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# RESEARCH ON TESTING A GENUINE DAMASCUS STEEL. A CASE STUDY

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***Abstract***

*Based on the fascinating legends and excellent properties of Damascene blades, 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 catalog 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. Additional studies, such as finite element analysis and strength of materials, were conducted to understand and evaluate the behaviour of Damascus steel under various scenarios and loadings. 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***: *Genuine Damascus Steel; Manufacturing; Treatment; Resistance calculation; ANSYS simulation; Finite element analysis.*

## Introduction

Books and papers [1–5], based on the fascinating legends about the excellent properties of Damascene blades [6-8], created the impulse to manufacture and research the mechanical characteristics of this steel.

Genuine, original Damascus blades, also called *wootz*, known in Russia as "bulat," were manufactured in mediaeval Damascus. The so-called "wootz" steel was used, which in turn was manufactured in India, and it was characterised by a specific content of impurities. Swords, edged weapons, and daggers made of Damascus steel became renowned for their hardness and resistance to wear from the cut. There are mysterious secrets to forging, hardening, tempering, and the annealing procedure. These knives have a nice characteristic pattern of light-coloured wavy fine bands across the steel grey background, as was obtained in the present study through numerous attempts to manufacture Damascus steel in the laboratory. Museum-quality wootz

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Damascus blades were mainly produced in the $16^{th}$ century. In the early $19^{th}$ century, the last secrets of the original Damascus steel were lost.

Genuine Damascus steel is a type of steel obtained by combining two or more different types of steel. These types of steels 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, genuine Damascus steel has very good mechanical properties, including hardness and wear resistance [8].

The present study is a continuation of our research from the work [8], in which the detailed manufacturing of a professional Damascus steel kitchen knife was shown.

Applying optical microscopy to the polished slides, *N.T. Belaiew* identified the beautiful undulation of colours on the slides as if "milky ways" of cementite ($Fe_3C$) and concluded that the round-shaped cementite is embedded in the structure of Damascus steel, thus avoiding the typical fragility of hypereutectoid steels with acicular cementite [9]. The spheroidization appeared to be the consequence of repeated blows and heating during forging and welding. Cementite approaches the edge of the blade, thus providing good cutting properties and better wear resistance.

*N.T. Belaiew* [9] assumed that the properties and distribution of the carbides play a more considerable role than that of the quenching martensite. *K. Von Harnecker* [10] 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 and, after the heat treatment, to its spheroidization ($Fe_3C$). Annealing above the Acm temperature would cause the cementite to disappear and the material to acquire the exceptional properties of the desired steel [11].

*J. Wadsworth et al*. [2] assumed that the major process route was heating the steel above the temperature of Acm to form large austenite grains. After the slow-cooling process, there's an appearance of cementite on the austenite grain boundaries, which breaks up the barrier, and the aforementioned cementite spreads out as an effect of the subsequent forging.

*J.D. Verhoeven et al*. [5] and *J. D. Verhoeven* [12], however, observed the dissolution of the cementite from the structure of the original Damascus steel. The cementite distribution after heating to ~925°C for 30 minutes and subsequent slow cooling leads to the conclusion that the first-only part of the cementite is formed by cooling the blade to around 50°C below Acm and breaking up the much thinner arrays of cementite in the first forging steps.

The rest of the equilibrium cementite is forced to precipitate on the already fragmented cementite by maintaining a temperature around 50–100°C below Acm for the first stages of forging and then slow cooling to temperatures around 750–800°C for final forging. Austenite recrystallization (i.e., the formation of new grains) has to be devoid of any small plastic deformation.

*J. Wadsworth et al*. [13] pointed out that the results in [12] seem to relate to a blade that was not genuine. The apparent conflicting results could reflect different pathways of processing [13].

It's important to mention the role of minor amounts of alloying elements, other than carbon, in the formation of cementite in the structure of the material.

