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SIMULATION OF THE MECHANICAL STRESS BEHAVIOR IN THE CASE OF THE DAMASCUS STEEL AFTER HEAT TREATMENTS FOR IMPROVEMENT

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ABSTRACT

The paper aims to study the behavior of Damascus steel at a maximum admissible load with a force of 250 N. Previous studies considered lower loading force values that did not produce cracks in the material. The processing of the samples and laboratory tests were carried out on specimens of Damascus steel obtained in the laboratory. The applied treatments were hardening and tempering to improve the material's properties. The processing of the results and the simulations were carried out using Autodesk Inventor Professional 2023.

KEYWORDS: Damascus steel, improvement treatment, structural aspects, mechanical properties, simulation

1. Introduction

High-carbon steels are known for their excellent mechanical properties, especially hardness and strength. These properties are achieved through the process of quenching and tempering, which involves heating the steel to a high temperature, holding it there, and then rapidly cooling it in a liquid such as oil or water. This process causes the crystal structure of the steel to change, increasing the amount of Martensite, which leads to higher hardness and higher tensile strength properties.

Damascus steel involves the hot forging of two high-carbon steels and subsequent heat treatment to improve their hardness.

According to the specialized literature [1], special studies have been conducted on Persian Damascus steel blades from the 18th century, original blades from Iran. In the work highlighted above, the morphology of the carbide bands was analysed in relation to the shape of the edge profiles. For example, the dagger blade (Khanjar) exhibited a transverse section with cross-shaped traces. Sukhanov *et al.* observed that in the case of the sword blade from Iran (Shamshir), the cross-section has a reticular profile.

Sukhanov [1, 2] also demonstrated that the morphology of the carbide bands in the structure of Damascus steel depends directly on the chemical composition – specifically the steels used to form the Damascus steel - and the distribution of inclusions in the material. These inclusions can be oxides and sulphides in the carbide layers.

The morphology of the carbide strips greatly modifies both the physical and mechanical properties, as well as the wave-shaped macrostructure of Damascus blades. It can be stated that the microstructure of the carbide strips determines the quality of Damascus steel and its resistance to loading stresses. The quality of oriental Damascus blade steels is directly related to the distribution of the carbide strips in the pearlitic matrix. In this regard, several important studies have been carried out on the appearance and morphology of the carbide strips in Damascus steel in the history of authentic Damascus steels [3-11]. According to research [12-14], the structure of Damascus steel has a unique characteristic specific to these samples compared to high-hardness tool steels.

Figures 1 and 2 present the essence of the research by Sukhanov's team on the morphology of carbide bands in the structure of original Damascus steel from Iran from the 18th century.

According to [3, 4], very distinct bands of Fe_3C particles can be observed in the matrix. The pearlite matrix has a band spacing of 50 μm. The matrix was formed by Pearlite (P), except for a thin DET region near the fat end. It is worth noting that the first mentions of Damascus steel date back to around 300 BC (originally called "wootz") [5-8, 12-15].

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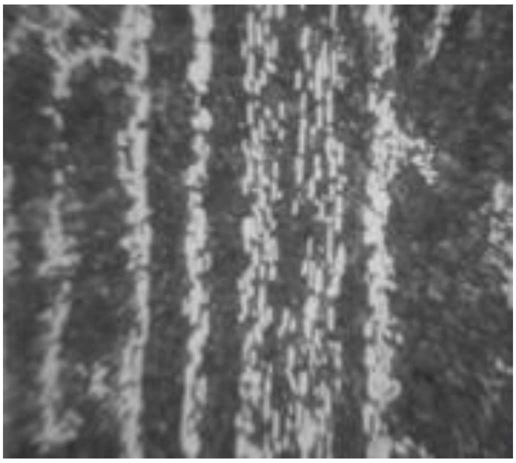

Fig. 1. *Carbide band in the longitudinal direction (cutting edge of the original blade): a Shamshir saber blade, according to* [1, 2] *(100 µm)*

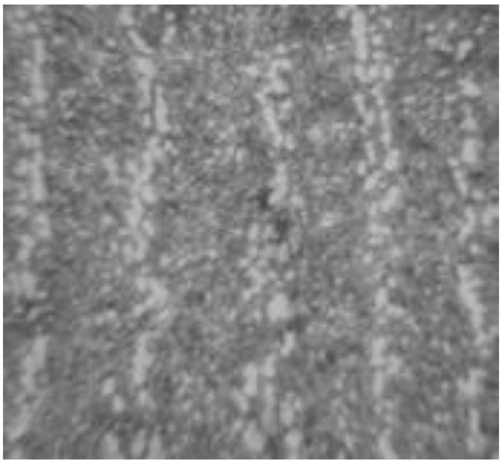

Fig. 2. *Carbide band in the case of the original Khanjar dagger blade, according to* [1, 3, 4]

Studies of this type of steel can help develop new technologies for producing high-strength knives and more.

