INTERNATIONAL JOURNAL OF CONSERVATION SCIENCE

ISSN: 2067-533X Volume 14, Issue 3, July-September 2023: 871-886 www.ijcs.ro

DOI: 10.36868/IJCS.2023.03.07

LEARNING FROM THE PAST: THE RECONSTRUCTION OF THE ORIGINAL DAMASCUS STEEL. EXPERIMENTAL STUDY

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Abstract

The original method of manufacturing Damascus steel has been forgotten over time. Due to differences in the raw material used and the manufacturing techniques, some of the current attempts at replicating Damascus steel have failed. The study of Damascus steel provided the opportunity to observe in detail the laborious process of manufacturing this material, which involves the free forging and welding of different layers of steel to obtain a particularly strong and durable final product. To carry out this research, high-quality materials were selected from a catalogue of steels, with a particular focus on achieving the best results. In this case, two types of steel were chosen to create Damascus steel: AISI 1095 and 15N20 steel. Both materials have been selected for their individual properties, such as mechanical resistance and durability, which contribute to the ultimate quality of Damascus steel. This rigorous selection of materials ensured a high-quality and authentic product. Throughout this study, a functional furnace was built capable of contributing to the welding and forging processes of these two different materials. This furnace played a crucial role in obtaining true Damascus steel. By applying a complex process of heating and forging and then 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. Processing and laboratory tests were carried out on the obtained Damascus steel to evaluate its mechanical properties, including the processing of the results using Autodesk Inventor Professional 2023 and simulation in Ansys 2023.

***Keywords**: Damascus Steel; Manufacturing; Original recipe; Treatment; Hardness; ANSYS simulation; Finite element analysis.*

Introduction

Knowing the properties and characteristics of the different types of steel used in the manufacture of knives, edged weapons, and swords since ancient times is essential for choosing the right knife for a specific use and for maintaining a professional kitchen knife, for example, to extend its life.

The study of these types of steels can help develop new technologies and materials for the production of better and more durable knives. Additionally, understanding the differences between the various types of steel used in knife production can help both manufacturers and

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consumers make informed decisions about purchasing or making the right knives for their specific needs.

There is a wide variety of types of steel used in knife production, from carbon steels to stainless steels, each with their own characteristics and properties that make them suitable for different applications and conditions of use. Therefore, research and study of the types of steels used in the manufacture of knives can help improve their quality and lead to the development of new steels with better properties and superior performance.

The existence of the legends about the special qualities of Damascus steel constituted the starting point of the study, and after extensive documentation, we moved on to making Damascus steel according to the original recipe.

But first of all, it must be specified what Damascus steel is. Damascus steel is a type of steel obtained by combining two or more different types of steel. These are heated together, freely hammered or forged, and bent repeatedly to create a specific pattern of characteristic striations and dots. This manufacturing process produces Damascus steel with a distinctive pattern and attractive appearance, which is often used in the production of knives, swords, and other bladed instruments. In addition, Damascus steel also has very good mechanical properties, including hardness, strength, and wear resistance.

Damascus steel has its origins in the Middle East but has also been used in other parts of the world, such as Europe and Asia. Today, it is highly valued in the production of knives and other high-quality bladed instruments.

A number of papers and books have been published on the fascinating legends and excellent properties of the Damascus blades [1–5].

It may be put on record that at the end of the high Middle Ages, the trade in steels and blades of oriental manufactures was concentrated precisely in the ancient city of Damascus, in Syria, the Dimisk as-Sham of the Arabs; here, indeed, it appears that important arms manufactories had existed as far back as the era of Diocletian. Yet the city of Damascus was conquered by the hordes of Timur i Leng (Tamerlane), which enslaved the inhabitants and removed the best artisans [1].

However, a flourishing textile industry remained in Damascus, and the DAMASC textile material reminds the viewer of the special appearance of knife blades made of this steel, much used in the past to make swords, but sharp weapons. This is where the name Damascus Steel comes from.

In figure 1, an Indo-Persian dagger with a Damascus steel blade has been presented [1].