Small additions of Mn, Si, P, and S appear to improve the breakdown of cementites ($Fe_3C$) in spheroidized agglomerates, according to [16, 17]. Later, *J.D. Verhoeven et al.* [16] noticed that the V, Cr, Ti, Mo, Nb, and Mn carbide-forming metals, present at individual levels of 20 to 100ppmw and micro-segregated in interdendritic regions, facilitate the formation of cementite bands during the heat treatment cycle performed at temperatures below Acm. Studies of the effect of Si and V on the mechanical properties of pearlitic steels have shown that vanadium (V) increases the strength of pearlite (P), while Si strengthens pearlite by solid solution hardening of ferrite. Ductility in hypereutectoid steels is increased with V and Si [18, 19]. *J.D. Verhoeven* [5] assumed that the lack of a certain level of impurities in early $19^{th}$ century manufactured Indian wootz may have been the reason for the decline of Damascus blade production at this time.

It is well known that steel with a carbon content between 1 and 2% by weight, after casting, produces a microstructure with massive cementite plates, giving rise to high hardness but low ductility and damaging brittleness.

*J. Wadsworth* [2] demonstrated that, by applying mechanical modelation and by machining at appropriate temperatures, the microstructure can be transformed into a very fine-grained structure, which, in turn, is superplastic, i.e., no longer very brittle.

## Experimental Part

Experimental program needs an evaluation of the properties of the two steels in the layers: AISI 1095/EN ISO and 15N20 (75NI8) [8].

Damascus steel itself is the result of forging welding of the layers of the two materials mentioned in [8].

### *Materials*

Chemical composition of steel AISI 1095 and 15N20 was detailed in table 1 [8].

**Table 1.** Chemical composition of the steel AISI 1095 and 15N20 [%]

| **Element** | **Percent (%)** | |
|---|---|---|
| | AISI 1095 | 15N20 |
| Iron, Fe | 98.38 – 98.8 | 98.00 |
| Carbon, C | 0.90 – 1.03 | 0.70 – 0.80 |
| Sulfur, S | ≤ 0.050 | - |
| Phosphorus, P | ≤ 0.040 | 0.04 (max) |
| Manganese, Mn | 0.3-0.5 | 0.40 – 0.70 |
| Silicon, Si | 0.4 | |
| Nickel, Ni | - | 2.00 |

Carbon steel (AISI 1095) is brittle and has high hardness and strength. Conventional techniques can be applied to form AISI 1095 steel. 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 [8, 11, 13]. AISI 1095 steel can be oil-hardened 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 [8].

Steel 15N20 or its equivalent 75Ni8 is mainly used for making band saw blades. It is a carbon steel with properties similar to 1075 steel but contains 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-hardened 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 steel tempering heat 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 [8, 11].

Procedures used for making samples have been presented in a previous work [8].

The AISI 1095 and 15N20 steel plates came from the supplier in the form of 2×40×1000mm bars, which were cut into 100mm pieces and cleaned using a belt sander to remove any oxide layers that may have formed.

Later, the material was placed one on top of the other, alternating the two layers of steel, and they were welded to create a package and avoid it falling apart in the oven (Fig. 1).

**Fig. 1.** Alternating the two layers of steels

**Fig. 2**. The samples are prepared for forging

After the making of the package, the procedure was as follows:

- Heating to a temperature of approximately 800°C;
- 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 1100-1200°C
- Forging (involves manual forging as well as the use of a hydraulic press)
- Polishing of the oxidized layer and immersion in hydrochloric acid for the visibility of the model as shown in the figure below.

  In figure 3 Damask steel with 30 layers (laboratory) has been presented.

**Fig. 3**. Damask steel with 30 layers

In figure 4, the wavy pattern on the surface of the knife blade created according to medieval technologies can be seen [8].


**Fig. 4**. Final shape of the blade (a) one side and the other (b)

***Treatments***

If the material supported thermical treatments, the hardness of the Damascus steel increased. The treatments applied are specificed in table 2 and figure 5.

