

Influence of Morphology Pattern of Genuine Damascus Steel on the Nature of Relief of Fracture Surfaces

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Abstract

It has been revealed that the structure of the transverse and longitudinal parts of the genuine Damascus knife of the XVIII century consists of troostite-carbide of the banding. The microhardness of the troostite layers is 450 HV; the carbide layers reach 950 HV. It is shown that such a banding structure in hardness will have a huge impact on the formation of a naturally patterned genuine Damascus structure. It is established that the form of the main drawings of the genuine Damascus pattern consists of separate elements of the topographic contour: hollows, hills, saddles, crosses and wavy dunes. It is shown that the damask pattern is a set of individual elements of the macrostructure alternating in a disordered form on different local areas of the surface. It is established that the destruction of genuine Damascus steels occurs under the action of two or more mechanisms, during the implementation of which traces remain on the surface of the fractures in the form of relief details of a mixed type. The mechanisms of mixed destruction are a combination of intragrain cleavage, micropore fusion and intergrain cracking. It is established that in order to implement the mechanism of separation of the main crack in the direction of the chopping blow, an optimum is required in the dispersion of troostite (61.8%) and carbide (38.2%) layers in genuine Damascus steel, the ratio of their volumes obeys the golden section rule. It is established that the damask pattern, consisting of elements of sinuous lines of a topographic contour, does not significantly affect the level of mechanical properties. This factor is a category of the quality of banding structures in genuine Damascus steel.

Keywords

Genuine Damascus Steel, Wootz Steel, Bulat Steel, Indo-Persian Steel

1. Introduction

The morphology and quality of the patterned surface on antique Damascus blades raise many questions from technical specialists. Without comprehensive structural studies, the answers to these questions lead to an incorrect interpretation of the damask pattern. Confusion in the identification of Damascus structures contributes to the fact that any pattern obtained on the surface of plates made of modern alloy steels is classified as patterns of genuine Damascus steels.

A number of scientific articles are devoted to the study of patterns, chemical composition and mechanical properties of genuine Damascus steels [1]-[21]. However, these articles do not pay attention to the relationship between the genuine structure and the nature of destruction.

As a rule, the destruction surface of samples from Damascus steel was evaluated by qualitative characteristics. For example, by the color of the fracture – matte (lusterless), shiny, or silky fracture, as well as by the type of relief of the fracture - fibrous, slate (layered), stone-like or chevron fracture. Based on laboratory data, conclusions were drawn about the nature of destruction during operation without taking into account the patterned macrostructure of the Damascus blade.

The study of the nature of the destruction of anisotropic structures of steel, which include genuine Damask steel, is an urgent scientific task. The ratio of longitudinal and transverse mechanical properties does not always indicate the advantages of bladed products made of Damascus steel compared to their modern counterparts. An integrated approach is important, in which the whole range of chemical and structural factors affecting the nature of the destruction of a knife blade will be considered.

The purpose of the work is to identify morphological features of individual elements of patterns on genuine Damascus steels of the XVIII century on the basis of layered chemical and structural analysis, with the aim of their contribution to the formation of details of the relief of the fracture surface.

Based on the data obtained, it will be possible to control the creation of a new variety of modern Bulat, achieving high-quality products. Taking into account the above morphological parameters, a new opportunity will appear for the systematization of Bulat varieties, both ancient genuine Damascus steels and modern Tools steels.

2. Materials and Methods

As the research material has selected a fragment of the Iranian Bulat knife (**Figure 1**). The Iranian household knife dates back to the end of the XVIII century is a genuine Damascus steel. The total length of the knife is 235 mm, the length of the knife blade is 140 mm. The width of the knife blade is 20 mm. The thickness in the butt is 3 mm, on the blade – 0.5 mm. The handle and guard of the knife are decorated with gilding. The handle is made of two halves of ivory, fastened to the blade with four through rivets. A patterned damask macrostructure

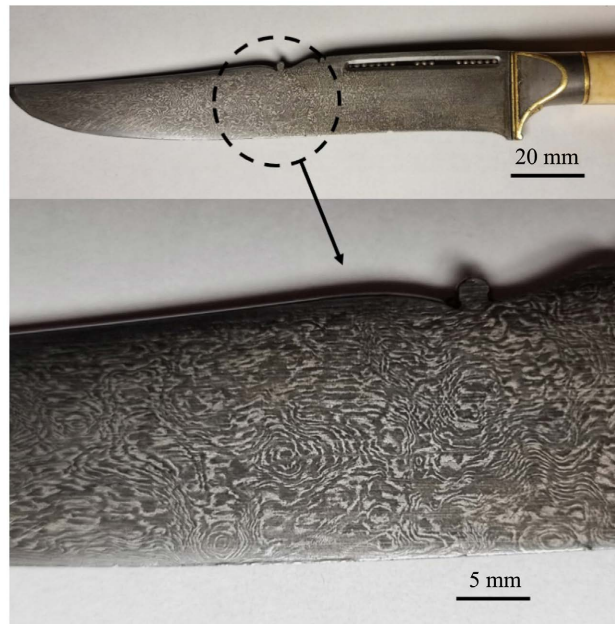


Figure 1. The appearance of an Iranian Bulat knife with a patterned structure.

is visible on a fragment of the surface of the knife blade. The knife blade has a dark shade (troostite matrix), the pattern on the blade is light lines (carbide banding).

The chemical composition of genuine Damascus steel was determined using an ARL 3460 optical emission spectrometer. According to the chemical analysis, the Iranian knife was assigned the Ds15P steel grade. In the marking, letters and numbers mean the following: Ds—genuine Damascus steel, containing less than 0.05% Manganese (Mn) and Silicon (Si), each separately; 15—the average mass fraction of Carbon (1.45%... 1.53%); P—Phosphorus with a mass fraction of at least 0.1%, but not more than 0.25% (0.171%... 0.192%). This indicator for phosphorus is hundreds of times higher than the threshold value for high-quality tools steels. All other alloying elements did not exceed thousandths of a percent. The studied fragment of the genuine Damascus steel according to the modern classification is unalloyed high-carbon steel with a high phosphorus content.

