

A COMPARATIVE APPROACH TO THE CHARACTERIZATION OF THE BEHAVIOR UNDER LOAD IN THE CASE OF THE LEGENDARY DAMASCUS STEEL

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Abstract

The study of the legendary Damascus steel provided the opportunity to study historical and specialized manufacturing techniques. Under these conditions, the laboratory samples could be made using plates of two high-carbon steels, interleaved and processed by free forging. This procedure led to the "welding" of these layers by successive hot pressing to realize a knife that is particularly resistant to stress and has high hardness. In carrying out this study, the laboratory tests and the modeling were carried out on laboratory-produced Damascus steel samples, thermally treated, strictly following the procedure described in the specialized literature. The investigated material consists of a hard steel with a carbon content higher than 0.9-1% C and a steel with a lower carbon content but above the eutectoid, which means it is above 0.7% C. The purpose of this study is to evaluate the behavior of the obtained material under mechanical stress and to process the results using Autodesk Inventor Professional 2023. The objective of this study was to analyze the behavior of the Damascus steel under various loading conditions. The study includes the evaluation of Von Mises stress and the displacement under different applied loads to obtain information about the steel sample response to the applied loads.

Keywords: *Damascus steel; Treatment; Mechanical stress; Simulation; Graphical models*

Introduction

Damascus steel originated in ancient India (circa 300–500 BCE) as Wootz steel, known in Russia as "*bulat*." Initially, a high-carbon material produced in crucibles was cast into ingots, especially in Tamil Nadu and Telangana—mentioning the ancient city of Golconda—and, later, in Sri Lanka. These steel ingots were exported to the Middle East, specifically Damascus, where smiths forged the iconic, patterned blades. Damascus steel was prized for its strength and sharpness and has been coveted since the Crusades in medieval Europe. It has been discovered that this steel is the real counterpart of Valyrian type. Therefore, according to a few, “Damascus” steel came from the Indian subcontinent.

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The paper on “Archaeo-metallurgical Investigation of a Fragment of a Medieval Sword Blade” [1] presents the use of different steel bars combined by hot hammering to achieve an optimal balance between mechanical properties such as hardness and impact resistance of the material.

In the article “Damascus Steel’s Indian Origins”—written by Anshika Jain in 2019 in *History of India* [2]—it is assumed that when European Crusaders first landed in Western Asia in the 12th and 13th centuries AD, full of religious zeal, they were greeted by soldiers wielding a sword that amazed them because of its resistance. Described as being able to cut a feather in the air and keep its edge in countless battles, they named this amazing sword after the place where they encountered it – Damascus [2-4]. There are mysterious secrets of forging, hardening, tempering, and the annealing procedure [5].

Applying optical microscopy to the polished slides, *N. T. Belaiew* identified the beautiful undulation of colors on the slides as “milky ways” of Cementite (Fe_3C). They look like waves in the wind. *N. T. Belaiew* concluded that the round-shaped cementite was embedded in the structure of Damascus steel, thus avoiding the typical fragility of hypereutectoid steels with acicular cementite [3], [6]. This is the explanation for the higher hardness of this material without the danger of the cracks in the structure during the stress.

J. D. Verhoeven et al. [7] and *J. D. Verhoeven* [8] observed the dissolution of the cementite from the structure of the original Damascus steel in special conditions. The Cementite distribution after heating to $\sim 925^\circ\text{C}$ for 30 min and subsequently slow cooling leads to the conclusion that in the first step, only a part of the cementite is formed by cooling the blade to around 50°C below Acm. They observed the breakup of the much thinner arrays of cementite in the first hot forging steps [4], [5], [9], [11]-[13].

The main characteristic of Damascus steel was the hardness. This mechanical property was given by the steel's components with a high carbon content [10].

At the same time, Damascus steel has good resistance, determined by the low-carbon steel component. In its structure, alternating “waves” of different shades of gray are observed, due to the “incorporated” spherical cementite, as stated in the lines above. From the own studies [4], [5], [9], it is observed that the martensitic structure appears after treatment, which gives the material exceptional hardness. However, the martensitic needles can create cracks in the structure at high loads. It is recommended to relieve the material stress also by heat treatment.

