



7<sup>th</sup> INTERNATIONAL CONFERENCE  
**FRACTURE MECHANICS OF MATERIALS  
AND STRUCTURAL INTEGRITY**

March 3-5, 2026 | Lviv, Ukraine

# BOOK OF ABSTRACTS

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Lviv, 2026

**За редакцією: З. Назарчука, І. Дмитраха, Г. Никифорчина, О. Звірко, А. Сиротюка**

**М 53** *Fracture Mechanics of Materials and Structural Integrity* : збірник тез доповідей 7-ї Міжнародної конференції, 3–5 березня 2026 р., м. Львів, Україна / за ред. З. Назарчука, І. Дмитраха, Г. Никифорчина, О. Звірко, А. Сиротюка; під егідою Європейського товариства з цілісності конструкцій (ESIS) ; організатори: Фізико-механічний інститут ім. Г. В. Карпенка НАН України, Українське товариство механіки руйнування матеріалів, Західний науковий центр НАН України та МОН України. – Львів : ПП «Видавництво «Бона», 2026. – 112 с.

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Розглянуто сучасний стан і основні напрями розвитку досліджень у галузі міцності та руйнування конструкційних матеріалів, а також проблем цілісності конструкцій. Висвітлено фундаментальні та прикладні результати, представлені на 7-й Міжнародній конференції “Fracture Mechanics of Materials and Structural Integrity”, що відбулася 3–5 березня 2026 р. у Фізико-механічному інституті ім. Г.В. Карпенка НАН України (м. Львів).

Конференцію організовано під егідою European Structural Integrity Society (ESIS) за участю Фізико-механічного інституту ім. Г. В. Карпенка НАН України, Українського товариства механіки руйнування матеріалів, Західного наукового центру НАН України та МОН України. Захід присвячено 100-річчю від дня народження академіка НАН України Володимира Панасюка (1926–2026) – видатного вченого у галузі механіки руйнування та міцності матеріалів, засновника попередніх конференцій цієї серії.

З огляду на умови воєнного стану в Україні, конференцію проведено у змішаному (очному та дистанційно-му) форматі. Робочою мовою конференції була англійська. У роботі конференції взяли участь представники 18 країн; загалом заслухано та обговорено 75 доповідей.

У збірнику тез доповідей узагальнено новітні результати досліджень у галузях механіки руйнування, міцності матеріалів, корозійно-механічного руйнування, неруйнівного контролю та прикладної механіки.

Видання призначене для науковців і фахівців у галузі механіки руйнування, матеріалознавства та цілісності конструкцій, а також викладачів, аспірантів і інженерів, діяльність яких пов’язана з енергетикою, машинобудуванням, транспортом, хімічною промисловістю та будівництвом.

**Edited by: Z. Nazarchuk, I. Dmytrakh, H. Nykyforchyn, O. Zvirko, A. Syrotyuk**

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The current state and main directions of research in the field of strength and fracture of structural materials, as well as problems of structural integrity, are presented. The abstract summarizes fundamental and applied results reported at 7th International Conference “Fracture Mechanics of Materials and Structural Integrity”, held on March 3–5, 2026, at Karpenko Physico-Mechanical Institute of the National Academy of Sciences of Ukraine (Lviv).

The conference was organized under the auspices of European Structural Integrity Society (ESIS) with the participation of Karpenko Physico-Mechanical Institute of NAS of Ukraine, the Ukrainian Society for Fracture Mechanics of Materials, and Western Scientific Centre of the NAS of Ukraine and of the Ministry of Education and Science of Ukraine. The event was dedicated to the 100th anniversary of the birth of Academician of the NAS of Ukraine Volodymyr Panasyuk (1926–2026) — an outstanding scientist in the field of fracture mechanics and strength of materials, and the founder of the previous conferences in this series.

Due to martial law in Ukraine, the conference was held in a hybrid format (on-site and online). The working language of the conference was English. In total, 75 presentations were delivered and discussed, with participants representing 18 countries.

The book of abstracts highlight recent advances in fracture mechanics, strength of materials, environmentally assisted cracking, non-destructive evaluation, and applied mechanics.

The publication is intended for researchers and specialists in fracture mechanics, materials science, and structural integrity, as well as for university lecturers, postgraduate students, and engineers working in energy, mechanical engineering, transport, chemical industry, and civil engineering.

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This conference was dedicated to the 100<sup>th</sup> anniversary of the birth of the Academician of the National Academy of Sciences of Ukraine

**Volodymyr Panasyuk (1926–2026)**

Professor Volodymyr Panasyuk was a prominent figure in Ukrainian science, whose achievements are recognized and highly appreciated by the international scientific community in the field of fracture mechanics of materials and structural integrity.



# Organization of Conference

The 7th International Conference “Fracture Mechanics of Materials and Structural Integrity” was held under the auspices of the European Structural Integrity Society (ESIS). The conference was co-organized by the Karpenko Physico-Mechanical Institute of the National Academy of Sciences of Ukraine, the Ukrainian Society for the Fracture Mechanics of Materials, the Western Scientific Centre of National Academy of Sciences of Ukraine and of Ministry of Education and Science of Ukraine.



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## Conference Venue

The Conference was held at the Karpenko Physico-Mechanical Institute  
of the National Academy of Sciences of Ukraine  
5, Naukova St., Lviv 79060, Ukraine

**Conference topics:**

- Fundamentals, physics, and mechanisms of fracture and fatigue
- Experimental fracture mechanics
- Computational fracture mechanics
- Solids mechanics
- Fatigue and fracture of structural materials
- Environmentally assisted degradation and cracking
- Failure analysis and case studies
- Structural integrity
- Damage tolerance and risk analysis
- Durability, safety, reliability, and life extension of components
- Non-destructive evaluation and structural health monitoring
- Advanced technologies for the repair of damaged objects
- Other aspects of fracture mechanics

Additional information about the conference can be obtained on the website:

<https://www.ipm.lviv.ua/fmsi2026>

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# PREFACE

Problems of strength and fracture of structural materials, as well as the related problems of structural integrity, have always been and remain the objects of theoretical and applied studies by a wide range of scientists and practical engineers. In particular, nowadays, the problem of technological and environmental safety of critical objects in industrial infrastructure is becoming increasingly important.

To analyse the fundamental and applied results in this field of science, the European Structural Integrity Society (ESIS) regularly organizes and supports international scientific conferences at the European, regional, and national levels.

The 7th International Conference “Fracture Mechanics of Materials and Structural Integrity” was held at the Karpenko Physico-Mechanical Institute of the National Academy of Sciences of Ukraine (NASU) from March 3 to 5, 2026.

Like the previous conferences in this series, it was held under the auspices of the European Structural Integrity Society (ESIS). The conference was co-organized by the Karpenko Physico-Mechanical Institute of NASU, the Ukrainian Society for the Fracture Mechanics of Materials, the Western Scientific Centre of National Academy of Sciences of Ukraine and of Ministry of Education and Science of Ukraine.

The conference was dedicated to the 100th anniversary of the birth of an outstanding scientist in the field of fracture mechanics of materials and structural strength – Academician of the NASU Volodymyr Panasyuk (1926–2026).

Given the martial law in Ukraine, the conference was organized in a hybrid version, i.e., “off-line” or “on-line”. The conference was held in English.

In total, 75 scientific reports and short communications were heard and discussed. Among the speakers and co-authors were representatives of 18 countries, including Great Britain, France, Germany, Italy, Spain, Belgium, Canada, Poland, Hungary, Slovakia, Mexico, Azerbaijan, Indonesia, and Ukraine.

This book briefly highlights the recent advances in fracture mechanics and the strength of materials, environmentally assisted cracking, non-destructive evaluation of structures, and applied mechanics that were presented at the conference.

The issue is intended for scientists and researchers in fracture mechanics, materials science, and structural integrity, as well as for high school lecturers and postgraduate students in the corresponding specialities. The book will also be useful for experts and engineers in industrial sectors such as energy generation, machinery, transport, the chemical industry, and civil engineering.

Editors

Z. Nazarchuk, I. Dmytrakh, H. Nykyforchyn, O. Zvirko, A. Syrotyuk

# **SECTION I: STRUCTURAL INTEGRITY**

## STRUCTURAL INTEGRITY AND LIFE OF HIP IMPLANTS

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Hip implants are nowadays high-quality, reliable components that rarely fail, even though they are exposed to static, impact, or amplitude loading in hostile environments such as our bodies. Nevertheless, they still sometimes do, requiring further analysis of factors that may affect both hip implant integrity and life, such as body weight, implant geometry, and material. In this paper, a review of recent investigations into hip implant fracture and fatigue behaviour is presented, with a focus on the effects of body weight, implant geometry, and material. It is shown that body weight plays an important role, especially in fatigue life, since the relationship between remaining life and stress (proportional to weight) is exponential. Regarding implant geometry, it is demonstrated that the main issue is stress analysis, indicating that implants with holes for fine adjustment according to patient bones configuration is not always a good idea, since it was shown that stress level in this case can be surprisingly high, especially with younger, active patients, Fig. 1. Finally, interaction between influencing factors should be taken into account, being relatively simple task when numerical methods are used. Here, the finite element method (FEM) was used for static calculations, and fatigue crack growth with ANSYS SMART, which was also analyzed by ABAQUS extended FEM (xFEM). Both methods were verified through an experimental investigation using digital image correlation (DIC) to measure strains and stresses. In particular, three case studies are presented here. The first one: standard/common analysis of a CoCr full cross-section hip implant; the second one: reverse engineering of a Ti6Al4V (ELI) “full” cross-section hip implant; and the third one: a Ti-6Al-4V hip implant with holes. A comparison between these three cases was made, pointing out the effects of material and geometry.

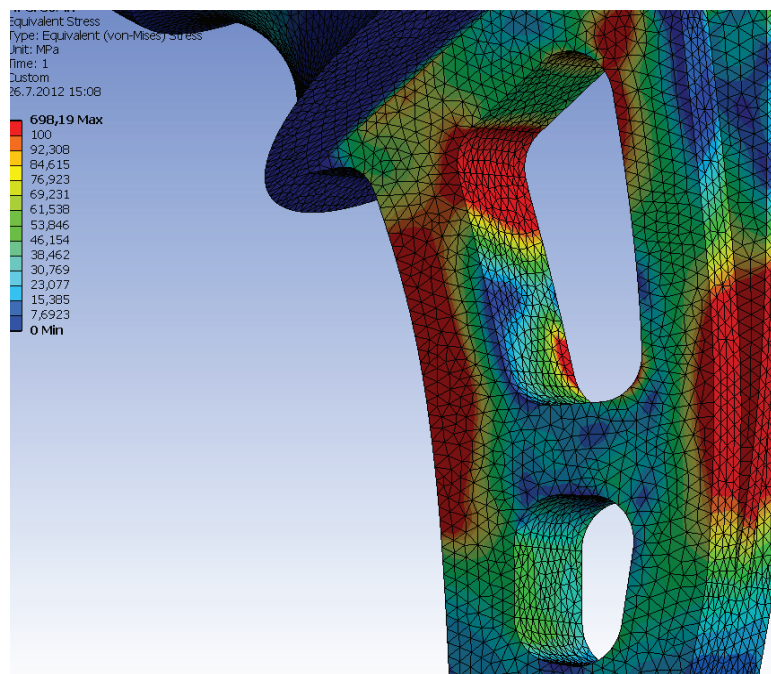


Fig. 1. The von Mises stress distribution

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## CONSIDERATION OF RISKS ASSOCIATED WITH HYDROGEN TRANSPORT

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New energy carriers, such as hydrogen, present potentially lethal risks in their use – risks that are often overlooked in discussions about the energy transition.

Hydrogen is a gas with a wide flammability range and a very low ignition energy.

The associated hazards include burns caused by torch effects or overpressure resulting from explosions. These risks are heightened by hydrogen embrittlement, which can lead to pipeline failure.

This presentation will address the following topics:

1. **Consideration of hydrogen-related risks in calculating the maximum operating pressure** – the maximum operating pressure is determined probabilistically, with the probability of a major hazard kept below 1 in 100,000 over an expected service life of 50 years.
2. **Consideration of major risk in hydrogen transport through seismic zones** – the calculation is based on strain-based design. Fracture strain is a mechanical property highly sensitive to hydrogen embrittlement.
3. **Calculation of the safety distance to prevent lethal risk from a hydrogen pipeline rupture** – the method is based on calculating the breach size using the CTOA (Crack Tip Opening Angle) criterion and a gas dispersion model.

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## WHAT IS THE MEAN GOAL OF “STRUCTURAL INTEGRITY ASSESSMENT”?

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The general tasks of engineering activities are to ensure the required circumstances of the engineering systems, tools, equipment, etc., for safe operation within the designed lifetime. The first – and most important step in this process is to define the goal, the task of the new product (system, tools, etc.). Similarly, handling the safety issue is important, which could be influenced in the design, production, and operation periods of the products. The paper intends to emphasize a correct definition of the SAFETY issue and to underline that in this definition, the “cost-effective solution” is also included. The sequence of ideas will be illustrated by an industrial case.

A vast number of definitions of the term “Structural Integrity Assessment” (SIA) exist in the technical literature. The title of the paper: “What is the Main Goal of the SIA?” We are working in some kind of engineering fields, having different kinds of engineering knowledge, that is why listening emphasized sentence everybody could have different meanings as well. If we would like to build a common view of this topic, we could consult general databases on the INTERNET. One of the suggested definitions is the following:

“Structural Integrity is the ability of a component, structure, or asset to operate at an optimum level under the pressure of a load, including the weight of the asset itself”.

Among them, some other questions are raised:

- What is structural integrity?
- How do you determine structural integrity?
- What are the principles of structural integrity?
- What is structural integrity in medical terms?

The situation becomes more complicated if we are trying to have an answer from an AI discussion. I am suggesting performing it! We could have a more stable basis for understanding the subject of “structural integrity” if we start from the general basis of all engineering (or human) activity, ie, SAFETY. This paper will illustrate the necessary knowledge for the structural integrity assessment of engineering components with characteristic features. The exemplar had to be selected from the oil and gas industry, an atmospheric 30.000 m<sup>3</sup> LPG tank.



Fig. 1. Atmospheric 30.000 m<sup>3</sup> LPG tank

The tank was put into operation (with a preliminary permit) in 1986. This tank type was the only one in Hungary, so the technical society had no experience in ensuring its safe operation over a long period. In the “lifetime” of the tank, the “integrity assessment” items were raised three times. They were the following:

1. What type of periodical control is required, and what is its frequency?
2. What kind of technology can be applied for total HC removal from the tank, and its discharging?
3. What kind of technology can be used for pulling down the tank?

*It will be suggested that the SIA is a tool, looking for cost-effective solutions based on the SAFETY issue.*

**Keywords:** structural integrity, engineering structures, damage, stress field, operating conditions, defects, flaws, non-destructive evaluation, NDT, maintenance, supervision, safety, reliability, risk

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## LOCAL AND GLOBAL MECHANICAL RESPONSE AND FAILURE MODE OF COMPRESSED TIMBER ELEMENTS

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Timber elements subjected to compression exhibit overall ductile behavior, with significant deformation beyond the force-displacement proportionality limit. However, this average continuous behavior may be accompanied by a scattered distribution of local fractures that can make the results rather dispersed. In this contribution, we analyze the output of an extensive experimental campaign conducted on components of the Chinese architectural heritage [1] to understand to what extent it is possible to define a reliable elastoplastic constitutive model of wood as an alternative to more realistic but more complex approaches based on fracture mechanics.

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## ANALYTICAL MODELING OF TRANSIENT THERMOELASTIC RESPONSE OF MULTILAYER SPHERICAL PRESSURE VESSELS

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Multilayer spherical pressure vessels are widely used in energy, aerospace, and chemical engineering applications where structures are exposed to combined mechanical loading and intense, time-dependent thermal effects. Accurate prediction of transient thermoelastic stresses in such systems is essential to ensure structural integrity, prevent failure, and optimize material layouts. This report presents an analytical study of the transient, spherically symmetric thermoelastic response of a multilayer spherical vessel subjected to internal pressure and nonstationary thermal loading.

The vessel under consideration consists of three concentric layers: a load-bearing core, an intermediate composite or functionally graded layer, and an external thermal insulation coating. The analysis is carried out within the quasi-static approximation, which is appropriate when inertial effects are negligible compared to thermal and mechanical loads. The temperature field is determined independently by solving the transient heat conduction problem governed by Fourier’s law. This solution is then introduced into the mechanical formulation as a prescribed thermal load, enabling a clear separation between thermal and mechanical analyses.