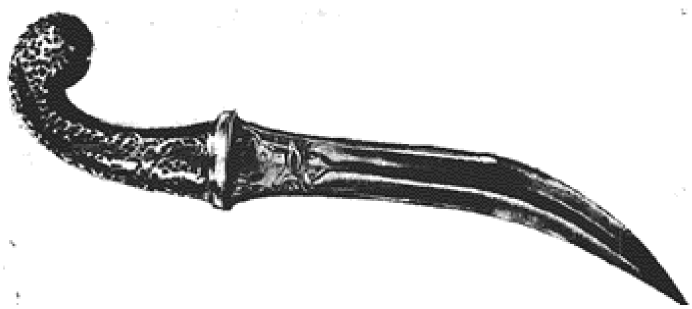


Fig. 1. Indo-Persian dagger with Damascus steel blade [1]

It is claimed [6] that Damascus steel was in existence as long ago as the time of Alexander the Great (ca. 323 B.C.). It is known more certainly that the steels were in use before the Islamic period (ca. A.D. 620 onward) because the descriptions of blades made from such steel are on record from A.D. 540 [2, 7].

The scientific conservation and museum valorization of old metal artefacts is a very important field [8–10]. Archaeometallurgy and its implications in establishing the raw material, the place of extraction of the ore or its origin, the manufacturing technology, the period of use, etc. represent a current science widely used in the investigation of newly discovered or less studied archaeological relics [11–15].

The work focuses on Damascus steel, where the laborious manufacturing process is presented in detail by free forging and welding different layers of steel to obtain a particularly strong and durable final product. Related to this aspect, high-quality materials were selected from a catalogue of steels, with a special emphasis on obtaining the best results. In this case, two types of steel were chosen to create Damascus steel: AISI 1095 and 15N20 steel, which have similar properties such as mechanical strength and durability, which contribute to the ultimate quality of Damascus steel. In order to achieve the layering by glueing the two materials, a functional furnace was built, capable of contributing to the welding through the forging process. By applying a complex process of heating and forging and then repeating this process, the steel layers were welded together, resulting in an extremely resistant final material with a unique aesthetic appearance. Processing and laboratory tests were performed on this Damascus steel to evaluate its mechanical properties, including processing the results using Autodesk Inventor Professional 2023 and simulation in Ansys 2023.

Damascus steel. Features, properties and use

No steel compares to Damascus steel. Damascus steel, used in the past for blades and knives, stands out for its distinctive patterns. It originated in the Near East and was made of Wootz steel imported from India [16]. The production of Damascus steel is a laborious process, and this study aims to highlight the complexity of this process. A comparison is also made between the mechanical properties of the initial layers of Damascus steel and the materials from which these layers are assembled. This work is an evaluation of the properties of steels in the layers: AISI 1095, EN ISO, and 15N20 (75NI8). Damascus steel itself is the result of the forging and welding of the layers of the two materials mentioned.

Damascus steel is a material with a characteristic internal structure in which layers of two or more types of steel (or other metals) are present [16]. Damascus steel, also known as Damascus, has a typical carbon composition of about 1–1.5% by weight. The layers are connected to each other by the forging welding method.

A layered structure, called waviness, is created after rectification, etching, and polishing (the appearance of waviness depends on several factors, but production technology plays an important role) [17]. The combination of high-carbon hard steel and low-carbon tough steel results in a material resistant to fracture and wear. A disadvantage of Damascus steel is its susceptibility to corrosion and the need for maintenance (except for Damascus steel produced by powder metallurgy technology). The first mentions of Damascus steel are recorded around 300 BC (its original name was "wootz") [16, 17]. The exact production method remains unknown and a mystery.

Damascus steel reached European countries during the early Middle Ages after being exported to the trading center of Damascus in Syria for further processing [18, 19]. The production technology of Damascus steel was perfected by Japanese craftsmen who made samurai swords in the 13th century. The production of patterned swords gradually declined until it disappeared completely around 1750, the reason for the cessation of production remaining unknown [20, 21].

Experimental Program

The experimental programme needs an evaluation of the properties of the two steels in the layers: AISI 1095/EN ISO and 15N20 (75NI8). Damascus steel itself is the result of the forging and welding of the layers of the two materials mentioned.

Materials

The chemical composition of steel AISI 1095 is detailed in Table 1.