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

J. Wadsworth [14] has shown that by applying mechanical shaping by hot forging at appropriate temperatures, the microstructure can be transformed into a very fine-grained structure, which, in turn, is superplastic. The fine grain size reduces the possibility of brittleness of the material and reduces the risk of cracking during mechanical stress.

A research team from Germany in 2006, with Professor *Peter Paufler*, published a report that carbon nanotubes were found in a forged Damascus steel blade [15], [16].

This study is a continuation of the research from the works [4], [5], [9], [17]—works in which the detailed manufacturing of a professional Damascus steel kitchen knife was shown.

Experimental program

Materials and Method

The material used for the laboratory tests was the laboratory-made Damascus steel with 30 layers obtained by hot forging (as a package) of interleaved lamellae of two types of steel: a hard steel with a carbon content higher than 0.9-1% C (AISI 1095) and a steel with a lower carbon content but above the eutectoid of 0.7% C, respectively 0.75% C (15N20).

In figure 1, the AISI 1095 and 15N20 steel plates had dimensions of $2 \times 40 \times 1000$ mm. To remove the oxide layers and impurities, a belt grinding machine was used. The semi-finished

products were cut into 100 mm length pieces and cleaned with a degreasing agent, as shown in figure 1 [17].

These steels were processed simultaneously by free hot forging. In figure 2, the thermal furnace used has been presented, and in figure 3, the hot forging procedure has been presented, too. After plastic deformation through the hot forging resulted in a hard structure that presents "waves" with different color shades as a structural aspect (see Fig. 4).



Fig. 1. Lamellae of two types of steel, Laboratory samples, before the hot Forging process



Fig. 2. The thermal furnace [4], [17]

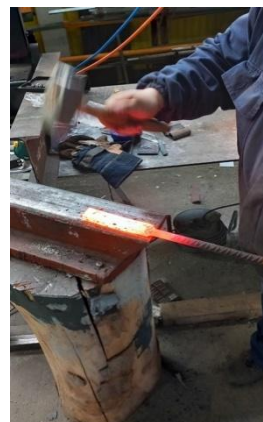


Fig. 3. Hot forging (photo from Laboratory)



Fig. 4. The "waves" with different color shades as a structural aspect in a sample from the laboratory

In table 1, the chemical composition of the steel AISI 1095 [4] has been presented. In Table 2, the chemical composition of the steel 15N20 has been presented [4], [5].

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

Chemical composition [%]						
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

Chemical composition (%)					
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.

The process of obtaining Damascus steel involved—among other steps—the gradual heating of the system, first to 800°C (degrees Celsius) and then to 1100°C, with the sprinkling of borax. After that, the system was forging under certain conditions.

After applying the quenching and tempering treatment, the steel was tested in the laboratory to determine the evolution of mechanical properties at different stress values, including by processing the results using Autodesk Inventor Professional 2023.

For this study, the loading/stress variants corresponding to a force of 30N and 230N were chosen.

After making the package, the procedure was as follows:

1. Heating to a temperature of approximately 800°C
2. Sprinkle with borax – $\text{Na}_2\text{B}_4\text{O}_7$ (an agent that helps to increase the temperature and dissolves unwanted oxides on the surface of the package)
3. Heating to a temperature of 1100-1200°C
4. Forging (involves manual forging as well as the use of a hydraulic press)
5. Grinding the oxidized layer and immersion in hydrochloric acid (HCl) for the visibility of the pattern according to figure 4.

Graphical models and equipment used

Sketching a Professional Kitchen Knife realized from Damascus Steel

The final shape of the blade was achieved with an angle grinder. The main edge was achieved using one belt grinder, and the shape of the knife was defined in the section according to figure 5.

Single-edged knives are preferred in Japanese cuisine due to their extremely sharp edge, with a sharpening angle of between 15 and 17 degrees. They allow for precise cutting, dicing and slicing, which is especially essential when preparing the fish. They also allow the chef to make long, continuous, thin cuts. This is because they only have one sharp side, which makes it easier to create a smaller, sharper angle.

