin steel plates are put on the two sides of the tang and the whitish adhesive

is put on these plates. The tangbands are less than 1 mm thick and about 1 cm wide and they are extended from the handguard to the pommel cap. The tang in these handles is about 5 mm thick near the handguard tapering towards the pommel cap and it is less than 2 mm thick close to the pommel cap. Usually two (sometimes one and sometimes three) rivets are used to further attach the scales to the tang and one rivet is used to attach the pommel cap to the tang. Generally, these rivets do not have a raised rivet head and sometimes their heads are hidden in the scales.

The handguard is usually about 10 cm long and 12 cm to 14 cm wide made of four plates with two semi-spherical knobs at each end (figure 3.a). Each knob is about 1 cm. The handguard is hollow everywhere except at the two knobs and close to them. The hollow regions of handguard are filled with an adhesive material. The handguard's weight is usually about 70 g without the whitish adhesive material. Metallic part of the handguard in some swords is made of a single piece of patterned crucible steel and in others it is made of four pieces of patterned crucible steel welded together (figure 5). The pommel cap in these swords is usually between 2 cm to 3 cm in diameter and about 3 cm long and its weight without adhesive is about 12 g. The pommel cap is usually filled by the same whitish adhesive material and in some cases the end of pommel cap is partially filled by some lead like material or solder like material (figure 6), probably to increase its weight and optimize weight distribution of the sword. The grip in these swords (scale) is about 10 cm long and between 2 cm to 3 cm in diameter.

Figure 4. Figure 4 shows x-ray radiography images of a typical highly curved Iranian sword. This is X-ray radiography of a typical highly curved Iranian sword

(sword 6 in table 1). a) Photograph of the handle and its dimensions. b) X-ray radiography image of handle from side view and c) X-ray radiography image of handle from top view.

Figure 5. Fabrication of a welded handguard from four pieces numbered from 1 to 4. a) Drawing of the four pieces which are making a welded handguard. b) knob piece (4) welded to a side piece (1). c) Knob piece (4) and side pieces (1) and (2). The blade and the whitish glue are visible here as well.

Figure 6. Bottom of a pommel cap (sword 7 on table 1) filled by a solder like material.

Although Zeller and Rohrer (1955, p, 98) state that *āhanak* (tangbands) are usually soldered to the tang, radiography images shown no sign of welding or soldering between *āhanak*, pommel cap and handguard. In most handles we have investigated, all of the segments are attached and dovetailed to each other by their shape and size and the only means of attaching them are rivets and the whitish glue.

Usually handle scales are not engraved in these swords and their surface is smooth to reveal the pattern of the crucible steel. However, there are some exceptions. It is not uncommon in high quality Iranian swords to have engravings and/or gold inlay on their handguard and pommel and even on tangbands in some swords.

4. MATERIAL ANALYSIS

Handguard and pommel in these handles are usually made of patterned crucible steel or *pulād-e gohardār* in Persian (figure 7). It is a well-known material with relatively low mass density and very high toughness and micro hardness with a beautiful woodgrain pattern (*Highly-Curved Iranian Swords: Structural Properties and Specifications*, Manouchehr Moshtagh Khorasani, Nima Arjmandi, to be published soon).

Figure 7. Woodgrain pattern of a high-quality patterned crucible steel, used as a sign of quality and a decoration on handles of highly curved Iranian swords (sword 8 in table 1).

Handle scales in high quality swords are made of primary dentine of walrus ivory (figure 8.a); in extremely high-quality swords it is made of secondary dentine of walrus ivory that has a marble like pattern (figure 3.b and figure 8.b) to resemble the so-called *johar* pattern of the blade (figure 9). Walrus ivory is not only one of hardest biological materials available on earth; it is a nonporous material that sticks to human hand, especially when it is wet. In some of highly curved Iranian swords, handle scales are made of ivory of Asian elephant –i.e., *Elephas maximus* (figure 8.c) or horn of stag – i.e. *Cervus elaphus* (figure 4.a) or Asian buffalo –i.e., *Bubalus arnee*. Recognition of scale materials in this work is done according to “Identification Guide for Ivory and Ivory Substitutes”, United States National Fish & Wildlife Forensics Laboratory, Ashland, Oregon, 1999.