In modern industry, high-carbon steels with such a carbon and phosphorus content are not used. According to its chemical composition, it should be attributed to steels with special properties used in the manufacture of cold weapons in the Indo-Persian region in the XVII-XIX centuries.

For comprehensive studies of the fracture surface, a fragment from the tip of a 50 mm long Iranian knife was cut out. It has a characteristic damask macrostructure (**Figure 2**). The morphology of the damask pattern was formed under natural causes of smoothing the peaks of hilly relief during forging. The structure of the transaction section of the blade has a characteristic banding structure (**Figure 2**). The width of carbide layers on average does not exceed 40... 45 microns, and the width of troostite layers on average is at least 75... 80 microns.

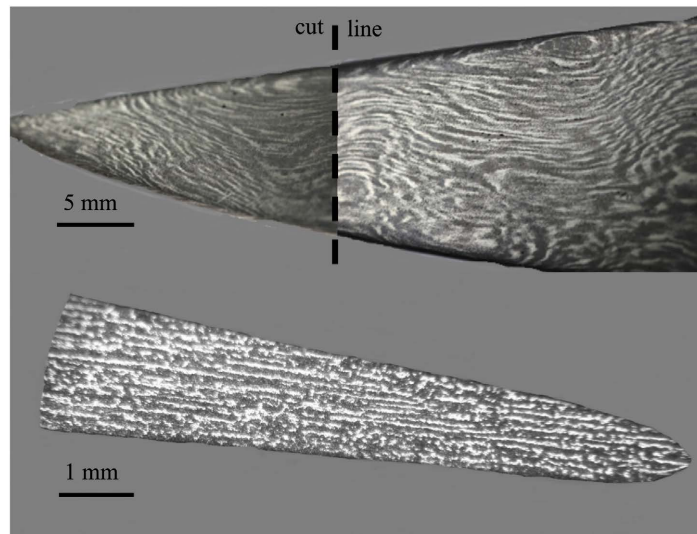


Figure 2. Fragments of the macrostructure of the knife from genuine Damascus steel: *the upper one figure is a patterned structure with a cross-section line; the bottom figure is the banded texture of the transverse part of the knife blade.*

The distribution of chemical elements in local areas of the fracture zone was determined using microprobe spectral analysis on a Zeiss EV050 XVP scanning electron microscope with an EDS X-Act probe microanalyzer system. The use of EDS spectrometers allows for quantitative chemical analysis at local points limited by the diameter of the electron probe of 2 microns.

The fracture surface of the sample from genuine Damascus steel was obtained at impact destruction according to the three-point bending scheme. Fractographic studies of the fracture zone were carried out using a Zeiss EV050 XVP scanning electron microscope. A transmission electron microscope FEI Tecnai G2 20 TWIN was used to identify the features of the finer structure of the genuine Damascus steel in the fracture zone.

3. Results and Discussions

When conducting structural studies, it was found that the structure of the transverse and longitudinal parts of the genuine Damascus knife of the XVIII century consists of troostite-carbide of banding (**Figures 3(a)-(e)**).

In the longitudinal part of the Damascus blade the internal microstructure has 100% carbide banding (**Figure 3(a)**). The carbide layers are not parallel to each other. In structure can observe both regularly directed layered banding with a volume fraction of at least 58% (**Figure 3(b)**) and wavy banding with a volume fraction of 22% (**Figure 3(c)**). Moreover, in the Damascus structure, there are torn and closed sections of the remains of the cementite network a volume fraction of 15% and of 5%, respectively (**Figure 3(d)** and **Figure 3(e)**). The curvature of the sections of the carbide banding in the troostite matrix leads to the fact that on the front side of the Damascus blade, after polishing and etching, patterns of various configurations appear.

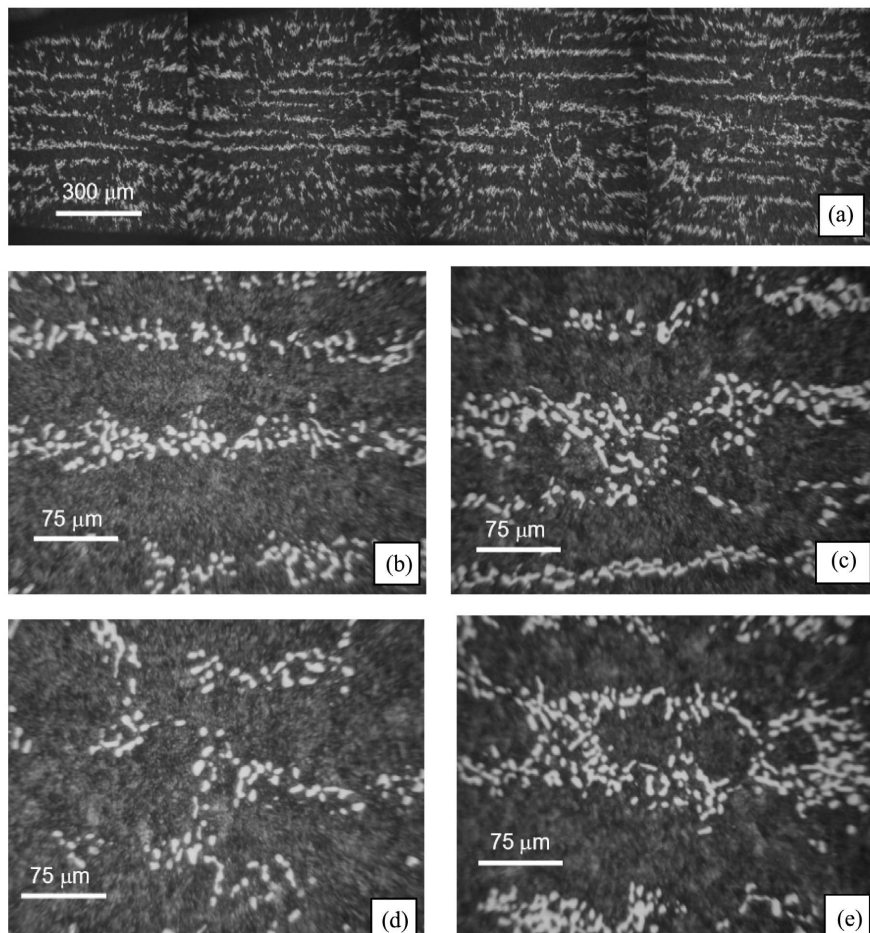


Figure 3. Forms of banded structures in the longitudinal part of the Damascus blade: (a) carbide banding (100%); (b) layered forms (58%); (c) wavy forms (22%); (d) cementite network is torn forms (15%); (e) cementite network is closed forms (5%).