**Table 2.** Treatments applied after manufacturing

| Thermical treatment | | | Micro-Hardness Vickers $HV_{0,1}$ [daN/mm²] | Samples |
|---|---|---|---|---|
| **Quenching** | **Hardening (time of maintaining at the treatment temperature : 2min)** | **Tempering** | | |
| **~900°C cooling in air ~ 2h;** | ~900°C - cooling in water; | 250°C (one cycle of 1h) | 890.6 | S1 |
| **~900°C cooling in air ~ 2h;** | - | - | 595.8 | S2 |
| **~900°C cooling in air ~ 2h;** | ~900°C – cooling in oil | 200°C (one cycle of 1h) | 888.5 | S3 |

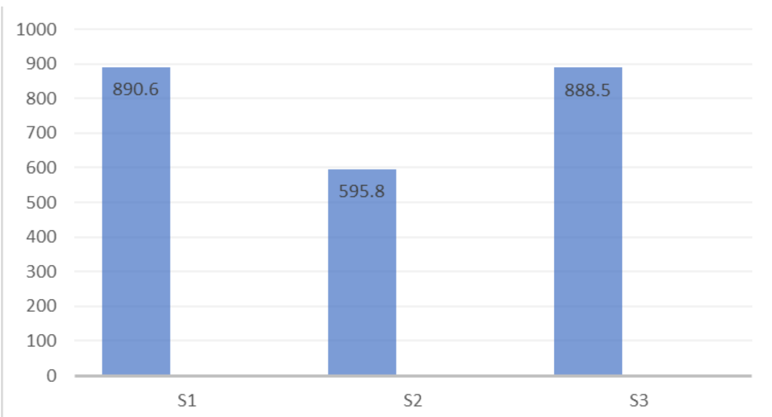


**Fig. 5.** Evolution of the Vickers microhardness of the Damask steel depending on the treatments S1, S2 and S3

***Calculation of the material resistance***

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

The Bending Moment (Mi) when the force is applied uniformly along the length of the knife made of Damascus steel created was shown in simulations and is displayed in figure 6, for the case of a normal load of F = 20N. Diagrams of efforts have been presented in Figure 6, and in Figure 8, Autodesk Inventor Professional 2023 was used.

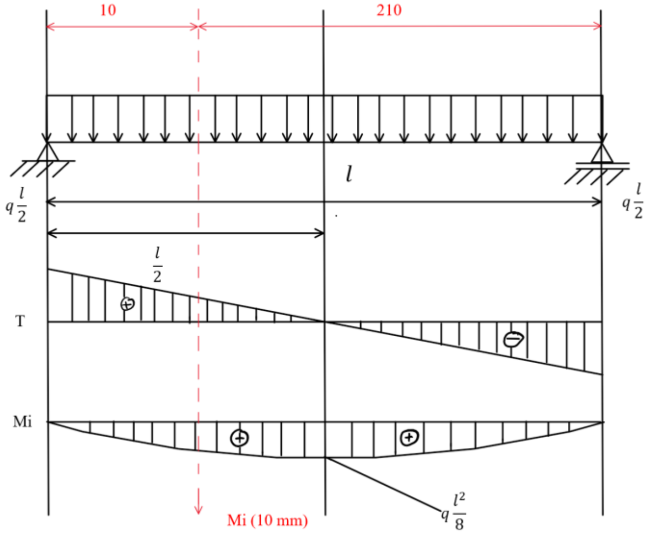


**Fig. 6.** Effort and Bending Moment diagrams

Bending moments (Mi) occur when the force is applied at a given distance away from the point of reference causing a bending effect.

The length of the blade of the knife taken into account in the calculation of resistance is l = 220mm and the considered force has a value of 20N (*for a normal load F = 20N*).

$$q = \frac{F}{l} = \frac{20N}{220mm} = 0.09\frac{N}{mm} \quad (1)$$

In section of the bar, for b = 3mm and h = 25mm, the Bending Moment (max.) will be calculated on the basis of the following mathematical relation:

$$M_{i_{max}} = q\frac{l}{2}\cdot\frac{l}{2} - q\frac{l}{2}\cdot\frac{l}{4} = q\frac{l^2}{8} \quad (2)$$

Firstly, we considered the area: 0 mm-210mm. For this section, the Bending Moment and the Resistance Module (Wy) have the following values:

$$M_i = M_{i_{max}} = q\frac{l^2}{8} = \frac{90\cdot(0.22)^2}{8} = 544.5\ N\cdot mm = 0.544\ N\cdot m \quad (3)$$

$$W_y = \frac{b\cdot h^2}{6} = 312.5\ mm^3 = 312.5\cdot 10^{-9}\ m^3 \quad (4)$$

$$\sigma_{max} = \frac{M_i}{W_y} = \frac{0.544 \cdot N \cdot m}{312.5 \cdot 10^{-9}\, m^3} = 0.0017408 \cdot 10^9 \frac{N}{m^2} = 1.7408 \cdot 10^6 \frac{N}{m^2} = 1.7408 \cdot 10^6 MPa \quad (5)$$