The mechanical problem accounts for internal pressure and thermally induced strains arising from nonuniform temperature distributions. Material inhomogeneity and multilayer interfaces are treated consistently by employing a direct integration method, which yields closed-form expressions for the radial displacement and stress components in each layer. The intermediate layer is modeled using a homogenization approach that captures its effective macroscopic behavior without explicitly resolving its microstructure. This significantly simplifies the analysis while retaining the essential influence of graded or composite material properties.

The analytical framework enables a systematic investigation of how material properties and geometric parameters affect the transient stress-strain state. Numerical results demonstrate that, for homogeneous spherical vessels subjected to internal heating, thermal stresses dominate over pressure-induced stresses even at moderate internal pressures of 10–20 MPa. Heating causes a redistribution of circumferential stresses, leading to compressive stresses near the inner surface and large tensile stresses near the outer surface, which may exceed the applied pressure by several orders of magnitude.

The introduction of an external thermal insulation coating is shown to significantly reduce tensile stresses in the load-bearing layer by decreasing temperature gradients. The effectiveness of this stress mitigation strongly depends on the contrast in thermal conductivity between the coating and the base material. Aluminum vessels benefit from relatively thin coatings, whereas steel vessels require thicker insulation to achieve comparable reductions in peak stresses. In addition, insulation coatings substantially reduce the heat flux required to maintain a prescribed inner-surface temperature, improving energetic efficiency by up to 29% for steel vessels and 54% for aluminum vessels.

However, homogeneous insulation coatings may introduce sharp discontinuities in thermomechanical properties at the coating-substrate interface, resulting in high tensile stresses within the coating. To overcome this limitation, an intermediate functionally graded layer is proposed. Such a layer provides a smooth transition of material properties, effectively reducing interfacial tensile stresses and confining local stress concentrations within less critical regions.

The transient analysis further reveals that circumferential stresses evolve monotonically with temperature during heating and cooling, with maximum tensile stresses occurring shortly after the inner-surface temperature reaches its peak. Overall, the developed analytical model serves as a practical and efficient tool for the design and optimization of multilayer spherical pressure vessels operating under transient thermal conditions, offering clear guidelines for material selection and layer configuration.

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**TEACHING FRACTURE MECHANICS AND STRUCTURAL INTEGRITY IN SPAIN:  
A TRIBUTE TO EDUARDO TORROJA**

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Fracture mechanics can be considered as an innovative teaching subject *per se*, since its theoretical background comes from the 60's vintage. This report is devoted to the Spanish experience in teaching fatigue, fracture mechanics, and structural integrity in the framework of engineering courses. Formative and cognitive objectives of teaching are mentioned, as well as different teaching programmes. Emphasis is placed on the degree of application of fracture mechanics techniques in engineering design, particularly in structural mechanics and civil engineering. Some open questions concerning specific problems in teaching fatigue and fracture mechanics, as well as structural integrity issues, are discussed in the final section.

*In Memoriam:* This paper is dedicated to the memory of the prominent Spanish civil engineer Eduardo Torroja, whose enthusiastic and forward-looking action allowed the pioneering development of prestressed concrete in Spain.

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## TOWARDS ASSESSMENT OF THE RISK OF DEVELOPMENT OF CRACKS OF DIFFERENT SHAPES IN STRUCTURAL ELEMENTS WITH HOLES

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In this work, an approach for assessing the risk of crack development of different shapes in structural elements with holes is proposed based on the concept of the structural element’s resistance to crack growth [1], defined as the rate of change of the stress intensity factor at the crack tip during crack propagation.

To implement this approach, structural elements with holes, near which cracks of different shapes may develop, were selected as model objects representing welding or manufacturing defects.

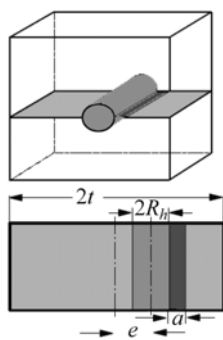


Fig. 1. Single crack from a hole in a plate under tension [2]:  
 $a$  – crack length;  $R_h$  – hole radius;  
 $2t$  – plate length;  
 $\sigma$  – applied stresses;  
 $e$  – eccentricity.

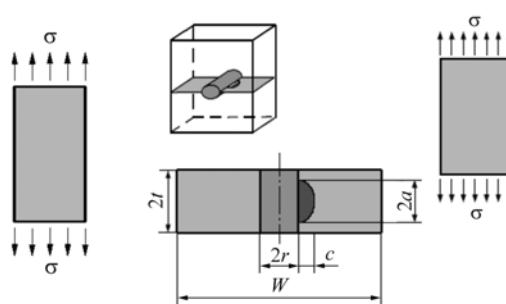


Fig. 2. Single semi-elliptical crack from a hole in a plate of finite dimensions under tension [3]:  
 $2a$  – crack length;  $c$  – crack width;  
 $r$  – hole radius;  $2t$  – plate thickness;  
 $2W$  – plate width;  
 $\sigma$  – applied stresses.

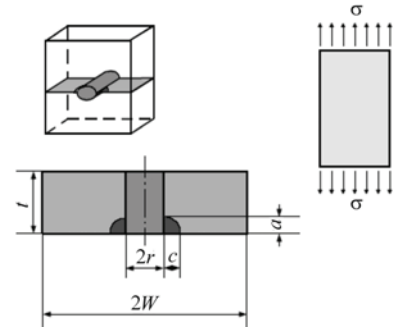


Fig. 3. Two quarter-elliptical cracks from a hole in a plate of finite dimensions under tension [3]:  
 $a$  – crack length;  $c$  – crack width;  
 $r$  – hole radius;  $t$  – plate thickness;  
 $2W$  – plate width;  
 $\sigma$  – applied stresses.

A comparative analysis of the risk of crack development for the considered models was carried out. The proposed approach can be applied to practical calculations of the strength and residual life of critical structures under long-term operation, as well as to the interpretation of technical diagnostics results.

**Keywords:** structural elements, crack growth rate, stress intensity factor, index material crack growth resistance

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**SECTION II:  
FRACTURE AND STRENGTH  
OF MATERIALS**

## HYDROGEN DAMAGE OF MEDIUM CARBON STEEL AS AN EFFECTIVE FACTOR FOR INCREASING ITS FRAGMENTATION UNDER STATIC EXPLOSION TESTS

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Based on the postulate of the irreversibility of the negative effect of hydrogen on the microstructure of structural medium carbon steels under the conditions of their electrochemical hydrogenation, a relationship was established between the hydrogen concentration in 60S2A steel, its mechanical characteristics, and steel fragmentation parameters under impact loading and static explosion loading.

Regimes of electrochemical hydrogenation of steel in special aqueous solutions were proposed, which cause its optimal damage, which was assessed based on the change in the fracture energy of samples under impact loading depending on the hydrogen concentration in the metal.

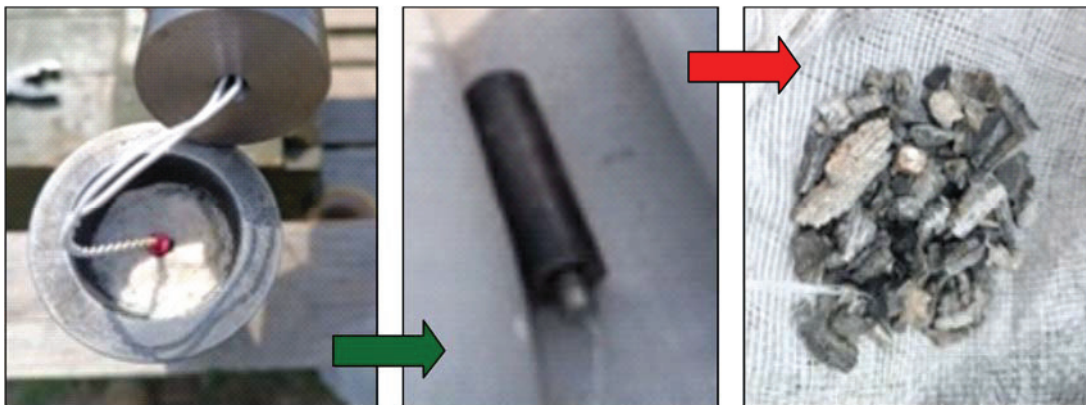


Fig. 1. Sequence of tests of hydrogen-charged model cylinders made of 60S2A steel by static explosion

It was shown that by treating 60S2A steel with electrochemical hydrogen, it is possible to realize its controlled fragmentation during static explosion testing (Fig. 1). For quantitative assessment of steel fragmentation, the parameter  $P_f$  was proposed, which is physically the number of fragments weighing 4–5 g and more per unit mass of material.

Comparison of the proposed method for increasing the fragmentation of 60S2A steel with the usual pre-hardening method showed an increase in the  $P_f$  parameter by 55%, indicating its effectiveness and the prospects for application in the manufacturing of special products.

**Keywords:** medium carbon steel, electrochemical hydrogenation, hydrogen concentration, static and impact loading, fracture energy, static explosion test, fragmentation

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**INNOVATIVE TEACHING OF FRACTURE MECHANICS IN ENGINEERING  
EDUCATION:**

**1. AN INNOVATIVE APPROACH COMBINING SCIENCE AND ART**

**2. A TRIBUTE TO PROFESSOR VOLODYMYR PANASYUK**

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A creative experience is described in the matter of teaching fracture mechanics in engineering education at the University of Salamanca (the oldest in Spain, an institution comprising both tradition and innovation). It has been successfully applied in real teaching courses of fracture mechanics and structural integrity in the framework of structural engineering education. The creative and innovative approach combines science and art, including concepts and ideas of the visual arts such as painting and sculpture.

With regard to *painting*, the approach consists of identifying the crack 3D profile exhibited by cold-drawn pearlitic steels with painting works by Caspar David Friedrich (*romantic*), the crack 2D profile with painting works by Picasso (*cubist*) of Larionov and Goncharova (*rayonist*), or the crack shape evolution with painting works by Victor Vassarely (*kinetic art*).

In the matter of *sculpture*, the approach consists of identifying the fractographies (microscopic fracture modes observed by scanning electron microscopy) in progressively cold-drawn pearlitic steels tested in the presence of hydrogen with the *Donatello Wooden Sculpture Texture* (DWST) or the *Michelangelo Stone Sculpture Texture* (MSST).

*In Memoriam:* The paper is dedicated to the memory of Professor Volodymyr Panasyuk, master and friend, prominent scientist and father of Ukrainian fracture mechanics, who passed away in 2023.

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**ErNiCrMo-3 AND ITS BEHAVIOUR IN THREE-POINT FATIGUE TESTS  
ON A DISSIMILAR JOINT OF INCONEL 600 IN AS-RECEIVED  
AND HEAT-TREATED CONDITIONS**

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Inconel alloys are widely used in various industries due to their excellent properties and corrosion resistance in diverse environments. This study focuses on the fatigue failure resistance of Inconel 600 welded-plate joints heat-treated at 700°C for 300 h and in the as-received condition, using an ER-NiCrMo3 filler material and the gas metal arc welding (GMAW) process, under three-point bending. The results reveal that the weld metal microstructure consists of an austenitic matrix with Ti-rich and Nb-rich precipitates, which are carbides or carbonitrides in the interdendritic regions. Tensile test results show a yield strength ( $\sigma_y$ ) of 426 MPa, an ultimate tensile strength (UTS) of 750 MPa, and an elongation of 11.11 mm. From these results, three-point bending was performed at different levels of the  $\sigma_y$ . The results of the fatigue testing show that, with a nominal stress of 340 MPa, the fatigue life, expressed as the number of cycles, was 542451. Conversely, with 440 MPa decreases up to 252140. The fracture surface of the samples under investigation exhibits different zones: crack initiation and stable propagation, with beach marks. The fatigue results reveal that the ER-NiCrMo-3 is a good choice for joining Inconel 600 plates.

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## DATA-DRIVEN MODELING OF SHAPE MEMORY ALLOY HYSTERESIS USING TREE-BASED MACHINE LEARNING ALGORITHMS

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Shape memory alloys (SMAs) belong to a class of functional materials whose mechanical behavior is governed by reversible phase transformations in the crystal lattice. One of the key characteristics of these materials is superelasticity, which manifests as the ability to undergo large deformations and fully recover their original shape upon unloading. Under cyclic loading, the deformation response of SMAs exhibits a pronounced hysteretic behavior caused by phase transformations between the martensitic and austenitic phases, while the area enclosed by the stress–strain loop is numerically equal to the energy dissipated within the material. Modeling such nonlinear behavior remains a challenging task. In this context, the application of data-driven approaches, particularly machine learning methods, is highly relevant for developing models that accurately reproduce the hysteresis behavior of SMAs.

In this study, three tree-based ensemble models (Random Forest, Gradient Boosting, and Extra Trees) were developed and evaluated. These models implement different ensemble construction strategies: bagging, boosting, and extreme randomization. Such a selection enables assessment of each approach's ability to reproduce the nonlinear hysteresis behavior of SMAs without introducing additional meta-levels of aggregation. The models were trained and tested using experimental loading–unloading data obtained for a NiTi alloy. Model performance was evaluated using MAE, MSE,  $R^2$ , and MAPE metrics. Fig. 1(a) illustrates the agreement between the predicted and experimental strain values for the test dataset, as well as the experimental hysteresis loop of the 260<sup>th</sup> loading–unloading cycle and the corresponding loop predicted by the Extra Trees machine learning model at a loading frequency of 1 Hz.

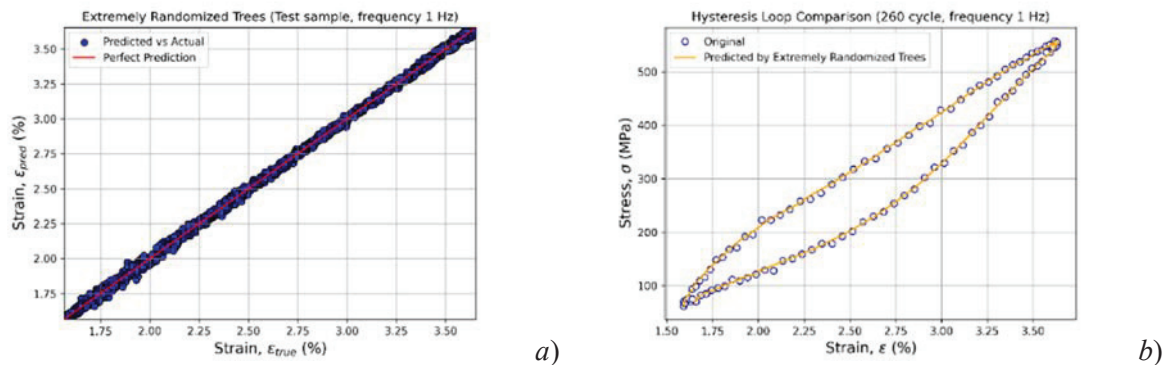


Fig. 1. Modeling of the hysteresis behavior of a NiTi alloy using the Extra Trees model:

(a) agreement between the predicted and experimental data for the test dataset;

(b) experimental hysteresis loop and the corresponding loop predicted for the 260<sup>th</sup> loading–unloading cycle.

The obtained results confirm the effectiveness of tree-based ensemble machine learning models for predicting the hysteresis behavior of shape memory alloys.

**Keywords:** shape memory alloys, hysteresis, tree-based models, machine learning

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## THE ROLE OF RESIDUAL STRESSES IN ASSESSING THE STRENGTH OF PLATES WITH FUNCTIONALLY GRADIENT OXIDE COATINGS

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Plasma-electrolytic oxidation of the valve group’s metal surfaces is an effective means of protecting parts from corrosion, overheating, and mechanical overload. Intense local heating in the phase transformation zone leads to significant incompatible deformations and, therefore, to the appearance of residual stresses. The purpose of the study is to analyze the influence of residual stresses on the bearing capacity of plates oxidized from two sides.

The study was conducted within the framework of the classical theory of layered functionally gradient plates in thickness. The stressed and limit state of the plate in the field of self-balanced residual stresses (compressive in the coatings) under the action of all-round tension was studied. The influence of residual-stress level on the permissible mechanical load is illustrated in detail for the compositions Al/Al<sub>2</sub>O<sub>3</sub> and Ti/TiO<sub>2</sub>.

