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RESEARCH REGARDING THE DURABILITY AND MECHANICAL PROPERTIES OF THE LEGENDARY DAMASCUS STEEL

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Abstract

The recipe for making Damascus steel was lost in ancient times. Based on the fascinating legends and excellent properties of Damascene swords, the study of Damascus steel provided the opportunity to realyse this laborious process of manufacturing this material. This manufacturing involves forging of different layers of two different steels to obtain a particularly strong and durable final product. For this research, were selected two types of steels with a high Carbon compond, particular focus on achieving the best results.
In this case, two types of steels: AISI 1095 and 15N20 steel were chosen to create the genuine Damascus steel. Both materials have been selected for their individual mechanical properties, which contribute to the ultimate quality of Damascus steel.
Additional studies such as hardness analysis and the strength of materials were conducted to understand and evaluate the behavior of the Damascus steel. Processing and laboratory tests were carried out on the obtained Damascus steel including, for simulation, a finite element analysis which was performed using Ansys R1 2023 and Autodesk Inventor Professional for the created Damascus steel knife blade.

Keywords*: Genuine Damascus Steel; Manufacturing; Treatment; Hardness, ANSYS simulation*

Introduction

European Crusaders first landed in Western Asia in the 12th and 13th centuries AD, religious and confident of victory. They were amazed to find local soldiers wielding a powerful, exceptionally durable sword with a special pattern. The Legend said that this sword was capable to cut a falling silk pillow or a feather in the air to retaining its sharpness after countless uses in battle. Because this amazing sword was first seen near Damascus, it was called the Damascus steel sword.

The Damascus steels of ancient times are located just to the right in the Diagram Fe-Fe3C, in the composition range of about 1-2% Carbon. The most famous swords are the Damascus steel swords and the Japanese swords. This type of sword has an original sharp cutting edge and is beautiful in structure, and the complex blacksmithing is necessary for their making.

As an example of Damascus steel swords (Persian scimitars), they are typically quite curved, more so, than Japanese swords [1].

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In figure 1 a dagger from Damascus steel was presented. This sword is exposed in the Louvre Museum.

Fig. 1. A Mughal dagger with a Damascus steel blade which can be vewed in the Louvre Museum [2]

Their pattern had been obtained by a complex forging procedure. The vertical arrays was called ”Mohammed’s ladder”- arrise from the different directions depending by the forging process. The beautiful pattern gives a special feeling and this pattern was beleived to have healing powers [3].

The combination of a hard high carbon steel with a tough low carbon steel possibly will conduct in a fracture of the structure. But this type of steel (Damascus steel) have a good wear resistance and it has a very good hardness. The disadvantage of the Damascus steel is its susceptibility to corrosion and high-maintenance (except for the Damascus steel produced by powder metallurgy technology). Initial mentions of Damascus steel are recorded around the year 300 BC (originally referred to as “wootz”) [3-6].

The recipe for making Damascus steel was lost in ancient times.

Damascus steel swords and daggers became renowned for their hardness, edge retention after use, and mysterious secrets of forging, hardening and annealing procedures, as well as a characteristically beautiful pattern of fine wavy light-coloured bands over a grey steel background. [7].

Museum-quality Damascus steel blades (wootz) were produced mainly in the 16th-17th centuries. By the early 19th century, the last secrets of authentic Damascus steel were lost, but since then several attempts have been made to rediscover recipes for making blades of comparable quality to Damascus steel (cf. [7-14]).

There have been several attempts to rediscover recipes for making blades of comparable quality to Damascus steel (cf. [8-10]). Applying the optical microscopy to polished blades, *Belaiew* [10, 11] identified the beautiful “milky way” structure of cementite (Fe_3C) and concluded that the spheroidal cementite is embedded in the rough mass of Damascus steel, thus avoiding the typical brittleness of hypereutectoid steels with their needle-shaped cementite (lamellar cementite [10-18]. Spheroidization seemed to be the consequence of repeated blows and heating.

The cementite needles approach the edge of the blade, thus providing good cutting properties. Belaiew assumes that the properties and distribution of carbides play a more important role than the (martensitic) matrix [18]. *K. Von Harnecker* [14] provided experimental evidence that forging at temperatures below the formation temperature of cementite from austenite, Acm (Acm ≈ 850°C), leads to the destruction of the cementite (Fe_3C) needles and, after heat treatment, to its spheroidization [6, 15-17].