The chemical analysis showed that the dark areas of the layers correspond to high-purity eutectoid steel with a troostite structure containing 0.86% Carbon and 0.03% Silicon. No other impurities and alloying elements were found (**Figure 4(a)**). The microhardness of the troostite layers is on average 450 HV.

According to electron microscopy data, it is confirmed that the eutectoid matrix is a pure quenching troostite with an interplate distance of no more than 100 nm. The volume fraction of lamellar troostite is about 80% of the total fraction of matrix structures (**Figure 4(b)**).

In the process of structural studies, troostite sites were found that differ from the morphology of lamellar structures. For example, there are areas of the matrix that can be identified as a divorced troostite. They're of the volume fraction not exceeding 15% of the total proportion of matrix structures (**Figure 4(c)**). This morphology of troostite is intermediate between lamellar and globular forms. Moreover, in the structure of damask steel, the globular form of troostite is extremely rare and, as a rule, does not exceed 5% of the total proportion of matrix structures.

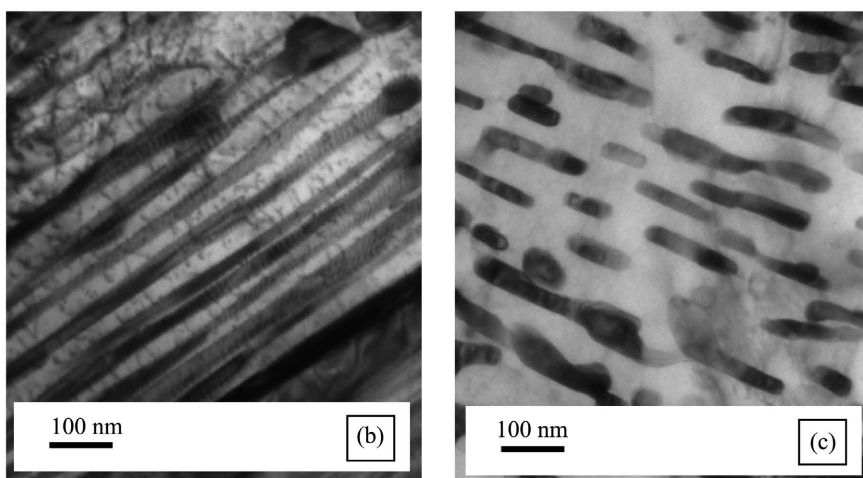
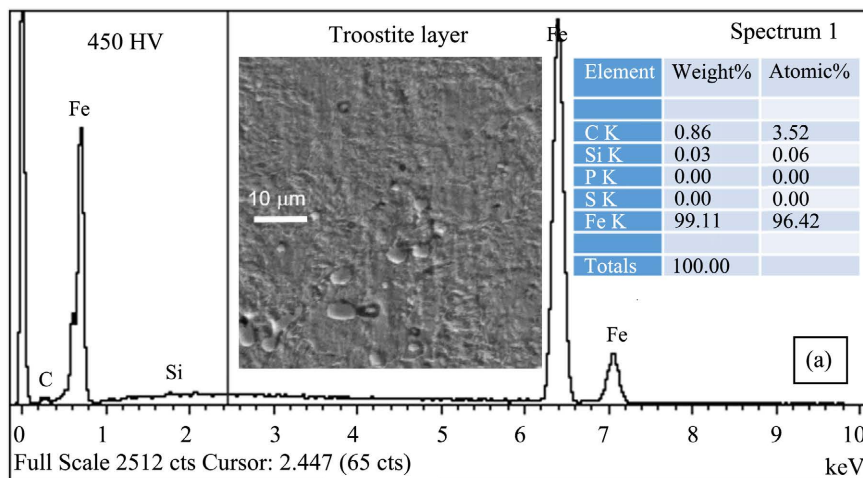


Figure 4. The structure and chemical composition of the genuine Damascus steel: (a) Stoichiometric chemical composition of the troostite matrix; (b) lamellar troostite (80%); (c) divorced troostite (15%).

The diversity in the morphology of troostite structures will affect the shape of the relief of the fracture surface. At the same time, brittle areas of intergranular cleavage and ductile areas of micropore fusion can be observed on the fractography of the fracture surface.

Another is observed in the carbide layers of genuine Damascus steel. The carbide layers in this steel are not monolithic. They are a troostite-carbide mixture, which corresponds to white eutectic cast iron (4.13% Carbon, 0.18% Silicon, 0.38% Phosphorus and 0.14% Sulfur). The sizes of excess carbides range from 2 microns to 12 microns with an interparticle distance from 5 microns to 15 microns (**Figure 5(a)**). The microhardness of the carbide layers is on average 950 HV.

According to the results of structural studies, it was found that the volume fraction of traditional globular excess carbides is no more than 15% of the total number of the carbide phase. Their dimensions do not exceed 2.5 microns in diameter (**Figure 5(b)**).