2. Materials and method

To fabricate Damascus steel in the laboratory, two high-carbon steels were considered, namely: AISI 1095 and 15N20. Hypereutectoid steels were used. For example, AISI 1095 steel contains 0.90-1.03% C and 15N20 steel contains 0.75% C and 2% Ni.

In the hypereutectoid range, above 0.77% C, secondary cementite (Fe3CII) appears, which leads to increased hardness but decreased plasticity and toughness. The tensile strength shows a maximum around 0.9-1% carbon because at higher carbon contents, secondary cementite separates in the form of a continuous network at the pearlite grain boundaries (where Ledeburite appears), producing an embrittlement effect.

In the experimental process of preparing the specimens (Damascus steel), plates in the form of rectangular shapes (see Fig. 3) with dimensions of 2 x 40 x 100 mm were used. These were alternated to obtain packages of 30 layers each, which, by free forging/hot hammering, resulted in the knife blade shown in Figure 4 [14, 15].

Fig. 3. *Specimens in the form of rectangular plates before the hot forging process*

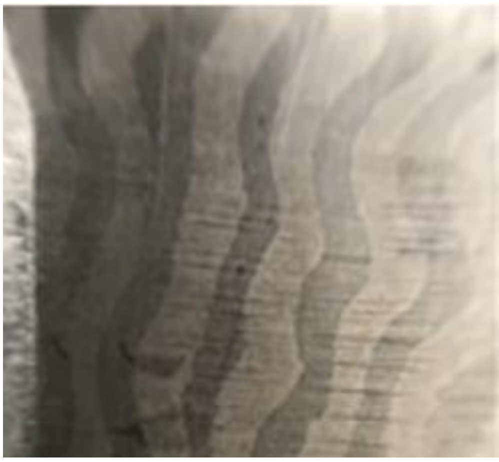

Fig. 4. *Sample obtained in the laboratory* [14, 15]

The samples obtained in the laboratory present waves with different shades of grey that can be compared to the microstructure of the ancient Iranian swords in Figures 1 and 2. A belt sander was used to remove oxide layers and impurities.

The semi-finished products were cleaned with a degreasing agent.

The applied treatments were hardening at 900 °C (1 h) followed by cooling in water and tempering

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at 250 °C to improve the mechanical properties, especially the hardness of the steel. After performing the heat treatment, the Brinell hardness of the Damascus steel obtained in the laboratory increased from 197 daN/mm^2 to 698 daN/mm^2 [12-14].

The processing of the results and the simulations were carried out using Autodesk Inventor Professional 2023.

3. Aspects of the Stress Analysis Report

The objective of this study was to analyse the behavior of the knife blade under loading conditions for F = 250 N. The study includes the evaluation of Von Mises stress, equivalent strain, and displacement to obtain information about how much the knife blade deforms under the load given above.

If a load F = 250 N is considered, the following results will be obtained, as presented below. In Table 1, the operating conditions corresponding to Force 1 are summarized.

In Table 2, the Reaction Force and the moment at the Fixed Constraint are presented. The type of load consists of a force F = 250 N.

As a result of this action, a moment with a magnitude of 43.406 Nm is generated, distributed across the X, Y, and Z components, as shown in Table 2.

Table 1. *Operating conditions*

Load Type	Force value
Magnitude	250.000 N
Vector X	0.000 N
Vector Y	250.000 N
Vector Z	0.000 N

In the first step, the test side of the knife blade and a fixed constraint (the knife handle, the right part) are selected. In Figures 5 and 6, the selected testing face [15] and the fixed constraint are shown.

