IOSUD - Universitatea Politehnica Timişoara
Şcoala Doctorală de Studii Inginereşti

CHARACTERIZATION OF THE ANISOTROPY OF S600MC STEEL BY EXPERIMENTALLY VALIDATED NUMERICAL METHODS

Doctoral Thesis – Abstract

for obtaining the scientific title of Doctor at
Universitatea Politehnica Timișoara
in the field of MECHANICAL ENGINEERING

author Eng. **Iulian-Ionuț AILINEI**
scientific supervisor Prof. PhD Eng. **Liviu MARȘAVINA**

July 2024

1. INTRODUCTION

Anisotropy, the property of a material to exhibit varying characteristics depending on the direction of measurement and observation, significantly impacts the mechanical behavior of materials under static or dynamic loads, such as shock and vibration. A thorough understanding of this phenomenon and accurate quantification of anisotropy are essential for the proper application of materials in structural design and for enhancing the performance and safety of products [1]. The lack of experimental data, particularly under the complex conditions of plastic deformation and impact loading, limits the ability to numerically model and predict material behavior under real operating conditions. This justifies a comprehensive investigation that combines advanced methods such as digital image correlation, finite element analysis, and testing under static, dynamic, and vibration-induced fatigue conditions.

Fig. 1 Lamination of a sheet metal

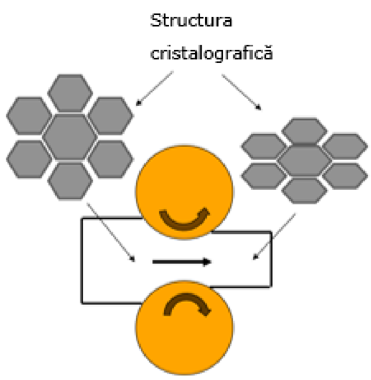


Fig. 2 Rearrangement of the Crystalline Structure Following the Rolling Process

This study investigates the phenomenon of anisotropy in rolled steel semi-finished products, specifically highlighting its crucial role in numerical simulation for manufacturing processes involving plastic deformation. Anisotropy, or the directional dependence of mechanical properties, emerges as a critical factor in accurately predicting the outcomes of such processes. The study focuses on the use of the strain ratio—also known as Lankford coefficients or R-values—and the Forming Limit Curve (FLC), both of which are industrial benchmarks for evaluating the plastic deformation capacity of metal sheets.

One of the main challenges highlighted is the frequent lack of comprehensive experimental data essential for the accuracy of numerical analyses. To overcome this barrier, the current research is directed towards the meticulous acquisition of material properties and verification data necessary for simulating cold plastic deformation processes. Through the application of uniaxial tests, the study meticulously traces the conventional characteristic curves of S600MC rolled steel semi-finished products in three principal directions: the rolling direction (RD), the diagonal direction (DD), and the transverse direction (TD). This methodical approach not only enriches the database for simulation but also enhances the accuracy of predictive modeling.

An industrial example is used to illustrate the impact of anisotropy on the formability of rolled steel semi-finished products. The integration of dynamic testing within the study provides valuable insights into the fatigue resistance of S600MC material, a crucial aspect for components that will be subjected to cyclic loads in their final applications. Correlating the data obtained from dynamic tests with the results of numerical simulation allows for not only the validation of the numerical model but also its adjustment to more accurately reflect the real behavior of the material under fatigue conditions. The use of electrodynamic actuators to obtain the fatigue curve highlights the ability to simulate specific operating conditions and evaluate the material's performance under dynamic forces.

2. STATE OF THE ART IN STEEL ANISOTROPY EVALUATION

Essentially, the objective focuses on integrating experimental methods with numerical analysis to achieve a comprehensive and validated understanding of the anisotropic behavior of S600MC steel, with potential applications in the development and enhancement of materials used in industry. The experimental plan of the research program is presented in Figure 3.

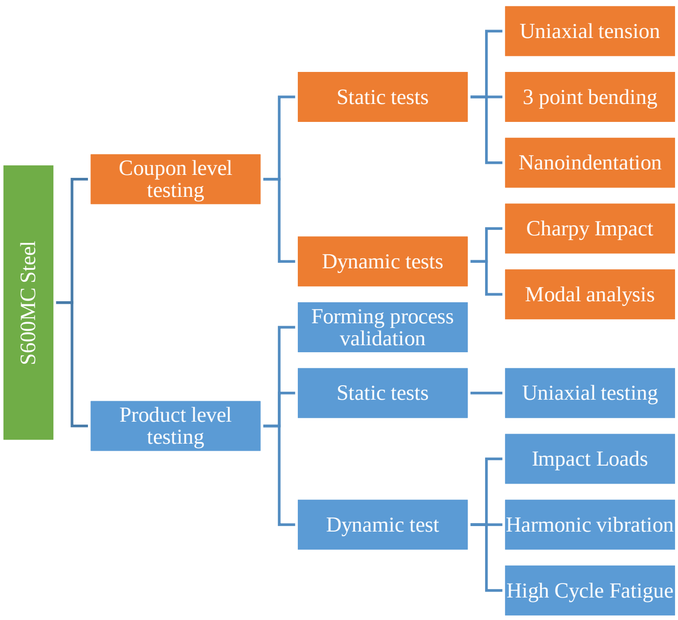


Fig. 3 Schematic Outline of the testing research program

Steel plates, particularly those processed through rolling, exhibit anisotropic behavior due to the alignment of the microstructure. This chapter reviews the current understanding of the anisotropic behavior of steels, highlighting the importance of parameters such as Lankford coefficients [2] (R-values) present in equation (1) and the Forming Limit Curve (FLC) in evaluating the formability of rolled metal sheets. These parameters are essential for predicting how materials will behave during manufacturing processes involving plastic deformation.