Figure 8. Scales of highly curved Iranian swords. a) Scale made of primary dentine of a walrus ivory (sword 5 in table 1). b) Scale made of secondary dentine of a walrus ivory (sword 37 in table 1). c) Scale made of *Elephas maximus* ivory (sword 30 in table 1).

Figure 9. a) Pattern of secondary dentine of walrus ivory on a sword handle (sword 37 on table 1). b) The so called *johar* pattern on blade of the same sword.

For a long time, the nature of the whitish glue that fills the gaps between tang, handle scales, tangbands, pommel cap and handguard remained unknown. This is a relatively hard material that adhered very strongly to steel and ivory, and even after centuries, we have found it impossible to separate it from the steel without breaking it and it is even difficult to scratch it with hammer and a chisel during the sampling. According to some records it is called *zāj-e sefid* in Persian (see Zeller & Rohrer, 1955, p. 98) that means white alum in English (see Moshtagh Khorasani, 2010). However, obviously, it is not pure alum and its properties like hardness, toughness, melting point, water solubility and adhesion to steel are far beyond alum.

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Figure 10. EDS analysis of the whitish adhesive of a sword from the 16th century (sword 7 in table 1). In this analysis acceleration voltage was 15 kv, beam current was 10 nA and magnification was 45000.

Table 2. Percentage of the elements in the whitish adhesive of a sword (sword 7 in table 1).

	Original historical adhesive		Reproduced adhesive	
	Weight %	Atoms %	Weight %	Atoms %
C	4.28	6.61	5.12	7.74
O	65.29	75.74	67.6	76.7
Al	7.43	5.11	7.55	5.08
Si	0.86	0.57	-	-
S	14.05	8.13	12.95	7.33
K	7.67	3.64	6.73	3.12
Ca	0.42	0.19	0.05	0.02

This combination of elements obviously matches a mixture of dairy

products (see Aabdel-Salam, Z. & A. el-Sayed, pp. 1117–1120), alum and lime. SEM images (figure 11.a) clearly show a ceramic material with small crystal grains. Largest grains are mainly composed of calcium (figure 11.b) and do not contain much aluminum (figure 11.c). These grains are cubic shaped (most of calcium and calcium oxide composites have a cubic or pseudo-cubic crystal structure) smaller than 10 μm . Large size of these grains suggests a long and mild thermal process that has enabled crystal growth. On the other hand, strengthening effect of egg white proteins on alumina ceramics is not unknown in modern science (see Xing He et al, 2010).

Figure 11. a) SEM images of whitish adhesive of a sword (sword 7 in table 1), obtained at 15 kv acceleration voltage and 10 nA beam current. b) Map of calcium concentration in the image in (a). c) Map of aluminum concentration in image in (a).

We have found an ancient recipe for making a very strong glue mainly for military applications in an ancient Persian manuscript titled *Javāher al-Sanāye'* (*Jewels of Crafts*) by an unknown author that is kept in the Library of Iranian Parliament with the number 2849. This is the only known manuscript describing this recipe. In this manuscript, this adhesive is called *serīšom-e panir*, which can be translated to casein glue in English. Recipe of this adhesive is described on pages 40 to 42 of this manuscript. The translation of the Persian text follows:

Page 40 - Third chapter about making casein glue and dissolving bodies that are used for dyeing and there are six types. First type: About characteristics of casein glue that is an exotic and secret science. But it is a necessity to explain as most operations in this book are done with the help of this type of natural glue. There is only one type. They bring fresh casein as much as they wish and cut it in narrow long pieces. The narrower the width the better it is. They bring a clean wooden plank and place it on an even ground.

They mix the casein pieces in dried limestone liquid and place them on the bottom of a crucible. Then they place another wooden plank on it. Then they place a heavy stone on the wooden plank with the same length and width under the sunlight. The heavier the stone the better it is. After ten days, they take them out and wash them so that they can wash off all traces of limestone. They place them under the sunlight for the whole day. After its water is vaporized, the fat appears. Like the first time, they add the limestone as before. Then they place the same wooden planks and stone on them as mentioned before. They do it as long as it is required. They keep them for seven days and on the eight day, they take them out and wash them with hot water and clean them with white fabric. They keep them under the sunlight for the whole day. On the other day, they place it in a big cauldron and put on it a trivet. They add salt water to it and place the [casein] pieces in it. They burn fire under it and boil it. After the water vaporizes, they add salt water again and keep boiling it for the whole day.