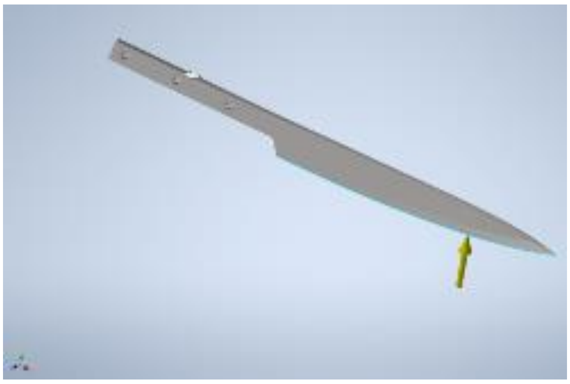

Fig. 5. *Selected testing face, corresponding to the specimen*

Table 2. *The Reaction Force and the moment at the Fixed Constraint*

Reaction Force		Reaction Moment		Constraint Name
Magnitude	Component (X, Y, Z)	Magnitude	Component (X, Y, Z)	
250 N	0 N	43.406 Nm	-0.500186 Nm	Fixed Constraint: 2
	-250 N		0 Nm	
	0 N		-43.403 Nm	

Fig. 6. *Fixed Constraint 2*

In Figure 7, the Von Mises Stress evolution is presented. The minimum value corresponding to the Von Mises Stress is 0.000351435 MPa and the maximum value is 582.919 MPa.

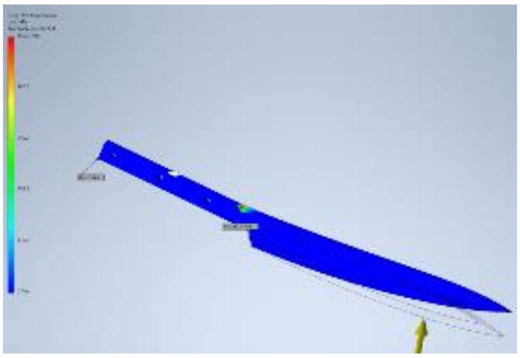

Fig. 7. *The Von Mises Stress evolution in the case of F = 250 N*

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This displacement signifies the minimal blade deformation under the given load (F = 250 N), highlighting its excellent rigidity and dimensional stability.

The maximum X-Displacement value in this case is 0.0829454 mm and the minimum value is -0.0609947 mm.

The maximum value corresponding to Y-Displacement is 1.1737 mm and the minimum value is -0.00069134 mm (Figures 8-10).

The total Displacement has a maximum value of 1.22852 mm (Figure 11).

The displacements have very small values; the knife blade used as a laboratory specimen does not deform plastically at this stress level.