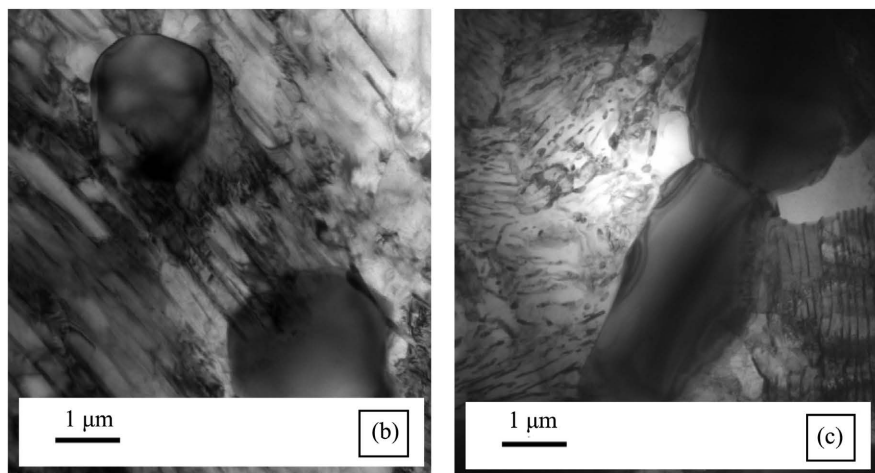
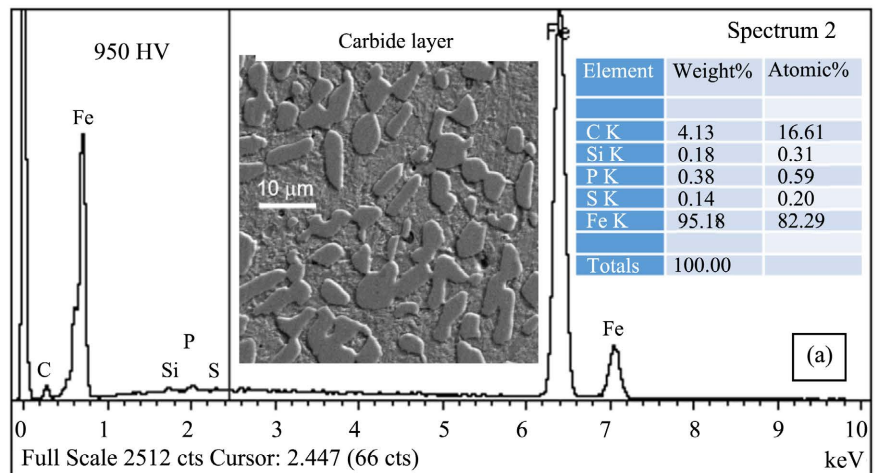


Figure 5. The structure and chemical composition of the genuine Damascus steel: (a) Stoichiometric chemical composition of the carbide layers; (b) globular carbides (15%); (c) carbides of oblong shape (85%).

Another part of the excess carbides is large elongated particles of an oblong shape. In places, you can observe thickening, tightening, kinks and accretions. Large oblong carbides have sizes from 6 microns to 12 microns. The volume fraction of such carbides in the Damascus structure is at least 85% of the total excess carbide phase (**Figure 5(c)**).

After conducting structural studies, it was found that the oblong carbide consists of separate isolated particles, outwardly resembling sea pebbles with a thickening in the middle part. Thus, large oblong carbides are not monolithic formations.

Large oblong carbides make the main contribution to the formation of carbide banding and, accordingly, the morphology of the details of the fracture relief. The oblong carbides are the hallmark of genuine Damascus steel.

Summing up the above, it can be summarized that in the layered structure of genuine Damascus steel, hardness maxima in carbide layers up to 950 HV and hardness minima in troostite layers 450 HV are observed. Such a striped texture

in hardness will have a huge impact on the formation of hilly surface relief on the front side of the Damascus blade. The size of the pattern will depend on the density of the distribution of layered carbide banding in the troostite matrix.

Layered banding is ideal for projecting sinuous lines onto the topographic plane. For the first time, Prof. Vinogradov pointed out the similarity of the damask pattern with hilly terrain on a topographic map [3].

A forged billet for the Damascus blade always has a relief of irregularities on the surface in the form of hilly burrs and concavities. There are large relief forms that form the surface of relatively extensive local areas measured in millimeters and smaller elementary forms of irregularities that make up the roughness of the surface, measured in tenths and hundreds of micrometers. The conditions for the formation of elementary forms of various orders depend on the size of the relief, and the lines which make up the damask pattern.

The relief of the damask surface is formed both for natural reasons during the forging process and with artificial relief application during drilling and stuffing dents. The natural relief combines sweeping undulating irregularities with hilly convex local areas. Let's decipher the fundamental concepts that lay the foundation of the Damascus structure.

The natural wavy relief is characterized by the absence of pronounced irregularities. It is formed during the final forging of the Damascus blade by the rounded surfaces of the hammer strikers. Due to the difference in the hardness of the layers, the banded structure of the metal seems to roll over one another in the longitudinal and transverse directions, creating wavy folds of higher-strength layers. As a rule, the crest of the wave with such deformation does not exceed 500 microns. The wave-like shape of the projection lines is one of the elements of the damask structure, an arbitrary combination that gives an elegant pattern in its beauty, giving the impression of sea ripples or sand dunes. Such a pattern in the East is called *Kum Hindi*, which means Indian wave.

Natural hilly relief is a large variety of wavy relief. It is formed mainly from a set of local bulges separated by longitudinal saddles and hollows (**Figure 6(a)** and **Figure 6(b)**). According to the shape and structure of convex and concave surfaces, this relief is characterized by irregularity along the length and significant fluctuations in the heights of convex hills, sometimes exceeding 1000 microns. The forms of the projection lines of the damask pattern represent elements of a topographic contour such as saddles, hollows and hills, an arbitrary combination of which gives the impression of flowing jets and whirlpools. Such a pattern in the East is called *Taban* or *Kara Taban*, which means resplendent or black-resplendent.

Artificial relief is formed in strictly defined places. Artificial alteration of the natural relief of the surface is used to enhance the contrast of the damask pattern. It is obtained by pressing dents or cutting (chopping, drilling) various irregularities on a wavy or hilly surface of a forged billet. When these artificial irregularities are smoothed with a hammer, after grinding and etching patterns typical of genuine Damascus steels of the ancient East are formed.