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**PULSED ELECTROMAGNETIC PROCESSES  
FOR OPTIMIZING RESIDUAL STRESS-STRAIN STATES OF WELDED JOINTS**

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The development of modern production has increased the requirements for the service characteristics and resources of welded structures. Residual welding stresses (RWS) of tensile significantly affect fatigue fracture resistance, corrosion resistance, and the precision of welded joints (WJ). A promising direction in engineering practice for regulating residual stress-strain states (SSS) in WJ is the use of electrophysical processes based on the interaction of electromagnetic and mechanical fields. One such process is the treatment of welded structures made of non-magnetic metallic materials with a pulsed electromagnetic field (TPEMF). Using the electronic speckle interferometry method on the example of thin-sheet butt WAs made of the non-magnetic alloy AMg6 (Al-Mg base), it has been proven that TPEMF during TIG fusion welding is more effective in reducing tensile residual stresses than TPEMF after TIG at room temperature ( $T_k^\circ$ ). Based on a method using a pressure sensor, the kinetics of the action of the magnetic field pressure force  $P$  on the residual displacement  $f$  and SSS of the samples during their TPEMF were investigated, which was carried out in two variants: without and with the use of an additional screen made of AMg6 alloy with a thickness of 5.0 mm. It was found that using a screen increases the value of  $P$  by up to 2 times, which is due to an increase in the active volume of the current-conducting medium. At the same time, TPEMF without shielding and with a screen reduces  $f$  values by 2 and 4 times, respectively, and residual tensile stresses by 50 and 80%, respectively. Based on the Prandtl-Reuss relations for the motion of an elastic-plastic medium, mathematical modeling was performed, the results of which substantiated the advantages of using electrodynamic treatment (EDT) of a butt-welded joint made of the AMg61 (1561) alloy in the TIG welding process compared to EDT at  $T_k^\circ$ . The results of model verification prove that EDT during TIG contributes to the formation of peak values of compression RWS by 60% more than EDT at  $T_k^\circ$ . The use of pulsed barrier discharge (PBD), which generates a low-temperature plasma at the surface of the metal being processed, promotes dispersion of its thin structure, thereby strengthening it. An increase in the  $HV$  hardness of 25HGNMT structural steel as a result of its PBD treatment from 420 to 510 units has been established, accompanied by an increase in the density of its dislocation structure.

**Keywords:** treatment of welded joints, pulsed magnetic field, pulsed barrier discharge, electrodynamic treatment, magneto-pulse treatment, aluminum alloy, structural steel, residual displacements, stress-strain state, steel hardness

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## INCREMENTAL CRACK PROPAGATION UNDER MIXED-MODE LOADING WITHIN A POTENTIAL-BASED COHESIVE ZONE FRAMEWORK

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Crack propagation under mixed-mode loading is governed not only by fracture resistance but also by the continuous selection of the crack-growth direction. Within linear elastic fracture mechanics, this direction is typically determined at the onset of kinking, whereas sustained crack growth requires additional assumptions regarding path evolution. In this work, crack propagation is formulated as a sequence of directional selection problems, each based on evaluating competing trial crack orientations within a cohesive zone model (CZM).

The proposed framework represents the crack as a polyline that is advanced incrementally. At each propagation step, a short cohesive continuation (“trial leg”) is introduced ahead of the current crack tip at a prescribed angle. For each candidate angle, a fully nonlinear critical state is computed using a potential-based mixed-mode cohesive law, which ensures energetic consistency and provides a symmetric algorithmic tangent for robust Newton iterations. The preferred propagation direction is then selected by minimizing a scalar diagnostic evaluated at the critical state, after which the crack is advanced along the selected direction, and the procedure is repeated.

A thin-channel meshing strategy with subsequent channel collapse is employed to generate a zero-thickness cohesive interface aligned with each trial leg, enabling controlled interface resolution while maintaining full automation of mesh generation during crack advancement. Crack growth is thus driven by the repeated selection of the trial-leg angle, rather than by an explicit crack-growth law or enrichment scheme.

Numerical examples in plane strain demonstrate stable crack-path evolution under mixed-mode loading, smooth development of cohesive zones, and consistent critical loads across successive propagation steps. The results show that the proposed approach provides a transparent and physically motivated framework for simulating mixed-mode crack propagation as a sequence of well-posed cohesive kinking problems.

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## EXPERIMENTAL STUDIES OF THE INFLUENCE OF RARE-EARTH METALS ON COLD STRENGTH AND VISCOUS-PLASTIC PROPERTIES OF PIPE STEELS

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Currently, traditional alloying methods have largely exhausted their potential to increase cold resistance and resistance to brittle fracture at sub-zero temperatures, significantly limiting their ability to extend the operational (failure-free) life of steel structures, particularly pipelines (oil and gas). As an alternative, the use of ligatures with rare-earth metals may be promising. The effectiveness of such additives is associated with changes in the morphology, distribution, and dispersion of the structural components of the metal, as well as non-metallic inclusions, which ultimately allow for control of the metal's structural and phase composition, its secondary phase, and the state of its boundaries. An analysis of the literature indicates that the influence of rare-earth metals on cold resistance and viscoplastic properties, especially at subzero temperatures, has not been sufficiently studied to fully understand the mechanisms by which micromodifiers influence the failure of pipe steels under simultaneous exposure to such an environment and alternating loads. Comprehensive experimental studies and industrial (field) testing have substantiated the optimal contribution of rare-earth metal master alloys and their particle-size distributions. The influence of complex ligatures with rare-earth metals on the resistance to brittle fracture of pipe steels is examined in detail.

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## STRESS INTENSITY CALCULATION IN THE VICINITY OF CORNER POINTS AND CRACKS INITIATED BY THEM BY THE MUSHELISHVILI METHOD

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Structural elements often contain holes with corner points and V-shaped cuts, near which a high concentration of stresses occurs. Similar concentrators are also characteristic of welded structural elements that contain corner joints, non-welded zones, and undercuts. The stressed state in the vicinity of corner points exhibits power-law behavior and is characterized by generalized stress intensity factors (GSIFs). To determine the GSIF using numerical methods, the finite element method (FEM) and boundary element method (BEM) employ rather complex algorithms that involve mesh refinement of finite or boundary elements in the vicinity of corner points. It is indicated in [1] that the GSIF found by different authors often differ significantly from each other. The most effective methods for calculating stresses near polygonal holes include the Muskhelishvili method, based on conformal mapping, which is accurate if the mapping function is expressed as a segment of a Laurent series.

To calculate the stresses near the vertices, the report developed an algorithm that uses an arbitrary number of series terms, allowing the hole boundary to be described with high accuracy. The GSIF is based on the well-known Williams image for stresses near the corner vertex, with additional use of the least-squares method to calculate stresses near it. The results of GSIF calculations for holes in the shapes of equilateral polygons and rectangles under different loading conditions are presented. In some cases, the results obtained are consistent with the data [1] obtained by the method of integral equations.

It is known that high stress concentration near corner points causes the occurrence of edge cracks. The paper presents a method for calculating the SIF for cracks originating from a corner point using a function that conformally maps the region with a crack to the exterior of the hole. The results of the SIF calculations are in good agreement with the literature data obtained by other methods for larger cracks. However, for small crack lengths, it turned out that the SIF calculations are complicated due to the slow convergence of the Laurent series for regions with edge cracks, and a problem similar to the Gibbs effect that arises in Fourier series.

At the same time, the problem of studying the fracture process must be considered in detail at the stage of crack formation, i.e., when they have a small length. In this regard, for edge and internal cracks of arbitrary length, including curvilinear ones, the paper proposes to use the method of integral equations. To increase its efficiency, the kernels of the equations are written in Green's solutions, under which the conditions on the boundary contour described by the segment of the Laurent series are satisfied identically. Green's solution is constructed by the Muskhelishvili method and is reduced to solving systems of linear algebraic equations. The solution of singular integral equations is carried out numerically using Chebyshev-Lobatto quadrature formulas. The results of SIF calculations for cracks of different lengths, which emanate from the vertices of polygonal holes, are presented. In some cases, the SIFs found are in good agreement with the literature data, including for cracks of small length. Thus, it is shown that the algorithm developed in the work for determining generalized GSIF and SIF for edge cracks is, on the one hand, relatively simple and, at the same time, provides high accuracy of calculations.

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## SURFACE EFFECTS IN THREE-DIMENSIONAL SMALL-SCALE MECHANICS OF CRACKED SOLIDS

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Fracture problems for the nanomaterials involve a consideration of the small-sized cracks, surfaces of which possess their own mechanical energy [1]. The membrane-type Gurtin-Murdoch model of the surface with stretching stiffness and residual tension [2] provides the effective theoretical tool for a continuum mechanics-based determination of the corresponding surface effects and associate size-dependency following from its perfect agreement with the results of atomistic simulation [3] and experiment [4]. In particular, such a model was successfully applied to the solution of axisymmetric problems involving surface stresses of a penny-shaped crack [5].

The proposed investigation concerns the three-dimensional manifestation of the surface tension in a small-scale analysis of nonhomogeneous static loading of a mode-I penny-shaped crack in an infinite elastic solid. Applying the Gurtin-Murdoch surface elasticity relations in the statement of boundary conditions on the opposite crack faces, the considered problem is reduced to the boundary integro-differential equation relative to the dynamic crack opening displacement in the normal direction. Partial inversion is used for the transformation of this equation to the weakly-singular integral one, where a priori vanishing of the solution at the crack front is considered as the uniqueness condition. The singularity-subtraction technique is proposed for constructing a regular analogue of the equation, which is subsequently solved by the collocation method. Numerical results reflect the influence of surface tension on the crack opening displacement, as well as on the normal stresses in the crack plane. It was revealed that the surface tension factor yields qualitative and quantitative changes in pertinent parameters, up to non-classical stress boundedness, in the crack vicinity. An analysis includes the situations with the different outer loading distributions, surface tension magnitudes and crack sizes involving nanosize range.

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## THE EFFECT OF ELECTRIC FIELDS AND POLING DIRECTION ON THE FRACTURE BEHAVIOR OF PIEZOELECTRIC BIMATERIALS WITH AN ELECTRICALLY CONDUCTIVE INTERFACIAL CRACK

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With the widespread application of piezoelectric materials in smart and adaptive structures, the fracture mechanics of such materials has attracted considerable research interest. Experimental studies indicate that, similarly to stress fields, electric fields may become highly intensified near crack tips, leading to strong local nonlinear electromechanical effects. In most existing investigations, the polarization direction of piezoelectric materials is assumed to be fixed, typically either normal or parallel to the crack plane. However, the poling angle is a crucial additional parameter, as the polarization orientation substantially influences the material properties, crack propagation behavior, and fracture characteristics of piezoelectric media. Therefore, a systematic investigation of the combined effects of applied electric field direction and poling orientation on fracture behavior is of significant importance.

A bimaterial composed of two dissimilar piezoelectric materials with an electrically conducting crack  $-a < x_1 < a$ ,  $x_2 = 0$  along the bimaterial interface is considered. The upper and lower components of the bimaterial are piezoelectric materials with poling directions at the angle  $\omega$  with the axis  $x_1$  in the  $(x_1, x_2)$ -plane. Uniform stresses  $\sigma_{22}^\infty$ ,  $\sigma_{12}^\infty$  and electric field  $E_1^\infty$  remote loading, providing plane strain conditions in the  $-plane$  are applied at infinity  $(x_1, x_2)$ .

Following the paper [1], the following presentations at the bimaterial interface were obtained

$$\begin{aligned} h_{k1}\sigma_{12}(x_1, 0) + h_{k2}\sigma_{22}(x_1, 0) + h_{k3}E_1(x_1, 0) &= F_k^+(x_1) + \gamma_k F_k^-(x_1), \\ r_{k1}\langle u_1'(x_1) \rangle + r_{k2}\langle u_2'(x_1) \rangle + r_{k3}\langle D_2(x_1) \rangle &= F_k^+(x_1) - F_k^-(x_1), \end{aligned} \quad (1)$$

where  $F_k(z)$  are the functions analytic in the whole complex plane except the crack region;  $r_{kj}$ ,  $h_{kj}$ ,  $\gamma_k$  ( $j, k = 1, 2, 3$ ) are constants defined by the material's properties. Exact expressions for  $F_k(z)$  are found from the inhomogeneous combined Dirichlet-Riemann boundary value problem. Clear analytical expressions for the field quantities at different parts of the bimaterial interface can be obtained using formulas (1). According to the crack closure integral, the energy release rate (ERR) at a crack tip  $a$  can be presented in the form

$$G = \lim_{\Delta l \rightarrow 0} \frac{1}{2\Delta l} \int_a^{a+\Delta l} \left\{ \sum_{i=1,2} \sigma_{i2}(x_1, 0) \langle u_i(x_1 - \Delta l) \rangle - E_1(x_1, 0) \langle \hat{D}_2(x_1 - \Delta l) \rangle \right\} dx_1. \quad (2)$$

Substituting the obtained asymptotic expressions for the main characteristics of the electromechanical field into (2) and performing the integration, we arrive at the analytic formula for the ERR.

Numerical analysis demonstrates that both the applied electric field and the poling angle significantly influence the fracture parameters and the electromechanical field distribution along the bimaterial interface. It is shown that an appropriate combination of these parameters can substantially reduce the maximum energy release rate, thereby decreasing the likelihood of crack propagation. In the homogeneous case, the obtained results show good agreement with available experimental data reported in [2].

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## OPTIMIZATION OF THE OVERLAP FACTOR IN LASER SURFACE HARDENING OF PRECISION PARTS

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Vacuum laser surface hardening is an efficient method for improving the wear resistance and service life of precision mechanical parts while preserving the base material's properties. In contrast to conventional heat treatment, laser hardening provides highly localized energy input and rapid heating–cooling cycles, which makes it suitable for precision components where dimensional stability and surface integrity are critical. Performing the process in a vacuum environment further enhances stability by suppressing oxidation and unwanted surface reactions, which supports cleaner surfaces and more repeatable hardening conditions. This paper investigates the problem of selecting the optimal track overlap factor in vacuum laser surface hardening of fuel-pump precision parts. The overlap factor ( $K_n$ ) governs microhardness uniformity and surface roughness by controlling the balance between hardened regions and softened zones produced by repeated heating in overlapped tracks. The optimal overlap was justified using a geometric criterion based on the hardened-zone area, the softened-zone area, and a layer-filling coefficient. Track width and hardening depth were varied, while the tempering-zone width was assumed constant. For a representative case (track width 2 mm, hardening depth 0.5 mm), the filling coefficient reaches a maximum of approximately 0.67 at  $K_n \approx 0.88$ , indicating that continuous hardening requires an overlap close to unity but slightly lower. An operational map based on the hardening-depth-to-track-width ratio is proposed to support regime selection in practical applications.

**Keywords:** fuel pump, precision parts, vacuum laser surface hardening, track overlap, overlap factor, softened zone, filling coefficient

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## STRESS CONCENTRATION NEAR SOFT ELLIPTIC AND ELLIPSOIDAL ELASTO-PLASTIC INCLUSIONS

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Actual structural elements are often heterogeneous in structure; in particular, they contain inclusions with mechanical characteristics differing from the base material. The existing literature extensively covers methods for determining stresses in such structures under the assumption of elastic deformation of both the matrix and the inclusion. In practice, however, cases of “soft” inclusions are widespread, where mechanical and strength characteristics are significantly lower than those of the matrix. Under such conditions, it is necessary to account for the inclusions’ plastic deformation in calculations.

In this work, a methodology has been developed to determine stresses in plates that account for the plastic deformation of a soft elliptical inclusion, based on Hardiman’s principle of polynomial conservation of stresses. For a soft ellipsoidal inclusion, Eshelby’s solution was employed. Elasto-plastic deformation within the inclusion was determined using the deformation theory of plasticity, the von Mises yield criterion, and Birger’s method of variable parameters.

An infinite isotropic elastic plate (matrix) containing a homogeneous isotropic elliptical core (inclusion) of a different material with semi-axes  $a$  and  $b$  is considered in detail. It is assumed that the matrix is subjected to tension at infinity such that the inclusion enters the plastic state while the matrix remains elastic. It is well known that in the elastic formulation of this problem, uniform (constant) stresses arise within the inclusion. Consequently, it is evident that, under elasto-plastic deformation, the stresses and components of the plastic strain tensor within the inclusion will remain constant. The unknown initial (plastic) strains in the inclusion  $\varepsilon_x^0, \varepsilon_y^0, \varepsilon_{xy}^0$  were determined numerically using established relations from plasticity theory, accounting for linear strain hardening of the material. Stresses in the inclusion and the matrix were studied for various loading types and elliptical inclusion shapes. It is shown that accounting for plastic deformation significantly increases stress concentration in the matrix near the inclusion’s major axes.