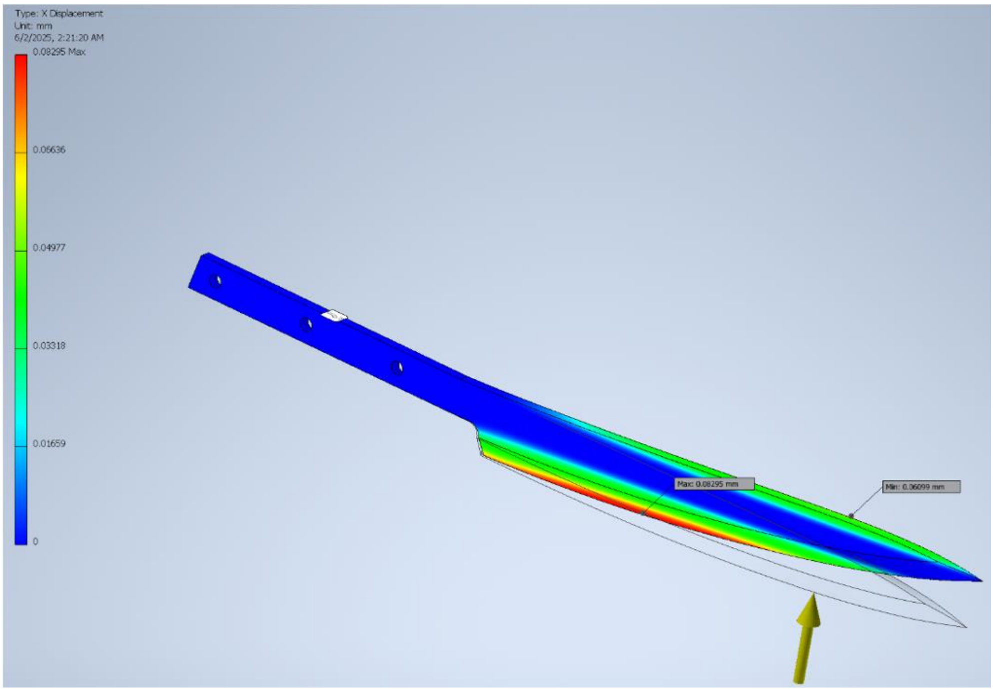

***Fig. 8.** X-Displacement evolution*

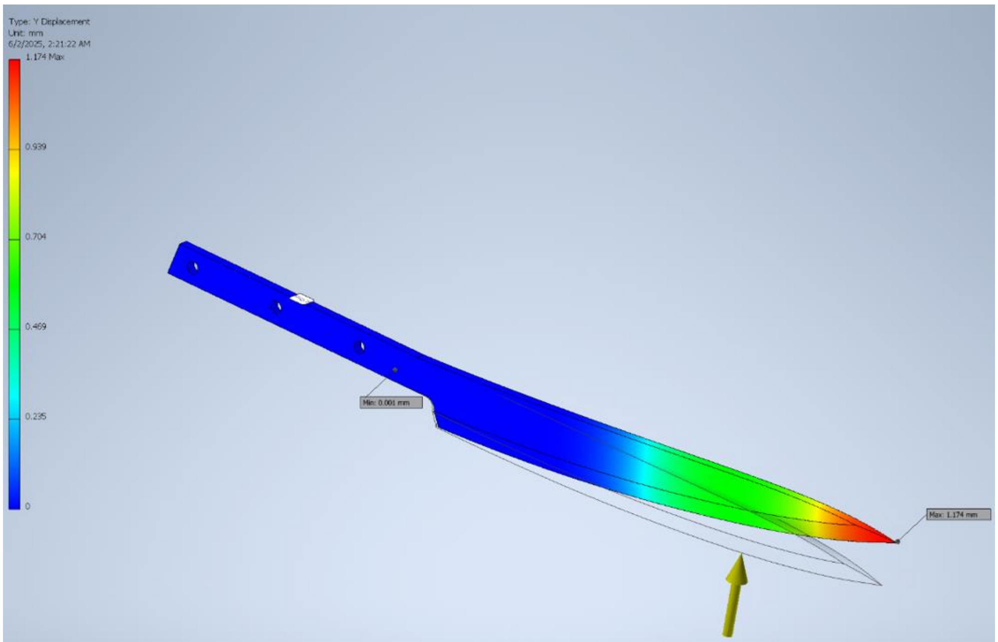

***Fig. 9.** Y-Displacement*

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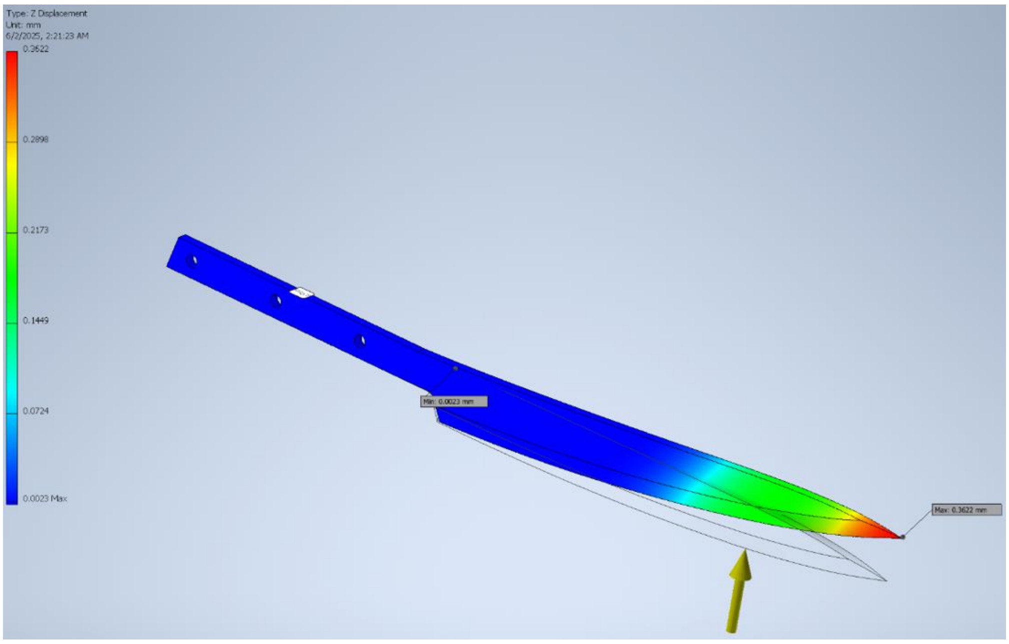