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

Element	Quantity (%)
Iron, Fe	98.38 – 98.8
Carbon, C	0.90 – 1.03
Sulfhur, S	≤ 0.050
Phosphorous, P	≤ 0.040
Manganese, Mn	0.30 – 0.50

Carbon (C) is the main alloying element present in carbon steels. The steels mentioned also contain 0.4% silicon (Si) and 0.5% manganese (Mn). Elements such as nickel (Ni), copper (Cu), aluminium (Al), and molybdenum (Mb) are present in small amounts. Carbon steel, AISI 1095, is brittle and has high hardness and strength.

Conventional techniques can be used to form AISI 1095 steel. However, more force is required than with low-carbon steels.

All welding techniques can be used for welding AISI 1095 steel. Preheating at temperatures between 260°C and 315°C is required, followed by post-heating at temperatures between 648 °C and 788°C.

AISI 1095 steel can be oil quenched at 899°C, followed by tempering to increase the hardness of the steel. AISI 1095 steel can be forged at temperatures between 955°C and 1177°C. Before carrying out this process, the steel is subjected to annealing at a temperature of 898°C and gradually cooled to homogenise the steel. AISI 1095 steel can be tempered between 372°C and 705°C. The obtained Rockwell C hardness is 55 (HRC) [22, 23].

The chemical composition of steel 15N20 is detailed in Table 2.

Table 2. Chemical composition of the steel 15N20

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

Steel 15N20 or its equivalent, 75Ni8, is mainly used for making bandsaw blades. It is a carbon steel with properties similar to 1075 steel but containing a significant proportion of nickel.

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

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

15N20 steel can be forged at temperatures between 955°C and 1177°C. Before carrying out this process, it is subjected to annealing at a temperature of 898°C and gradually cooled to homogenise the steel. Through thermal recovery treatment, 15N20 steel can be tempered between 372°C and 705°C. The obtained Rockwell C hardness is 55 (HRC). Steel 15N20 is mainly used for cutting tools and springs [22, 23].

Graphic modeling and used equipment

The final shape of a professional kitchen knife for filleting fish, called the Yanagiba, was established. Yanagiba knives are mainly used to slice boneless pieces of fish, especially for sashimi and sushi dishes [18].

In figure 2, a sketch of the Yanagiba knife has been presented.

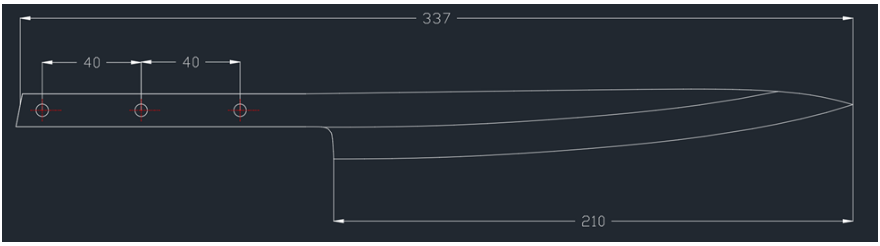


Fig. 2. Sketch of the Yanagiba knife

This sketch was graphically modelled using Autodesk Inventor 2023 to prepare the finite element study (Fig. 3).

Fig. 3. 3D rendering of the Yanagiba knife

The thermal oven in which the samples were heated was constructed from a helium cylinder with dimensions of 245x430x250mm. The furnace was lined with a ceramic blanket resistant to temperatures up to 1400°C (Fig. 4). In addition to the classic hearths with coals where the metals were heated for their hot forging, for this kind of application to manufacture professional knives, it is possible to opt for a liquefied gas furnace having a forced draft with the help of an air compressor to reach temperatures up to a maximum of 1300°C.

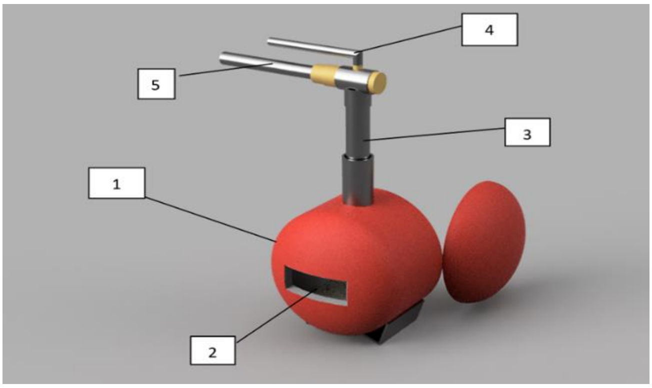


Fig. 4. Components of the system: 1. Oven; 2. Orifice; 3. Burner; 4. Gas inlet; 5. Air inlet

Liquefied petroleum gas is injected through inlet 4 and mixed with compressed air from inlet 5 into burner 3. To ensure high pressure, the gas passes through a MIG/MAG bulb.

