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GRAPHIC MODELING AND EQUIPMENT USED IN THE RECONSTRUCTION OF THE ORIGINAL DAMASCUS STEEL

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Abstract

Damascus steel was used in the manufacture of swords and hunting knives before medieval times. The original method of the manufacturing of this type of steel has been lost to time. The research set out to create Damascus steel knives reconstituted according to the recipe from documents written many years ago. The study of Damascus steel provided an opportunity to observe in detail the laborious process of manufacturing this material, which involves free forging and pressure welding of different layers of steel to obtain a particularly strong and durable finished product. To carry out this research, two types of steel were selected to create Damascus steel: AISI 1095 and 15N20 steel. During this study, a functional furnace was built, able to contribute by heating the samples to the hot forging process of these two different materials. By applying a complex process of heating and forging and then repeating this process, the layers of steel were welded together, resulting in an extremely resistant material with a unique aesthetic appearance. Sample processing and the laboratory tests were performed on the obtained Damascus steel to evaluate its mechanical properties, including processing the results using Autodesk Inventor Professional 2023 and simulation in Ansys 2023.

***Keywords**: Damascus Steel; Manufacturing/Reconstruction; Equipment; Treatment; Modeling; Autodesk Inventor Professional 2023.*

Introduction

Damascus steel was named after the Syrian Capital. Some version of Damascus steel has been produced for centuries, everywhere from Indonesia to the Middle East. But the formula for Wootz Damascus steel has been lost to history, because this kind of steel have been prodused by the 6-th Century [1]. In the early 19th century, the last secrets of the original Damascus steel were lost. The first mentions of Damascus steel are recorded around 300 BC. (originally named "wootz") [2].

A series of books and research [1-6], works from specialized literature, started from famous legends regarding the special mechanical characteristics of the original Damascus steel [7-9]. It was said that a hunting knife created from this special material could very easily cut a scarf left in free fall. Precisely these legends [1, 3, 5] created the desire of researchers to

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reconstruct the original Damascus steel. This study presents aspects regarding the methodology and the equipment that led to the creation of the Damascus Genuine steel.

In [8, 9] was presented that the Genuine, the original Damascus blades - called *wootz*, also known in Russia as "*bulat*" and was manufactured in medieval Damascus. The so-called "wootz" steel was manufactured in India and it was characterized by a specific content of impurities. Swords and daggers made of the Damascus steel became renowned for their hardness and for their resistance to wear of the cutting part. These knives have a nice specific pattern of lights colored wavy fine bands across the steel gray background, as was obtained in the present study, through numerous attempts to manufacture Damascus steel in the laboratory [8, 9].

The present study complements the research from the works [8, 9]. In [8] some aspects regarding the detailed manufacturing of a professional Damascus steel kitchen knife have been presented.

Original Damascus steel is a type of steel obtained by combining two or more different types of high carbon steels. These types of steels are heated together, freely hammered/pressed (through hot free forging welding) and repeatedly bent to create a specific pattern of characteristic striations and points.

By studying the specialized literature, it was found that applying optical microscopy on the polished slides, *N.T. Belaiew* [6] identified a particularly beautiful undulation of the colours on the slides as if they were the "milky ways" of Cementite (Fe_3C) and concluded that round (globular) cementite is embedded in the structure of Damascus steel. The presence of cementite in this form avoids the brittleness of hypereutectoid steels with acicular cementite [9]. The question was: How was globular cementite obtained in the structure?

Its spheroidization appeared to be the consequence of repeated blows and heating during forging and hot free forging welding. Cementite approaches the edge of the blade, resulting in remarkable cutting properties and very good wear resistance. It is known that cementite has high hardness [10, 11].

On the other hand, in their works, *J.D. Verhoeven* [5] and *J.D. Verhoeven et al.* [12] achieved the dissolution of cementite from the structure of the original Damascus steel by heating this material. Cementite distribution is achieved after heating to ~925°C for 30 minutes and subsequent slow cooling. It is concluded that firstly only a part of the cementite is formed by cooling the blade of the Damascus steel knife to approximately 50°C below Acm and eventually, the matrices segment into much thinner parts of cementite in the first stages of forging [13-15].