In the production of Viking-age swords, various types of steel were utilized, often involving complex metallurgical techniques. The research papers provided do not specifically focus on Viking-age swords, but they do offer insights into the types of steel and metallurgical practices that might have been relevant during that period. For instance, the paper on the "Archeometallurgical Investigation of a Fragment from a Medieval Sword Blade" [19] discusses the use of different steel bars combined through hammer welding to achieve an optimal balance of hardness and toughness. This technique involved wrapping a steel bar around a composite billet, crafted by enclosing a hypoeutectoid steel bar around a near-eutectoid steel core, and applying quenching heat treatment to increase hardness.

Additionally, the paper "Microstructural Study of Medieval Crucible Steels from Archaeological Sites in Central and Northwest Asia: Identifying the Bulat" [19] describes the use of ultra-high-carbon crucible steel, known as *Bulat*, which is characterized by a high carbon content and a patterned microstructure. While this study focuses on Central and Northwest Asia, similar high-carbon steels could have been used in Viking-age sword production.

Overall, Viking-age swords likely utilized a variety of steel types, including hypoeutectoid and near-eutectoid steels, and employed advanced metallurgical techniques such as hammer welding and heat treatment to enhance their mechanical properties.

The microstructure of 9th–15th century artifacts made of crucible steel, found at sites in Central and Northwest Asia, is described. Metallographic study of items from settlements and burials with precise data on chronology, location, and accompanying artifacts is important for reconstructing the history of Bulat steel and the technology of melting and processing ultra-high-carbon crucible steel.

The study of the macro- and microstructure, and the chemical analysis of such items indicate an extremely high content of carbon—1.7–2.1 %. Other studies show a content of 1-1.6%C, depending on the types of steel used [3, 8, 11].

A characteristic feature of their microstructure is a dark matrix with white inclusions of ledeburite and iron carbides.

The combination of structural components is reflected in the patterned structure of the metal. These properties suggest that such metal is identical to bulat steel. Findings of macrostructural analysis extend our knowledge of the varieties of this metal, its structural features, phase composition of separate groups of ultra-high-carbon crucible steel, smelting technology, plastic and thermal treatment, and physical properties [19].

Experimental part

Damascus steel itself is the result of forging welding of the layers of the two materials mentioned in previous studies [16].

Materials

Damascus steel itself is the result of forging the layers of the two steels mentioned in [16, 17]: AISI 1095/EN ISO and 15N20 (75NI8) with over 0.8% carbon in the structure. So, we are talking about two hypereutectic steels, with a high carbon content, to obtain high hardness in the finished product.

Chemical composition of steel AISI 1095 was detailed in table 1[16].

Table 1. Chemical composition of the steel AISI 1095 [%]

Element, Symbol	*Quantity (%)*
Iron, Fe	98.38 – 98.8
Carbon, C	0.90 – 1.03
Sulfur, S	≤ 0.050
Phosphorus, P	≤ 0.040
Manganese, Mn	0.3-0.5
Silicon, Si	0.4

Elements such as nickel (Ni), copper (Cu), aluminum (Al) and molybdenum (Mb) are present in small quantities, so they cannot appreciably influence the hardness of the steel. However, AISI 1095 carbon steel is brittle and has high hardness and strength. The higher the hardness, the lower the plasticity of the steel. A high carbon content determines high hardness. As the carbon concentration approaches 2.1%, the steel becomes more susceptible to cracking, it can be brittle.

Remarcable is that the Conventional techniques can be applied to form AISI 1095 steel.

All welding techniques can be used for this kind of steel. Preheating to temperatures between 260 and 315°C is required, followed by post-heating to temperatures between 648°C and 788°C [16, 17].

AISI 1095 steel can be oil-quenched from 899°C, followed by tempering to increase the hardness of the steel. Tempering has the duty to detension of the structure after hardening. AISI 1095 steel can be forged at temperatures between 955 and 1177°C. Before this process, the steel is annealed at a temperature of 898°C and gradually cooled to homogenize the steel. AISI 1095 steel can be tempered between 372 and 705°C. The Rockwell C hardness obtained after annealing, befor other treatments is 55 (HRC) [16, 17, 21]

The chemical composition of 15N20 steel has been detailed in Table 2 [16, 17].

Table 2. Chemical composition of the steel 15N20

Element, Symbol	*Quantity (%)*
Iron, Fe	98.00
Carbon, C	0.70 – 0.80
Manganese, Mn	0.40 – 0.70
Nickel, Ni	2.00
Phosphorus, P	0.04 (max)

15N20 steel or its equivalent 75Ni8 is mainly used for the manufacture of band saw blades. It is a carbon steel with similar properties to AISI 1075 steel but contains a significant proportion of nickel (2%).