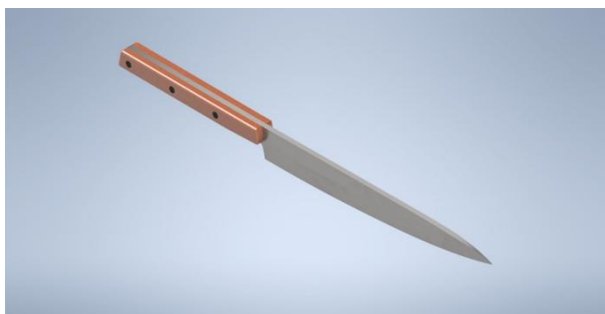


Fig. 5. The shape of the knife was defined in the section

The stretching operation in hot free forging consists of increasing the length of the blank by reducing its cross-section. This involves successive partial extrusions, but in the case of the stretching, horizontal deformation occurs freely in both directions, except for the horizontal direction in which it is restrained by the outer forming ends. In other words, in stretching, widening is hindered due to the presence of the outer ends. For this reason, the non-uniformity of deformations in the first pass is much greater in the case of stretching compared to extrusion. It should also be noted that the deformation during stretching does not occur simultaneously in the entire mass of the material, and its flow occurs in all directions. After every pressing, the position

of the sample is changed. Rotating the blank during forging changes its position relative to the tools. Therefore, in the end, the non-uniformity of deformations can be lower in the case of a correct management of the stretching operation, even if it is higher in the first pass compared to the pressing operation in free forging.

A sketch of a knife is shown in figure 6. Following this sketch, graphical modeling studies were carried out using the Autodesk Inventor 2023 program. This prepared the basis for the finite element study.

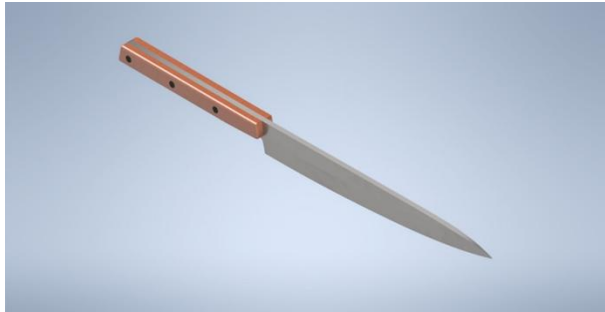


Fig. 6. 3D rendering of the Yanagiba knife

A sketch of a knife is shown in figure 6 [4], [9]. Following this sketch, graphical modeling studies were carried out using the Autodesk Inventor 2023 program. This prepared the basis for the finite element study. In figure 7, the Yanagiba knife has been presented (details) [9].

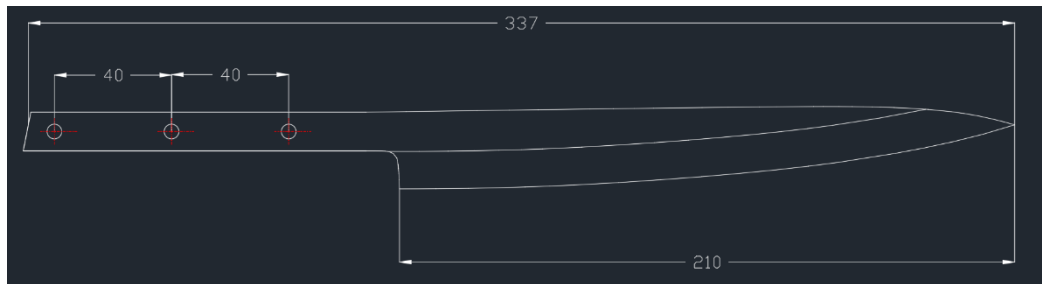


Fig. 7. Detailed sketch of the Yanagiba knife

Results obtained by processing data with Autodesk Inventor Professional 2023

After applying the hardening treatment and tempering treatments presented in [4], [5], [9], the steel was tested in the laboratory to determine the evolution of the mechanical properties at different stress values *including processing the results using Autodesk Inventor Professional 2023*.

The objective of this study was to analyze the behavior and the performance of this type of steel under various loading conditions. The study includes the evaluation of Von Mises stresses and the displacement under different applied loads to obtain information about the steel sample's response to the applied loads.