$$r = \frac{\epsilon_w}{\epsilon_t} = \frac{\ln\left(\frac{b}{b_0}\right)}{\ln\left(\frac{L_0 b_0}{L b}\right)} \qquad (1)$$

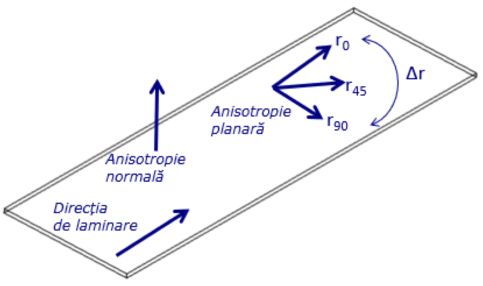


Fig. 4 Anisotropy types

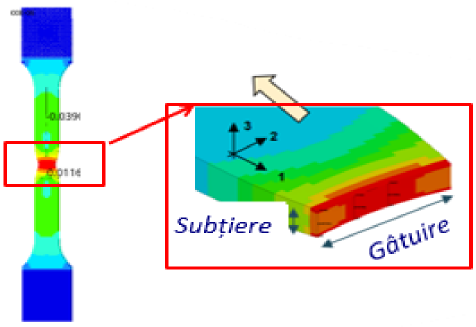


Fig. 5 Localized stress

This chapter details various numerical methods used to model anisotropic behavior. Techniques such as implicit and explicit integration in Finite Element Analysis (FEA) are discussed, along with different yield criteria such as the von Mises, Hill [3] (2), and Barlat [4] criteria. These criteria help describe the plastic anisotropy of metals, which is essential for accurate numerical modeling. The review also covers advanced models that incorporate anisotropy into the simulation of plastic deformation, enhancing the predictive capabilities of numerical analyses.

$$F(\sigma_{22} - \sigma_{33})^2 + G(\sigma_{33} - \sigma_{11})^2 + H(\sigma_{11} - \sigma_{22})^2 + 2L\sigma_{23}^2 + 2M\sigma_{31}^2 + 2N\sigma_{12}^2 = 1 \qquad (2)$$

Where F, G, H, L, M, N are constants that must be determined experimentally, and σij are the stress components. This predicts the same yield limit in tension and compression.

Ductile fracture modeling in Radioss employs a simplified criterion based on linear damage accumulation [5]. The elongation at fracture is characterized by two parabolic functions, which are calculated based on the elongation at fracture under various types of loading. This is determined according to the triaxiality ratio [6], as illustrated in Figure 5.

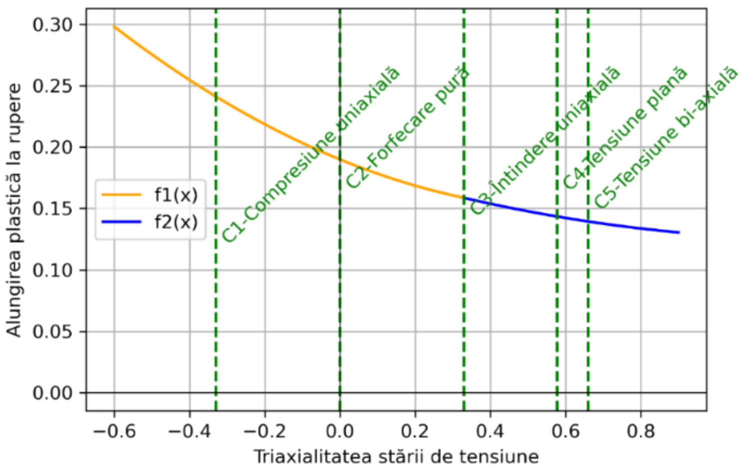


Fig. 6 Failure strain as a function of triaxiality stress state

3. EXPERIMENTAL CHARACTERIZATION AND NUMERICAL VALIDATION OF S600MC STEEL ANISOTROPY

This chapter describes the static experimental tests conducted to characterize the anisotropy of S600MC steel. The test specimens were cut at different orientations, as shown in Figure 7.