Elastic soft inclusions in plates of various shapes were also considered using the method of integral equations. It was established that for a wide range of problems, virtually constant stresses arise within the inclusion (analogous to Hardiman’s problem). Based on this, stress calculations were performed for a broad class of finite bodies (semi-infinite plates, strips, rectangular plates, and cylinders) with soft elasto-plastic inclusions with sufficient accuracy for practical applications.

The developed methodology is generalized to the case of massive structural elements containing spheroidal soft elasto-plastic inclusions. For unbounded bodies, the solution was obtained using a numerical-analytical method incorporating Eshelby’s solution and the method of variable parameters.

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## ENERGY-BASED CONDITIONS FOR FRACTURE INITIATION IN FUNCTIONALLY GRADED OXIDE PEO COATINGS ON TITANIUM ALLOYS

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Functionally graded oxide coatings obtained on titanium alloys via plasma electrolytic oxidation (PEO) are widely used to enhance surface strength and resistance to thermomechanical loading. At the same time, the pronounced heterogeneity of PEO coatings, including gradients in porosity, phase composition, and defect density, promotes localized energy accumulation, which can lead to premature failure. This study presents an energy-based analysis of the conditions governing fracture initiation in functionally graded oxide PEO coatings on VT1-0 and VT6 titanium alloys.

The proposed approach is grounded in fracture mechanics concepts associated with Griffith's energy criterion and subsequent developments by Irwin, Orowan, and the school of Volodymyr Panasyuk, integrating energy and deformation aspects of crack initiation comprehensively. The local fracture condition is formulated as a balance between the energy release rate  $G(x)$  and the critical fracture energy  $G_c(x)$ , accounting for spatial variations in elastic properties, microstructural state, and defect content throughout the coating thickness.

The critical fracture energy is represented as a combination of interphase cohesion energy and a defect-related contribution, reflecting the influence of porosity, microcracks, and non-equilibrium structural states inherent to PEO coatings. The spatial distribution of microhardness is employed as an integral diagnostic parameter characterizing the local energy state and linked to the energy imbalance that triggers fracture initiation. This enables identification of distinct structural-energy zones, from stable regions to critically unstable layers.

Based on the proposed model, the critical depth for fracture initiation is defined as the location where the local driving force associated with the energy imbalance exceeds the coating's fracture resistance. The results demonstrate that fracture initiation in functionally graded oxide PEO coatings is governed by the interaction of physical parameters characterizing energy gradients, defect-induced dissipation, and structural mechanical inhomogeneity. The developed criteria provide a physically grounded basis for assessing structural failure risk and optimizing PEO process parameters in heterogeneous surface systems on VT1-0 and VT6 titanium alloys.

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## THE INFLUENCE OF DIFFUSION SATURATION IN CONTROLLED GAS MEDIA ON THE FATIGUE LIFE OF TITANIUM

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The effect of a hardened surface layer formed by diffusion saturation with interstitial elements (oxygen and nitrogen) on the physical and mechanical properties of VT1-0 titanium was investigated. The fatigue behavior of specimens with a modified surface layer was experimentally studied under symmetric pure bending ( $\pm\varepsilon_a = 0.9\%$ ) in air at temperatures of 20 and 380°C. It was established that oxygen-induced surface hardening with a hardness increase of  $\delta H^{\text{surf}} = 70\%$  and a layer thickness of  $l \approx 30 \mu\text{m}$ , corresponding to the controlled strengthening regime, provides the highest fatigue life of VT1-0 titanium compared with both unmodified specimens ( $\delta H^{\text{surf}} = 0\%$ ) and excessively hardened specimens ( $\delta H^{\text{surf}} = 140\%$ ). A reduction in fatigue life at test temperatures above 150 °C was fractographically attributed to coarsening of the hardened surface layer. Fracture surfaces of specimens tested at 300°C revealed an increased density and the opening of secondary cracks, indicating intensive oxygen-induced surface cracking of the modified layer. At the optimal level of surface hardening, the formation of an ordered dislocation structure was observed, which contributes to enhanced fatigue resistance.

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## **FRACTURE ANALYSIS OF FUNCTIONALLY GRADED TITANIUM MATERIALS FOR DENTAL IMPLANTS: RECOMMENDATIONS FOR ENHANCED STRENGTH AND RELIABILITY**

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Functionally graded materials (FGMs) based on titanium alloys offer a transformative approach to dental implants by enabling a controlled gradient in mechanical properties – from a high-strength metallic core to a bioactive, bone-mimicking surface. Building on Academician V.V. Panasyuk's foundational contributions to fracture mechanics and material strength, this study investigates the stress-strain state (SSS) and fracture criteria of FGMs in titanium-based implants, such as Ti/HAP composites.

Drawing from prior research, FGMs reduce peri-implant mechanical stresses through tailored elasticity modulus gradients (e.g., 110 GPa at the core to ~20 GPa at the surface), promote superior osseointegration, and limit corrosive ion release, particularly in basal implantation scenarios with limited bone volume. These adaptations enhance construct stability and long-term clinical performance.

Using approaches from linear elastic fracture mechanics (LEFM), along with the Griffith criterion for brittle fracture and the Leonov-Panasuk-Dugdale criterion for cohesive crack growth, the analysis of materials enables obtaining crucial information for modeling the initiation, propagation, and arrest of cracks and microcracks in gradient structures under cyclic loading. Finite element simulations reveal a 20–30% reduction in stress concentration factors (SCF) relative to homogeneous Ti-6Al-4V implants, with critical stress intensity factors (SIFs) shifting in a favorable direction due to property gradients.

Recommendations:

Optimize gradient profiles (e.g., exponential decay of modulus) to further minimize SCF hotspots.

Integrate nondestructive evaluation techniques, such as ultrasonic phased arrays and acoustic emission monitoring, for in-service defect detection.

Develop porous hydroxyapatite (HAP) surface layers (porosity 40–60%) tailored for basal implantation, balancing biocompatibility and mechanical integrity.

These strategies enhance the prediction and prevention of fracture conditions in dental implants, improving their long-term reliability and durability under cyclic loading.

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## DUCTILITY-DIP AND BRITTLE TEMPERATURE RANGE PHENOMENA IN ARC-BASED ADDITIVE MANUFACTURED INCONEL 625 SUPERALLOY INFLUENCED BY NITROGEN AND IRON CONTENT

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The tensile mechanical properties and microstructure (scanning electron microscopy and EDX analysis) of multilayer-deposited nickel superalloy Inconel 625 vertical wall specimens were investigated. Six variants were produced using three arc-based additive manufacturing technologies: microplasma powder deposition, TIG, and MIG welding.

For Inconel 625 deposited metal in the as-built structural state (ISO/ASTM 52900), the ductility dependence on temperature in the range of 20...1100°C exhibits two distinct intervals of critical ductility reduction. The first interval occurs at 600...900°C with a trough-like shape, showing minimum critical fracture strain  $\varepsilon_{cr} = 14.5...32.5\%$ . The second interval occurs at 1000...1100°C with a descending character and minimum  $\varepsilon_{cr} = 3.2...17.0\%$ . These phenomena correspond to the ductility dip and the brittle temperature range, respectively, which are well documented in the literature on the weldability of nickel-based superalloys.

The presence of these ductility-loss intervals in additively manufactured components with elevated structural rigidity significantly reduces Inconel 625's resistance to hot cracking via solid-state mechanisms, including ductility-dip cracking, segregation cracking, strain-age cracking, and post-weld heat-treatment cracking. The ductility reduction at 1000...1100°C represents the most critical concern for structural integrity. Using microplasma powder deposition as an example, these ductility-loss intervals persist even after solution annealing at 1050°C for 2.5 hours, demonstrating strong technological heredity.

Fractographic and compositional analysis revealed that the high-temperature ductility reduction is attributed to specific chemical composition factors. At 1000...1100°C, elevated nitrogen content [N] = 0.05...0.08 wt.% (exceeding the recommended [N] < 0.03 wt.%) is the primary cause. At 600...900°C, elevated iron content of 1...2 wt.% reduces the minimum critical fracture strain by approximately 50% to  $\varepsilon_{cr} = 14.5...16.0\%$ . Nitrogen contamination primarily originates from welding consumables, such as atomized powders, while iron is introduced through ferroalloys used for primary alloying.

To ensure structural integrity and minimize solid-state cracking susceptibility in arc-based additively manufactured Inconel 625 components, welding consumables should be selected to maintain nitrogen content below 0.02...0.03 wt.% and iron content below 0.5...1.0 wt.%.

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## MECHANICAL AND FATIGUE PERFORMANCE OF TWO-PHASE TITANIUM ALLOY AFTER COMBINED SURFACE TREATMENTS

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Due to their excellent mechanical and anti-corrosion properties, the aircraft industry widely uses the high-strength two-phase titanium alloy (Ti–5Al–5Mo–5V–Cr–Fe, also known as VT22). However, this titanium alloy has low wear resistance, which limits its use in tribo-pairs without additional surface treatment and, therefore, determines the need to develop effective surface engineering methods. For these reasons, gas nitriding is a promising, technologically simple, and economically efficient surface engineering method for enhancing wear resistance in titanium alloys. Generally, the treatment temperature for conventional gas nitriding of titanium alloy is near 950°C, with a processing time of several tens of hours. This results in high energy consumption and significant adverse effects on mechanical and fatigue properties, due to grain growth in the titanium alloy matrix. Therefore, the issue of intensifying nitriding of a titanium alloy becomes especially relevant. Our study shows that the combination of gas nitriding and a strengthening heat treatment of the VT22 titanium alloy in a single technological cycle enables the formation of a hardened surface layer and the achievement of regulated volume characteristics. Rotary bending tests showed that combining gas nitriding with a strengthened heat treatment results in higher fatigue limit values and greater durability in the low-cycle stress zone than conventional isothermal gas nitriding.

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**ANALYSIS OF THE IMPACT OF CYCLIC THERMAL LOADING IN CRITICAL ZONES  
OF WELDED JOINTS ON THE STRUCTURAL INTEGRITY OF A METAL SHELL  
DEPLOYABLE STRUCTURE**

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This paper presents a conceptual design for a welded, deployable structure based on an origami structure with a thin-walled metallic shell. The use of metals and alloys (such as stainless steel, aluminum, and titanium) for the load-bearing shells of such structures enhances reliability, improves mass-dimensional characteristics, and ensures predictable performance under operating conditions typically characterized by high thermal gradients across the shell surface. At the same time, the structural transformation of these shells, followed by cyclic thermal exposure, induces critical stress concentration zones and increases the risk of structural integrity loss.

The primary challenge in developing self-supporting transformable shell structures is ensuring their stiffness, stability, and durability after deployment without initiating fracture in the heat-affected zones of welded joints. This study proposes an approach to addressing this issue by analyzing and optimizing the stress-strain state in the critical zones of a welded origami structure, considering the shape transformation process. Particular emphasis is placed on assessing local buckling, stress concentrations in the welds, and damage initiation conditions.

The research focuses on the welded joints of transformable thin-walled shell structures. The results demonstrate that the inherent trade-offs between stiffness, compactness, and the mass-dimensional characteristics of the transformable shell can be effectively resolved using lightweight metal alloys combined with optimized origami geometry and the rational placement of welded joints.

**Keywords:** deployable structures, thin metal shells, load-bearing shells, structural integrity, welding joints

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**SECTION III:  
ENVIRONMENTALLY ASSISTED  
FRACTURE**

## CORROSION FATIGUE: THE EARLY STAGES OF DAMAGE

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The knowledge that corrosion reduces the fatigue life of components and structures has been recognised for 100 years, following McAdam’s [1] published studies on the effect of the environment on fatigue life. Since this time, numerous studies have been conducted to understand the synergistic effect of corrosion on stress intensification and stress on corrosion kinetics, with both effects significantly impacting fatigue lifetime.

This presentation provides an initial summary of the fatigue-cracking mechanism in air, introducing the role of corrosion in this mechanism. The role of metal dissolution is acknowledged as a key mechanism in overcoming the inherent resistance of a material’s microstructural features, therein reducing fatigue lifetime. The different damage regimes of corrosion fatigue emanating from nominally “defect-free” surfaces are discussed, notably, surface film breakdown, pitting, pit-crack transition, and cracking.

The presentation will also discuss the role of strain localisation in the formation and location of cracks associated with both individual and multiple pits. Mention will also be made regarding crack coalescence associated with pit-pit interactions.

Historically, pitting corrosion fatigue models have been proposed based upon the linear elastic fracture mechanics stress intensity threshold value  $\Delta K_{th}$ . However, given that cracks initiate from pits at values below this threshold value, an alternative model is presented, notably a probabilistic approach, that of cellular automaton, extended finite element method (CAxFEM).

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## EVALUATION OF HYDROGEN INFLUENCE ON FENIAL ALLOYS BY THREE-POINT BENDING TESTS

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The rapid development of a hydrogen-driven economy poses constant challenges regarding the material behaviour under hydrogen exposure [1, 2]. In this study, the influence of hydrogen on two iron-nickel-aluminium alloys has been investigated. The FeNiAl alloys are a class of bcc iron-based precipitate-strengthened materials with a matrix-precipitate structure similar to that of Ni-based superalloys [3]. Among the three investigated alloys, the Fe65-Ni10-Al25 at% is a single-phase alloy, while Fe65-Ni15-Al20 at% and Fe65-Ni17-Al18 at% possess a Fe-matrix and NiAl precipitates.

Both alloys were cast in a vacuum induction melting plant, followed by a two-step heat treatment to achieve the desired microstructure. The samples were charged electrochemically by varying current density and exposure duration, allowing the achievement of a wide range of hydrogen concentrations. To evaluate the influence of hydrogen on the mechanical properties of the alloys, three-point bending tests were conducted. Further, the fracture surfaces of the tested samples were evaluated using the scanning electron microscope.

The results show brittle behaviour in both alloys during 3-point bending tests, along with a general tendency towards strength reduction due to charging. The mechanical test results were related to the hydrogen concentration in the samples. Despite the brittle fracture behaviour, the fracture surface analysis of the charged samples shows characteristic features of the hydrogen effect, in particular, feathered structures, secondary cracks, and terrace structures.

**Keywords:** hydrogen embrittlement, mechanical properties, hydrogen concentration, Fe-Ni-Al alloys

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## EVALUATION OF IN-SERVICE DEGRADATION OF SEA PORT CRANE STEEL OPERATED UNDER CYCLIC LOADING

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Cyclic loading is considered a significant factor influencing the mechanical state of structural steels; thus, its consideration is required for a proper assessment of steel's in-service degradation. This paper discusses methodological aspects and presents some experimental results on evaluating the mechanical state of steels subjected to cyclic loads during operation, including in the presence of corrosive media. The results have been analysed from the point that steel degradation under cyclic loading can be divided into two stages: deformation strengthening and damage development. It was noted that the steel strength characteristics ( $\sigma_{YS}$ ,  $\sigma_{UTS}$ ) and impact toughness  $KCV$ , as a brittle fracture resistance parameter, had opposite effects on fatigue limit  $\sigma_0$  (stress ratio  $R = 0$ ) at the stage of cyclic deformation strengthening. However, these parameters act in the same direction during the damaging stage, both leading to a decrease in fatigue strength. A low-carbon rolled steel St-38b-2, taken from two sections of a sea port crane after 33 years of operation, was tested to assess the fatigue strength in air and 3% NaCl solution ( $\sigma_0^c$ ). Specimens have been cut out transversely relative to the rolling direction of steel components to evaluate standard mechanical characteristics, impact toughness, and fatigue parameters. Their configuration enabled localizing the fatigue fracture origin at its flat surface. Comparison of the sensitivity of the considered steel characteristics to operational degradation showed that the  $KCV$  values differed by more than twice for the steel specimens from different sections. At the same time, the fatigue limit  $\sigma_0$  changed by only 15% after operation.  $KCV$  is thus more sensitive to steel degradation than to fatigue characteristics, thereby eliminating the need to conduct complex fatigue experiments to assess operational degradation.