This analysis provides valuable information about the blade's response to applied loads and its overall stability.

Two values for the load are considered, namely, $F_1 = 30\text{N}$ and $F_2 = 230\text{N}$. A low value and a very high value that can be reached during use by shock have been considered.

Operating conditions

I. $F = 30N$

In the case of $F = 30N$, the results obtained have been presented below. In Tables 3 and 4, the operating conditions have been presented, corresponding to Force 1. In figures 8, 9, and 10, selected faces correspond to Force, Moment and the Fixed Constraints have been represented.

Table 3. Operating conditions

Load Type	Force value
Magnitude	30.000 N
Vector X	0.000 N
Vector Y	30.000 N
Vector Z	0.000 N

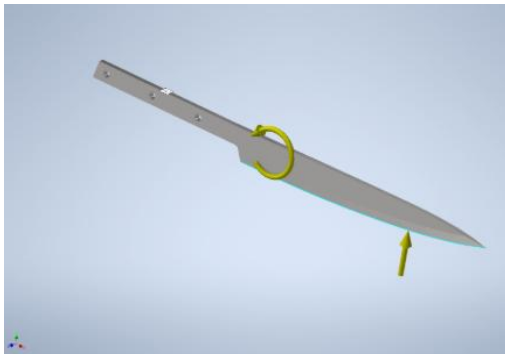


Fig. 8. Force 1: selected face

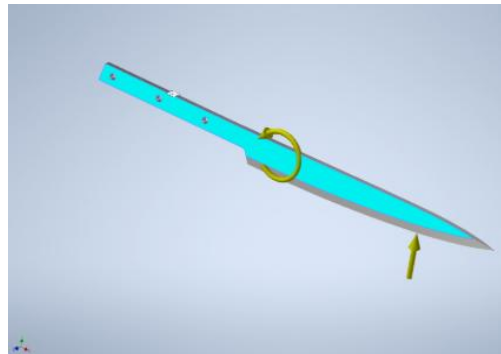


Fig. 9. Moment 1: selected face

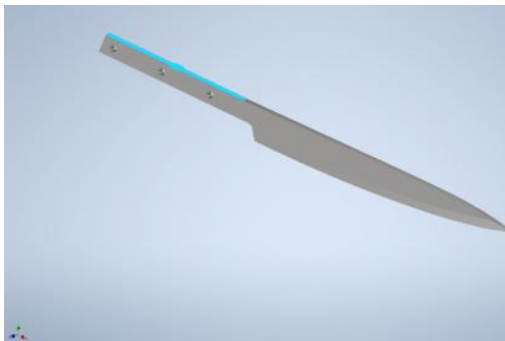


Fig.10. Fixed Constraints: selected face

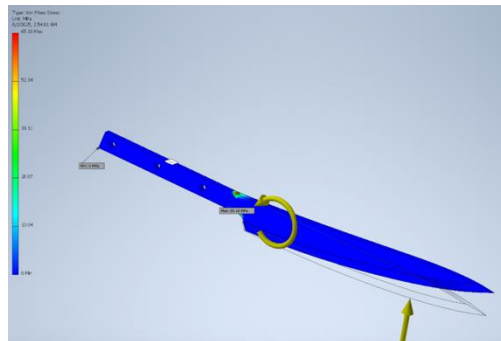


Fig. 11. Von Mises Stress

Table 4. Operating conditions

Load Type	Moment
Magnitude	3.810 N·m
Vector X	0.000 N·m
Vector Y	0.000 N·m
Vector Z	3.810 N·m

Table 5. The Reaction Force and the Reaction Moment on Fixed Constraint

Constraint Name	Reaction Force		Reaction Moment	
	Magnitude	Component (X, Y, Z)	Magnitude	Component (X, Y, Z)
Fixed Constraint: 2	30 N	0 N	5.21253 N m	-0.0600223 N m
		-30 N		0 N m
		0 N		-5.21218 N m

The Reaction Force and the Reaction Moment corresponding to the Fixed Constraint have been presented in Table 5.