It must not be forgotten that the role of minor amounts of alloying elements, which - in addition to carbon - can influence the formation of cementite in the structure of the material [9].

According to [16, 17], small additions of Mn, Si, P and S seem to improve the decomposition of cementites (Fe_3C) in spheroidized agglomerates. But also *J.D. Verhoeven et al.* [16] observed that the carbide-forming metals V, Cr, Ti, Mo, Nb and Mn, present at individual levels of 20 to 100ppmw and microsegregated in the interdendritic regions, also facilitate the formation of cementite bands during heat treatment with a cycle performed at temperatures below Acm. Another important observation is that vanadium (V) increases the strength of pearlite (P), while Si strengthens pearlite by ferrite solid solution hardening [9, 16]. The ductility of hypereutectoid steels is increased with V and Si [18-20].

Experimental part

Metodology and 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. They can also be used to clean and fillet small and medium-sized fish. Thanks to their narrow blade and sharp blade angle, the effort required to cut ingredients is significantly reduced. In addition to cutting fish, the knife found other uses in the kitchen. It can be used to cut thin, clean slices of raw boneless meat, including chicken. The blade can also cut fruit, bread and cheese. It is not recommended for bones as this will damage the blade.

The final dimensions are illustrated in the figure 1, according to [8].

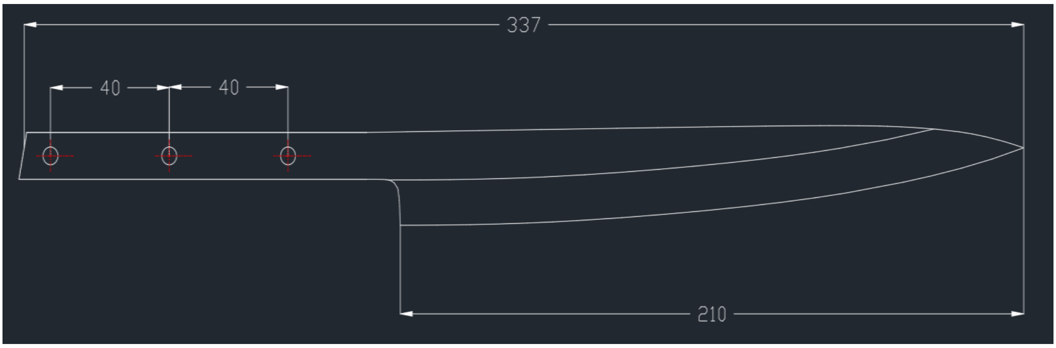

Fig. 1. Sketch of the Yanagiba knife with the final shape

This sketch was graphically modeled using Autodesk Inventor 2023 to prepare the finite element study.

The thermal furnace in which the samples were heated was constructed from a helium cylinder with dimensions 245 x 430 x 250mm. The furnace was lined up with a ceramic blanket resistant up to 1400°C (Figs. 2 and 3) [8].

Fig. 2. The thermal furnace (in Laboratory)

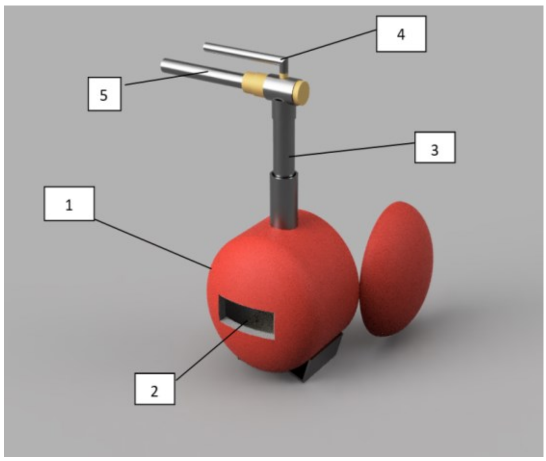

Fig. 3. Components of the system:
1. Oven; 2. Orifice; 3. Burner; 4. Gas inlet; 5. Air inlet [8]

In addition to the classic furnance with coals where the metals were heated for their hot forging, for this kind of application to manufacture the knife from Damascus steel it is possible to opt for a liquefied gas furnace having a forced draft with the help of a compressor to reach temperatures up to at a maximum of 1300°C. To achieve a neutral atmosphere, 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.