Analogously, the calculations for the section 210-220mm are carried out:

$$M_{i\,(10\,mm)} = \frac{l^2}{8} = \frac{90 \cdot (0.01)^2}{8} = 0{,}001125 N \cdot m \quad (6)$$

$$\boldsymbol{W_y = \frac{b \cdot h^2}{6} = 312.5\, mm^3 = 312.5 \cdot 10^{-9}\, m^3} \quad (7)$$

$$\sigma_{max} = \frac{M_i}{W_y} = \frac{0.001125 \cdot N \cdot m}{312.5 \cdot 10^{-9}\, m^2} = 0.3 \frac{N}{m^2} = 0.3 MPa \quad (8)$$

**The case of the beam of equal strength for blades with variable section**

A knife blade can be compared to a beam with variable section but of equal strength, thus providing a constant maximum normal tension in any section, for example, having the same value as the allowable strength.

The beams must meet the following condition:

$$\sigma_{max}(x) = \frac{|M_i(x)|}{W_y(x)} = \sigma_a = const \quad (9)$$

So the Resistance Module (Wy) must have the same law of variation along the bar as the Bending Moment (Mi):

$$W_y(x) = \frac{M_i(x)}{\sigma_a} \quad (10)$$

The above formula determines the shape of the equal-strength beam, which is influenced by loading, support, and cross-sectional shape. In the case of pure bending, the beam of equal strength has a constant section, while in the case of simple bending, it has a variable section (Fig. 7). According to this relation, in the sections where the bending moment is zero, the cross-section should also be zero, but this is not possible because in those sections there is a non-zero shear force that stresses the beam in shear.

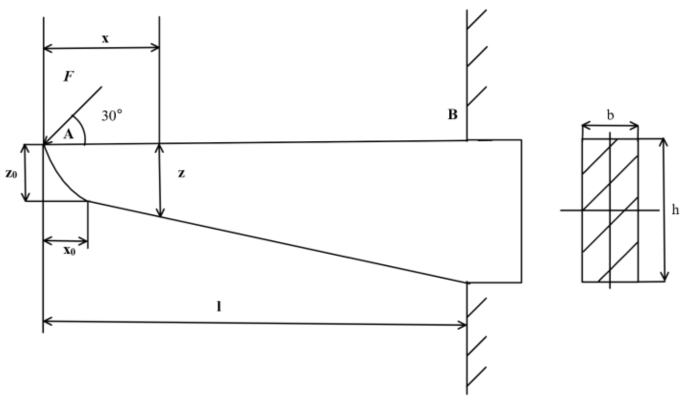


**Fig. 7.** Beam with variable section of equal strength

The shear stress allows determining the dimensions of the cross sections where the bending moment is zero.

Embedded beam of rectangular section of constant width and loaded with a concentrated force at the free end was worked out using the following relations:

$$\sigma_{max}(10\ mm) = \frac{M_i}{W_y} = \sigma_a = const. \quad (11)$$

$$\sigma_{max}(10\ mm) = \frac{M_i}{W_y} = \sigma_a = 2.554\ MPa = const \quad (12)$$

Using the mathematical relation above, the height of the section (z) can be determined.

$$z = \sqrt{\frac{6F \cdot x}{b \cdot \sigma_a}} = 12.515\ mm \quad (13)$$

The previous mathematical relation describes a parabolic variation of the section height along the length of the beam. To avoid shearing at the end of the beam in the area under the influence of the force, the following condition must be met:

$$\tau_{max} = \frac{3F \cdot cos\ 30}{2b \cdot z_0} = \tau_a = \frac{60 \cdot cos\ 30}{2 \cdot 3 \cdot 10}\frac{N}{mm^2} = 0.86602\ MPa \quad (14)$$

The minimum height of the cross section ($z_0$) and the distance ($x_0$) are obtained:

$$z_0 = \frac{3F \cdot cos\ 30}{2b \cdot \tau_a} = \frac{60 \cdot cos\ 30}{2 \cdot 3 \cdot 0{,}86602} = 1\ mm \quad (15)$$

and

$$x_0 = \frac{3F \cdot cos\ 30 \cdot \sigma_a}{8b \cdot {\tau_a}^2} = 1.3\ mm \quad (16)$$

***Processing the results using Autodesk Inventor Professional 2023***

Autodesk Inventor Professional 2023 was used. The finite element analysis revealed significant results regarding the stress distribution on the knife blade.