The carbon content is very close to the eutectic, so it has a predominantly pearlitic structure.

All welding techniques can be used to weld 15N20 steel. Preheating is required at temperatures between 260 and 315°C, and then the post-heating is performed at temperatures between 648 and 788°C.

As a heat treatment, 15N20 steel can be quenched in oil from 899°C, followed by tempering to maintain the hardness and strength of the steel.

The tempering heat treatment has the role of relieving the material after quenching.

15N20 steel can be forged at temperatures between 955 and 1177°C. Before this process, it is annealed at a temperature of 898°C and gradually cooled to homogenize the steel. By tempering heat treatment of steel, 15N20 steel can be tempered between 372 and 705°C. The Rockwell C hardness obtained is 55 (HRC). 15N20 steel is mainly used for cutting tools and springs [9, 12].

The procedures used for making the samples were also presented in the works [16, 17].

Experimental procedure

The AISI 1095 and 15N20 steel plates came from the supplier in the form of 2x40x1000mm bars which were cut into 100mm pieces and cleaned using a belt sander to remove any oxide layers that may have formed (Fig.2).

Later, the material was placed one on top of the other, alternating the two layers of steels and they were welded to create a package and avoid it falling apart in the oven (Fig. 3). In figure 4, alternating the layers of two different steels, the package was formed.

After the making of the package, the treatments applied were the following:

- Heating to a temperature of approximately 800° C, using the furnace presented in Figures 3 and 5
- Sprinkling with borax – $Na_2B_4O_7$ (agent that helps the increase of the temperature and dissolves unwanted oxides from the surface of the package)
- Heating to a temperature of approx.1100°C
- Forging (involves manual forging as well as the use of a hydraulic press)
- Polishing of the oxidized layer and the immersion in hydrochloric acid for the visibility of the model as shown in the figure below.

Fig. 2. The Samples with a length of 100mm

Fig. 3. The furnace in the laboratory

Fig. 4. Alternating the two layers of steels, the package (Laboratory photo) [17, 21]

a)

b)

Fig. 5. a). The samples are prepared for forging (Laboratory photo); b). Hot Forging operation

In figure 6, a piece from Damascus steel with 30 layers (from laboratory) has been presented. In figure 7, the wavy pattern on the surface of the knife blade created according to medieval technologies can be seen [16].

Fig. 6. Damascus steel with 30 layers (laboratory photo), view of the fracture surface, normal size

Fig. 7. Final shape of the blade - S1 sample (laboratory photo)

Results and discussion

If the material supported thermical treatments, the hardness of the Damascus steel increased. The treatments applied are specificed in table 3.

Table 3. Treatments applied after manufacturing and results obtained

Thermical treatment			Results		Samples
Annealing	**Hardening (time of maintaining at the treatment temperature : 2mins)**	**Tempering**	Micro-Hardness Vickers $HV_{0,1}$ [daN/mm^2]	HRC	
~900°C cooling in air ~ 2h;	~900°C - cooling in water;	250°C (one cycle of 1h)	890.6	66.7	S1
~900°C cooling in air ~ 2h;	-	-	595.8	55	S2
~900°C cooling in air ~ 2h;	~900°C – cooling in oil	200°C (one cycle of 1h)	888.5	66.6	S3
~900°C cooling in air ~ 2h;	~900°C - cooling in water;	200°C (one cycle of 1h) Cooling in water	829.9	65	**S4**

Better values for the microhardness of the Damascus steel after thermical treatments (hardening and tempering) have been obtained (Fig. 9.).

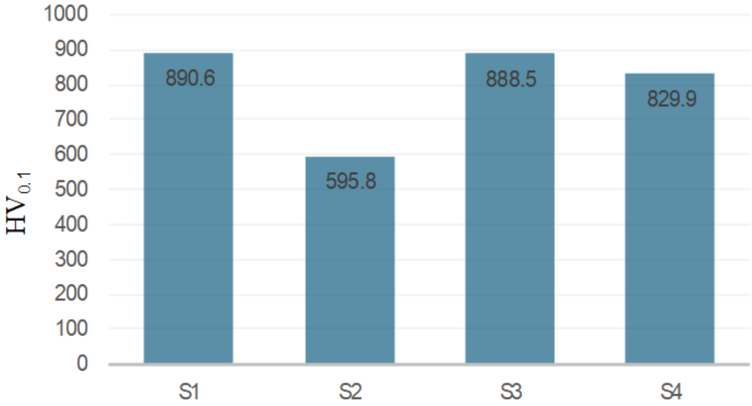

Fig. 9. Evolution of the HV0.1 Micro-hardness Vickers depending on the treatment applied to the samples, corresponding to the Table 3.