Materials

Damascus steel itself is the result of forging the layers of the two materials mentioned in [8, 9]: AISI 1095/EN ISO and 15N20 (75NI8).

The procedures used to make the tests have been presented in published works [8, 9].

AISI 1095 and 15N20 steel plates came from the supplier as 2x40x1000mm bars which were cut into 100mm pieces and cleaned using a belt sander to remove any surface oxide layers.

The materials were placed on top of each other, alternating the two layers of steel and these were welded by hot free forging to create a package as in figure 4 and in figure 5 the samples with a length of 100mm have been presented.

Fig. 4. The package [9]

Fig. 5. The Samples with a length of 100mm. (hard and resistant samples, laboratory photo) [8]

In table 1, chemical composition of the steel AISI 1095 have been presented [8] and in table 2, chemical composition of the steel 15N20 have been presented, too.

Table 1. Chemical composition of the steel AISI 1095 (%)

Element	Fe	C	S	P	Mn	Si
Quantity	98.38 – 98.8	0.90 – 1.03	≤ 0.050	≤ 0.040	0.3-0.5	0.4

Table 2. Chemical composition of the steel 15N20

Element	**Fe**	**C**	**Ni**	**P**	**Mn**
Quantity	98	0.70 – 0.80	2	≤ 0.040	0.40-0.70

Elements such as Nickel (Ni), Copper (Cu), Aluminum (Al) and Molybdenum (Mb) are present in small amounts. Carbon steel AISI 1095 is brittle and has high hardness and strength.

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, 9, 11, 13].

AISI 1095 steel can be in oil hardened from 899°C followed by tempering to increase the hardness of the steel and to prevent the broken process during the stress. AISI 1095 steel can be forged at temperatures between 955°C and 1177°C. Before carrying out this process, the steel is subjected to an annealing at a temperature of 898°C and gradually cooled to homogenize the structure of the steel. AISI 1095 steel can be tempered between 372°C and 705°C. [8]

Steel 15N20 or its equivalent 75Ni8 is a carbon steel with properties similar to AISI 1095 steel but contains a significant proportion of nickel (Ni).

All welding techniques can be used for welding 15N20 steel. Preheating is required at temperatures between 260°C 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 from 899°C followed by tempering to maintain the hardness and strength of the steel and to prevent the broken process during stresses.

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 homogenize the structure of the steel. In the case of the steel tempering heat treatment, 15N20 steel can be tempered between 372°C and 705°C. Steel 15N20 is mainly used for cutting tools and springs [8, 9, 11].

After the making of the package, in according to [8, 9], the following procedure had been applied:

- Heating to approximately 800°C
- Sprinkling with borax – Na2B4O7 (to increase of the temperature and dissolves unwanted oxides from the surface of the package)
- Heating to 1100-1200°C
- Manual Forging
- Polishing of the oxidized layer and immersion in hydrochloric acid for the visibility of the model of the knife as shown in the figure below.

In figures 6 and 7 Damask steel with 30 layers (laboratory) has been presented.

Fig. 6. Special pattern that appears on the blade of the knife

Fig. 7. Damask steel with 30 layers (laboratory photo)

Treatments

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

It can be observed that a particularly high hardness was obtained after the heat treatments of tempering and tempering.

However, the steel failed when the following procedures were applied:

• Normalization to approx. 870°C for 15 minutes, then allowed to cool in air at 2°C. It should be mentioned that the work area was not heated and the temperature was 1-2 degrees, because it was winter.

• Tempering at 900-910°C, in water.

The sample was slightly hit with a metallic sample and the steel showed three small crack primers, visible on the surface, marked in red, as in figure 8 and visible crack material has been presented in figure 9.