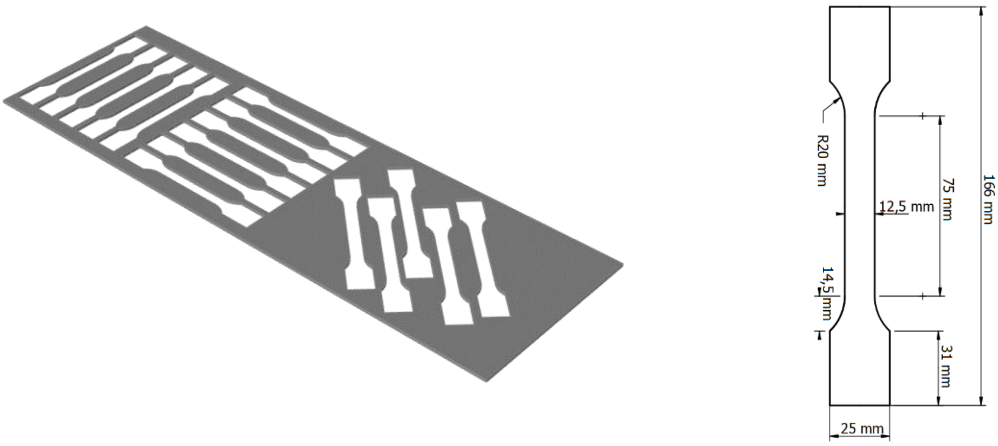


Fig. 7 CAD Sketch of the Test Specimen Orientations and Specimen Dimensions According to ISO 10113:2006 Standard

Uniaxial tensile tests were performed for all these orientations, and the primary and secondary elongations were measured using optical methods, specifically digital image correlation (Figure 8).

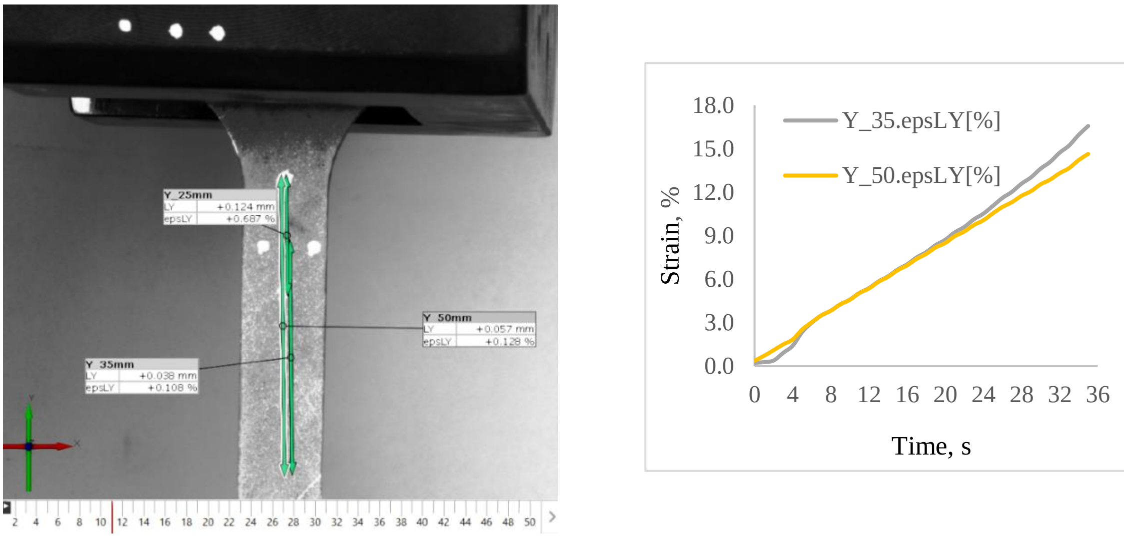


Fig. 8 GOM graphical user interface and strain measurements

Based on these results (Figure 9), the plastic deformation limit curve and the ductile fracture criterion were constructed, both of which are used in numerical simulations.

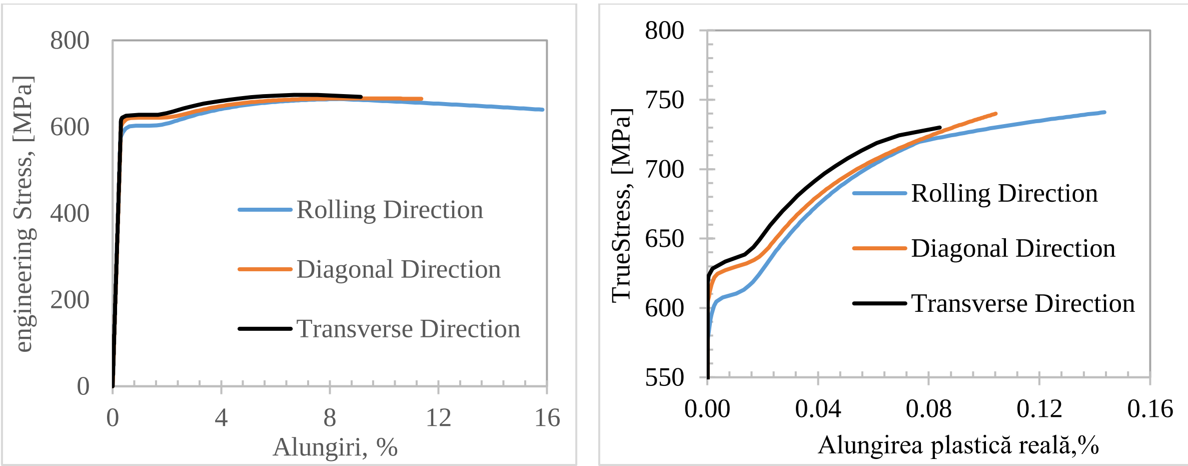
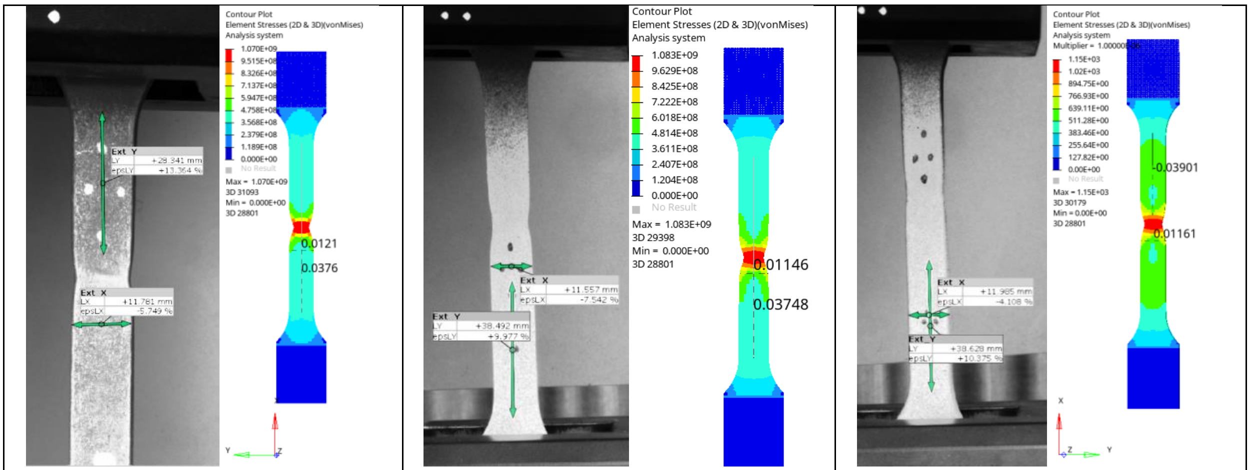