In the sample S4 case, the element Ni (Nickel) is present in a visibly large amount (1.06%) compared to the other elements, which gives the steel a high hardness. Other elements such as: Cr, Cu, M and Nb are present in very small amounts and cannot greatly influence the mechanical properties of hardness and strength of the material structure. The Annealing above Acm would lead to the disappearance of cementite (Fe_3C), and the material could acquire the exceptional properties of the steel whose recipe has been lost. This can eliminate the susceptibility to shock cracking because cementite is hard but has a certain brittleness. In the following figures 10 and 11, the microstructure obtained in the laboratory of the Centre for Interdisciplinary Research in the field of Eco-Nano Innovative Technologies and Materials (CC-ITI), Galati, Romania have been presented.

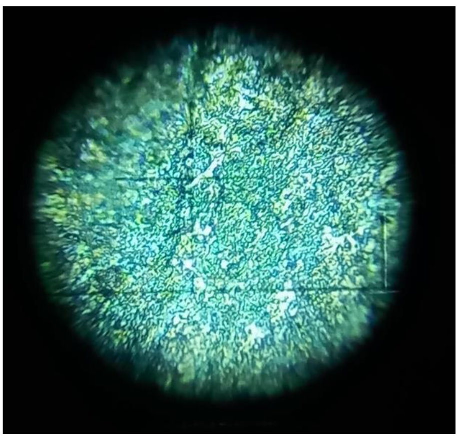

Fig. 10. Damascus steel, 30 layers: normalisation/annealing, hardening, tempering, without Nital attack, magnified 40x, the microstructure obtained in the laboratory, Sample S1.

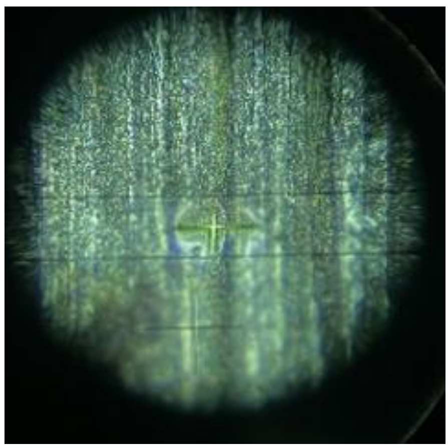

Fig. 11. Damascus steel, 30 layers: normalisation/annealing, hardening, tempering, without Nital attack, magnified 40x, the microstructure obtained in the laboratory, Sample S4.

Simulation in Ansys R1 2023

For simulation, a finite element analysis was performed using Ansys R1 2023 for the Damascus steel knife blade corresponding to sample S1, with the highest hardness obtained by heat treatment (Table 3). The analysis was performed only on the length of the blade, excluding its handle. The results obtained indicate a maximum von Mises Stress of 0.85106MPa in the case of applying a force F = **15N** (Fig. 12) and a maximum shear stress with a value of 0.04126MPa (Fig. 13).

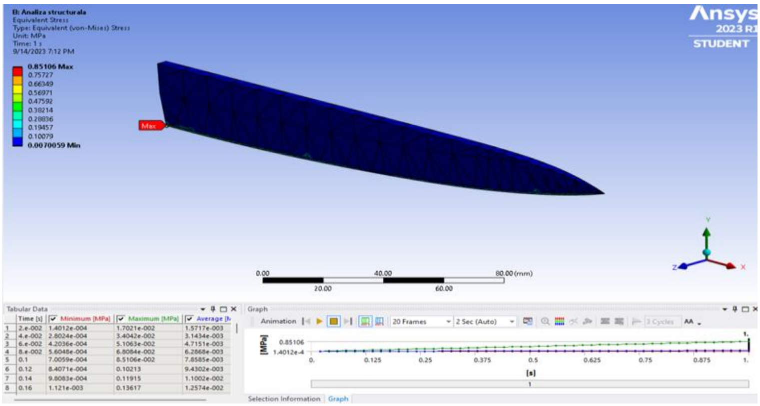

Fig. 12. Von Mises Tension evolution corresponding to applying F = 15N, for sample S1

If a normal force is applied to the length of the blade F = **25N**, then a maximum von Mises stress of 1.4014MPa is obtained, and the maximum shear stress will be 0.0679MPa (see Figs. 14 and 15). The maximum von Mises stress represents the maximum tension supported by the blade during loads, falling within the allowable limits for the material used.