In figure 5, the furnace in which samples were taken in the laboratory has been presented.

Fig. 5. Furnace in trials, in the laboratory

Gas is flammable, but it needs air to burn. When an excessive amount of air is mixed with the gas, excess oxygen remains. This oxygen, in turn, oxidises the steel inside the furnace. The degree of oxidation can be assessed by the amount of slag produced on the steel. The use of a neutral atmosphere can virtually eliminate this slag. A neutral atmosphere contains only the amount of oxygen necessary to allow complete consumption of the gas and any excess oxygen. As the fire consumes all the oxygen, there is not enough left to oxidise the steel and cause slag and decarburization. To achieve a neutral atmosphere, it needs to adjust the gas pressure and air flow in the furnace until equal amounts of gas and oxygen are obtained and the furnace is at maximum temperature. There is no excess burning of gas outside the furnace, and the furnace should emit a steady, well-tuned sound. The interior of the oven should be bright red or yellow. Steel placed in a neutral furnace should have minimal slag (if any) and an even heat. The correct ratios are about 12 to 1 air to fuel, depending on the specific design and type of furnace and its temperature at the time. As the furnace heats up, less air is needed to support combustion and heat [24].

Procedures used for making samples

The experimental material was Damascus steel (with 30 layers) composed of a hard and a resistant component, AISI 1095 steel, and 15N20 steel, the characteristics of the materials being presented previously.

In the experimental process of sample preparation (Damascus steel), the previously mentioned steels were used, obtaining a 30-layer Damascus steel.

AISI 1095 and 15N20 steel plates had dimensions of 2x40x1000mm. A belt sander was used to remove oxide layers and impurities (this treatment ensures the elimination of unwanted errors in the final appearance). The semi-finished products were cut into 100mm pieces and cleaned with a degreasing agent (Fig. 6).

Fig. 6. The Samples with a length of 100mm (hard and resistant samples, laboratory photo)

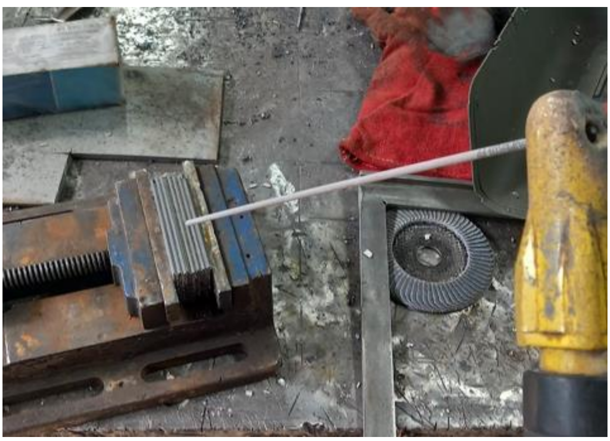


Fig. 7. Welding the package (photo from laboratory)

This material was placed on top of each other, alternating the two layers mentioned during folding (hard steel vs. resistance steel), fixed, and welded using the shielded metal arc welding (SMAW) method on the edge and in the middle, thus resulting in a package (Fig. 7).

When making the package, the procedure was as follows:

- ✓ Heating to a temperature of approximately 800°C;
- ✓ Sprinkling with borax – Na2B4O7 (this agent helps to increase the temperature and dissolves unwanted oxides from the surface of the package);
- ✓ Heating to a temperature of 1100–1200°C;
- ✓ Forging (which involves manual forging as well as the use of a hydraulic press);
- ✓ Grinding the oxidised layer and immersion in hydrochloric acid for the visibility of the model according to figure 8.