Fig. 9 Conventional Characteristic Curves and the Plasticity Region



Rolling direction	Diagonal direcțion	Transverse direction

Fig. 10 Comparison of Physical Test Results with Numerical Simulations

The results of the numerically simulated tests, experimentally correlated, are presented in Figure 10.

In addition to the uniaxial tensile tests, three-point bending tests, nano-indentation, and metallographic analysis were also performed. These experiments provide detailed data on the mechanical properties of the material in different directions, which are essential for the development of precise numerical models.
Alongside the static tests, the dynamic behavior of S600MC steel is evaluated through mechanical vibration tests and Charpy impact tests. These experiments assess how the material responds to cyclic loads and high-speed impacts, providing information about its fatigue behavior and resistance to dynamic stresses. The chapter highlights the importance of understanding the dynamic characteristics of materials used in components subjected to repetitive or high-speed loads, such as in automotive and aerospace applications. Figures 11 and 12 highlight the results in the transverse direction, demonstrating the material's pronounced anisotropic behavior.

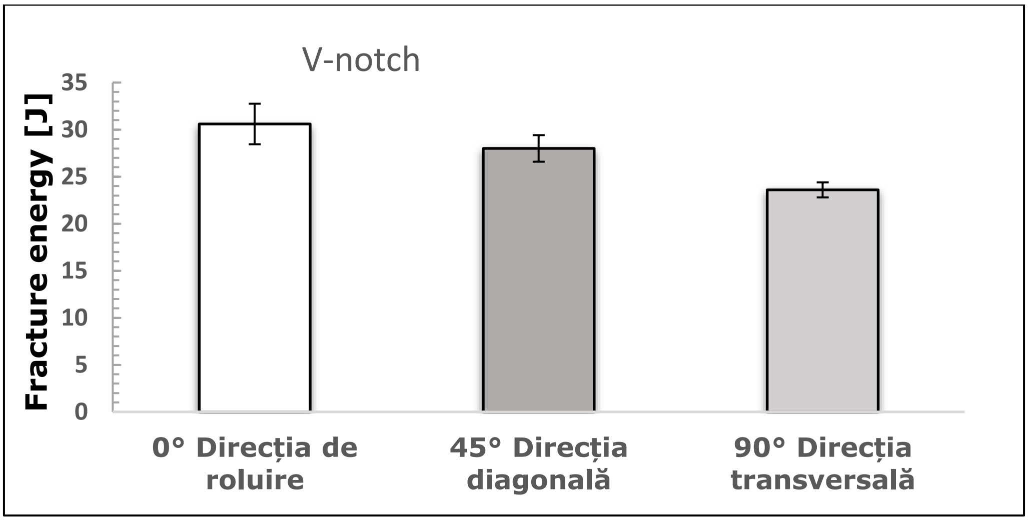


Fig. 11 Results of the Resilience Tests for V-Notched Specimens

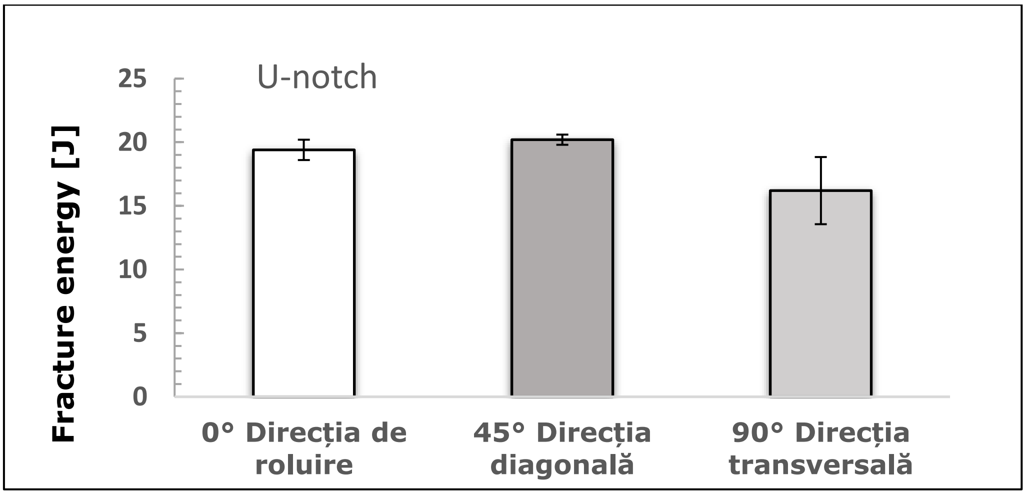


Fig. 12 Results of the Resilience Tests for U-Notched Specimens

These results show how fracture energy varies with the rolling direction of the material.

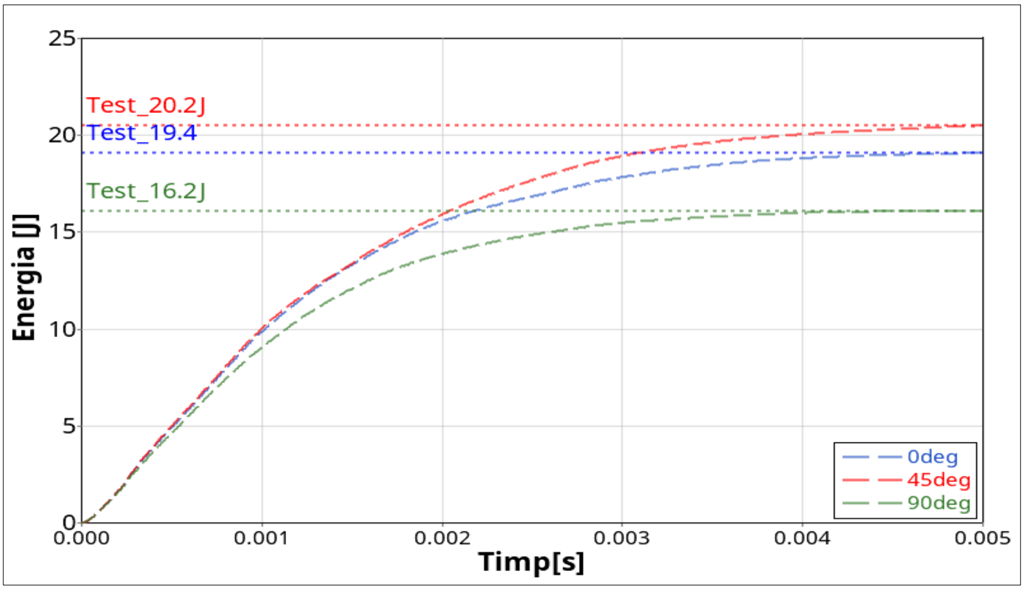
- For the rolling direction, the average fracture energy is 19.4 Joules. This suggests that the material has relatively high fracture resistance when the force is applied along the rolling direction.