Table 3. Treatments applied after manufacturing

Thermical treatment			**Micro-Hardness Vickers $HV_{0,1}$ [daN/mm^2]**	**Samples**	**BRINELL HB [daN/mm^2]**
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	698
~900°C cooling in air ~ 2h;	-	-	595,8	S2	542
~900°C cooling in air ~ 2h;	~900°C – cooling in oil	200°C (one cycle of 1h)	888,5	S2	697
Witnes sample	-	-	207	S0	197

Fig. 8. Cracked sample

Fig. 9. Visible crack in the material

In figure 10, in section, it can be seen two colours: the dark area is AISI 1095 steel, the silver area is 15N20 steel. Figure 11 presents an overview in the blade section; it can be seen the homogenization of the 30 layers.

Fig. 10. AISI 1095 steel – the silver area is 15N20 steel

Fig. 11. Overview in the blade section – homogenization of the 30 layers.

Results processed with Autodesk Inventor Professional 2023

The finite element analysis revealed significant results regarding the stress distribution on the knife blade. The objective of this study was to analyze the structural behavior and performance of the blade under various loading conditions. The study includes evaluation of Von Mises stress and the displacement to obtain information on the response of the blade to applied loads. Finite element analysis revealed significant results on the knife blade stress distribution.

I. If the load is **F = 10N**, the Von Mises Stress was determined to be 2.627Mpa (Fig. 12), 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 0.0000494474mm, considered insignificant. Additional data have been presented in tables 4 and 5.

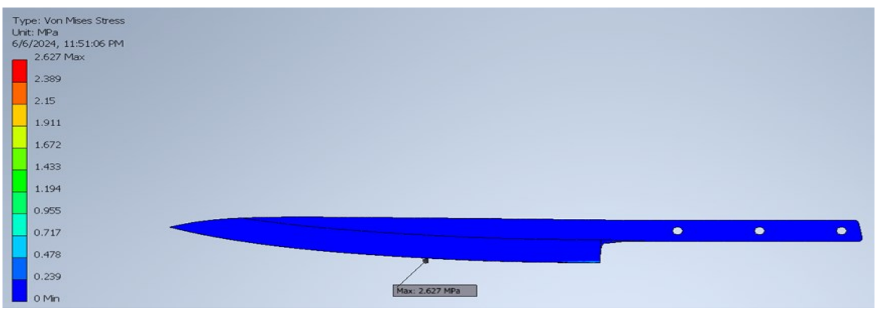

Fig. 12. Von Mises Stress (F = 10N)

In table 4 the Reaction Force and the Reaction Moment have been presented. Table 5 presents Summary results in the case of F = 10N.

Table 4 Reaction Force and the Reaction Moment (F = 10N)

Constraint Name	Reaction Force		Reaction Moment	
	Magnitude	Component (X, Y, Z)	Magnitude	Component (X, Y, Z)
Fixed Constraint:1	9.98953N	0.0622601N 9.98934N 0.0N	0.134017N m	0.0N m 0.0N m -0.134017N m

Table 5. Results Summary

Name	Minimum	Maximum
Volume	18481.7mm^3	
Mass	0.145081kg	
Von Mises Stress	0.0000000570614MPa	2.62745MPa
1st Principal Stress	-0.00287942MPa	0.495158MPa
3rd Principal Stress	-2.68987MPa	0.0000950799MPa
Displacement	0.0mm	0.0000494474mm
Safety Factor	15ul	15ul

In figure 13, the Displacement for F = 10N have been presented. In figure 14, Safety Factor in the case of F = 10N, have been presented.