The batch of 15-layers Damascus steel samples was divided into 2 pieces of 10cm length, and the oxides and impurities on each piece were removed. These pieces were then re-welded into a new package, following the procedure described in points 1 to 4. This resulted in a 30-layer Damascus steel with dimensions of 350x30x4mm. In free forging, in the given situation, there are reflations or comprimations of the material through hot pressing. It should be kept in mind that the flow mode of the material during forging is different from the flow mode during extrusion. These differences are valid in the case of simple stretching performed between flat tools. For sample preparation, type II annealing (normalisation), quenching, and tempering were used.

Fig. 8. Damask steel with 30 layers (laboratory)

Results

Four samples were sent for the microhardness analysis of the blades to the mechanical testing laboratory, Corp AN, Laboratory 003 within the Interdisciplinary Research Centre in the field of eco-nanotechnology and innovative materials (CC-ITI), within the Faculty of Engineering, "Dunărea de Jos" University from Galati, Romania, and the results from Table 3 were obtained.

Table 3. Microhardness Vickers & Rockwell C obtained

Sample Code	Q [N]	Duration [s]	Treatment: Annealing	Treatment: Hardening -treatment maintaining:2min	Treatment: Recovery	Microhardness Vickers $HV_{0,1}$ [daN/mm^2]	Hardness Rockwell [HRC]
Sample 1	4.9	10	~900°C slow cooling in air ~ 2h;	~900°C, cooling in water	250°C / 1h	890.6	66.7
Sample 2	4.9	10	~900°C slow cooling in air~ 2h;	-	-	595.8	55
Sample 3	4.9	10	~900°C slow cooling in air~ 2h;	~900°C, cooling in oil	200°C/ 1h	888.5	66.6
Martor sample 4	4.9	10	-	-	-	207	13

Figures 9 and 10 show the evolution of Rockwell hardness in samples treated differently and the stratigraphic section of a Damascus steel bar.

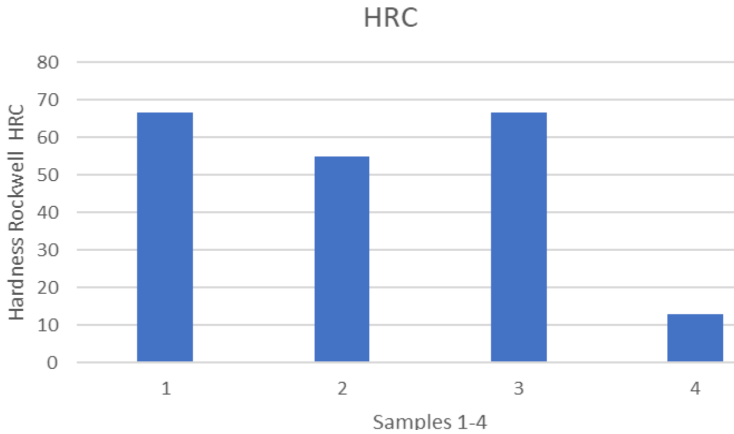


Fig. 9. The evolution of Rockwell hardness in samples treated differently.

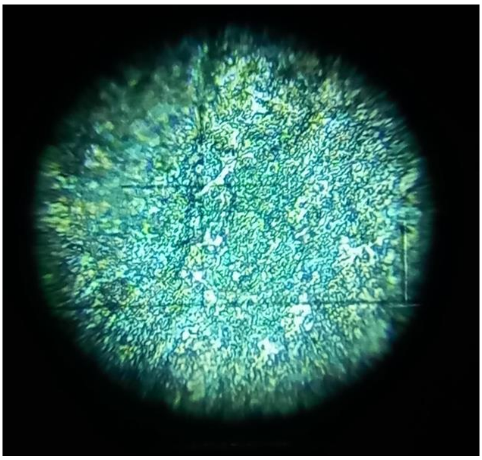


Fig. 10. Damascus steel, 30 layers: normalisation, hardening, tempering, without nital attack, magnified 40x, the microstructure obtained in the laboratory of the Centre for Interdisciplinary Research in the field of Eco-Nano Innovative Technologies and Materials (CC-ITI)

Fig. 11. Forged samples

Figure 11 shows forged samples with the two analysed steels, looking from top to bottom, as follows: Blade with 20 layers; Crate with 15 layers to be folded; 10-ply blade; 10-ply blade.