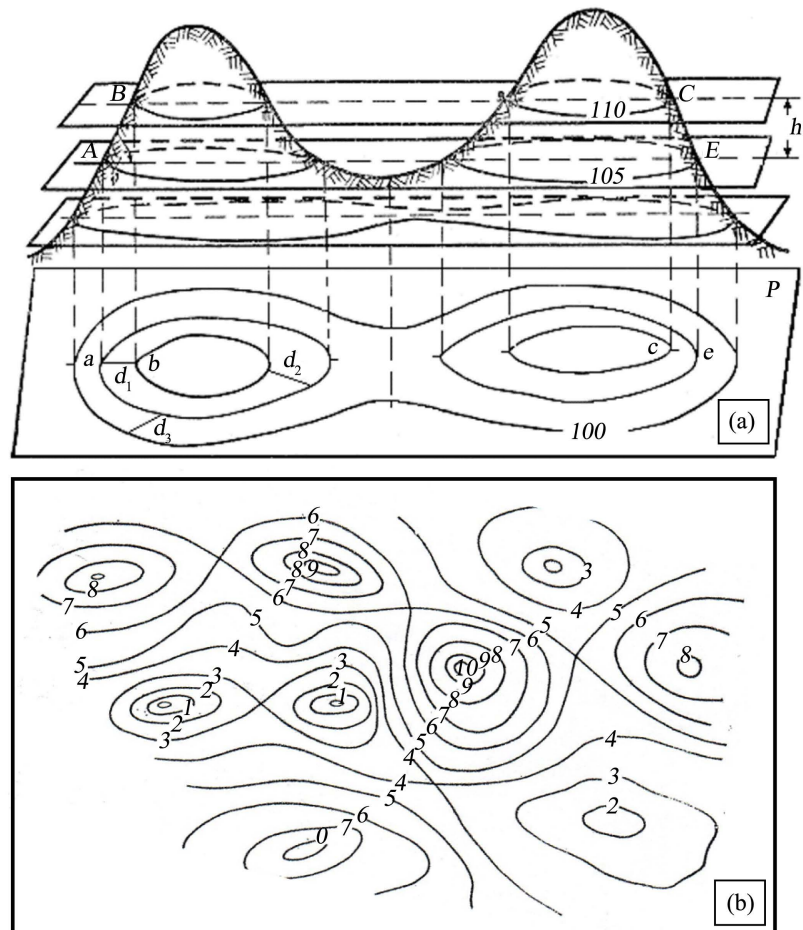


Figure 6. Diagrams of projections of hilly terrain on a plane: (a) diagram of the saddle between the hills and its projection on the plane; (b) diagram of the topographic contour of a hilly area.

This approach to the formation of a patterned surface seems to be the most relevant. The Damascus blade with a wavy pattern of the “*Kum Hindi*” type (**Figure 7(a)**) was probably the most mass-produced semi-finished product in Eastern technology for obtaining more complex mesh patterns of the “*Taban*” type (**Figure 7(b)**). Or, for example, a Damascus blade made of wavy damask was given the appearance of a mesh damask with steps of the “*Kirk Narduban*” type (**Figure 7(c)**), using improvised forging and stamping tools. Such Bulat was attributed to the highest grade of Persian weapons. The number of steps reached forty. Their called steps of the ladder of Mahomet.

Based on the conducted literary and structural studies, it becomes obvious that the shape of the pattern on genuine Damascus blades does not appear by chance. The regularity in local areas and the repeatability of the main projections of geometric shapes are traced. Such a pattern in the morphology of the elements of damask structures is characteristic of most sheet products made of high-carbon steels, in which a regular carbide layered texture was formed during deformation.

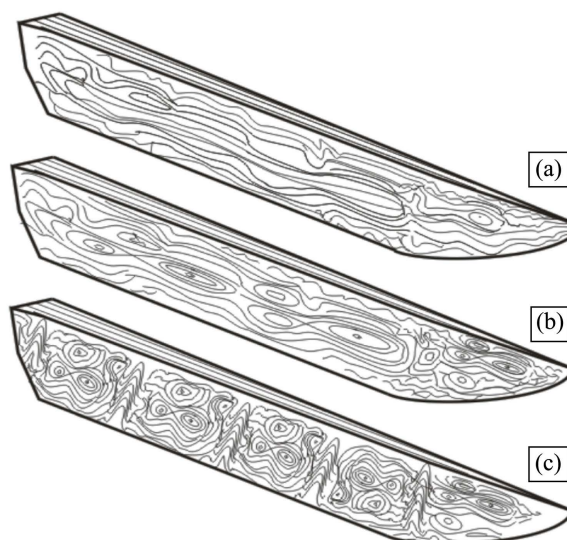


Figure 7. Schemes of transformation of patterns in genuine Damascus blades: (a) *Koum Hindi* (Indian wave); (b) *Taban* (Resplendent); (c) *Kirk Narduban* (Forty steps).

Let's look at the shapes of the patterned surface more clearly in the photographs taken on local areas of the surface of the Damascus blade. Most of them are similar to the elements of projections of undulating or hilly terrain on a topographic map, which can be reduced to several elementary forms.

The element of the damask structure, which looks like eyes, with relatively wide spherical horizontals and a spot in the center in the form of a pupil, is a topographic element of the figure “*Basin*”, that is, a closed cup-shaped dent with gentle slopes (**Figure 8(a)**).

The element of the damask structure, which is horizontal sinuous lines superimposed on each other after a certain step in the form of slopes or steps, is a topographic element of the figure “*Hollow*”, that is, a linearly elongated depression descending in one direction (**Figure 8(b)**).

The element of the damask structure, which is a concavity located between two adjacent peaks of the bulges in the form of hills, is identified as a topographic element of the figure “*Saddles*” (**Figure 8(c)**).

Moreover, the term “*Hilly*,” from topography, should be interpreted as a domed or conical elevation on local areas of the surface. Irregularities in the form of hills can be rounded or oval in shape with gentle slopes. This element of the damask pattern is represented in the form of closed irregularly shaped horizontals encircling each other.