In the case of F = 20N, the Von Mises stress/strain was determined to be 1.77584 MPa, 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 [8]. This displacement means minimal deformation of the blade under the given loads, highlighting its excellent rigidity and dimensional stability [8].

The maximum normal stress σ was determined to be 2.554MPa, corresponding to F = 20N, indicating the maximum stress level experienced by the blade frame structure. This information allows a thorough assessment of the blade's ability to withstand the applied loads without exceeding the limits of the steel used.

In addition, the frame analysis considered a bending moment of 544N·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. 8).

Indeterminate static calculation provides a comprehensive understanding of the structural behavior of the knife blade under various loading scenarios.

If the value of the loading force (normal load F) is changed, the situations in figures 9 and 10 will be obtained.

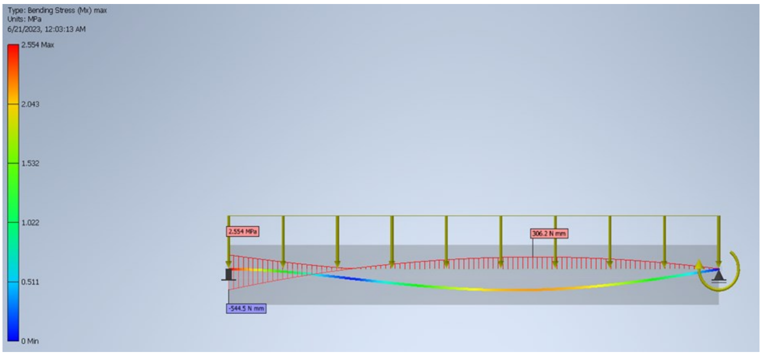


**Fig. 8.** Indeterminate static analysis [8], for F = 20N, Bending Stress in material [MPa]

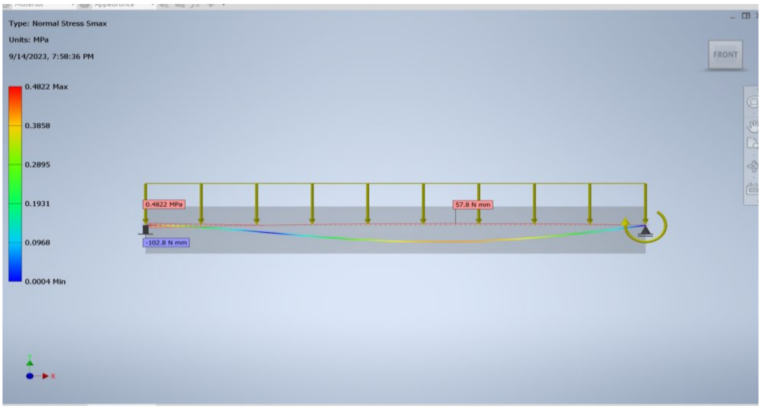


**Fig. 9.** Indeterminate static analysis, for F = 15N, Normal Stress/Tensions in material

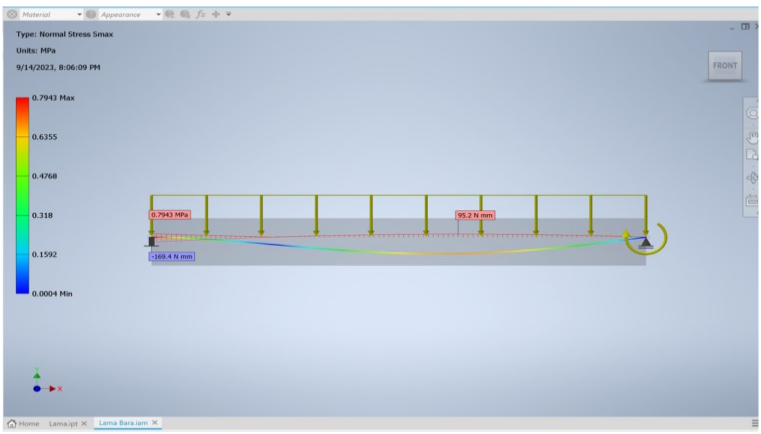


**Fig. 10**. Indeterminate static analysis, for F = 25N, Stresses/Tensions in material

***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 blade subjected to different values of the loading force. 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.