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**CORRELATIONS OF MARINE ENVIRONMENTAL CASUALTIES  
AND SHIP STRUCTURE DAMAGE UNDER ACCIDENTAL CONDITIONS:  
COLLISION AND GROUNDING CASES**

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Common maritime accidents – particularly collisions and groundings – remain a significant safety concern because they arise from an interacting chain of operational, organisational, and environmental drivers. For example, EMSA’s analysis of navigation accidents reported in the European Marine Casualty Information Platform (EMCIP) highlights that collisions, groundings, and contacts constitute a substantial share of reported occurrences (on the order of ~28% of the overall dataset in the referenced period) and notes that around 78% of investigated navigation accidents are linked to “human action”, while also emphasizing that this should not be interpreted as simplistic blame but as the endpoint of a complex socio-technical event chain (procedures, bridge teamwork, technology use, workload, organisational factors, etc.). These accidents can escalate into marine environmental damage, especially when they lead to oil spills or cargo losses: once released, pollutants can be transported far from the accident site, since most oils float at the sea surface and can spread over vast areas under the combined action of waves, wind, and currents, creating potentially persistent contamination footprints on coasts and sensitive habitats. Critically, the extent and rate of pollutant release is strongly conditioned by the structural outcome of the accident – e.g., base-structure deformation, rupture at critical joints, and (most importantly for tankers) cargo-tank penetration – because once a tank bounding the shell is breached, oil outflow can be expected due to impact exchange losses and dynamic effects that are further influenced by sea-state conditions. Based on the risk level of the accident phenomena, this work aims to assess the correlation between structural damage to ships resulting from collisions and groundings, pollution, and other related casualties in the maritime environment. Framing this issue through SDG 17 (Partnerships for the Goals) is essential because a single stakeholder cannot achieve meaningful risk reduction: preventing collisions/groundings and limiting pollution consequences requires coordinated partnerships among ship operators, port authorities, coastal states, classification societies, technology providers, and the research community – supported by shared casualty databases, harmonized investigation taxonomies, and the systematic translation of investigation findings into cross-industry corrective actions and safety recommendations.

**Keywords:** ship structure, failure and damage, collision and grounding, environmentally sound technologies, global partnership for sustainable development, international cooperation, marine pollution, evacuation method

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## INFLUENCE OF HYDROGEN SULFIDE AND CARBON DIOXIDE ON THE CORROSION-MECHANICAL PROPERTIES OF STEELS IN CHLORIDE-CONTAINING ENVIRONMENTS

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Corrosion-mechanical degradation of steels and alloys in the presence of hydrogen sulfide, carbon dioxide, and other impurities in working environments is one of the most dangerous forms of damage to structural materials in the oil and gas production and processing industries. Gas-containing solutions in mineralized environments decrease the medium pH, accelerating uniform and localized corrosion of steels and intensive hydrogen absorption, leading to corrosion and mechanical degradation.

This study aims to deepen the understanding of the influence of hydrogen sulfide and carbon dioxide in aqueous environments on the mechanical and tribological characteristics of steels, accounting for corrosion behavior, hydrogen absorption, and mechanical parameters.

The mechanical properties under static and cyclic loading, hydrogen absorption, and tribological characteristics of steels were investigated in a solution of 5 wt.% NaCl + 0.5 wt.% CH<sub>3</sub>COOH, bubbled with mixtures of hydrogen sulfide with argon and carbon dioxide at different partial-pressure ratios.

It was established that the corrosion cracking of the 17Mn1Si steel does not occur in a chloride–acetate solution at a partial-pressure ratio of  $P_{Ar}:P_{H_2S} = 30:1$ . At the same time, the relative reduction in area of the steel is 6-9 times lower than in air, indicating hydrogen embrittlement. Static and asymmetric cyclic loading increase hydrogen absorption by a factor of 2–4, but under static loading at  $\sigma_{max} < 0.8\sigma_{0.2}$  the steel specimens do not fail. Hydrogen-induced cracks initiate in 17Mn1Si steel at a partial-pressure ratio of  $P_{Ar}:P_{H_2S} = 3:1$ , and 1:1, and promote fracture under static and asymmetric cyclic stresses. Considering the different tendencies of corrosion-mechanical degradation of 17Mn1Si steel at partial-pressure ratios of 30:1 and 3:1, it can be assumed that the process is influenced not only by the degree of metal hydrogenation but also by the nature of sulfides formed on the surface and their protective properties.

It is shown that hydrogen sulfide in a chloride–acetate solution reduces the wear resistance of 17Mn1Si steel. At partial-pressure ratios of  $P_{Ar}:P_{H_2S} = 30:1$  and 3:1, the wear resistance of steel decreases by 9%, and at  $P_{Ar}:P_{H_2S} = 1:1$ –by 40% due to its hydrogenation and grain refinement.

The effect of CO<sub>2</sub>–H<sub>2</sub>S gas mixtures in a chloride–acetate solution on the corrosion and mechanical properties of 17Mn1Si steel was investigated. Unlike hydrogen sulfide, carbon dioxide has virtually no effect on the mechanical properties of steel. The relative reduction in the area of the steel decreases with increasing partial pressure of hydrogen sulfide, from  $P_{CO_2}:P_{H_2S} = 30:1$  to 0:1, similar to solutions bubbled with mixtures of H<sub>2</sub>S and Ar. At  $P_{CO_2}:P_{H_2S} = 30:1$ , the corrosion fatigue resistance of 17Mn1Si steel decreases in 2.5–3.2 times, while at  $P_{CO_2}:P_{H_2S} = 3:1$  it decreases in 4.6–5.6 times, compared with a CO<sub>2</sub>-saturated medium.

The crack growth rate in a CO<sub>2</sub>-saturated solution is only about 5% higher than in air, although the incubation period is reduced by more than half. In the presence of hydrogen sulfide, the incubation period of crack initiation is practically absent. At partial-pressure ratios of  $P_{CO_2}:P_{H_2S} = 30:1$  and 3:1, the crack growth rate increases by approximately 1.7 and 4.5 times, respectively. Thus, carbon dioxide does not significantly influence the crack propagation rate, whereas the dominant factor reducing corrosion fatigue resistance and crack resistance in H<sub>2</sub>S–CO<sub>2</sub> environments is hydrogen sulfide partial pressure, caused by the enhanced hydrogen absorption and metal embrittlement.

The wear resistance of 17Mn1Si steel in a chloride–acetate solution bubbled with CO<sub>2</sub>–H<sub>2</sub>S mixtures decreases with increasing H<sub>2</sub>S concentration and exposure time, which is associated with the formation of sulfides of different natures. The formation of mackinawite Fe<sub>1+x</sub>S<sub>x</sub> causes only minor changes in tribological characteristics (10–40%), whereas its transformation into hard acicular troilite (FeS) leads to a 2–3-fold increase in wear due to the activation of an abrasive wear mechanism.

Thus, hydrogen sulfide plays a major role in reducing the corrosion fatigue resistance, crack resistance, and wear resistance of 17Mn1Si steel in hydrogen sulfide-carbon dioxide-containing environments.

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**THE ESIS TC10 COMMITTEE ON ENVIRONMENTALLY ASSISTED CRACKING AND  
HYDROGEN EMBRITTLEMENT**

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This paper reviews the history of the Technical Committee 10 (TC10) of the European Structural Integrity Society (ESIS). The ESIS TC10 is devoted to scientific research and technical development in the matter of fracture and structural integrity issues in the field of environmentally assisted cracking (EAC) or stress corrosion cracking (SCC) in general and hydrogen embrittlement (HE) in particular, the latter concept associated with different deterioration phenomena such as hydrogen degradation (HD), hydrogen assisted micro-damage (HAMD), hydrogen assisted cracking (HAC) or hydrogen assisted fracture (HAF).

*In Memoriam:* The paper is dedicated to the memory of Dr. Wolfgang Dietzel, the first ESIS TC10 Chairman, a prominent scientist and excellent friend, who passed away in 2018.

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## EFFECT OF HYDROGEN DAMAGE ON THE FRACTURE BEHAVIOUR OF FERRITE-PEARLITE STEELS

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Hydrogen gas is increasingly recognized as a promising energy carrier for a low-carbon transition, with existing natural gas pipeline infrastructure offering a cost-effective means to store and transport hydrogen. Nevertheless, atomic hydrogen can reduce toughness and facilitate crack initiation and propagation in steels, leading to hydrogen damage, primarily hydrogen embrittlement. Existing infrastructure was not designed for high-pressure hydrogen, and its suitability for such service requires careful assessment. During long-term operation, pipeline steels become more susceptible to hydrogen-assisted degradation. The hydrogen properties of API 5L X67 ferrite-pearlite pipeline steel are investigated in this study. The influence of hydrogen on the mechanical behaviour is evaluated by tensile and fracture toughness tests on uncharged and hydrogen-charged specimens. Hydrogen charging is performed electrochemically, and hydrogen concentration in the metal is also considered. The investigation compares hydrogen damage properties in API 5L X67 pipeline steel, accounting for long-term operation.

**Keywords:** steel, pipeline, mechanical properties, fracture toughness, J-integral method, hydrogen embrittlement, degradation

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## FINITE ELEMENT ANALYSIS OF RESIDUAL STRESSES AND PLASTIC DEFORMATION IN SURFACE-MODIFIED LAYERS OF LOW-ALLOY STEELS FOR HYDROGEN PENETRATION BARRIERS

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The operational reliability of low-alloy steels in hydrogen infrastructure systems depends significantly on the intensity of hydrogen penetration into the material volume and the conditions of its localization in near-surface areas and near stress concentrators, both of which are directly related to the risk of hydrogen embrittlement. The controlled physico-mechanical modification of the base metal to form a functional near-surface layer without external coatings is a promising approach to reduce hydrogen charging. A defect-dislocation structure in such a layer can act as a hydrogen traps, reducing its effective penetration into the material. The barrier capacity of the surface-modified zone is determined by its thickness, the level of accumulated plastic deformation, and the residual stress field formed after unloading; these parameters can also significantly influence the spatial redistribution of hydrogen.

A numerical approach based on the finite element method (FEM) for quantitative reproduction of the stress-strain state and residual stresses in a surface-modified layer formed by the controlled surface plastic action is proposed in the paper. The calculation scheme is based on nonlinear elastic-plastic analysis with a mandatory "loading–unloading" sequence, which ensures the correct formation of residual stresses. Depending on the surface treatment mode, the problem is formulated in several equivalent variants: (i) indentation of a rigid indenter with controlled displacement; (ii) application of local distributed pressure or contact with a rigid roller on a limited area of the surface; (iii) thermomechanical influence, simulated by a given temperature gradient with subsequent cooling. The behavior of the steel is described by an elastic-plastic model with isotropic hardening, with the model parameters set based on the experimental deformation diagram. The refinement of the finite element mesh near the surface and the load application zone is used to correctly reproduce the high gradients of deformation and stresses in the near-surface area.

Postprocessing is performed after the model is fully unloaded. The data normal to the surface, in particular the distribution of equivalent plastic deformation and selected stress components, which are important for assessing hydrogen transfer conditions, are analyzed. The effective thickness of the modified layer is determined by a single criterion, for example, as the depth at which the equivalent plastic deformation decreases below a given threshold level. This approach ensures the correct comparison of results in a series of calculations.

In a parametric study, the intensity of the surface action (depth or force of indenter contact, level of applied pressure, number of passes, or equivalent parameters) is changed. The quantitative dependencies of the type "processing intensity – thickness of the modified layer – deformation level" are established. The residual stresses at the surface and their depth-dependent changes are also estimated.

A FEM model of the near-surface modified layer formation, which can be used for further combination with hydrogen transfer models and for experimental verification, is the expected result of the study. The obtained dependences allow selecting the modes of surface plastic treatment to create barriers to hydrogen penetration in low-alloy steels.

### Acknowledgment



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## CORROSION INHIBITION OF ALUMINIUM ALLOY BY SODIUM ALGINATE–ZINC ACETATE COMPOSITION UNDER MECHANICAL SURFACE ACTIVATION IN CHLORIDE ENVIRONMENT

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The protective properties of a sodium alginate–zinc acetate composition were investigated under mechanical activation of the aluminium alloy surface in a chloride environment. Mechanical activation of the metal surface in a corrosive environment was carried out using a reciprocating indenter on a tribological setup operating under a “ball-on-flat” friction scheme.

It was shown that, under friction conditions, the proposed composition promotes the formation of a protective film on the alloy surface, with improved antifriction properties and greater mechanical durability than the native oxide film. As a result, the friction coefficient decreases approximately twofold, while the polarization current is reduced by a factor of three, indicating effective suppression of metal ionization processes and reduced wear intensity. Scanning electron microscopy of the aluminium alloy surface after corrosive wear confirmed the protective action of the composition. The wear track width decreased in 1.3 times in the inhibited medium compared to the control solution. According to profilometric analysis, the highest values of wear track surface microroughness were observed after testing the aluminium alloy in the uninhibited solution.

The formation of a protective film consisting of alginate complexes with  $Al^{3+}$  and  $Zn^{2+}$  cations on the aluminium alloy surface was confirmed using micro-X-ray spectroscopy. Thus, the investigated composition is promising for protecting aluminium alloy structures operating under corrosion–mechanical degradation.

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## CORROSION AND TRIBOCORROSION INHIBITION OF ALUMINUM ALLOY IN CHLORIDE-CONTAINING ENVIRONMENT BY A SYNERGISTIC MALTODEXTRIN-BASED COMPOSITION

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Corrosion–mechanical degradation is a key factor limiting the durability of aluminium alloy structures operating under simultaneous mechanical loading and aggressive environmental conditions. Tribocorrosion processes are particularly detrimental, as they lead to local destruction of the protective oxide film, thereby intensifying anodic metal dissolution and promoting the formation of microdamage that subsequently serves as crack initiation sites. Given the toxicity of conventional synthetic corrosion inhibitors, the development of environmentally friendly “green” alternatives has become an urgent challenge. The use of biopolymers and organic complexes enables the formation of stable adsorption layers on alloy surfaces, providing effective protection while minimising environmental impact.

This study investigates the inhibition of corrosion and tribocorrosion of AA2024 aluminium alloy using a synergistic composition based on maltodextrin and zinc gluconate in a chloride-containing environment. Potentiodynamic polarisation, electrochemical impedance spectroscopy, scanning electron microscopy, energy-dispersive X-ray spectroscopy, and optical 3D profilometry were employed. An optimal component ratio in the inhibitory formulation was identified, at which the corrosion inhibition efficiency of the aluminium alloy reaches approximately 90%.

It was demonstrated that the “maltodextrin + zinc gluconate” system significantly suppresses tribocorrosion processes: the friction coefficient of the “aluminium alloy/corundum” tribological pair decreases by nearly threefold, while the wear track width is substantially reduced. Electrochemical measurements within the wear zone indicate a marked deceleration of corrosion kinetics, particularly evidenced by an approximately sixfold increase in polarisation resistance in the presence of the inhibitory composition. Post-tribological analysis revealed the reduction in surface roughness parameters, indicating the formation of a protective surface layer and stabilisation of the tribological contact.

Overall, the results confirm the effectiveness of the biopolymer-based inhibitory composition in mitigating tribocorrosion-induced degradation of aluminium alloys. The observed reduction in tribocorrosion intensity is considered a critical factor in enhancing structural integrity and potentially delaying crack initiation and propagation in structures operating in aggressive environments.

### Acknowledgment



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**SECTION IV:**  
**MATHEMATICAL METHODS AND**  
**FRACTURE MODELLING**

## COMPRESSION OF A HYPERELASTIC MATERIAL WITH A THIN COATING ALONG DEFECTS ON THE INTERFACE

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Using the relations of the three-dimensional linearized theory of stability of deformable bodies, plane strain problems on the compression of bilayer systems along a crack and along a smooth sliding zone located on the interface of two rigidly connected media – a semi-infinite substrate and a thin coating layer – are investigated. The materials of the substrate and coating are considered to be nonlinearly elastic (hyperelastic) compressible or incompressible materials with an arbitrary structure of their elastic potentials.

The proposed semi-analytical method for determining critical compression loading parameters consists of using representations of general solutions to the linearized equilibrium equations to transition from the original boundary value problems to boundary value problems formulated in terms of potential harmonic functions – the components of these representations. Using the Fourier integral transform technique, the specified boundary value problems are reduced to an integral equation (in the case of an interfacial smooth sliding zone) or to a system of Fredholm integral equations of the first kind (in the case of an interfacial crack), which are investigated numerically. At the same time, the unknown loading parameter – the critical value of relative contraction, which corresponds to the loss of stability of a part of the material in the defect area – enters the kernels of the integral equations in a complex nonlinear manner.

Critical loading parameters are determined for a number of one- and two-parameter constitutive models, and the nature of their dependence on the mechanical parameters of the bilayer system and on the relative thickness of the coating layer is studied. The influence of the elastic potential structures of the body materials and of the loss of contact between the faces of the interfacial defect on the values of these parameters is investigated. In the case of an interfacial crack, the limits of applicability of known approximate formulas are examined.