Another picture is observed when considering an element of a damask structure of the “*Crosses*” type, which is a cruciform concavity between four hilly bulges (**Figure 8(d)**). This complex element of the damask structure is surrounded on four sides by elementary topographic elements in the form of “*Hills*”. Between these domed elevations, in the vicinity of the geometric saddle, the contour of the carbide inhomogeneity is a set of hyperbolic lines that give the damask pattern the appearance of a cruciform pattern.

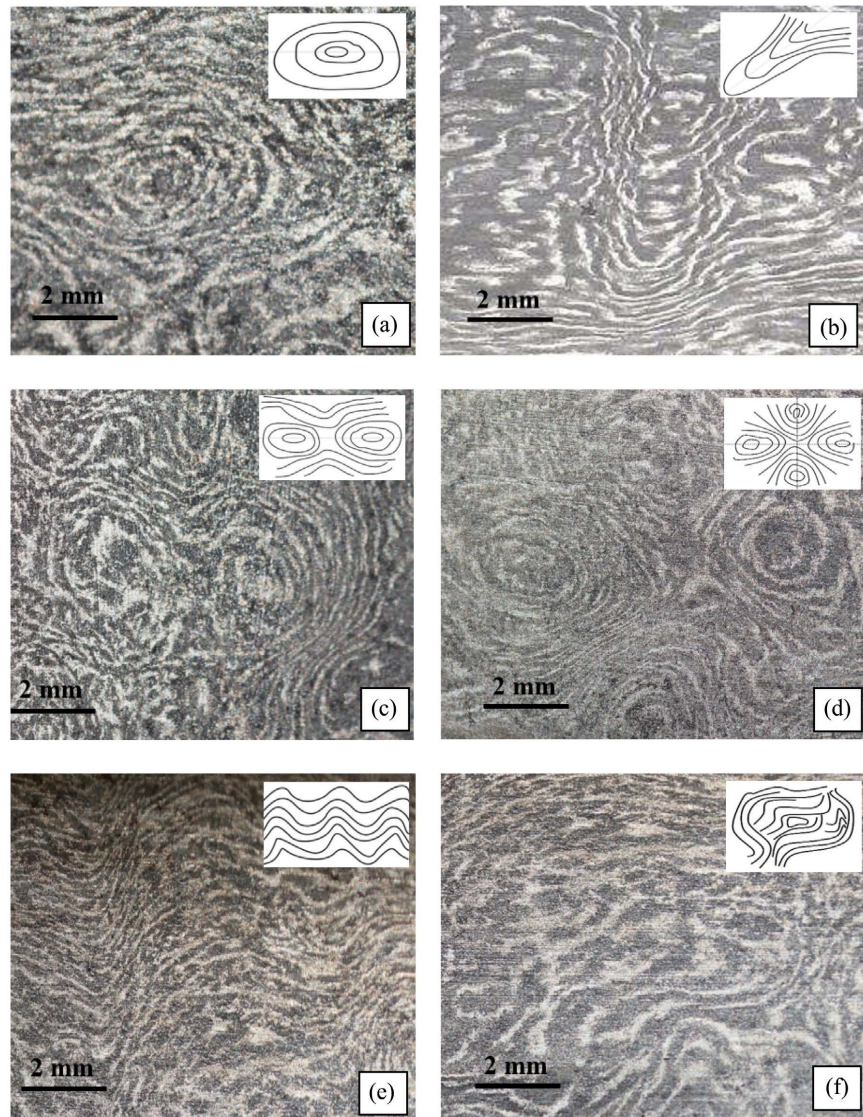


Figure 8. The elements of the damask structure in the genuine Damascus steel: (a) Basin; (b) Hollow; (c) Saddle; (d) Crosses; (e) Dunes; (f) Knottiness.

The most common element of the damask structure should be considered “*Dunes wavy*”, that is, an irregularity linearly elongated along the blade in the form of elevations and deflections (**Figure 8(e)**). In this case, the “*Dunes*” are a chain of oblong bulges and concavities in the form of wave crests. In the longitudinal section, the crests of the dunes are undulating horizontal. On the damask pattern, the image of “*Dunes*” has a sinuous appearance, which gives the pattern a wavy character.

The typical element of the damask structure of the “*Knottiness*” type was found for layered structures, which is a sinuous arrangement of a cluster of striped structures (**Figure 8(f)**), that is, an undulating arrangement of short light lines forming a trickle texture on the polished and etched surface of the damask blade. This term is well known when considering defects on wood.

And most importantly, the overlay of the topographic map on the surface of the damask pattern showed that it coincides with its main parameters. All forms of projections of the pattern lines are described mathematically; therefore, when using a specially shaped tool, it is possible to control the damask macrostructure.

However, it should be understood that the damask pattern, consisting of elements of sinuous lines of a topographic contour, does not significantly affect the level of mechanical properties. This external structural factor is rather a category of the quality of banded structures in genuine Damascus steel.

Thus, most of the studied samples made of genuine Damascus steel have a layered structure, differing from each other either by external features obtained using shaped forging. For example, Bulat varieties with a fibrous structure will not be inferior elasticity parameters to Bulat varieties with a mesh structure if identical thermomechanical treatment is properly carried out in them.

As described above, the damask structure has a characteristic carbide banded with minima and maxima in hardness; therefore, in the process of impact destruction, the main crack will leave different traces on the fracture surface in the form of characteristic relief details.

The destruction of anisotropic materials such as Damascus steel will occur under the action of two or more mechanisms that cause the destruction of a mixed type. The mechanisms of mixed destruction are a combination of intragrain cleavage and micropore fusion in a small local area, or a combination of chipping and interlayer cracking, etc. The reasons for the occurrence of destruction by a mixed mechanism are enormous, and its consequence may be the details of the fracture surface relief visible on the fractogram, which are difficult to identify.

When examining the fracture surface of genuine Damascus steel, characteristic details of the fracture relief were revealed in troostite and carbide layers (**Figures 9(a)-(c)**).