Finite element analysis revealed significant results regarding the stress distribution of the knife blade. The Von Mises stress was determined to be a minimum of 0.0000308387 MPa and a maximum of 65.179 MPa, indicating the magnitude of the maximum stress experienced by the blade. This value, below the yield strength of the obtained material, suggests that the blade can withstand the applied loads without risk of deformation.

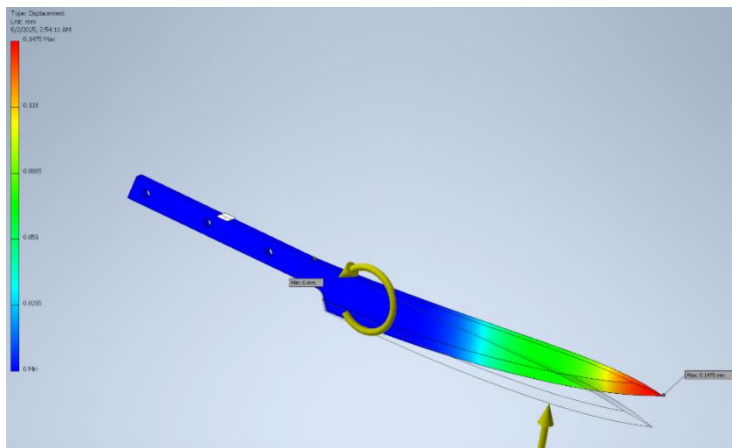


Fig. 12. The Displacement of the sample during the load evolution

This displacement signifies minimal sample deformation under given loads, highlighting its excellent rigidity and dimensional stability. The maximum Displacement value in this case ($F=30N$) is 0.14754 mm (see Fig. 12).

It can be stated that X-Displacement is the change in the blade position along the horizontal x-axis. In this case, the X-Displacement has a minimum of -0.00732299 mm and a maximum of 0.00994089 mm. In figure 13, the X-Displacement has been represented.

Y-Displacement has a minimum of -0.0000832574 mm and a maximum of 0.140759 mm (Fig. 14). Z-Displacement has a minimum of -0.0441333 mm and a maximum of 0.000215998 mm (Fig. 15).

In figure 16, the 1st Principal Stress Has a minimum of -10.4913 MPa and a maximum of 42.008 MPa. In figure 17, the 3rd Principal Stress has a minimum of -78.8798 MPa and a maximum of 1.23503 MPa.

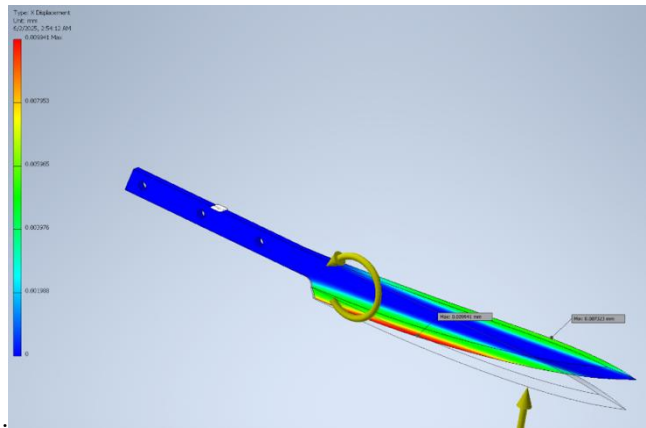


Fig. 13. X-Displacement

In figures 14 and 15, the Y- and Z-Displacement have been represented.