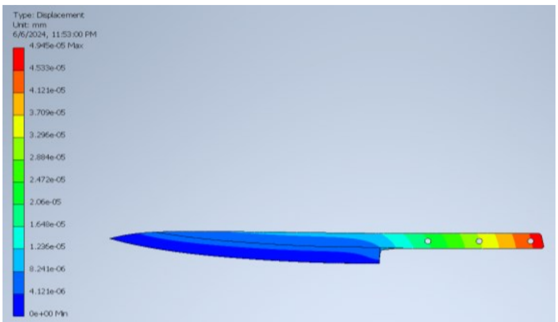

Fig. 13. Displacement for F = 10N

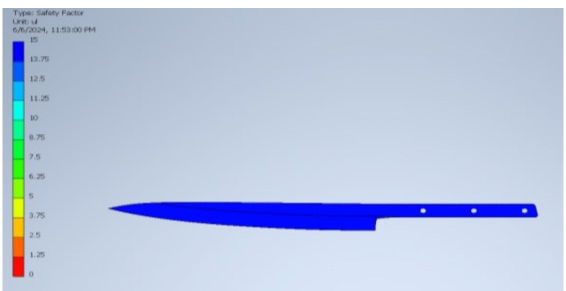

Fig. 14. Safety factor, in the case of F = 10N

This displacement means minimal deformation of the blade under the given loads, highlighting its excellent rigidity and dimensional stability. The negligible displacement also emphasizes the ability of the blade to maintain its shape and performance even during demanding cutting tasks. The study was performed along the entire length of the blade, measuring 350mm, to capture the overall behavior 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.

II. If the load is **F = 15N,** the Von Mises Stress was determined to be 3.94118MPa (Figs. 15-17), indicating the magnitude of the maximum stress experienced by the blade.

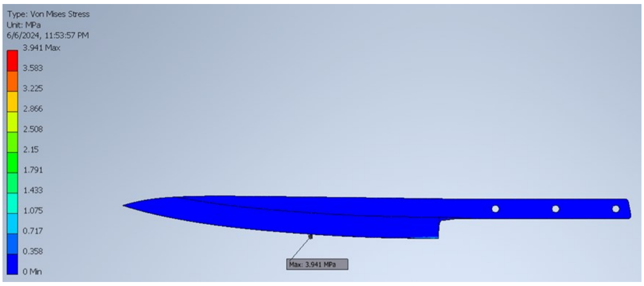

Fig. 15. Von Misses Stress for F = 15N

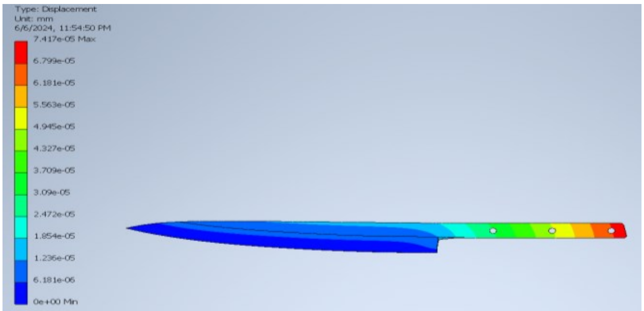

Fig. 16. Displacement for F = 15N

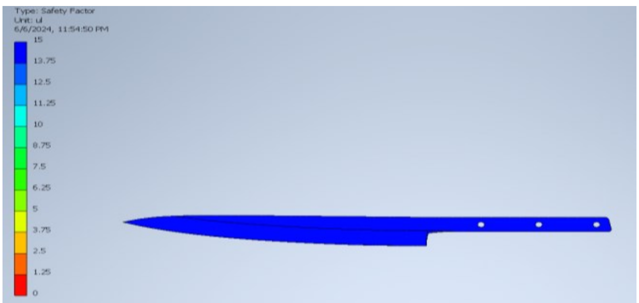

Fig. 17. Safety factor, in the case of F = 15N

In addition, the analysis revealed a displacement of 0.0000741713mm, considered insignificant. Supplementary data have been presented in tables 6 and 7.

III. In the case of **F = 20N**, the Von Mises stress/strain was determined to be Max. 5.25491 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 (Figs. 18-20).

Table 6. Reaction Force and the Reaction Moment (F = 15N)

Constraint Name	Reaction Force		Reaction Moment	
	Magnitude	Component (X, Y, Z)	Magnitude	Component (X, Y, Z)
Fixed Constraint:1	14.9843N	0.0933901N 14.984N 0.0N	0.201026 N m	0.0N m 0.0N m -0.201026N m

Table 7. Results Summary (F = 15N)

Name	Minimum	Maximum
Volume	18481.7mm^3	
Mass	0.145081kg	
Von Mises Stress	0.0000000949611MPa	3.94118MPa
1st Principal Stress	-0.00431914MPa	0.742737MPa
3rd Principal Stress	-4.03481MPa	0.00014262MPa
Displacement	0 mm	0.0000741713mm
Safety Factor	15ul	15ul