On the fractogram of the fracture surface of the troostite layer of the damask structure, relief details consisting of cleavage facets are found (**Figure 9(a)**). Such a relief fracture by the nature of the gloss is sometimes called a silky fracture. Cleavage is a type of destruction is splitting along crystallographic planes in places where slipping deformation is difficult. One of the main features of the destruction of troostite layers by chipping is relief details in the form of cleavage facets with a wavy pattern, which are steps directed along the same general slip plane. Striving to minimize the internal energy of the fracture of the second and third-order cleavage steps unite like waves in the direction of crack propagation.

Individual facets of cleavage with a wavy pattern are separated by ridges of the tears-off, on which the forms of the relief are identified in the form of small cups. The Cup-and-cone fracture formed when micropores merge. Thus, the destruction of the troostite layer in the damask structure occurs by a mixed mechanism, which is a combination of facets of cleavage and fusion of micropores on the ridges of tears-off.

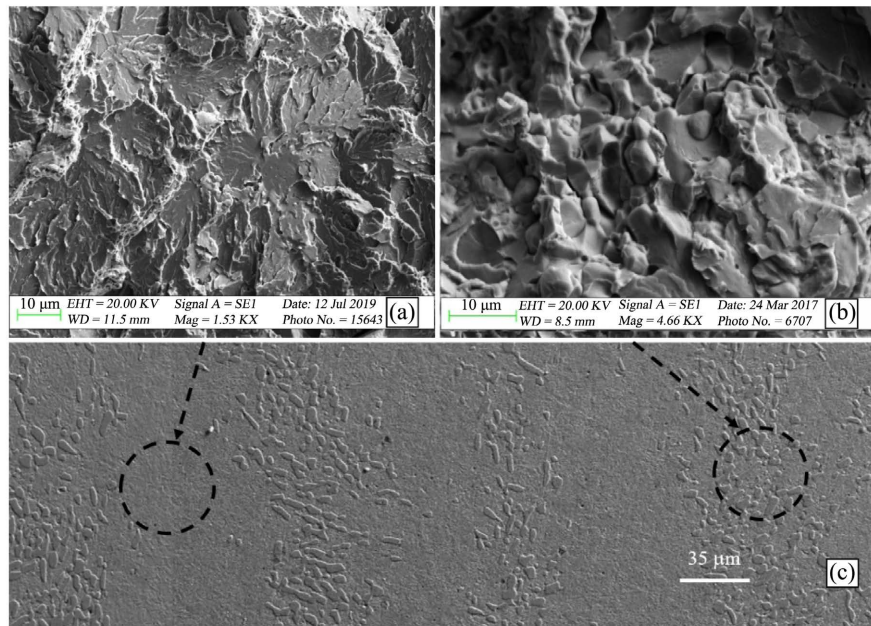


Figure 9. The structure and details relief of the fracture of genuine Damascus steel: (a) fracture of the troostite layer; (b) fracture of the carbide layer; (c) panoramic photo of the structure of the butt of Damascus blade.

When studying the fractogram of the fracture surface of the carbide layers of the damask structure, randomly distributed carbides embedded in the troostite matrix are observed (**Figure 9(b)**). The destruction of the carbide layers occurs by a mixed mechanism combining relief-free cleavage and intergrain cracking. The details of the relief of the fracture surface of the carbide layers consist of smooth shiny facets of the cleavage which do not have a wavy relief and ridges of tears-off.

The size factor of the layered structure in the presence of a brittle carbide phase uniquely affects the nature of the fracture. For example, the details of the relief of the fracture surface of the carbide layer indicate the absence of a reserve of plasticity. In these layers, stress relaxation does not occur in front of the moving crack front. It is possible only with a large stratification of the damask structure. If the genuine Damascus steel consists exclusively of finely dispersed carbide banding, it will be brittle and will break under small bending loads. Therefore, it is necessary to have an optimum thickness of both brittle carbide layers and more viscous troostite layers.

It is desirable that high-purity troostite layers always exceed high-strength carbide layers by volume fraction. Ideally, the optimum in the ratio of carbide and troostite layers in genuine Damascus steel obeys the golden section rule and makes up a troostite matrix with a volume fraction of 61.8%, and carbide layers—38.2%.

As a result, in the direction of the chopping blow on the end part of the knife blade, the main front of the crack will grow along the direction of the layers. The hardness of the carbide layers here is 950 HV, and the hardness of the troostite

layers is 450 HV on average. In carbide layers, the rate of destruction will prevail over troostite layers. The crack begins to branch along with the layers, reducing the propagation energy due to the separation of its front. In the process of destruction, a wave front of the main crack is formed. The wave's topography of the fracture surface indicates the mechanism of dividing the main crack front into several parts. In general, catastrophic destruction does not occur. The impact resistance of the genuine Damascus knife will increase.

It is in the implementation of the mechanism of separation of the main crack front in the layered damask structure that the uniqueness of the ancient Eastern technology of manufacturing bladed weapons consists. The damask structure has a good margin of survivability in case of shock destruction. With the elasticity of a spring with good impact resistance, the genuine Damascus blade has become a legend of the Indo-Persian region.

4. Conclusions

1) Layer-by-layer chemical analysis of the genuine Damascus steel showed that the dark areas matrix corresponds to high-purity eutectoid steel with a troostite structure, microhardness 450 HV. The volume share of lamellar troostite forms is 80%, divorced troostite forms are 15%, and globular troostite forms are 5% of the total share of matrix structures. The destruction of the troostite layers occurs by a mixed mechanism, which is a combination of relief details in the form of facets of cleavage with a wavy pattern, framed by ridges of tear-off formed by the fusion of micropores.

2) Layer-by-layer chemical analysis of the genuine Damascus steel revealed that the light areas are carbide-troostite structures corresponding to white eutectic whit cast iron in terms of carbon content and impurities. The microhardness is at least 950 HV. The destruction of carbide layers occurs by a mixed mechanism combining relief-free cleavage and intergranular cracking. The details of the fracture surface relief consist of a scattering of carbide phases against the background of smooth facets of the cleavage without ridges of tear-off.