In figure 12, you can see the wavy pattern on the surface of the knife blade created according to mediaeval technologies.

a). b).

Fig. 12. Final shape of the blade (laboratory photo)

Processing the results using Autodesk Inventor Professional 2023

The objective of this study was to analyse the structural behaviour and performance of the blade under various loading conditions. The study includes an evaluation of Von Mises stress and displacement to obtain information about the blade's response to applied loads.

Finite element analysis revealed significant results for the knife blade stress distribution. The Von Mises stress was determined to be 1.77584MPa, indicating the magnitude of the maximum stress experienced by the blade. This value, below the yield strength of the material, suggests that the blade can withstand the applied loads without risk of deformation.

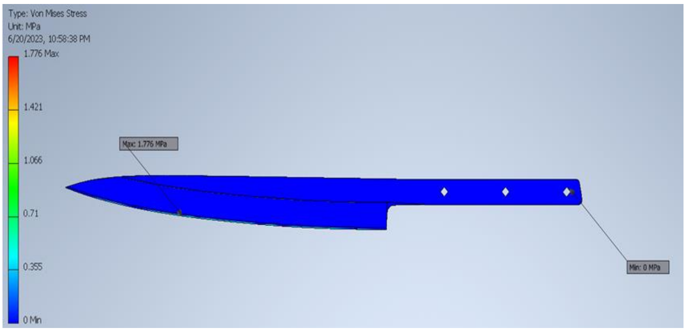
In addition, the analysis revealed a displacement of 0.0000261297mm, considered insignificant (Fig. 13).

This displacement means minimal deformation of the blade under the given loads, highlighting its excellent rigidity and dimensional stability. The negligible displacement also emphasises the ability of the blade to maintain its shape and performance even during demanding cutting tasks.

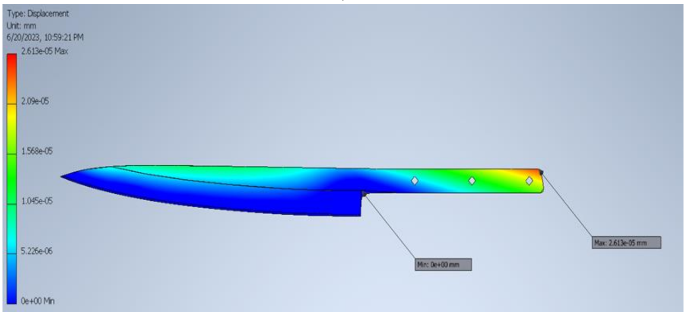
This study was carried out along the entire length of the blade, measuring 350 mm, to capture the overall behaviour and stress distribution accurately. This comprehensive analysis allows for a holistic understanding of how the blade responds to various loading scenarios along its entire length.

To ensure accurate simulations, the material properties of the blade were defined according to the specifications shown in figure 14. By using these material properties, finite element analysis provides an accurate representation of blade behaviour and its response to external forces.

The loads considered in this study include a pressure of 0.023MPa and a torque of 0.09 N/mm. These loads simulate actual usage conditions and help evaluate blade performance in typical usage scenarios.



a).



b).

Fig. 13. Von Mises tensions (a) and displacement (b)

Material(s)

Name	1095	
General	Mass Density	7.85 g/cm^3
	Yield Strength	525 MPa
	Ultimate Tensile Strength	685 MPa
Stress	Young's Modulus	200 GPa
	Poisson's Ratio	0 ul
	Shear Modulus	100 GPa
Part Name(s)	Lama.ipt	