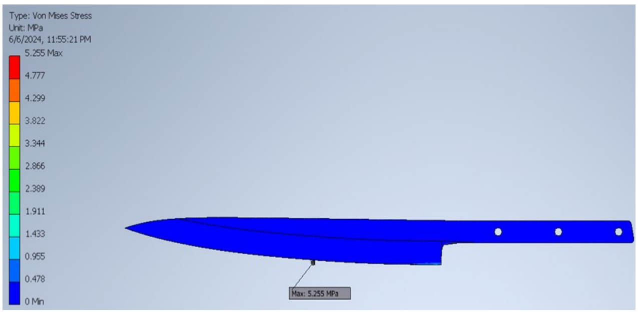

Fig. 18. Von Misses Stress for F = 20N

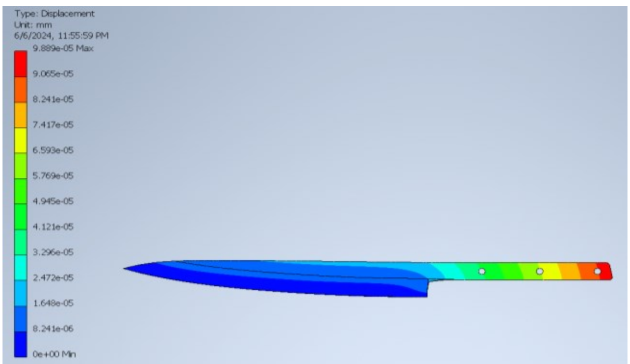

Fig. 19. Displacement in the case of F = 20N

In addition, the analysis revealed a displacement of 0.0000988949 mm, considered insignificant. This displacement means minimal deformation of the blade under the given loads, highlighting its excellent rigidity and dimensional stability [8]. Supplementary data have been presented in tables 8 and 9.

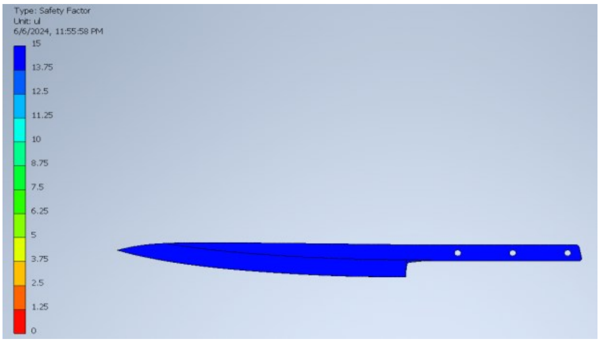

Fig. 20. Safety factor, in the case of F = 20N

Table 8. Reaction Force and the Reaction Moment (F = 20N)

Constraint Name	Reaction Force		Reaction Moment	
	Magnitude	Component (X, Y, Z)	Magnitude	Component (X, Y, Z)
Fixed Constraint:1	19.9791N	0.12452N 19.9787N 0.0N	0.268034N m	0.0N m 0.0N m - 0.268034N m

Table 9. Results Summary (F = 20N)

Name	Minimum	Maximum
Volume	18481.7mm^3	
Mass	0.145081kg	
Von Mises Stress	0.000000126378MPa	5.25491MPa
1st Principal Stress	-0.00575885MPa	0.990316MPa
3rd Principal Stress	-5.37975MPa	0.00019016MPa
Displacement	0mm	0.0000988949mm
Safety Factor	15ul	15ul

IV. In the case of **F = 25N**, the Von Mises stress/strain was determined to be Max. 6.56863 MPa, indicating the magnitude of the maximum stress experienced by the blade (Figs. 21-23).