Damascus steel is a material with a characteristic internal structure, in which layers of two types of steel are present. Damascus steel has a typical carbon composition of about 1 - 1.5%. In this case, 1%C content was obtained.

The layers are connected to each other by the method of hot forging welding.

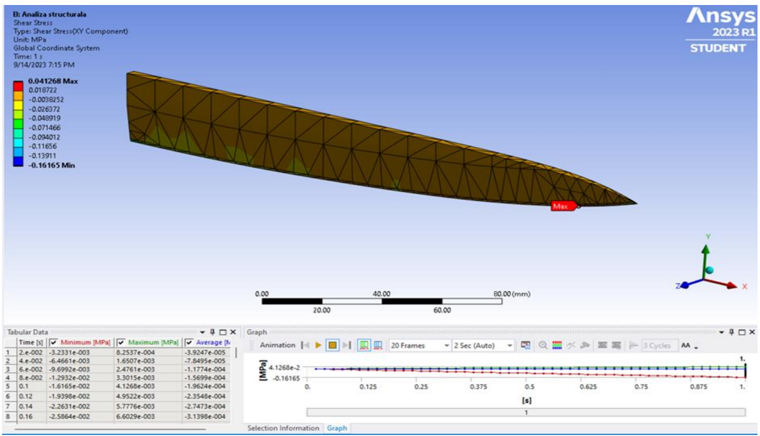

Fig. 13. Shear Stress evolution corresponding to applying F = 15N, for sample S1

A layered structure, called corrugation, is created after grinding, etching and polishing (see Fig. 7). The appearance of corrugations depends on several factors, but the production technology plays an important role. The combination of hard steel with a high carbon content and resistant steel with a low carbon content turns into a material resistant to wear and shock loads. A disadvantage of Damascus steel is its susceptibility to corrosion and the need for maintenance (apart from Damascus steel produced by powder metallurgy technology).

The exact method of production remains unknown and is a mystery.

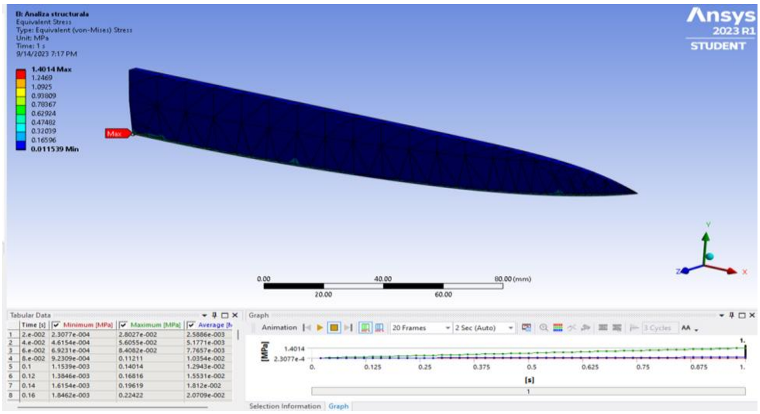

Fig. 14. Von Mises Tension evolution corresponding to applying F = 25N, for sample S1

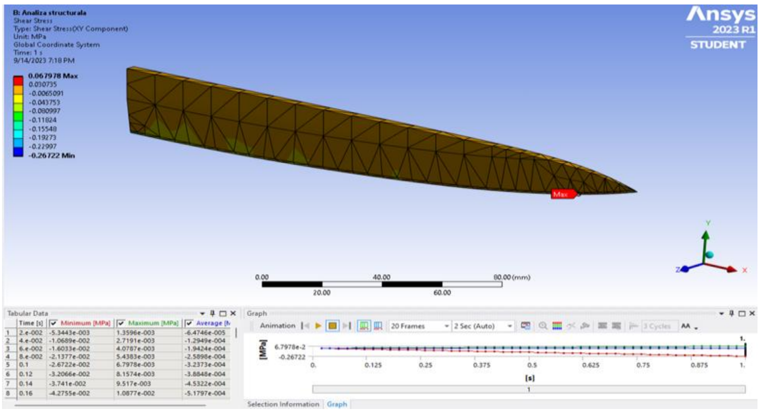

Fig. 15. Shear Stress evolution corresponding to applying F = 25 N, for sample S1

Processing the results obtained using Autodesk Inventor Professional, for high loads

The case of a higher load was considered. For example, it was considered **F = 35N**. In this case, the Von Mises Stress was determined to be minimum 0.000048927MPa respectively, maximum 81.6075MPa, indicating the magnitude of the maximum stress experienced by the blade. Additional data have been presented in the Table 4, with the mention that the Reaction Force and the Reaction Moment have been presented too.