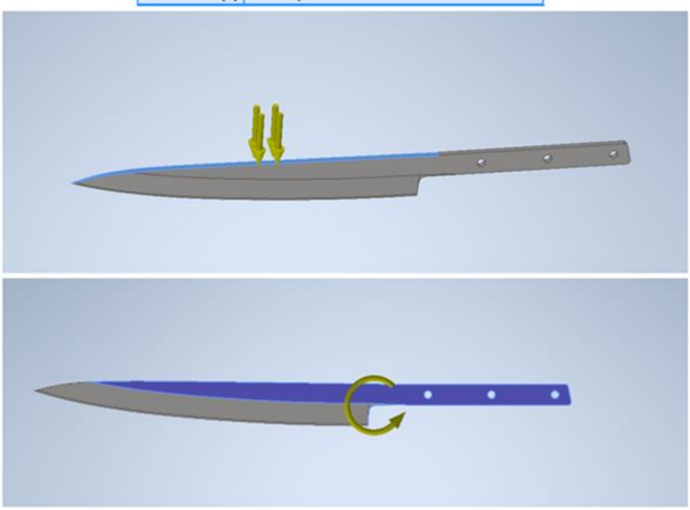


Fig. 14. Material properties and location of tests

Using Autodesk Inventor Professional 2023, this finite element study provides valuable information on the structural analysis of knife blades. By evaluating Von Mises stress and displacement and considering applied loads, engineers and designers can make informed decisions to optimise blade design, improve blade durability, and ensure reliable cutting performance.

The knife blade was considered a straight bar to investigate the structural behaviour of the knife blade in more detail (Fig. 15). This analysis provides valuable information about the response of the blade to applied loads and its overall stability.

Using the same data and Autodesk Inventor Professional 2023, the analysis revealed important findings related to the structural integrity of the blade. The maximum normal stress σ was determined to be 2.554MPa, indicating the maximum level of stress experienced by the blade frame structure. This information allows a thorough assessment of the blade's ability to withstand applied loads without exceeding the material limits.

In addition, the frame analysis considered a bending moment of 544 N·mm. This bending moment represents the torsional force applied to the blade, which can induce bending moments and stresses. By evaluating the blade's response to this bending torque, the analysis provides information on the blade's resistance to bending and torsional forces, thereby enhancing its stability and performance.

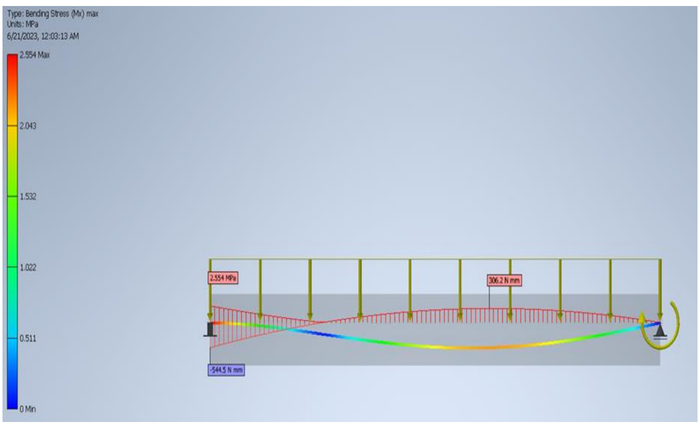


Fig. 15. Indeterminate static analysis

Combining the results from both studies, finite element analysis and indeterminate static calculation, provides a comprehensive understanding of the structural behaviour of the knife blade under various loading scenarios.

Simulation in Ansys R1 2023

A comparison was made between the results obtained from the finite element analysis using Ansys R1 2023 and Autodesk Inventor Professional 2023 for the knife blades (Figs. 16 and 17). The analysis was performed only on the length of the blade, excluding its handle. The results obtained in the two programmes proved to be similar, indicating the consistency and precision of both analysis methods.

Finite element analysis performed in Ansys R1 2023 provided the following results:

- The total deformation of the blade was $9.5 \cdot 10^{-6}$mm, which indicates minimal deformation under the applied load.
- The maximum Von Mises stress in the blade was recorded at 1.1507MPa and represents the maximum stress sustained by the blade during loading, falling within the permissible limits for the material used.
- Similar results obtained in finite element analysis using Autodesk Inventor Professional 2023 confirm the accuracy and validity of the analysis method used. This agreement between the two programmes demonstrates that both are capable of providing consistent and reliable results in evaluating the structural behaviour of the knife blade.