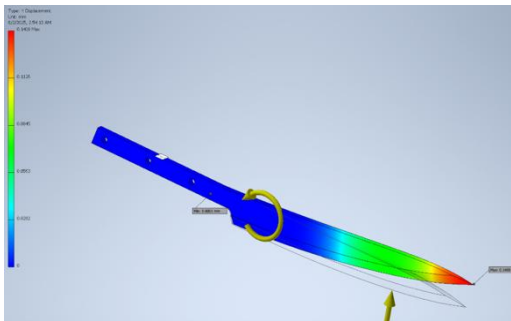


Fig. 14. Y-Displacement

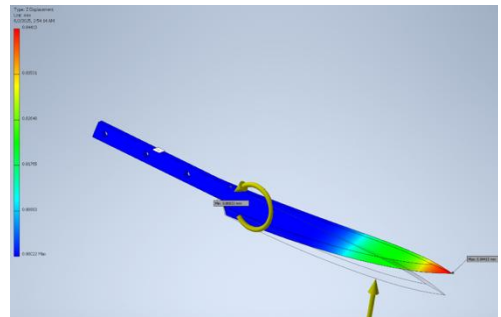


Fig. 15. Z-Displacement

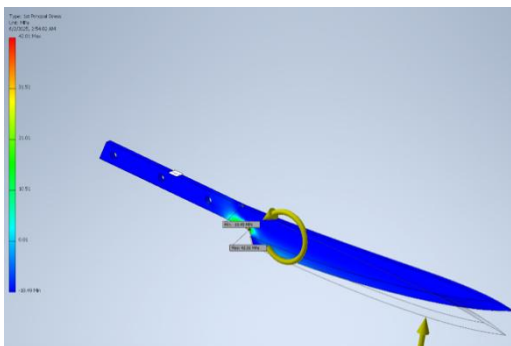


Fig. 16. 1st Principal Stress

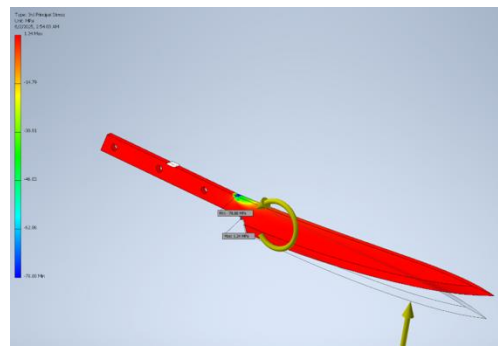


Fig. 17. 3rd Principal Stress

The Safety Factor corresponding to a load of $F = 30\text{N}$ has been represented in figure 18.

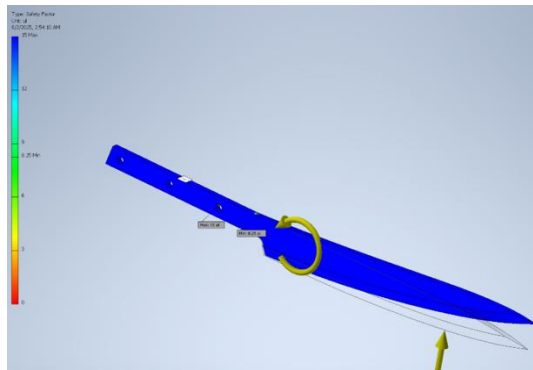


Fig. 18. Safety Factor corresponding to $F = 30N$

II. $F = 230N$

In the case of $F = 230N$, the results obtained have been presented below. In Tables 6 and 7, the operating conditions have been presented, corresponding to Force 1.

Table 6. Operating conditions

Load Type	Force value
Magnitude	230.000 N
Vector X	0.000 N
Vector Y	230.000 N
Vector Z	0.000 N

Table 7. Operating conditions

Load Type	Moment
Magnitude	29.000 N·m
Vector X	0.000 N·m
Vector Y	0.000 N·m
	29.000 N·m

The Reaction Force and the Reaction Moment corresponding to the Fixed Constraint have been presented in table 8.

Table 8. The Reaction Force and the Reaction Moment on Fixed Constraint

Constraint Name	Reaction Force		Reaction Moment	
	Magnitude	Component (X, Y, Z)	Magnitude	Component (X, Y, Z)
Fixed Constraint: 2	230 N	0 N	39.9625 N m	-0.46017 N m
		-230 N		0 N m
		0 N		-39.9598 N m

Finite element analysis revealed significant results regarding the stress distribution of the knife blade. The Von Mises stress was determined to be a minimum of 0.000230533 MPa and a maximum of 499.714 MPa (see Fig. 19).

In figure 20, the maximum Displacement value in this case ($F=230N$) is 1.130 mm (see Fig. 20).