Table 4 Reaction Force and the Reaction Moment (F = 35N)

Constraint Name	Reaction Force		Reaction Moment	
	Magnitude	Component (X, Y, Z)	Magnitude	Component (X, Y, Z)
Fixed Constraint:2	35N	0.0N -35N 0.0N	6.07684Nm	-0.0700259Nm 0.0Nm -6.076435Nm

The displacement generated for Maximum value of Von Mises Stress (81.6075MPa) has the following value: 0.171993mm (Table 5). This result implies very good behaviour of the Damascus steel during the solicitation because the displacement means minimal deformation of the blade under the given loads. This displacement evolution describes an excellent rigidity of the sample and a dimensional stability.

These values show that the knife blade can be used under this load force F = 35N without risk of deformation or breakage. Table 5 presents Summary results corresponding to a load F = 35N.

In figures 16 and 17 the Von Misses Stress and the 1-rst Principal Stress have been presented.

Table 5. Results Summary

Name	Minimum	Maximum
Volume	20684.8mm^3	
Mass	0.16237kg	
Von Mises Stress	0.000048927MPa	81.6075MPa
1-st Principal Stress	-12.2565MPa	48.8344MPa
3rd Principal Stress	-93.1746MPa	0.841923MPa
Displacement	0.0mm	0.171993mm
Safety Factor	6.16753ul	15ul

In Figure 17, the maximum value corresponding to the 1-rst Principal Stress is 48.83 MPa.

The 1st Principal Stress shows that it acts in the shear zone of the knife during use. At its maximum value, it is possible to appear cracks between the blade and the handle. In figure 18, the 3-rd Principal Stress has a Maximum 0.8419 MPa.

In Figs. 19 and 20, the Displacement respectively, the Safety Factor have been presented, too.