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.

Figure 11 shows the total deformation (0.0000095204 mm), in the case of F = 20N.

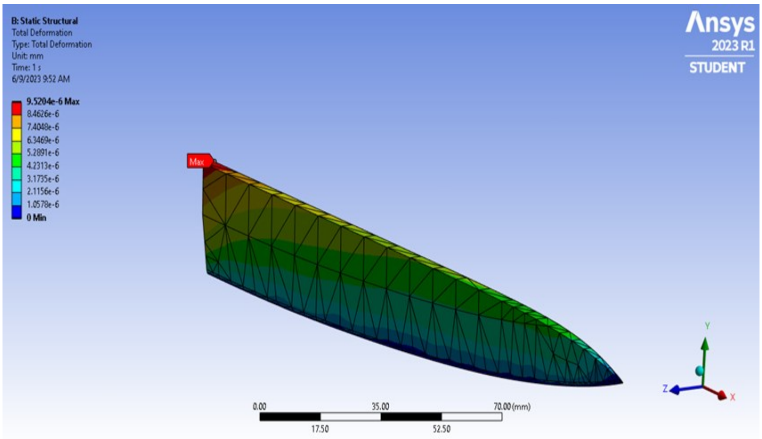


**Fig. 11.** Total deformation (0.0000095204 mm), in the case of F = 20N

Figure 12 shows the maximum Von Mises tension is 1.1507MPa.

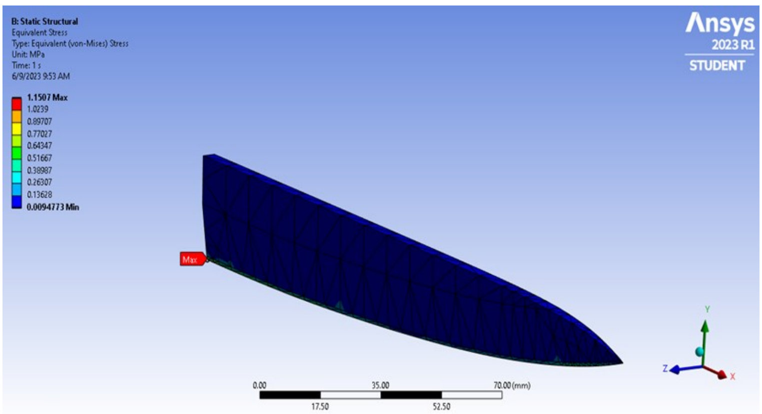


**Fig. 12.** Equivalent stress (von Mises), in the case of F = 20N

In figure 13, Shear stresses evolution, in the case of F = 15N, has been presented and in figure 14, Shear stresses evolution, in the case of F = 25N have been presented too.

In figures 15 and 16, Equivalent stresses have been presented in the cases of F = 15N and F = 25N, respectively. Total deformations of the experimental knife have been presented in figures 17 and 18, for both values of the applied normal load F.