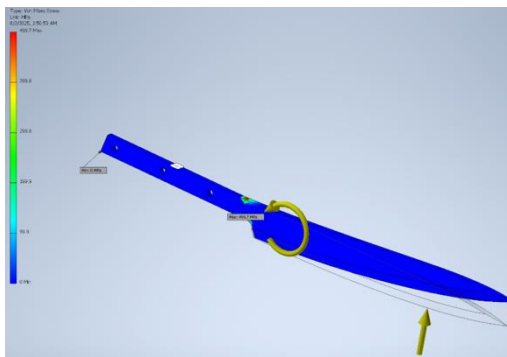


Fig. 19. Von Mises Stress corresponding to a load of $F = 230$ N.

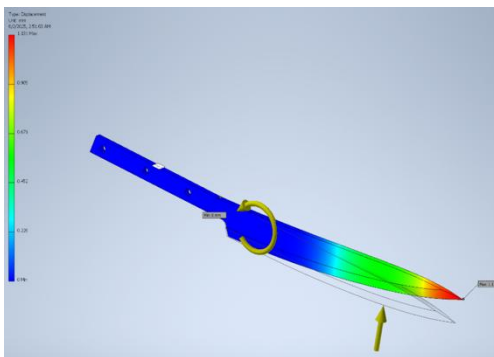


Fig. 20. The Displacement of the sample during the load evolution

In figure 21 it can be observed that the Safety Factor has a minimum of 1.03 and a maximum of 15. It is important to note that in figure 22 Y-Displacement has a maximum above 1.

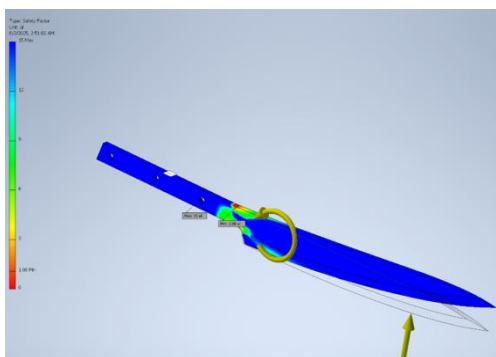


Fig. 21. Safety factor in case of the load of $F = 230$ N

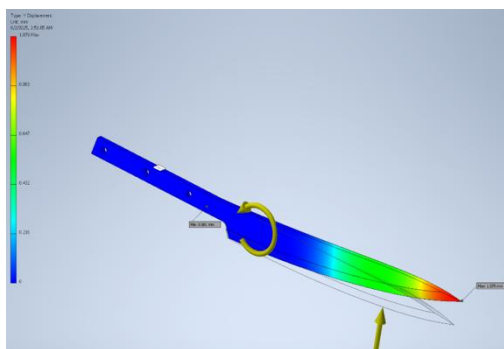


Fig. 22. Y-Displacement in case of $F = 230$ N

It was found that a force of ~ 230 N would be able to crack the blade, the Displacement reaching 1.03. It should be undervalued by 1 to not bring significant deformations.

The study was conducted over the entire length of the blade, measuring in our case 350 mm, to accurately capture the overall behavior and the stress distribution. This comprehensive analysis allows for a holistic understanding of how the blade/sample responds to various loading scenarios along its entire length.

Conclusion

Two variants were analyzed: a force of 30 N, reasonable as a stress for a knife blade made of Damascus steel, and the case of a large force $F=230$ N that breaks the sample as if it were subjected to shock stress.

Using Autodesk Inventor Professional 2023, this finite element study provides valuable insights into the structural analysis of knife blades. By evaluating the Von Mises stress, the displacement, and the previously presented elements and considering applied loads (30N and 230N), engineers and designers can make informed decisions to optimize blade design, improve durability, and ensure reliable cutting performance.

At the same time, the Damascus steel has good resistance, determined by the low-carbon steel component. In its structure, alternating "waves" of different shades of gray are observed, due to the "incorporated" spherical cementite, as stated in the lines above. From our own studies [4], [5], [9], [17], it is observed that the martensitic structure appears after quenching/hardening treatment at approx. 900 °C and tempering at 250°C, which gives the material exceptional hardness. But, after quenching, the martensite needles can create cracks in the structure at high loads. It is recommended to relieve the material stress also by heat treatment, by tempering.

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