- At 45° (diagonal direction), the average fracture energy slightly increases to 20.2 Joules. This minor increase indicates that the material's fracture resistance is somewhat higher when the force is applied diagonally relative to the rolling direction, potentially due to the orientation of the grains or internal structures providing more resistance in this direction.
- At 90° (transverse direction), the average fracture energy significantly decreases to 16.2 Joules. This decrease highlights that the material is less resistant to fracture forces applied in the transverse direction, clearly demonstrating anisotropic behavior where the material's resistance varies depending on the direction of the applied force.
- 

Fig. 13 Comparison of Physical Test vs. Numerical Simulation for V-Notched Specimens

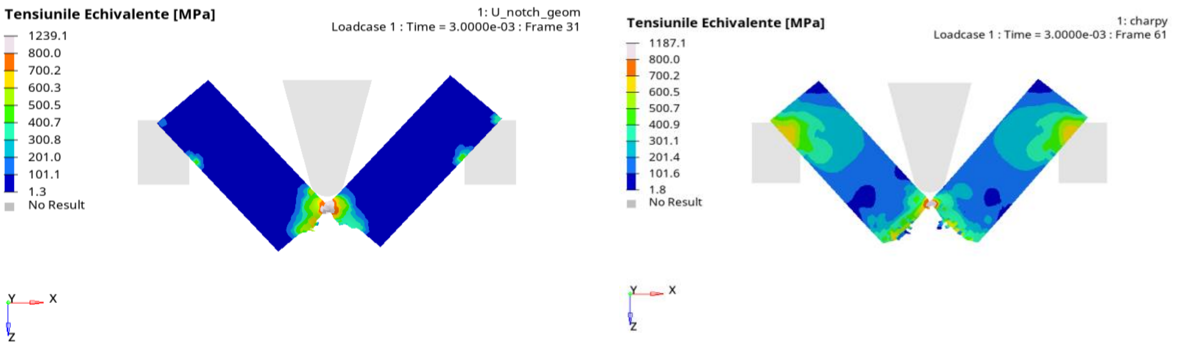


Fig. 14 Comparison of Equivalent Stresses During Resilience Tests for U-Notched Specimens (Left) and V-Notched Specimens (Right)

The results of the static and dynamic tests (presented in Figures 13 and 14) are used to validate the numerical models developed in this research. This chapter describes the process of integrating experimental data into these models, ensuring their accuracy and reliability. This validation step is crucial for establishing confidence in the predictive capabilities of the numerical simulations. [7]

4. ASSESSMENT OF THE PERFORMANCE OF S600MC STEEL PRODUCTS

This chapter focuses on predicting the behavior of the "seat belt support" component using numerical methods based on previously experimentally determined material models. A numerical simulation of the plastic deformation process was conducted, with the results being compared to the physical components (Figure 15).