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## MATHEMATICAL MODELS OF 3D TIME-HARMONIC ELASTICITY OF ANISOTROPIC SOLIDS WITH THREAD-LIKE ELASTIC INHOMOGENEITIES

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This study is devoted to the mathematical modeling of three-dimensional time-harmonic elasticity problems for solids containing thread-like elastic inhomogeneities. Such problems arise in the analysis of modern composite and textile materials, where thin reinforcing elements interact with an elastic matrix and significantly affect the structure's dynamic response. The presence of thread-like inhomogeneities leads to substantial mathematical challenges, since their transverse dimensions are much smaller than their characteristic length. Although this disparity in scales justifies the use of reduced-dimensional models, their application raises additional difficulties beyond the construction of sufficiently accurate mathematical models, including the solution of the corresponding elasticity problems and the interpretation of the results.

In this study, the inhomogeneities are described within the framework of the coupling principle for continua of different dimensions. The surrounding medium is modeled as a three-dimensional elastic continuum, while each thread-like inhomogeneity is represented by a one-dimensional line carrying an unknown distribution of interaction forces. The mechanical behavior of the inhomogeneities is governed by the dynamic theory of curved elastic rods subjected to these forces.

The analysis is restricted to spatial problems of steady-state, time-harmonic oscillations. The governing equations of three-dimensional elasticity are formulated in the frequency domain, and the interaction with inhomogeneities is introduced via line distributions of forces, acting as generalized boundary conditions. As a result, the boundary value problem for the elastic medium is ill-posed in the classical sense, since boundary conditions are prescribed on lines rather than on surfaces.

To overcome this difficulty, the boundary integral equation method is employed. The displacement field in the elastic medium is represented in terms of dynamic fundamental solutions, leading to integral equations defined along the centerlines of the thread-like inhomogeneities. Due to the reduced dimensionality of the inclusions, the corresponding integrals are singular and generally divergent. Therefore, a regularization procedure is required.

A regularization methodology is proposed that explicitly accounts for the finite, though small, thickness of the thread-like inhomogeneities. The Hadamard theory of finite-part integrals is employed, enabling the extraction of physically meaningful finite values. A computational procedure for the numerical evaluation of the regularized integrals is developed.

The formulation is written for three-dimensional time-harmonic problems for anisotropic elastic media with thread-like inhomogeneities. The corresponding integral equations for the unknown force distributions are derived. It is shown that the kernels of these equations can be decomposed into static singular and dynamic regular parts, so that the singular contribution is evaluated in the same manner as in static problems.

A numerical solution strategy based on the boundary element method is constructed, and several numerical examples are presented. The proposed approach is applicable to the analysis of advanced composite and textile materials, including problems of fiber–matrix interaction and fiber debonding under dynamic loading. The combination of the method with the discrete Fourier transform also enables the analysis of certain non-stationary problems for elastic bodies with thread-like inhomogeneities.

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## MULTIPLE ELECTRICALLY CHARGED CONDUCTING CRACKS AT THE INTERFACE OF TWO QUASICRYSTALS

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A system of collinear cracks along the interface of two coupled one-dimensional piezoelectric quasicrystalline half-spaces is considered. The cracks are assumed to be electrically conductive, and an electric charge can be prescribed at each crack. The quasiperiodic axis, as well as the axis of polarization, is co-directed with the crack fronts. Remote uniformly distributed antiplane phonon and phason shear stresses are given, and the electric field acts in the plane perpendicular to the crack front. Matrix-vector representations of all required field variables through a vector function that is holomorphic in the entire complex plane, except for the crack region. Transforming these representations similarly to [1], the problem of the linear relationship is formulated on segments coinciding with the crack regions. The solution to this problem is obtained in analytical form. Based on this solution, analytical expressions for phonon, phason, and electrical components are obtained for different parts of the material interface. It is found that the obtained solution exhibits an oscillatory root singularity near the crack tips. The energy release rate at each crack tip is obtained analytically. Numerical analysis carried out for different numbers of cracks demonstrated their interaction and the dependence of global and local fracture parameters on mechanical and electrical remote loading, as well as on the prescribed crack charge.

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**LOCAL AND INTEGRAL ASSESSMENTS OF THE LIMIT EQUILIBRIUM OF A BENT  
CYLINDRICAL SHELL WITH CIRCUMFERENTIAL  
COLLINEAR CRACKS**

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The stress state and limit equilibrium of an isotropic cylindrical shell weakened by two collinear circumferential cracks are investigated with consideration of edge contact under bending loading. Crack closure due to bending deformation was accounted for using a model of contact between the crack edges along a line on one of the shell faces. A boundary-value problem for the equations of the theory of shallow shells with interconnected boundary conditions along the contours of defects was formulated. The numerical solution of the problem was constructed by the method of singular integral equations. Local and integral energy criteria of linear fracture mechanics were used to analyze the limit state of the shell. These criteria determine, respectively, the lower and upper values of the limit load at which stable crack growth begins and avalanche-like shell failure occurs. Dependences of limit loads on the dimensionless parameters of the distance between defects and shell curvature were constructed.

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## ON THE STRESS STATE OF THE POROELASTIC CYLINDER WITH A THIN INTERFACE

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The poroelastic cylinder ( $0 < r < 1$ ,  $0 < z < h$ ,  $-\pi < \varphi < \pi$ ) is considered in terms of Biot's framework. It consists of two main parts  $\Omega_- = \{0 < r < d - h_0/2, 0 < z < h\}$ ,  $\Omega_+ = \{d + h_0/2 < r < 1, 0 < z < h\}$ , and a thin interface  $\Omega_0 = \{d - h_0/2 < r < d + h_0/2, 0 < z < h\}$ , where  $h_0 \ll d$ . The cylinder's edges are impermeable under sliding contact conditions. The cylindrical surface is loaded.

The assumptions about poroelastic constants of the cylinder's main parts and the interface made it possible to consider 8 basic and 10 auxiliary cases of the transmission conditions between the parts  $\Omega_-$  and  $\Omega_+$ . These conditions were derived using the asymptotic method.

The original problem was reduced to one-dimensional vector boundary value problems for  $\Omega_-$  and  $\Omega_+$ , and transmission conditions between them with the help of finite sine- and cosine-Fourier transform. The general solutions to these problems were constructed using the matrix differential equation solver. The unknown constants were found from the boundary and transmission conditions. The application of the inverse integral transform completed the construction of the problem's solution for each of 18 cases.

The numerical results showed a qualitative difference in most of the considered transmission conditions compared with the classical ideal-contact conditions, which underscores the relevance of the conducted research.

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## EXTENDED METHOD OF MATCHED SECTIONS FOR MODE I CRACK IN ELASTIC PLANE BODY

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Method of matched sections, MMS, is an emerging technique for numerical treatment of multiphysics problems formulated in terms of particular differential equations. The main idea of MMS is to reduce the difficult task of mathematical physics to a set of ordinary differential equations by introducing auxiliary constants that characterize the interactions between the governing parameters in different directions. The unknown auxiliary constants are derived from the continuity requirements at the conditional center of the element. Thus, the prominent advantage of the MMS is that the exact equilibrium of the element and the whole body is satisfied – a property that is highly demanded but is still unattainable in traditional FEM. The main prerequisite for MMS is a good understanding of the 1D problem we want to reduce our 2D or 3D problems.

The MMS is similar to the finite element method (FEM). Like FEM it envisages the following five steps: (1) Preprocessing: subdividing the problem domain into finite elements; (2) Element formulation: development of equations for elements; (3) Assembly: obtaining the equations of the entire system from the equations of individual elements; (4) Solving the equations; (5) Postprocessing: determining quantities of interest and obtaining visualizations of the response". The same can be said about MMS, where the element formulation is, of course, the core of the method. So, in FEM, the unknown parameters are prescribed at the nodes (vortexes) of the elements where the continuity and (approximately) equilibrium are provided. On the contrary, in the MMS, all unknown parameters are prescribed to the middle of each side (borders between neighboring elements). The essence and number of the unknown (governing) parameters on each side are identical to those of their 1D counterparts. A lot of successful applications of MMS to bending and vibration of plates, transient heat problem, torsion of the rod, plane body deformation – all this testify to its great potential and prospects.

This paper is a further development of the method and is devoted to enhancing the plane body analysis to account for cracks. The parameter of interest is the stress intensity factor, SIF. Similar to extended FEM, we introduce in MMS the special element which embrace the crack tip. The salient feature of this element is the accounting for the well-known first term in the theoretical Williams crack tip solution series. This special element borders on the sides of many smaller regular elements, where, according to the previously proposed "merging and division" capacity, this special (extended) element predetermines the kinematic parameters in them, and the force parameters at these sides are integrally equilibrated by force and moment within the extended element. Numerical tests on symmetric 2D cracked bodies demonstrate the accuracy and efficiency of the proposed (extended) X-MMS.

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### 3D THERMOELASTIC MODELING OF QUASICRYSTALLINE SOLIDS CONTAINING THIN SHELL-LIKE COMPLIANT INHOMOGENEITIES

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Quasicrystalline coatings are widely used to improve the tribological properties of engineering components. Due to imperfections in manufacturing processes, these coatings may contain cracks, microcracks, and internal thin inclusions within the quasicrystalline layer. In this study, the coating material is modeled as a three-dimensional quasicrystalline solid containing thin, shell-like elastic inhomogeneities that represent these internal defects. Understanding the thermoelastic response of such materials, including the interaction between the quasicrystalline matrix and embedded defects, is crucial for predicting their mechanical performance and durability.

The governing equations of three-dimensional thermoelasticity in quasicrystals are formulated in terms of extended vectors and tensors, providing a unified description of mechanical and thermal fields. These extended fields include both phonon and phason components, thus capturing the full physical behavior of the quasicrystalline medium. Using the theory of generalized functions and the Radon transform, the resulting singular integral equations are derived in a form that avoids volumetric temperature integrals, in contrast to classical formulations, thereby offering significant advantages for the practical implementation of the boundary integral equation method.

To model the medium with shell-like inhomogeneities, the coupling principle for continua of different dimensions is applied. Each compliant shell-like inclusion is replaced by a surface representing jumps in the thermoelastic fields within the material. Since this is a two-dimensional surface, the corresponding boundary value problem is well-posed. The compliant inclusions are modeled using a simplified spring-type interface, which allows the consideration of partially plastic or flexible behavior.

This approach also enables the modeling of cracks, including interactions between crack faces and partially healed cracks. In all cases, the phonon and phason stress fields near the front of the inhomogeneity exhibit square-root singularities. A modified boundary element method that incorporates special shape functions to account for this singular behavior is proposed to solve these problems. These functions enable accurate computation of field characteristics along the inhomogeneity's frontal line, including phonon–phason stress intensity factors.

Furthermore, relationships are established between these stress intensity factors and the stress concentration coefficients for rounded inhomogeneities, accounting for the front rounding radius. This provides a consistent way to analyze the effect of geometric and material features of the inclusions on the local stress fields. The approach enables a direct evaluation of the influence of shell-like inclusions and cracks on the overall thermoelastic response of quasicrystalline solids.

Numerical examples are presented to demonstrate the applicability of the proposed methodology. The results show how the presence of compliant inclusions and cracks affects both phonon and phason stress distributions. The method allows the analysis of various configurations, including interacting defects and inhomogeneities of different shapes. Accurate determination of stress intensities and local field variations is achieved using singular boundary elements with adapted shape functions.

The developed framework is particularly relevant for the design and analysis of quasicrystalline coatings in tribological applications, when the coating material can be treated as a three-dimensional quasicrystalline solid. It provides a reliable tool for predicting the influence of internal manufacturing defects, such as microcracks and thin inclusions, on the coating material's thermoelastic response and overall performance.

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## CRITICAL HYDROGEN ACCUMULATION AND FAILURE IN BIMETALLIC JOINTS DURING THERMAL CYCLING

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A computational and experimental procedure for determining the critical hydrogen concentration in a bimetallic compound was considered. The experimental part of the procedure consisted of hydrogenation of cylindrical samples with cladding in an autoclave. The experimental conditions and results meet the requirements of ASTM G146-01 for bimetallic compounds and for operating conditions of oil hydrocracking reactors. After cooling, the development of damage in the samples was monitored using acoustic emission. The time of the beginning of crack formation was established.

The computational part of the procedure consisted of solving the FEM problem of heat and mass transfer for a cylindrical bimetal sample. An example of numerical modeling of hydrogen redistribution in a bimetal due to non-stationary thermal effects is given. It was found that heat exchange alters hydrogen diffusion in bimetallic structures, leading to non-equilibrium hydrogen oversaturation in the local volumes of the fusion zone. The reliability of surfacing here depends on the kinetics of thermal processes. The hydrogen concentration in the fusion zone, critical for the integrity of the bimetallic compound, has been established.

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## STRESS STATE AND LIMIT EQUILIBRIUM OF A TWO-LAYER COATING UNDER LOCAL LOADING NEAR THE EDGE

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The elastic and limit equilibrium of a composite coating composed of an external rigid layer and an interface flexible layer are studied. The conditions of plane deformation under local loading near the free edge of the coating are considered. An engineering model is developed in which the rigid layer is treated as a plate in bending, and the soft layer is modeled according to the Winkler hypothesis. Violation of the structural integrity of the composition is assessed using the von Mises criterion recorded for each component.

The influence of the distance from the indenter to the edge on the stress state and bearing capacity of the coating is investigated. A detailed analysis is carried out for a ceramic coating formed by oxidation of sputtered aluminum.

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## ANALYSIS OF NATURAL VIBRATIONS OF A SHELL WITH A CRACK

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The vibrations of a combined shell, which is a combination of a cylindrical shell and a hemisphere, were investigated (Fig.1). The shell thickness is 4 mm. Boundary conditions are set as rigid fixation on the open contour. The shell material is structural steel.

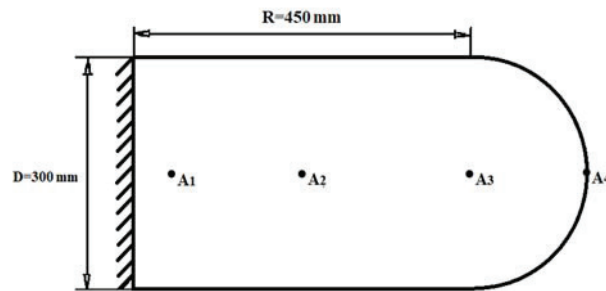


Fig.1

In Fig.1, points A1, A2, A3, and A4 indicate the locations of different variants of cracks for which calculations were performed.

Various variants of through cracks are investigated, with lengths ranging from 50 mm to 200 mm and rotated at angles of  $0^\circ$ ,  $45^\circ$ , and  $90^\circ$  relative to the open contour.

The diagram (Fig. 2) shows the dependence of the magnitudes of the natural vibration frequencies (for example, the 11th frequency at which resonance is observed) on the location and angle of rotation of the crack. Fig.3 shows the dependence of these natural vibration frequencies on the crack length (for example, a crack at point A2 is considered).

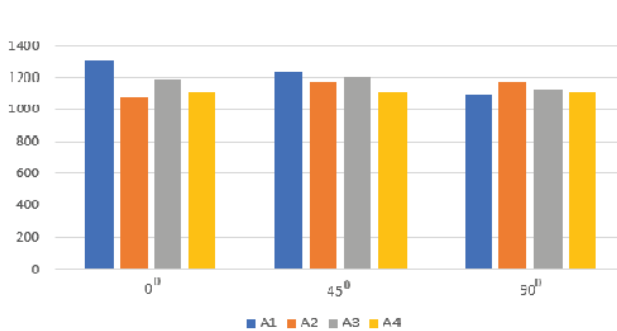


Fig.2

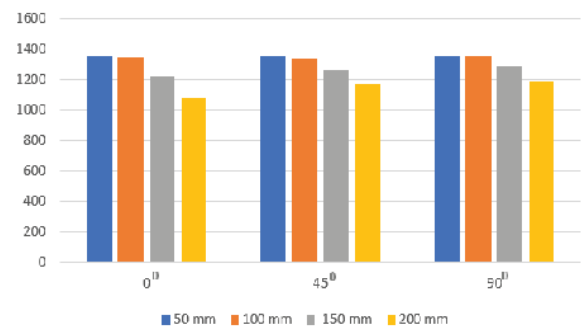


Fig.3

As shown, the vibration frequency of the shell with a crack near the attached edge (point A1) decreases with increasing rotation angle of the crack. At the same time, for the variants with cracks in zones A2, A3, and A4, the natural vibration frequencies show only small changes. Increasing crack length decreases the vibration frequency.