3) It is shown that the shape of the damask pattern on the ancient Eastern blades does not appear by chance. The regularity and repeatability of the main projections of geometric shapes on different local areas of the blade surface are traced. Together they create a complete picture of the damask pattern. All forms of projections of the pattern lines are described mathematically, so when using a special tool, you can control the damask structure.

4) It is assumed that in order to implement the mechanism of separation of the main crack in the direction of the chopping blow, an optimum is needed in the dispersion of troostite (61.8%) and carbide (38.2%) layers in genuine Damascus steel, the ratio of their volumes obeys the golden section rule. The impact resistance of the Damascus knife is increased by reducing the energy intensity of the crack front when it is divided into separate parts.

5) It is established that the damask pattern, consisting of elements of sinuous lines of a topographic contour, does not significantly affect the level of mechan-

ical properties. This structural factor is a category of the quality of striped structures in genuine Damascus steel.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

- [1] Belaiew, N.T. (1918) Damascene Steel. *Journal of the Iron and Steel Institute*, **97**, 417-437.
- [2] Zschokke, B. (1924) Du Damasse et des Lames de Damas. *Revue de Métallurgie*, **21**, 635-669. <https://doi.org/10.1051/metal/192421110639>
- [3] Vinogradov, A.P. (1928) Soft Damask Steel and the Origin of the Bulat Pattern. *News Dnepropetrovsk Mining Institute*, **15**, 115-213.
- [4] Panseri, C. (1965) Damascus Steel in Legend and in Reality. *Gladius*, **4**, 5-66. <https://doi.org/10.3989/gladius.1965.188>
- [5] Gaev, I.S. (1965) Bulat and Contemporary Iron-Carbon Alloys. *Metal Science and Heat Treatment*, **9**, 17-24.
- [6] Tavadze, F.N., Amaglobeli, V.G., Inanishvili, G.V. and Eterashvili, T.V. (1984) Electron Microscopic Studies of Bulat. *Bulletin of the Academy of Sciences of the Georgian SSR*, **113**, 601-604.
- [7] Sherby, O.D. and Wadsworth, J. (1985) Damascus Steel. *Scientific American*, **2**, 112-120. <https://doi.org/10.1038/scientificamerican0285-112>
- [8] Verhoeven, J.D., Pendray, A.H. and Gibson, E.D. (1996) Wootz Damascus Steel Blades. *Materials Characterization*, **37**, 9-22. [https://doi.org/10.1016/S1044-5803\(96\)00019-8](https://doi.org/10.1016/S1044-5803(96)00019-8)
- [9] Verhoeven, J.D., Pendray, A.N. and Dauksch, W.E. (1998) The Key Role of Impurities in Ancient Damascus Steel Blades. *Journal of Metallurgy*, **50**, 58-64. <https://doi.org/10.1007/s11837-998-0419-y>
- [10] Levin, A.A., Meyer, D.C., Reibold, M., Kochmann, W., Patrke, N. and Paufler, P. (2005) Microstructure of a Genuine Damascus Sabre. *Crystal Research and Technology*, **40**, 905-916. <https://doi.org/10.1002/crat.200410456>
- [11] Taganov, I.N. and Kalinin, B.D. (2009) Influence of Phosphorus Impurity on the Technology of a Genuine Damascus Steel. *Metalworking*, **2**, 40-46.
- [12] Kalinin, B.D. and Taganov, I.N. (2009) The X-RAY Fluorescent Analysis Use for Examination and Attribution of the Indo-Persian 17th Century Genuine Damascus Steel Arms. *Analytics and Control*, **3**, 135-140.
- [13] Barnett, M., Sullivan, A. and Balasubramaniam, R. (2009) Electron Backscattering Diffraction Analysis of an Ancient Wootz Steel Blade from Central India. *Materials Characterization*, **60**, 252-260. <https://doi.org/10.1016/j.matchar.2008.10.004>
- [14] Sukhanov, D.A., Arkhangelsky, L.B., Plotnikova, N.V. and Belousova, N.S. (2016) Morphology of Excess Carbides Damascus Steel. *Journal of Materials Science Research*, **5**, 59-65. <https://doi.org/10.5539/jmsr.v5n3p59>
- [15] Sukhanov, D.A. and Plotnikova, N.V. (2016) Wootz: Cast Iron or Steel? *Materials Sciences and Applications*, **7**, 792-802. <https://doi.org/10.4236/msa.2016.711061>
- [16] Sukhanov, D.A., Arkhangelskiy, L.B. and Plotnikova, N.V. (2017) Nature of Angu-

- lar Carbides in Damascus Steel. *Metallurgist*, **61**, 40-46. <https://doi.org/10.1007/s11015-017-0451-7>
- [17] Verhoeven, J.D., Pendray, A.N., Dauksch, W.E. and Wagstaff, S.R. (2018) Damascus Steel Revisited. *The Minerals, Metals & Materials Society*, **7**, 1331-1336. <https://doi.org/10.1007/s11837-018-2915-z>
- [18] Sukhanov, D.A. (2018) Influence of Phosphorus Impurity on the Structure and Nature of the Destruction of the Genuine Damascus Steel. *International Journal of Engineering Technologies and Management Research*, **5**, 26-37. <https://doi.org/10.29121/ijetmr.v5.i4.2018.205>
- [19] Ghasem, D. (2018) An Archaeometallurgical Investigation of a Steel Sword from the Safavid Dynasty. *The Minerals, Metals & Materials Society*, **2**, 243-247. <https://doi.org/10.1007/s11837-017-2696-9>
- [20] Sukhanov, D.A. and Plotnikova, N.V. (2019) Influence of the Distribution of Excess Carbide on the Properties of Genuine Damascus Steel. *Materials Sciences and Applications*, **10**, 118-136. <https://doi.org/10.4236/msa.2019.102010>
- [21] Sukhanov D.A. and Plotnikova N.V. (2020) Mechanical Properties of XVIII Century Persian Bulat Steel Compared with Modern Tools Steels. *Metallurgist*, **63**, 1192-1203. <https://doi.org/10.1007/s11015-020-00942-9>