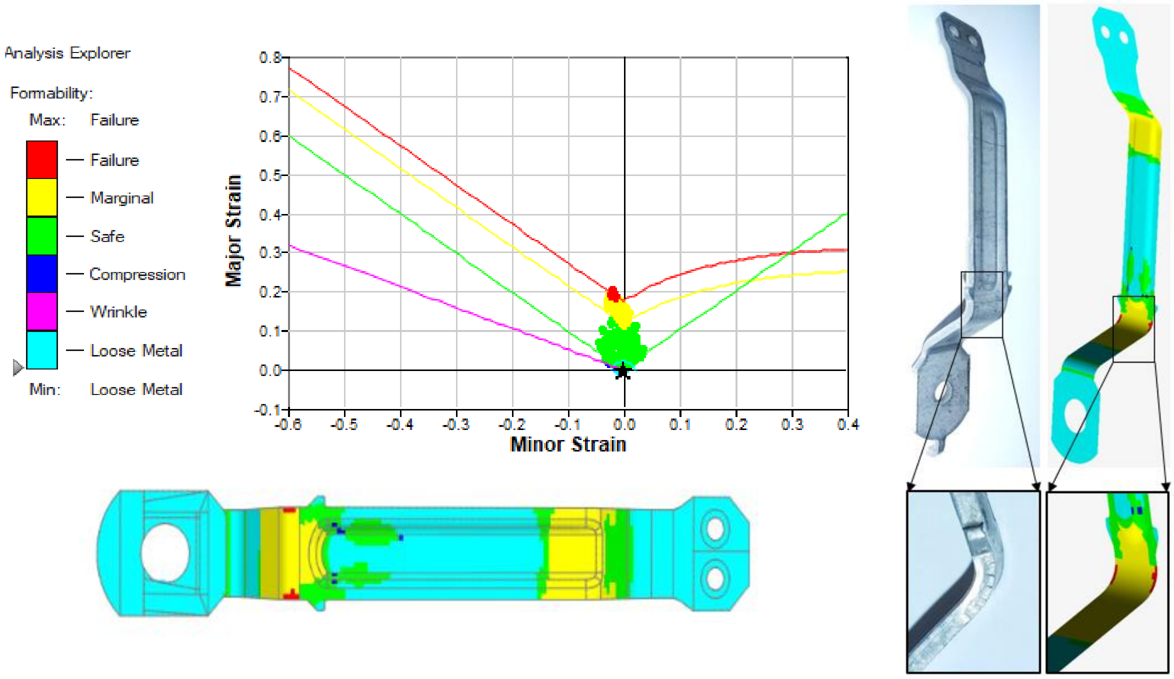


Fig. 15 Numerical Study of the Plastic Deformation Process, experimentally validated

The results of the finite element analysis (FEA) of the cold deformation process are presented in Chapter 4.1. This analysis provides essential information regarding the distribution of plastic deformation and thickness variations along the formed part, which are direct indicators of the material's ductility and post-deformation strength.

Following the cold plastic deformation simulation, data on thickness variations (Figure 16) and plastic deformation (Figure 17) of the component were extracted. The software solution Altair HyperCrash [7] was used for this stage. The extracted data were then processed and formatted appropriately for compatibility with structural analysis software. This post-processing includes interpolating or smoothing the data to ensure they accurately represent the physical reality of the deformed geometry without introducing numerical artifacts.

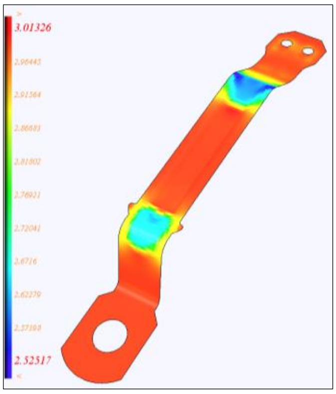


Fig. 16 Thickness variation

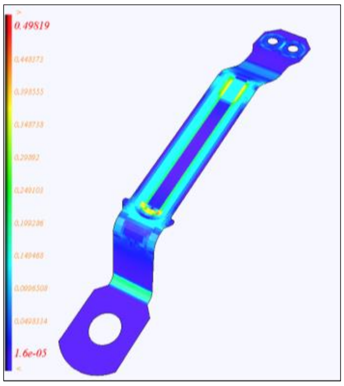


Fig. 17 Plastic strain variation

Following the numerical simulation of the cold plastic deformation process, a numerical analysis of the impact resistance for the same component was conducted.
To verify the numerical results against the experimental ones, the pendulum apparatus shown in Figure 18 was utilized. It is used to generate controlled mechanical shocks with energies of 250 and 500 Joules.