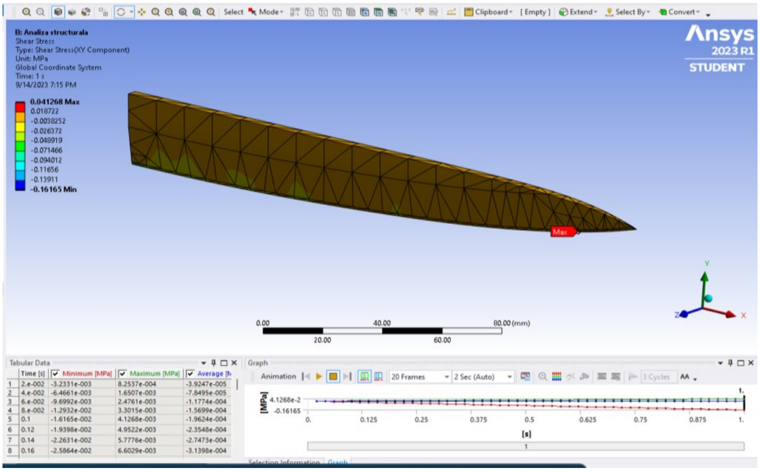


**Fig. 13.** Shear stress, in the case of F = 15N: Maximum value is 0.041268MPa

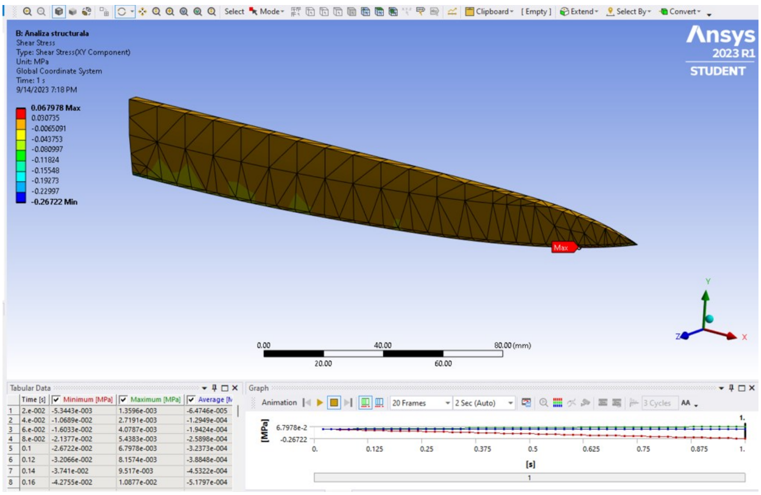


**Fig. 14.** Shear stress, in the case of F = 25N: Maximum value is 0.067978MPa

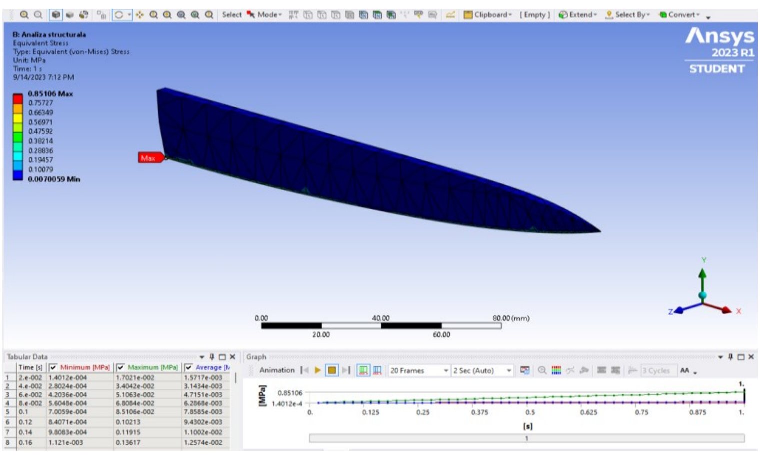


**Fig. 15**. Equivalent stress, in the case of F = 15N

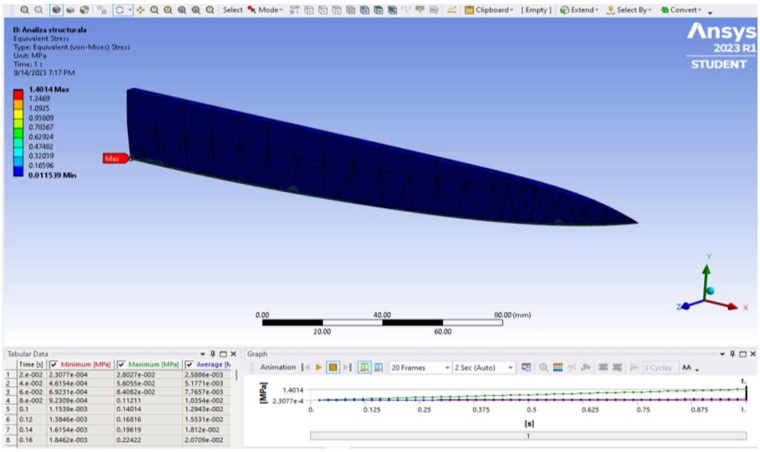


**Fig. 16.** Equivalent stress, in the case of F=25N

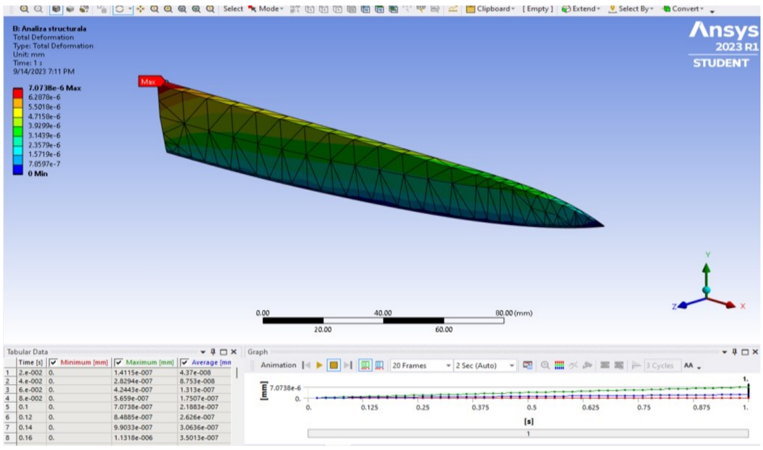


**Fig. 17**. Total deformation of the knife (0.0000070738mm), for F=15N

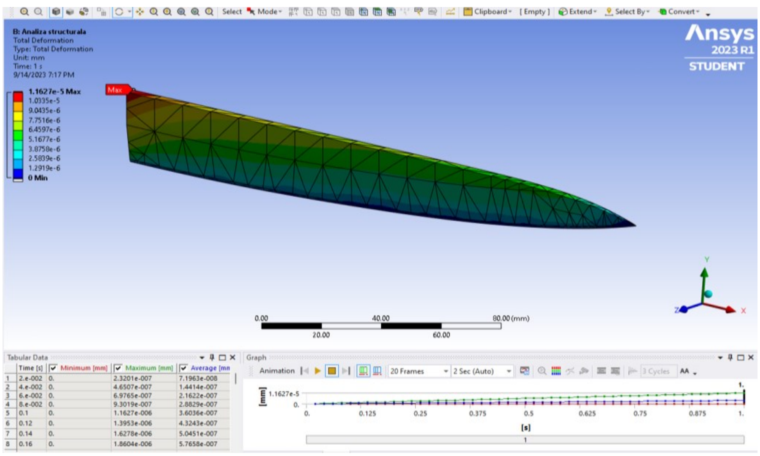


**Fig. 18**. Total deformation of the knife (0.000011627mm), for F=25N

The study is interested in understanding the structural response and behavior of the blade itself under different loading conditions, assessing how the blade responds to varying levels of external force, which is crucial in understanding its strength and performance characteristics.

This data suggests that both analysis methods provided consistent and precise results. Consistency is essential in engineering simulations to ensure the reliability of the obtained data.

The similarity in results implies that either software tool can be confidently used for the analysis of the knife blade in question.

## Conclusions

Damascus steel is a type of steel obtained by combining two or more different types of steel. These are heated together, hammered or forged, and bent repeatedly to create a specific pattern of characteristic striations and dots.

This manufacturing process produces Damascus genuine 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 and wear resistance.

The final shape of a professional kitchen knife for filleting fish, called the *Yanagiba*, was established. *Yanagiba* knives (Sashimi knives) are mainly used to slice boneless pieces of fish, especially for Sashimi and Sushi dishes. These knives can also be used to clean and fillet small and medium-sized fish. The *Yanagiba* is a thicker knife with a long, slim profile and a single-bevel grind.

In order to perform strength calculations on the obtained material and to determine the evolution of shear stresses, deformations, and bending stresses, the knife blade was considered to be similar to a beam with a variable section on which a uniformly distributed loading force acts, as shown in the figures presented above.

It should be noted that, under the imposed demands, the total deformations of the sample were imperceptible. The hardness of the Damascus steel obtained is much higher than the hardness of the steel with which the desired material was made.

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 blade subjected to different values of the loading force. Similar results were obtained in the case of both research methods.

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