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## TREE-BASED MACHINE LEARNING FOR FATIGUE CRACK GROWTH PREDICTION OF TITANIUM ALLOY STRUCTURAL ELEMENTS

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The prediction of fatigue crack growth (FCG) is one of the key tasks for ensuring the reliability and safety of structural elements operating under cyclic loading conditions. Classical analytical approaches often have limited capacity to adequately describe the nonlinear nature of crack evolution under different loading conditions. In this work, tree-based machine learning methods, namely random forest and boosted tree regression models, were used to predict fatigue crack length.

The input parameters for the models were the number of loading cycles  $N$  and the stress ratio  $R$ , while the crack length  $a$  was considered as the output variable. The models were trained and tested on experimental fatigue crack growth data for different values of the stress ratio  $R$ . The effectiveness of the models was evaluated using the mean absolute error (MAE), mean square error (MSE), coefficient of determination ( $R^2$ ), and mean absolute relative error (MAPE) metrics.

The results of the study showed that both tree models provide high accuracy in predicting crack length over a wide range of loading cycles. Fig. 1a shows that the random forest model demonstrated stable prediction quality across all stages of crack growth, whereas the boosted trees method in Fig. 1(b) achieved higher accuracy in the accelerated growth zone. Analysis of the importance of input parameters confirmed the dominant influence of the number of loading cycles and the modifying role of the stress ratio  $R$ .

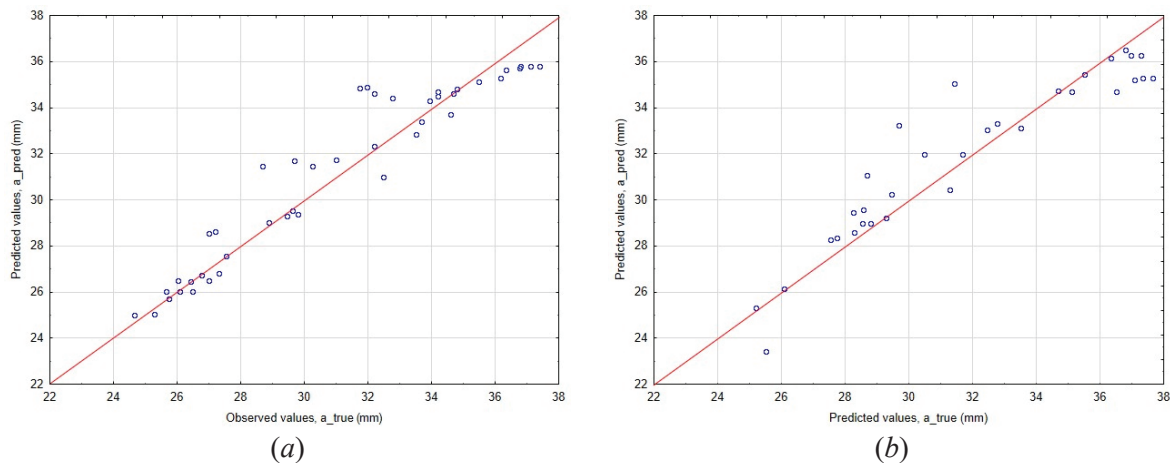


Fig. 1. Comparison of experimental crack length  $a$  and predicted, obtained by methods of:  
(a) random forest; (b) boosted trees for the test dataset.

The results obtained demonstrate the effectiveness of tree-based machine learning methods for interpreted prediction of fatigue failure of structural materials.

**Keywords:** fatigue crack growth, stress ratio, machine learning, boosted trees, random forest

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## RESIDUAL BEARING CAPACITY OF LAYERED SHELLS AND PLATES WITH DAMAGES AT THE INTERFACE OF COMPONENTS

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Shells and plates are integral elements of modern structures in aerospace and various branches of mechanical engineering. Quite often, their operational purpose requires a layered structure in terms of thickness. The specific functional purpose of each component determines the specific physical and mechanical characteristics of that component. Therefore, determining the bearing capacity of such structures requires discrete consideration of each component and separate modeling of its stress-strain state [3].

The bearing capacity resource of layered structures depends largely on the state of contact interaction at the interface of the components [1, 3]. The nature of this interaction is determined by both the completeness of the requirements for technological processes and the long-term effects of intensive operational power and temperature loads [2].

Based on the previously proposed and verified version of the refined theory of composite shells, a new mixed scheme of the finite element method for calculating layered structures has been developed. The essence of the scheme is to specify both displacements and interlayer contact stresses as nodal unknowns in two-dimensional finite elements, dividing the medial surface of each component. This allows for accounting for the presence or appearance of interlayer damage of technological or operational origin. The proposed scheme was tested. A high-pressure balloon with an interlayer defect between two macro layers is considered. Its holding capacity under various loads is evaluated.

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## **TIME-DEPENDENT PROPAGATION OF A COIN-SHAPED CRACK IN A VISCOELASTIC SOLID WITHIN A COHESIVE-ZONE FRAMEWORK**

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The paper presents a computational study of time-dependent crack propagation in a three-dimensional viscoelastic solid, with particular emphasis on the evolution of a coin-shaped (penny-shaped) crack under sustained loading. The analysis is motivated by long-term fracture processes in polymeric and composite structural elements, where crack growth may occur as a result of stress relaxation rather than instantaneous failure.

Crack propagation is modeled within a cohesive-zone framework embedded into a finite-element formulation. A cohesive interface with a finite process zone is introduced along the crack surface and is governed by a trapezoidal traction–separation law, allowing gradual damage accumulation and a smooth transition from intact material to fully separated crack faces. The viscoelastic behavior of the bulk material is described by incremental constitutive relations with internal variables updated analytically at each step.

A key feature of the proposed approach is the implicit determination of the physical time increment associated with crack evolution. Instead of prescribing an artificial time step, the physical time increment is obtained by solving a nonlinear scalar condition that matches the applied external stress with the crack-front stress level obtained from the viscoelastic equilibrium solution for a prescribed crack length and damage state. This condition is solved using a robust root-finding procedure, which directly links the crack-growth process to the intrinsic relaxation properties of the material.

Crack advance is controlled by a local opening-based damage criterion evaluated at the crack front. The computational procedure proceeds through a sequence of quasi-static equilibrium states, explicitly tracking the crack front without introducing ad hoc remeshing or phenomenological crack-growth laws. Numerical results reveal the presence of an incubation stage with stationary crack geometry, followed by stable quasi-static crack propagation driven by viscoelastic relaxation.

The evolution of crack-opening profiles, stress redistribution near the crack front, and the resulting time–radius relationship are analyzed in detail. The results demonstrate that the proposed framework provides a physically consistent and numerically stable tool for investigating delayed fracture and long-term crack propagation in viscoelastic materials.

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## **CLOSURE OF CRACK IN SEMI-INFINITE TRANSVERSELY INHOMOGENEOUS PLATE UNDER BENDING**

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The problem of contact interaction of faces of a through crack during bending of semi-infinite functionally graded through-thickness plates is considered in a two-dimensional formulation. Based on the rigid normal hypothesis, the incomplete through-thickness crack closure is interpreted as the joining of crack faces at the outer surface of the plate (model of contact along a line).

A boundary value problem is formulated for a pair of biharmonic operators in domains with cuts corresponding to such a model. The asymptotic and numerical solutions of singular integral equations are constructed for a semi-infinite plate with a symmetrical structure containing a rectangular crack oriented perpendicularly to the free edge.

The influence of material inhomogeneity and the location of a defect on the magnitude of stress intensity factors and the distribution of contact reactions on the closed crack faces is analyzed. The destructive load level was also determined using both integral and local failure criteria.

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## HOT CRACK PREDICTION IN LASER WELDING BASED ON STRAIN FIELD ANALYSIS USING DIGITAL IMAGE CORRELATION

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This work is dedicated to investigating the mechanisms of hot cracking in weld seams during laser welding. Digital Image Correlation (DIC) combined with the Controlled-Tensile-Weldability (CTW) test was employed to analyze deformation kinetics. Experimental studies were conducted within the critical temperature range of 800–1300°C. To visualize the surface under intense thermal radiation, a speckle pattern was generated using external laser illumination (active lighting), resulting in high image contrast.

Special attention was paid to the transient nature of the process and to minimizing optical noise. During the study, DIC algorithm parameters were optimized to achieve high displacement measurement accuracy in a dynamic, high-noise environment. The measurement results revealed that an intensive accumulation of local transverse strains precedes crack initiation. An empirical dependency was established between hot crack occurrence and the combination of strain rate and maximum strain during the CTW test. The obtained data demonstrate the feasibility of effective hot crack prediction in materials during the solidification stage based on local strain field analysis. The proposed approach is universal and can be applied to optimize parameters for laser welding, cladding, and additive manufacturing, as well as to enhance the structural integrity of critical joints.

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## **ENERGY APPROACH IN FRACTURE MECHANICS AND LIFE OF STRUCTURAL ELEMENTS**

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The issue of the safe operation of power equipment elements, facilities of the chemical and petrochemical industries, nuclear power plants, and pipeline transport remains one of the most urgent, given that a significant part of such equipment in Ukraine has already exhausted or is approaching exhaustion of its calculated resource. The paper develops a general energy-based approach for assessing the residual life of structural elements under static, cyclic, and maneuver loads, in combination with aggressive environments (hydrogen-containing and corrosive-active environments, elevated temperatures, radiation exposure, and their combinations). Some basic principles of physical chemistry and physics were used in developing the approach. The general energy-based approach is founded on a mechanical analogue of the first law of thermodynamics – the balance of energy components formulated for an elementary fracture event (crack jump), as well as the balance of the energy components change rates. Its universality lies in the fact that if, for a given problem, it is possible to formulate a balance of energy components, then that problem can be solved within this approach. The proposed approach enables the construction of an appropriate mathematical model for a specific operating case as a differential equation with initial and final conditions. The solution of such a model allows for determining the residual life of the considered structural element under given operating conditions.

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## STRENGTH OF AN ANISOTROPIC ELASTIC-PLASTIC BODY WITH A FILLED CRACK UNDER TRANSVERSE SHEAR

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Let an infinite anisotropic elastic–plastic body contain an inclusion (a filled crack) with a smooth, flattened surface symmetric with respect to the plane  $y=0$ . At infinity, the body is loaded by monotonically increasing shear forces that are skew-symmetric with respect to the plane  $y=0$ . As the load increases, shear stresses concentrate near the inclusion edges; upon reaching the shear yield limit, a zone of inelastic deformation (a plastic core) is formed, surrounded by elastically deformed material (Fig. 1).

Considering the small thickness of the filler, the “body–inclusion” contact is modeled by a shear (Winkler-type) relation that links the interfacial shear stresses to the displacement jump across an effective interlayer thickness.

After transferring the boundary conditions to the crack axis and applying the superposition principle, the boundary-value problem is reduced to a singular integro-differential equation for the unknown distribution of the displacements of the cut faces. For an elliptical inclusion geometry and the adopted plasticity localization scheme, an approximate analytical solution is obtained, enabling the determination of the plastic zone sizes and the evaluation of the influence of system parameters.

In particular, from the requirement that stresses remain bounded at the ends of the cut, the size of the plastic zone in the direction of the axis  $x$  was obtained.

A parametric analysis of the role of the inclusion relative stiffness and its geometry in the evolution of pre-fracture zones was performed; it is shown that as the filler stiffness increases, the sizes of the plastic zones decrease (Fig. 2). The limiting load was determined from the condition that the critical opening is reached at a characteristic point  $2u_x(a) = \delta_{IIc}$ .

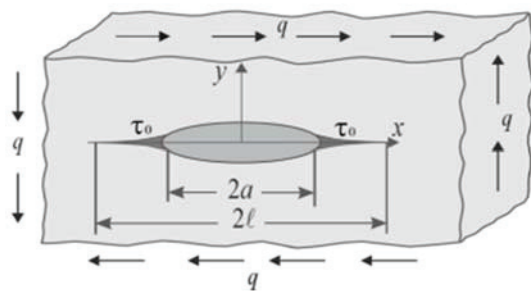


Fig. 1. Filled crack (inclusion) and plastic zones under transverse shear

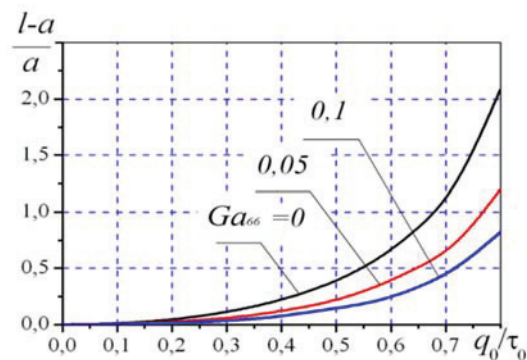


Fig. 2. Effect of the external load and the relative stiffness of the inclusion on the size of the plastic zones

The obtained relations can be used for engineering assessment of the residual strength of anisotropic elements with “healed” defects and for selecting filler parameters (stiffness, thickness, shape) that ensure the maximum reduction of stress concentration and an increase in the limiting load under transverse shear.

**Keywords:** anisotropic body, transverse shear, filled crack, fracture mechanics

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## HEALING OF A PENNY-SHAPED CRACK IN A CONTINUOUSLY NONHOMOGENEOUS MATERIAL UNDER TENSION

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A nonhomogeneous material has properties that vary as a function of position in the body. The mathematical theory of cracks in continuously nonhomogeneous materials is of particular importance, since the variation of mechanical properties along one coordinate is characteristic of many modern materials, which is associated with the conditions of their manufacture and operation.

The object of the study is an isotropic cylindrical body containing a penny-shaped crack of radius  $a$  located in the plane  $z=0$  of the rectangular Cartesian coordinate system  $(x, y, z)$  (Fig. 1). It is assumed that the shear modulus  $\mu$  is a continuous function of the coordinate  $z$ , namely  $\mu(z) = \mu_0|z|^n$ ,  $n \geq 0$ .

The Poisson's ratio  $\nu$  is assumed to be constant. The external loading is taken as a uniform tensile stress of intensity  $p$ , applied symmetrically with respect to the crack plane. Let the crack be healed by an injected material which, after hardening, bonds the crack surfaces and forms an interlayer of thickness  $2h(x, y)$ .

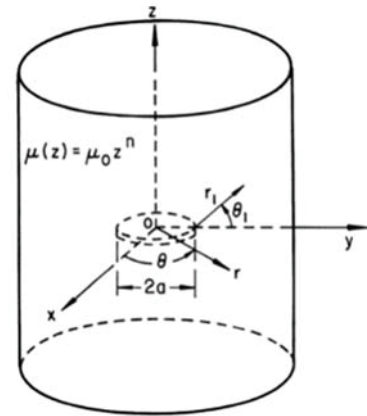


Fig. 1

The boundary conditions of the problem, formulated using the Winkler model for a thin elastic interlayer, are given by:

$$\sigma_z(r, 0) = -p + u_z(r)E_1/h(r); \quad r < a, \quad u_z(r, 0) = 0, \quad r \geq a. \quad (1)$$

$E_1$  – the Young's modulus (tensile modulus of elasticity) of the injection material. By applying Hankel integral transforms to the equilibrium equations expressed in terms of displacements, together with the boundary conditions (1), the problem is reduced to solving a Fredholm integral equation of the second kind with respect to the function  $u_z(r)$ . The numerical solution of this equation is obtained using the quadrature method.

The asymptotic expression for the stress  $\sigma_z$  in the vicinity of the crack contour, it can be represented by the following relation:  $\sigma_z(r, 0) = k_1/(2r_1)^\beta + O(2r_1^0)$ .

The stress intensity factors are defined as

$$k_1 = \frac{pa^\beta \sin(\pi\beta)}{\pi\beta} - \frac{2p \sin(\pi\beta)\varepsilon}{\pi a^\beta} \int_0^a \frac{ru_z(r)}{h(r)(a^2 - r^2)^{1-\beta}} dr. \quad (2)$$

$\varepsilon = E_1/\mu_0$ ,  $\beta = 0.5(1-n)$ ,  $0 \leq \beta \leq 0.5$ ,  $n \geq 0$ . The case of a homogeneous body is recovered by setting  $\beta = 0.5$ . For an unhealed crack ( $\varepsilon = 0$ ), the stress intensity factor  $k_1$  reduces to  $k_1 = pa^\beta \sin(\pi\beta)(\pi\beta)^{-1}$  which coincides with the result reported by Kassir M. K. As can be seen, a characteristic feature of the stress distribution in a nonhomogeneous body is its singularity, which depends on the inhomogeneity parameter  $n$  and thus qualitatively differs from that in a homogeneous body. The studies were conducted to analyze the influence of material inhomogeneity and the stiffness of the filler material on the normalized stress intensity factor.