Fig. 18 Instrumented Pendulum for Dynamic Destructive Testing

As shown in Figure 19, the model that does not include residual stresses significantly overestimates the maximum forces by approximately 30% compared to the test data. After analyzing the two numerical models, with and without the inclusion of residual stresses from the cold plastic deformation process, the results align more closely with the initial force peak of the experimental data. This overestimation highlights the importance of accounting for residual stresses in simulations to avoid a more conservative mechanical design, which could lead to an oversized structural form.

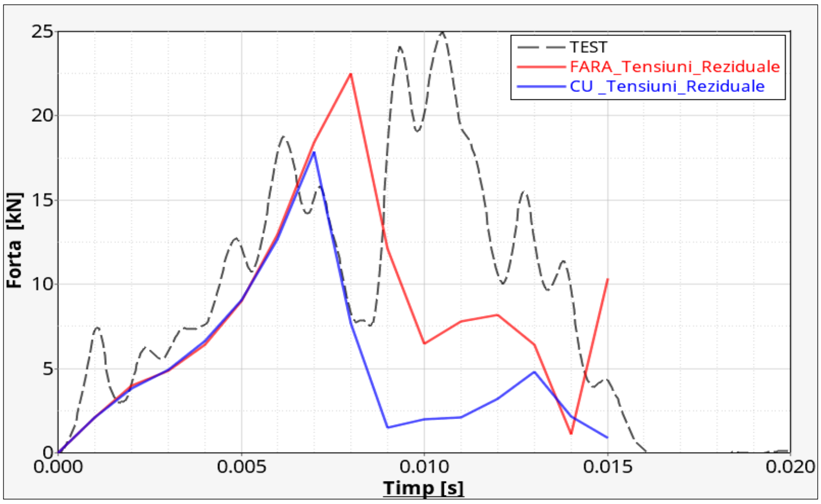


Fig. 19 Comparison Between Experimental Tests and Numerical Simulations

"The primary cause for components failing to fulfill their intended function is material fatigue and accumulated wear over time, resulting from stress states induced by vibrations" [9]. The stresses generated by vibrations cause micro-cracks and structural defects that are not immediately evident but can eventually lead to the total degradation of the material or component. To evaluate the fatigue behavior of the component under high-cycle loading, a hybrid approach was employed. This involves testing with an electrodynamic actuator [10], maintaining the tested component at resonance [11] (Figure 20), and numerical simulations to determine the stress fields. A sudden drop in the resonance frequency indicates crack propagation and, consequently, a change in the structure's stiffness [12]. This method allows for the creation of the fatigue curve (Figure 21), showing stress versus the number of cycles, using different resonance frequencies by varying the weight at the free end of the tested component [13].

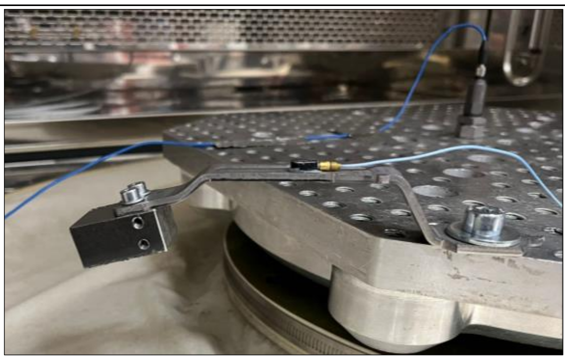


Fig. 20 High-Cycle Fatigue Testing setup

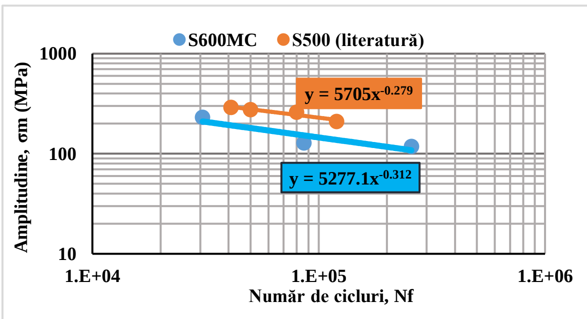


Fig. 21 The S-N curve obtained using the electrodynamic actuator for S600MC steel, compared with a fatigue curve for S500 steel [10]

5. CONCLUSIONS AND PERSONAL CONTRIBUTION

In the context of this thesis, the necessity of characterizing the anisotropy of S600MC steel, a research topic that presents significant challenges and broad industrial applicability, is addressed. The main contributions in this field are as follows:

Characterization of anisotropy was achieved through static tests using advanced Digital Image Correlation (DIC) techniques to characterize the anisotropic behavior of S600MC steel under static tensile loads. This approach enabled a deeper understanding of the material's response to stresses, highlighting the varying levels based on rolling directions. For example, it was shown that in the transverse direction, the energy absorbed per unit volume or deformation energy density is 9% lower compared to the rolling direction.

Based on these results, forming limit curves (FLC) and the elastoplastic material curve of the steel were constructed using the Johnson-Cook model, and experimentally correlated numerical simulations were performed.