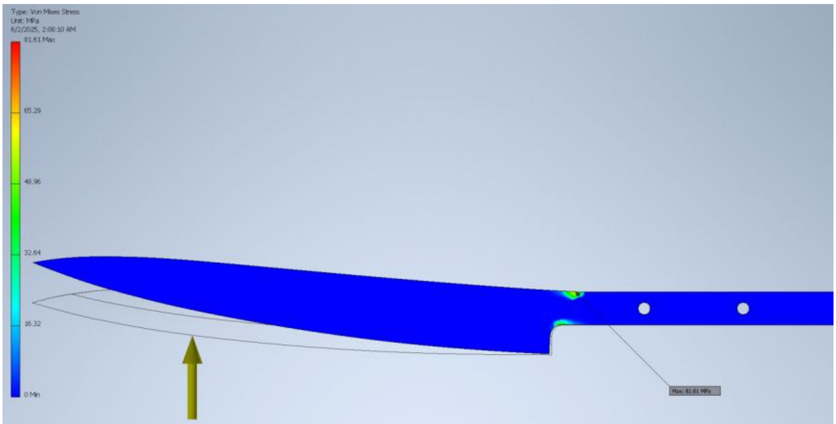

Fig. 16. Von Mises Stress coresponding to F=35N

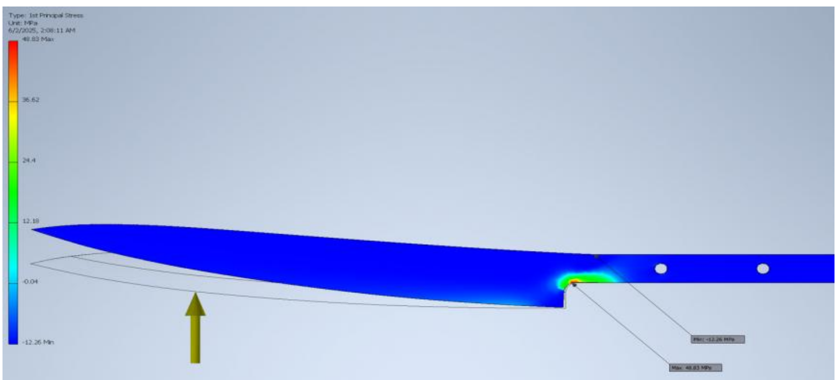

Fig. 17. The 1-st Principal Stress evolution

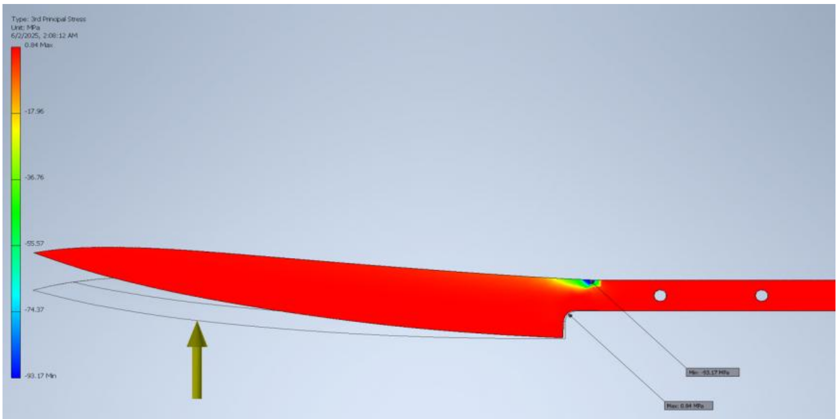

Fig. 18. The 3-rd Principal Stress evolution

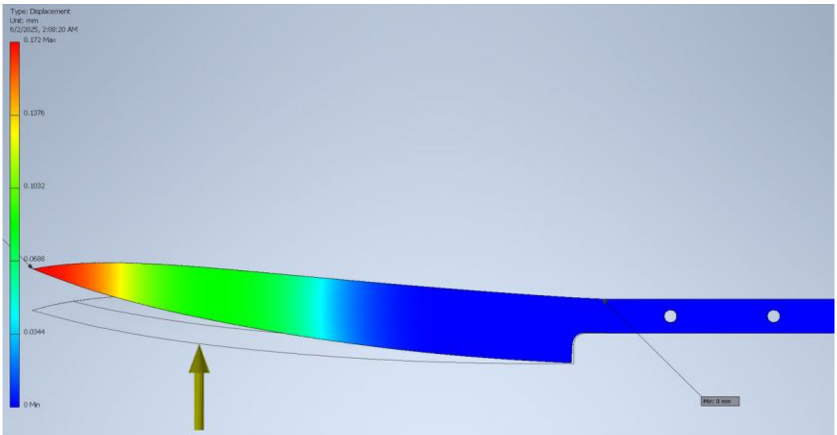

Fig. 19. The displacement evolution, for a load F = 35N

Figures 20-22 show the knife displacements at a load of 35 N, corresponding to the three main axes of coordinates, in relation to which the study was carried out.