Page 41 - *Then they take them out and wash them with fresh water. They clean them in fabric and dry them under the sunlight for the whole day. Then they boil them in salt water again. As mentioned before, they clean them with fresh water and a piece of fabric. Then they dry them under the sunlight. They keep the dust away. They keep doing this process for couple of times so that no fat from the casein appears under the sunlight. If it appears, they repeat the whole process again so that its fat and redness disappear. It should look like a "lime stone clay". They grind them into mill powder. They place it in a glass vessel and keep the dust away and that is an absolute requirement. When they want to use it, they bring fresh white egg (albumen) and place it in a container and stir it. They take its foam and keep stirring it for couple of times so that it starts to shine and it does not foam anymore. They place a bit of that casein on [polishing stone made of] porphyry or "polisher made of glass" and add the white egg by dropping it and rubbing them together. They keep doing it until the mixture sticks to the lower stone. If they want it to get more fluid, they dissolve dried limestone in water so that that the water looks like "yoghurt drink". They distill it with great care and add some of that water to it and rub it so that it becomes fluid and is not very thick. Then they can use it the way they want. To use it, they dissolve the powder of casein [in water]. If it remains long and more than one hour, it*

becomes hard, and they cannot scratch it with anything and they cannot take pieces of it out. This is the glue and it is so hard that it neither boils in water

Page 42 - nor does it burn in fire. Iron cannot penetrate it and no gun, no arrow, no spear/lance, and no push-dagger can damage it. If they make shields, kotalhāyejanneh [meaning of this word is unknown], atkarkahi [meaning of this word is unknown], armguards, helmets, kančom or [meaning of this word is unknown], similar things they will be very hard, light and flexible and nothing can penetrate them. One cannot even imagine all things that can be made of this. It is a rarity which is unprecedented. It is common and is a tested method.

Figure 12. Page 40 of the manuscript *Javāher al-Sanāye'* (Jewels of Crafts)

Figure 13. Reproduction of the whitish adhesive (casein glue) according to the ancient manuscript (*Javāher al-Sanāye'*). a) Slices of two types of cheeses covered by quick lime on a piece of wood. b) The white powder obtained after baking the processed cheese slices in alum solution, drying and milling it. c) Processed white egg. d) Prepared adhesive by mixing (c) and (b). e) Wet adhesive put on a piece of stone and in a two centuries old piece of steel. f) Dried adhesive used for comparison with the original whitish adhesive on swords.

There was an unclear point in this manuscript; it mentions the addition of salt water at some point in preparation of the adhesive. Salt (*namak* in Persian) is a name used not only for sodium chloride, but it is used for a wide range of materials, which are all ionic crystalline and water-soluble solids. Having the elemental analysis of the whitish glue used in sword handles, we knew it could not have a large percentage of sodium chloride and there should be more of a material composed of aluminum, potassium and sulfur. On the other hand, we know from a few travelers' records, which are mentioned above, that this whitish glue was called *zāj-sepid* (alum in English). Thus, we guess this salt should be alum ($KAl(SO_4)_2 \cdot 12H_2O$). During the reproduction of this adhesive material following the advice of the above-mentioned manuscript, alum was added to the mixture (figure 9). After several attempts to optimize process parameters and after gaining enough experience, a whitish adhesive material with

similar mechanical properties to the adhesive materials used in historical swords was obtained (figure 13.f).

To further compare the reproduced adhesive with the ancient one, we have used EDS to obtain elemental finger print of the reproduced adhesive (figure 14). Interestingly, elemental analysis of the reproduced adhesive matches the ancient one as well (table 2). The Largest difference between the historical original sample and the reproduced one, is the presence of small amounts of silicon (0.57%) in the original sample that is probably caused by dust. Because the reproduced sample is prepared in a cleanroom environment which probably was not available before the 20th century, unlike the original one, it cannot be contaminated by dust. Thus, we believe that we have found the formulation and fabrication process of the whitish adhesive material used in handles of highly curved Iranian swords. Therefore, we believe that the most suitable phrase to call this adhesive material is casein glue (*seriřom-e panir* in Persian) as mentioned in the manuscript *Javāher al-Sanāye'* (*Jewels of Crafts*). Although alum (*zāj-e sepid*) is used in its production as one of the ingredients, it is not purely made of alum (*zāj-e sepid*).