Fig. 10. *Z-Displacement*

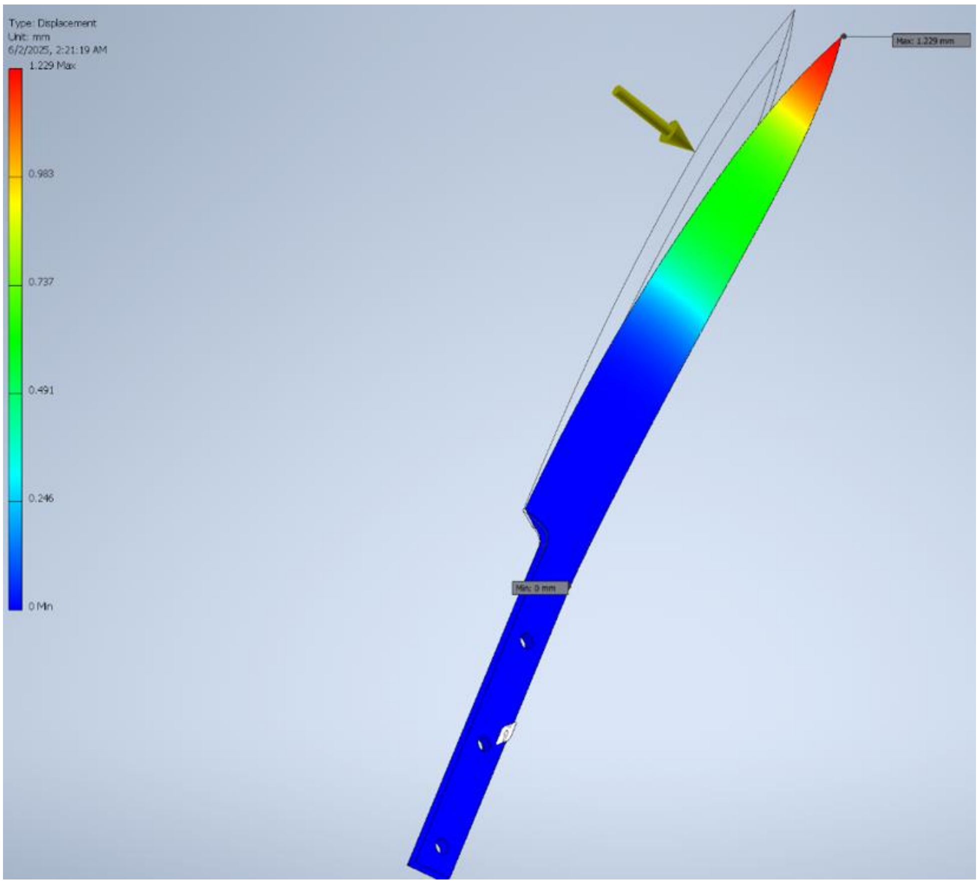

Fig. 11. *The Displacement of the sample during the action of the Load (F = 250 N) corresponding to the First Principal Stress*

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Considering that a "displacement" of the blade is still achieved during loading, it can be observed that the Damascus steel made in the laboratory has very little elasticity. No plastic deformations were recorded during this loading.

4. Conclusion

The objective was to create Damascus steel in the laboratory. The original recipe was lost at the end of the 16^{th} century.

Searching the specialized literature, laboratory tests for this type of steel were found, as well as tests carried out on original swords from the 14^{th}-16^{th} centuries. The structure of the original steel from the 16^{th} century was compared with the specimens obtained in the laboratory.

After performing the heat treatment, the Brinell hardness of the Damascus steel obtained in the laboratory increased from 197 daN/mm^2 to 698 daN/mm^2.

Additional studies, such as finite element analysis and the evaluation of material strength properties, were carried out using Autodesk Inventor Professional 2023.

By stacking plates of different high-carbon steels and using hot forging, a Damascus steel with excellent strength properties was obtained.

The steel made in the laboratory performed exceptionally well at a load value of 250 N.

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