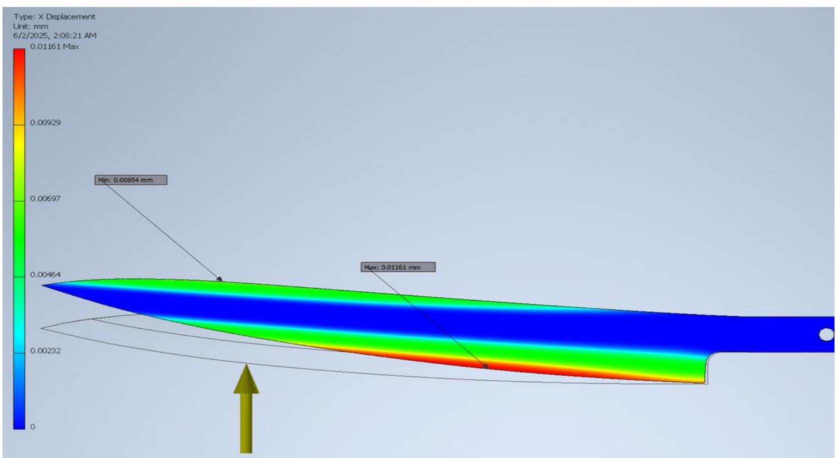

Fig. 20. X - Displacement, for a load F = 35N

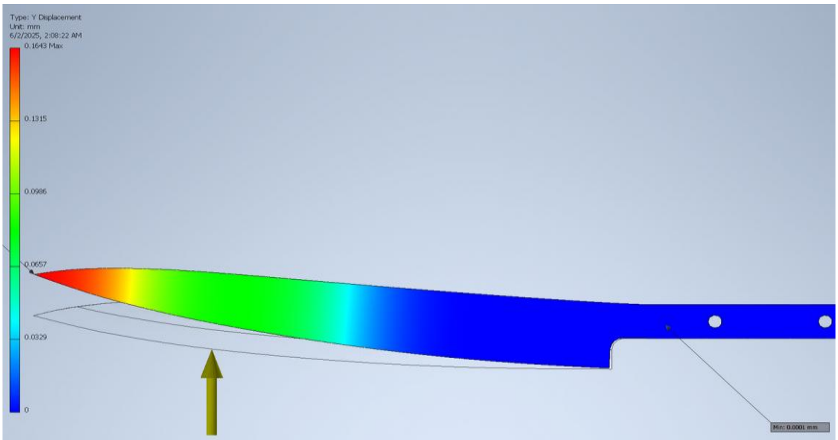

Fig. 21. Y Displacement, corresponding to F = 35N

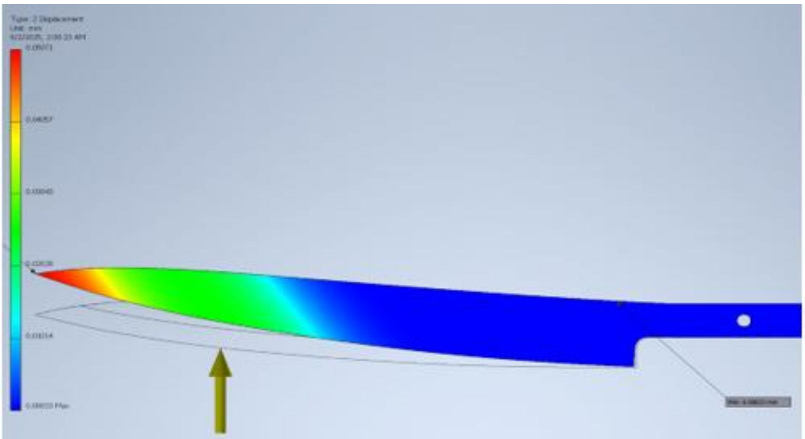

Fig. 22. Z Displacement, corresponding to F=35N

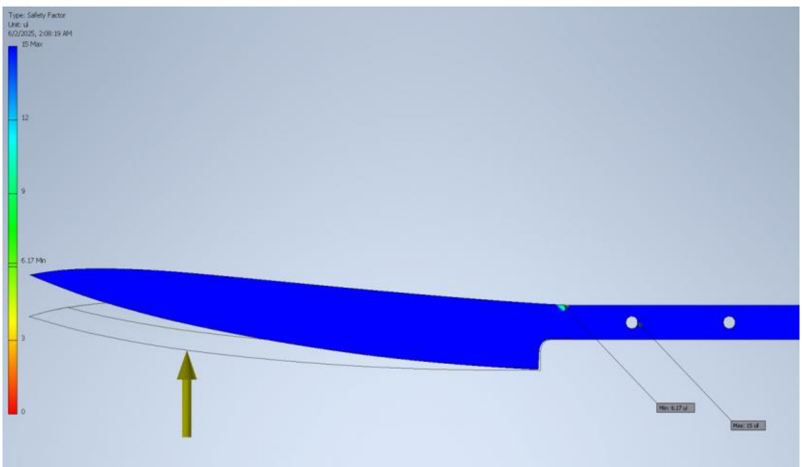

Fig. 23. The Safety factor evolution, for a load F=35N

If it is analyzed the displacement of the knife blade considered as the laboratory sample under a load of 35N, the following data will be obtained:

- ✓ Relative to the X axis, the minimum displacement value is -0.00853933mm, and the maximum value is 0.0116123mm (Fig. 20).
- ✓ Relative to the Y axis, the minimum displacement value is -0.0000967793mm, and the maximum value is 0.164319mm (Fig.21).
- ✓ Relative to the Z axis, the minimum displacement value is -0.0507088mm, and the maximum value is 0.000326709mm (Fig. 22).

Conclusions

The principal objective of this study was to analyse the structural behaviour and the real performance of the Damascus steel blade under various loading conditions, respectively, under 15N, 25N and 35N. The study of Damascus steel provided the opportunity to detail the laborious process of making this legendary steel. It is a process that involves the hot-forging welding of different layers of two high-carbon steels to obtain a particularly strong and durable final product. In this case, two types of steel were chosen to create authentic Damascus steel: AISI 1095 steel and 15N20 steel. The strength and durability of these steels contribute to the supreme quality of Damascus steel. This selection resulted in an authentic and high-quality product.

During the study, there was the opportunity to design and build a functional furnace. This furnace played a crucial role in obtaining authentic Damascus steel. By applying a complex process of heating, forging and repeating this process, the layers of steel were welded together, resulting in a final material that is extremely strong and has a unique aesthetic appearance. After obtaining the Damascus steel, this material was processed into a knife blade. This process involved grinding and shaping the material to give it shape and sharpness. Care and precision were required in carrying out this step, to obtain a high-quality final product.

Laboratory tests were carried out on the obtained Damascus steel to evaluate its hardness and the behavior under different loads using simulation with Ansys R1 2023 or Autodesk Inventor Professional.

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