Experimental bending tests were conducted under static and dynamic conditions. In static conditions, the anisotropy of the studied steel does not significantly influence the bending results. In dynamic conditions, it was shown that in the transverse direction, perpendicular to the rolling direction, the impact energy absorption capacity is 16.5% lower compared to the rolling direction. Based on Charpy impact tests and corresponding numerical models, a ductile fracture model, BIQUAD, was calibrated to more accurately represent the ductile fracture mode and the influence of anisotropy on impact energy absorption capacity.

Based on the material properties obtained from specimens, experimental tests were performed at the component level. Thus, the cold plastic deformation manufacturing process of the "seat belt support" component was numerically simulated, allowing for the quantification of residual stresses and plastic deformations. These residual stresses were then included in the numerical model used for dynamic impact loading.

It was shown that without implementing residual stresses, numerical simulations overestimate the energy absorbed on impact and do not reflect reality, with potentially dangerous consequences.

For dynamic loading, an impact pendulum with triaxial acceleration sensors was instrumented to obtain additional verification of the accelerations developed during the impact.

Additionally, the behavior of the steel and the component under dynamic loading induced by harmonic and random vibrations was studied. In this case, the anisotropy of the steel was quantified by the damping coefficient values at different orientations, and experimentally correlated numerical models were developed.

Fatigue tests induced by harmonic vibrations were also conducted, and a stress-number of cycles curve until failure was plotted, which was compared with those available in the literature.

These contributions highlight the in-depth relevance of anisotropy characterization in the design and manufacture of S600MC steel components, providing new perspectives and methodologies in this vital research field.

6. Bibliography

[1] P. J. Withers, "Residual stress and its role in failure," *Reports on Progress in Physics,* vol. 70, no. 12, 2007.

[2] W. T. S. S. C. B. J. A. Lankford, „New criteria for predicting the press performance of deep drawing sheets.," *Trans. ASM,* vol. 40, p. 1197–1205, 1950.

[3] R. Hill, „A theory of the yielding and plastic flow of anisotropic metals," *27 May 1948,* vol. 193, nr. 133, 1948.

[4] M. Y. C. K. Y. M. B. J. H. Barlat F, „Yield function development for aluminum," *Journal of the Mechanics and Physics of Solids,* vol. 45, nr. 11-12, pp. 1727-1763.

[5] K. M. D. Pack, „Combined necking & fracture model to predict ductile failure with shell finite elements," *Engineering Fracture Mechanics,* vol. 182, pp. 32-51, 2017.

[6] F. C. S. F. M. H. M. H. A. Andrade, „Estimation of stress triaxiality from optical measured Strain Fields," în *12th European LS-DYNA Conference*, Koblenz, Germany, 2019.

[7] Q. L. F. Liu, „Strain-rate effect on the compressive strength of brittle materials and its implementation into material strength model," *International Journal of Impact Engineering,* vol. 130, pp. Pages 113-123,, 2019.

[8] „https://altair.com/docs/default-source/resource-library/hw_0000_datasheet_hypercrash_8.5x11_052019.pdf?sfvrsn=bb90a3d9_3," 1 3 2024. [Interactiv].

[9] *Mil-Std-810, Section 514.6.*

[10] M. B. M. B. Benjamin Ellyson, „Characterization of bending vibration fatigue of SLM fabricated," *International Journal of Fatigue,* vol. 99, pp. 25-34, 2017.

[11] C. V. J. A. G.-J. C. Campos-Pozuelo, „Comparative study of the nonlinear behavior of fatigued and intact samples of metallic alloys," *EEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control,* vol. 53, nr. 1, pp. 175-184, 2006.

[12] J. S. M. C. M. B. Primož Ogrinec, „Vibration fatigue at half-sine impulse excitation in the time and frequency domains," *International Journal of Fatigue,* vol. 123, pp. 308-317, 2019.

[13] D. B. R. T. Davide Zanellati, „Vibration fatigue tests for tri-axis shaker: design of an innovative system for uncoupled bending/ torsion loading," în *Procedia Structural Integrity*, Pisa, 2018.

[14] S. Gothivarekar, C. J. Peña, S. Coppieters, R. Talemi și D. Debruyne, „Fatigue behaviour and lifetime prediction of cold-formed high strength steel," în *Proceedings of the 22nd International ESAFORM Conference on Material Forming (ESAFORM 2019)*, Vitoria-Gasteiz, 2019.

[15] H. G. L. Tomasz Trzepieciński, „Study of Material Anisotropy in Metal Forming Using Finite Element Methods," *Anisotropy Research: New Developments,* November 2012.

[16] D. Banabic, F. Barlat, O. Cazacu și T. Kuwabara, „Advances in anisotropy and formability," *Mater Form,* vol. 3, pp. 165-189, 2010.

[17] B. F. Cazacu O, „Generalization of Drucker's yield," *Mathematics and Mechanics of Solidsd,* vol. 6, nr. 6, pp. 613-630, 2001.

[18] B. F. Cazacu O, „Application of representation theory to describe yielding of anisotropic aluminium alloys," *International Journal of Engineering Science,* vol. 41, nr. 12, pp. 1367-1385, 2003.

[19] K. H. R. D. Yuanxin Luo, „A new sheet metal forming system based on the incremental punching, part 1: modeling and simulation," *The International Journal of Advanced Manufacturing Technology,* vol. 51, nr. 5-8, pp. 481-491, 2010.