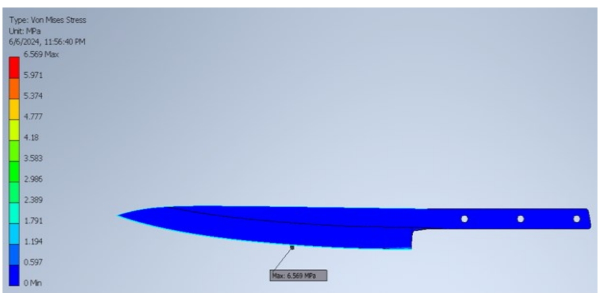

Fig. 21. Von Mises Stress (F = 25N)

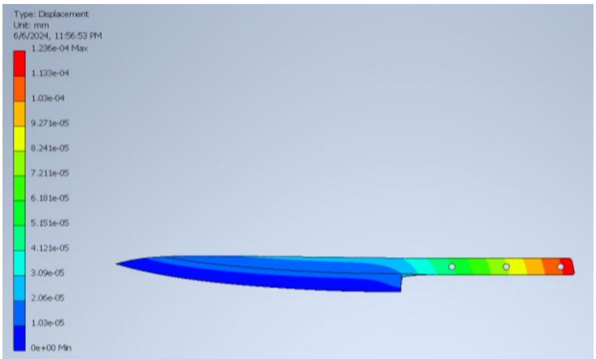

Fig. 22. Displacement in the case of F = 20N

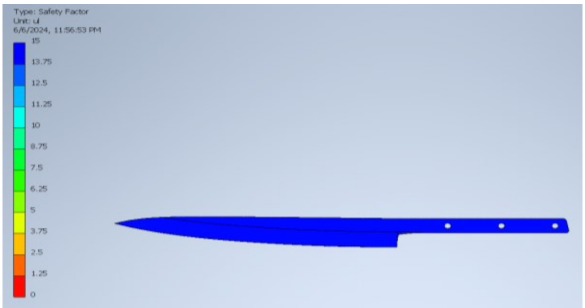

Fig. 23. Safety factor, in the case of F = 25N

This value, below the yield strength of the material, suggests that the blade can withstand the applied loads without risk of deformation. Supplimentary data have been presented in tables 10 and 11.

In addition, the Stress Analysis Report revealed a displacement of Max. 0.00012362mm and this values is considered insignificant.

Table 10. Reaction Force and the Reaction Moment (F=25N)

Constraint Name	**Reaction Force**		**Reaction Moment**	
	Magnitude	Component (X, Y, Z)	Magnitude	Component (X, Y, Z)
Fixed Constraint:1	24.9738N	0.15565N 24.9738N 0.0N	0.335043N m	0.0N m 0.0N m - 0.335043N m

Table 11. Results Summary (F=25N)

Name	**Minimum**	**Maximum**
Volume	18481.7mm^3	
Mass	0.145081kg	
Von Mises Stress	0.00000014310MPa	6.56863MPa
1st Principal Stress	-0.00719856MPa	1.2379MPa
3rd Principal Stress	-6.72468MPa	0.0002377MPa
Displacement	0.0mm	0.00012362mm
Safety Factor	15ul	15ul

Corresponding to the Stress Analysis Report, we have the following data:

Mass 0.0195865kg

Area 24834.8mm^2

Volume 38224mm^3

Center of Gravity: x = -111.289mm; y = 13.0437mm; z = 0.000000141679mm.

Indeterminate static calculation which provides a comprehensive understanding of the structural behavior of the knife blade under various loading scenarios, have been presented in [9]. These calculations depend on a number of factors mentioned in the specific Analysis Reports.

Conclusions

In this study, Damascus Steel is a type of steel obtained by combining two different steels with a relatively high carbon content. These are heated together, welded by free forging and repeatedly bent resulting in a specific pattern of characteristic striations and points (see figure 8).

This manufacturing process produces genuine 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 is renowned for very good mechanical properties, including hardness and wear resistance, especially after classic heat treatments. However, it was possible to damage this Damascus steel through inadequate treatments, obtaining small crack primers in the blade of the knife.

After the final shape of the professional kitchen knife for filleting fish, called Yanagiba, was established using Inventor 2023, modelling and analysis of von Mises stresses and other data necessary for the study were carried out. The case where the knife blade is similar to a beam with variable cross-section subjected to a uniformly distributed loading force, as in the figures presented above, has been considered.

It should be noted that at the imposed stresses, the total deformations of the sample were imperceptible. The hardness of the Damascus steel obtained is much higher than the hardness of the steels 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 in [9]. Similar results were obtained in the case of both research methods [8, 9].

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