Figure 14. Result of EDS elemental analysis of the reproduced casein glue. Insert

shows SEM image of the reproduced adhesive material.

5. FUNCTIONALITY OF THE HANDLE

We should remember that the functionality of a sword was the most important aspect of it. The handle in highly curved Iranian swords probably served several purposes:

- Reducing the probability of falling the sword from its user's hand,
- Diminishing the probability of undesired rotation of the sword in the user's hand,
- Optimizing the weight distribution along the sword to reduce the impact shock force on the user's hand and increasing the impact force on the target,
- Protecting the user's hand from the opponent's weapon,
- Providing a comfortable surface to hold to prevent any skin injury on the user's hand,
- Making the sword more beautiful.
- Preventing the transfer of impact shock waves to the user's hand,

Handles in highly curved Iranian swords are usually tight and they press against the user's hand by the handguard and the pommel cap. This tightness certainly gives a sense of a reliable grasping. Moreover, the right-angle pommel cap reduces the chance of falling of the sword; especially when the user needs to pull it out of the target's body, and also in close combats when the impact point is closer to the handguard than the percussion point and the reaction shock force tends to move the grip upward.

The two knobs (or spatula in spatulated crossguards) on the crossguard of these handles that are pieces of solid steel increase the moment of inertia of these swords around the longitudinal axis of the blade. Hereby, they reduce the probability of an undesired rotation of the sword in the user's hand. It is especially an important feature in highly-curved swords because a heavy impact on their side near their tip may produce a huge torque around their longitudinal axis. This torque tends to rotate the sword in the user's hand and if the sword's moment of inertia around this axis is not sufficiently high, it may dangerously accelerate and rapidly rotate in the user's hand.

The pommel cap in these handles reduces the reaction shock force on the user's hand by about 10 % and moves the center of percussion by about 10 % towards the blade's tip [Highly-Curved Iranian Swords: Structural Properties and Specifications Manouchehr Moshtagh Khorasani & Nima Arjmandi, to be published soon].

The so-called crossguard protects the user's hand in most situations.

Additionally, some warriors covered their hand and fingers by using *bāzuband* (armguard). Thus, there was no need to protect the user's hand further by using a knuckle-guard, a loop-guard, or a back-guard.

Walrus ivory that is the mainly used material for scales of these handles is a natural material that usually does not introduce any allergic reaction on the user's skin. Usually it is smooth and it is not engraved. Thus, it is not rough to the user's hand and may not cause friction blister of the skin. Furthermore, walrus ivory, unlike elephant ivory, is a hydrophilic and nanoporous material that not only efficiently absorbs sweat, it even sticks better to the user's hand when wetted.

6. CONCLUSION

One of the most important functionalities of these handles is to prevent the transmission of impact shock waves to the user's hand. This is a function that has not been studied before. Anyone who have used an impact weapon for long periods of time, especially with a metallic handle, may admit that this shock wave that transfers to the user's hand is the most worrisome and grueling aspect of this activity. There is a reason why the handle of Iranian *šamsīr* is made of different parts and this reason is to absorb the shock given to the hand of the swordsman upon the impact. In modern mechanical equipment like automobiles and aircrafts and weapons, usually spring and dumper systems and/or acoustic interfaces are used to reduce the transfer of impact shock waves to the users. This article has shown that the same approach and principles are used in these handles as well. First of all, not only the handle is not made of one piece (see Moshtagh Khorasani, 2006), the handle scales are also not directly in contact with the tang. Actually, in these handles there are several interfaces between the impact point (source of shock wave) and the user's hand:

- a) One between the tang and the casein glue,
- b) One between the casein glue and scales,
- c) One between the casein and tangband,
- d) One between the tangband and user's hand,
- e) One between the scales and the user's hand.

Since the tangbands are not soldered, there are interfaces between the tangbands and the handguard, between the tangbands and the pommel cap, between the tangbands and casein glue, and between casein glue and the tang. We know from basic physics that acoustic waves are partially reflected at each interface and having several material interfaces on the propagation path of these waves helps significantly reduce their transmission. On the

other hand, tangbands and the tang may function like a spring in a spring and dumper system here, and the casein glue may function as a dumper. This is probably the reason for the fact that the casein glue usually is the first part in these handles that breaks upon repeated heavy impacts. Further studies in this field should make a comparative analysis between different handles to establish a representative study.

6. REFERENCES

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