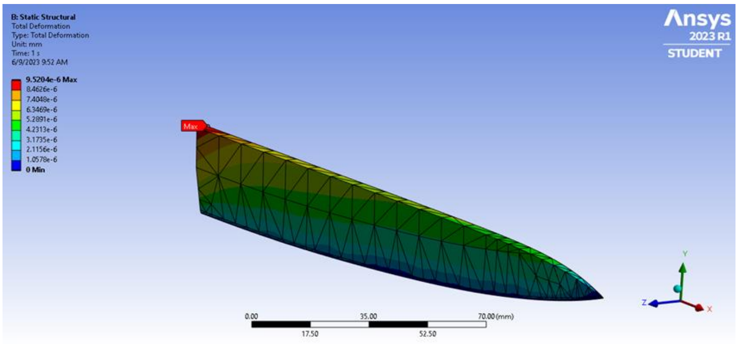


Fig. 16. The total deformation is 0.0000095204mm

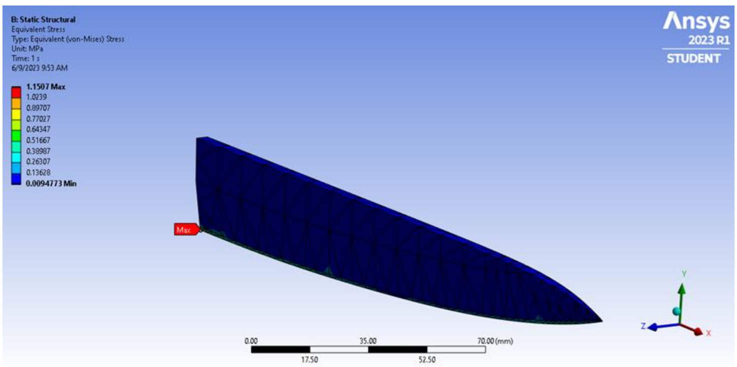
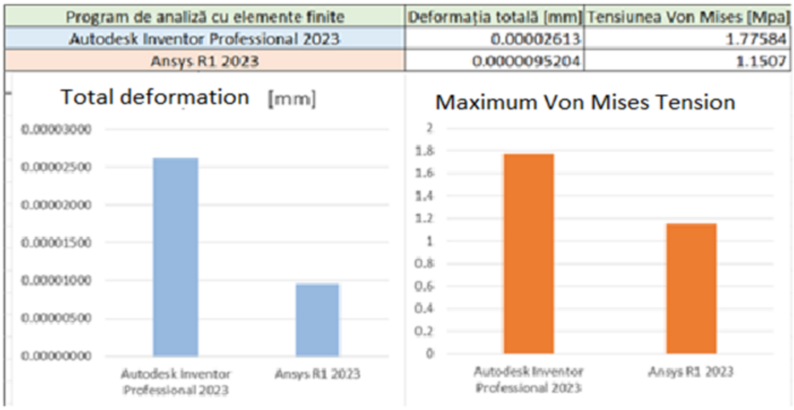


Fig. 17. Maximum Von Mises tension: 1.1507

In figure 18, a comparison was made, considering both simulation programmes.



Program de analiză cu elemente finite	Deformația totală [mm]	Tensiunea Von Mises [Mpa]
Autodesk Inventor Professional 2023	0.00002613	1.77584
Ansys R1 2023	0.0000095204	1.1507

Fig. 18. Compared results corresponding to total deformations and maximum Von Mises tensions

Conclusions

The study of Damascus steel provided the opportunity to observe in detail the laborious process of manufacturing this material, which involves forging and welding different layers of steel to obtain a particularly strong and durable final product. To carry out this research, high-quality materials were selected from a catalogue of steels, with a particular focus on achieving the best results.

In this case, two types of steel were chosen to create genuine Damascus steel: AISI 1095 and 15N20 steel. Both materials have been selected for their individual properties, such as strength and durability, which contribute to the ultimate quality of Damascus steel. This rigorous selection of materials ensured a high-quality and authentic product.

During the study, there was an opportunity to design and build a functional furnace capable of forging and welding the two different materials, AISI 1095 and 15N20. This furnace played a crucial role in obtaining true 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 Damascus steel, this material was processed into a knife blade. This process involved sanding and shaping the material to give it shape and sharpness. Care and precision were required in carrying out this step in order to obtain a high-quality final product.

In this study, laboratory tests were performed on the obtained Damascus steel to evaluate its mechanical properties and behaviour under different conditions. This involved the use of specific techniques and tools such as hardness tests, strength tests, and microstructural analysis.

Additional studies, such as finite element analysis, were also conducted to understand and evaluate the behaviour of genuine Damascus steel under various scenarios and loadings.

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Received: January 10, 2023
Accepted: August 2, 2023