**Keywords:** nonhomogeneous materials, crack, stress intensity factor

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## ANALYSIS OF HIGH-FREQUENCY OSCILLATIONS IN AN ELASTIC QUARTER-SPACE

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The present contribution addresses a problem in dynamic solid mechanics: the analysis of high-frequency oscillations in an elastic quarter-space. One face of the quarter-space is assumed to be rigidly fixed to a foundation, while a compressive harmonic load is applied to the other face. The study is based on the mixed boundary-value problem of elasticity for a quarter-space, formulated by Vaysfeld and Popov [1]. In a subsequent work, a direct solution of the corresponding dynamical elasticity problem was obtained in [2]. Using the method of integral transforms, the three-dimensional elastodynamic problem is reduced to a one-dimensional vector boundary problem, which is solved by the matrix differential calculus proposed by Popov G.Ya. The obtained solution explicitly describes the displacement and stress fields in the elastic quarter-space under harmonic loading.

Further analysis of the problem has shown that, in the high-frequency range, the obtained exact expressions become inconvenient for analytical investigation and practical evaluation. In particular, the frequency-dependent terms in the solution exhibit rapid oscillations, rendering their direct use ineffective.

It is demonstrated that for high frequencies, the solution requires the construction of asymptotic formulas. For this purpose, the expressions containing the frequency parameter are expanded into asymptotic series. Such expansions allow one to obtain simplified representations of the displacement and stress fields and to clarify the qualitative behavior of the solution in the high-frequency regime.

The amplitude of oscillations of the plane face of the elastic quarter-space is investigated as a function of the medium's material properties and large natural frequencies.

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## INVESTIGATION OF STRESS DISTRIBUTIONS IN AN ANISOTROPIC PLATE CONTAINING SMOOTH ORTHOTROPIC INCLUSIONS

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A plane elasticity problem for an infinite anisotropic body with smooth curvilinear orthotropic inclusions is considered. The methods of complex potentials (CP) and singular integral equations (SIE) are used. Based on the conditions of continuity of stresses and permissible jumps of displacements on smooth curvilinear contours of inclusions, a system of SIE of the first and second kind was constructed. For the one inclusion, the obtained SIE are reduced to the solution of a linear algebraic system by the quadrature method. The distributions of contour and contact stresses at the interfaces of inclusions and matrix materials are determined. The influence of the shape and location of the orthotropic inclusion on the stress state of a piecewise homogeneous plate for various values of the elastic constant of orthotropic materials is defined.

Let us consider a plane problem (plane stress) of elasticity theory for an infinite anisotropic plate  $S_0$  (matrix) with smooth curvilinear anisotropic inclusions  $S_j$  ( $j = 1, \dots, J$ ). At the material interfaces of the matrix and inclusions  $L_j$  the stresses are continuous, and the jumps of the displacement vector derivative are given:

$$[N(t) + iT(t)]^+ = [N(t) + iT(t)]^-, \quad t \in L_j, \quad (d/dt)[(u_x + iu_y)^+ - (u_x + iu_y)^-] = 4ia_{11}^0 g'_{j*}(t), \quad t \in L_j, \quad j = \overline{1, J} \quad (1)$$

Here  $a_{11}^0$  – elastic constant of the anisotropic matrix  $S_0$  material [1, 2]. The upper indices “+” and “-” indicate the limit values of the corresponding quantities when  $z \rightarrow t \in L_j$  to the left (+) and to the right (-) of the selected positive direction of the contour  $L_j$ , respectively. The anisotropic plate at infinity is under the action of biaxial tension and transverse shear  $\sigma_x^\infty = q$ ,  $\sigma_y^\infty = p$ ,  $\tau_{xy}^\infty = \tau$ .

The CP of stresses for anisotropic matrix and inclusions are piecewise-analytic functions in auxiliary mathematical planes  $z_k^j = x + \mu_k^j y$  ( $\mu_k^j = \alpha_k^j + i\gamma_k^j$  – complex roots ( $k = 1; 2$ ) of characteristic equations for corresponding plane problems of anisotropic mediums  $S_j$ ) and can be expressed through Cauchy integrals [2]. Satisfying the boundary condition (1), we obtain a complex SIE of the first and second kind

$$\int_{L_j} \left\{ \left[ K^j(\tau, t) g'^j(\tau) - K^0(\tau, t) g'^0(\tau) \right] d\tau + \left[ L^j(\tau, t) \overline{g'^j(\tau)} - L^0(\tau, t) \overline{g'^0(\tau)} \right] d\bar{\tau} \right\} = 0; \quad t \in L_j, \quad j = \overline{1, J}. \quad (2)$$

$$\frac{1}{2\pi} \int_{L_j} \left\{ \left[ M^j(\tau, t) g'^j(\tau) - M^0(\tau, t) g'^0(\tau) \right] d\tau + \left[ N^j(\tau, t) \overline{g'^j(\tau)} - N^0(\tau, t) \overline{g'^0(\tau)} \right] d\bar{\tau} \right\} - \quad (3)$$

$$-2 \left\{ a_{11}^j g'^j(t) + a_{11}^0 g'^0(t) \right\} = i \left\{ \Gamma_*^0(t) - \Gamma_*^j(t) \right\} - a_{11}^0 g'_{j*}(t), \quad t \in L_j, \quad j = \overline{1, J}.$$

where the core  $K^j(\tau, t)$ ,  $L^j(\tau, t)$ ,  $M^j(\tau, t)$ ,  $N^j(\tau, t)$  – kernels of an SIE,  $\Gamma_*^j(t) = f\{t, \Gamma_k^j\}$ ,  $j = \overline{0, J}$ .

Based on the numerical solution of SIE (2), (3) for one inclusion ( $J=1$ ) and  $g'_{j*}(t) = 0$  the distributions of contour  $\sigma_s^+(t)$ ,  $\sigma_s^-(t)$  and contact stresses  $N(t) + iT(t)$ ,  $t \in L_1$  are determined. Different levels of orthotropy and stiffness of anisotropic matrix and inclusion materials are considered for a range of smooth inclusion contour shapes.

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# **SECTION V: NON-DESTRUCTIVE EVALUATION**

## **SUB-MILLIMETER DEFECT DETECTION IN METALLIC AND COMPOSITE THIN-WALLED STRUCTURES USING DIGITAL SHEAROGRAPHY**

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The detection of internal flaws in thin-walled structures necessitates a shift toward more sensitive non-destructive testing methodologies. This study presents a digital shearography technology, integrated with automated thermal loading, specifically designed to identify internal sub-millimeter defects (diameters < 1 mm) in titanium and aluminum welded joints as well as thin-walled composites.

A custom portable shearographic system was developed, based on a modified Michelson interferometer optimized for enhanced defect detectability. Test specimens of 2.5 mm thickness were prepared, incorporating artificial internal defects in both weld zones and base materials. Defect diameters ranged from 0.3 to 1.0 mm in metallic samples and from 0.8 to 2.0 mm in CFRP composites with defects positioned at various depths.

Experimental investigations identified the optimal thermal loading parameters for clear defect visualization: a loading duration of 2–4 seconds resulting in a surface temperature increase of 3–7°C. The integration of this improved interferometer with specialized software and an automated thermal system enables rapid, efficient detection of ultra-small defects at various depths within materials, offering a robust solution for high-precision quality inspection.

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## **WAVEGUIDE–RESONATOR MODELS OF THE THIN DEFECTS IN AN ELASTIC SLAB FOR THEIR DIAGNOSTICS BY SH-WAVES**

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The formation of an elastic field on the stress-free surfaces of a layer with thin internal and interface defects is investigated when probed with an SH mode under harmonic antiplane loading. The defects are located parallel to the layer faces. This structure is viewed as a series of interconnected waveguides and resonators. Various types of boundary conditions are imposed on their surfaces: Dirichlet, Neumann, impedance, and combinations thereof. The key idea of our study is to consider models that support mathematically rigorous full-wave analysis and serve as references for developing theoretical bases for diagnosing layered structures across any frequency range. The analytical methods for solving the corresponding mixed boundary-value problems of diffraction theory for the Helmholtz equation were developed in this work, based on Wiener-Hopf functional equations. This enabled obtaining, for the first time, correct solutions to a number of spectral problems, new approximate formulas for estimating displacement fields in the vicinity of the damaged area, simple transcendental equations for determining its resonant frequencies, and insights into the features of corresponding resonant mode formation. Solutions to the model problems were obtained in real time. The information parameters for defect identification based on the distribution of displacement fields and mode probing were established. A model of an elastic wave spectrometer for detecting defects of a given length or monitoring changes in their dimensions is discussed.

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**LOW-FREQUENCY EDDY CURRENT TECHNIQUES FOR DETECTION  
OF INTERNAL FATIGUE CRACKS IN MULTILAYER AIRCRAFT STRUCTURES  
IN THE VICINITY OF RIVETS**

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Developed low-frequency eddy current (EC) probes of the double-differential type can be effectively applied to detect subsurface cracks in the internal layers of multilayer aircraft structures (AS). These EC probes were applied for the detection of subsurface defects in multilayer AS in the vicinity of rivets; detection of cracks through repair patches; and detection of corrosion pitting on the reverse side of AS skin, etc. The last results were related to detecting the fatigue cracks in the vicinity of ferrous steel rivets in the wing spar through a 5 mm thick aluminum alloy skin. The desired result was achieved by applying a developed low-frequency double-differential EC probe operating at 100 Hz. Two low-frequency EC probes with 15.0 mm and 10.0 mm diameters characterized with high spatial resolution were developed to solve this problem in real in-service conditions. The possibility of discriminating signals obtained for cracks of different lengths and a defect-free rivet was shown.

A special inspection algorithm was developed to separate permissible one-sided fatigue cracks (oriented in one direction from the rivets), which allow continued AS operation, from unacceptable two-sided fatigue cracks (oriented in both directions from the rivets). This algorithm uses two types of EC probes: a double-differential EC probe for detecting cracks on one side of the rivet and a ring (donut) EC probe.

Proposed EC techniques enable the timely detection of dangerous fatigue and corrosion damage without disassembling the AS or removing the protective coating.

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## USING THIN PLATE THEORY TO ESTIMATE THE SIZES OF INTERNAL DEFECTS IN ORTHOTROPIC COMPOSITES

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A new approach to estimating the sizes and resonance frequencies of circular and elliptical internal defects in orthotropic composite structures is proposed. This approach is based on the theory of thin plates. In this study, we consider thin orthotropic plates fixed at the edges, located directly over circular and elliptical defects, with dimensions corresponding to the defect sizes. Known methods for estimating the fundamental resonant frequencies and sizes of such defects use formulas for isotropic materials that do not account for their orthotropic properties. To establish the relationships between the fundamental resonant frequencies of circular and elliptical orthotropic plates fixed at the edges and the sizes of circular and elliptical defects, the relationships between the vibrational and elastic properties of orthotropic materials obtained by the Rayleigh–Ritz and Galerkin methods were used. Based on these relationships, working formulas were obtained for calculating the fundamental resonance frequencies of circular and elliptical orthotropic plates, which are considered the fundamental resonance frequencies of the corresponding defects located beneath them. To calculate dependencies of the fundamental resonance frequency on the internal defect size using these formulas, the values of the flexural moduli  $E_x$  and  $E_y$  in the carbon fiber-reinforced plastic (CFRP) tape samples were established for the two principal orthotropic directions in accordance with the International Standard ASTM D790–17.

Samples of CFRP tape-concrete adhesive joints with artificial circular and elliptical interfacial defects (debonds) at the interface between the tape and the surface of the concrete beam were used to experimentally confirm the working formulas for calculating the fundamental resonance frequencies of circular and elliptical internal defects. To prepare these samples, CFRP tapes "Sika CarboDur M514" and "Sika CarboDur M1214" were used. Thanks to these tapes, CFRP tape-concrete adhesive joints increase the load-bearing capacity of building structures and improve their impact resistance and fatigue strength. Nondestructive testing of defects was performed using an optical-acoustic system (OAS) prototype to detect internal defects in composite structures. This prototype can generate elastic waves in samples with a smooth frequency sweep from 0.5 kHz to 150 kHz, as well as determine the size of debonds ranging from 6 to 80 mm and their depth beneath the composite tape. The sizes of artificial defects were determined from the spatial optical responses they produced at the fundamental resonance frequencies of the detected defects. During debond detection in CFRP tape-concrete adhesive joint samples, the experimentally determined fundamental resonance frequencies matched those calculated using the working formulas. Deviations in the theoretically calculated fundamental resonance frequencies from those experimentally obtained for small elliptical and circular debonds located at a depth of  $h = 1.4$  mm are explained by the small ratio of the debond sizes to their depth. At such small ratios, the orthotropic plate above the defect should already be considered as a thick plate that vibrates similarly to the vibrations of a short rod with a significant contribution from shear deformation and rotational inertia.

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## EDDY CURRENT CRACK DETECTION OF THROUGH COMPOSITE BONDED REPAIRS FOR AERIAL STRUCTURES

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The reliable non-destructive evaluation (NDE) of aerial structures often requires the evaluation of crack presence or progression through composite repair structures. Such an approach, particularly for detecting damage under composite bonded repairs, is a critical challenge in structural integrity management. This article presents the application of eddy current testing (ECT) as a viable technique for detecting and characterizing subsurface cracks in composite-bonded repairs. The main challenge is maintaining sensitivity, which decreases as the probe is moved farther from the element. The article indicates the use of a specialized double-differential probe to maintain signal-to-noise ratio with relatively thick composite-bonded repairs.

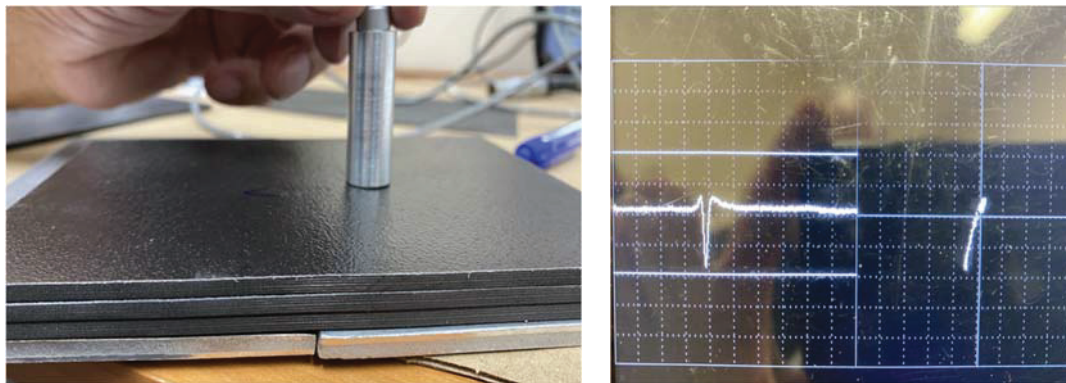


Fig.1. Structure thickness modelling and collected data

Traditional ECT methods have limitations in fully assessing the extent of damage beneath the repair layer, which often necessitates the use of multi-sensor and multi-frequency data fusion to improve defect detection and dimensional measurement. The presented approach highlights the advantages of specialized type probes over regular eddy current inspection.

The article presents the problem of fatigue crack propagation and structure repair, as well as further diagnostics.

This research focuses on optimizing the probe design and operating frequency of the eddy-current method to maximize sensitivity for crack detection while maintaining a relatively high SNR. The main objective was to establish an effective NDE procedure that can accurately map damage and assess the structural health of the repaired component, especially for service-life extension programmes of operating aircraft.

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## CONTACTLESS GEOMETRIC MEASUREMENT OF TURBINE BLADES BASED ON IMAGE PROCESSING

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Determining the geometric dimensions of objects is important in industry, both for quality control during manufacturing and for assessing their residual life during operation. Since traditional manual methods are subjective and dependent on the operator's experience, the development of automated methods for solving this problem using computer vision is important.

A method has been developed to evaluate the geometric dimensions of turbine blades by registering images of component sections, with a reference standard placed in the field of view. The dimensions of the reference standard are known in advance and calibrated. It is proposed to choose the final length measure 1-H2 as the reference standard, the main purpose of which is to preserve and transfer the size of a unit of length. These measures have an accuracy class of 2 (tolerance of 0.25  $\mu\text{m}$ , regardless of size) and comply with the Ukrainian state standard [DSTU ISO 3650:2009 Requirements for geometric dimensions of products. Length standards. Final measures (ISO 3650:1998, IDT), which is an identical translation of the international standard for requirements for geometric dimensions of products ISO 3650:1998 [International Organization for Standardization. ISO 3650:1998. Geometrical Product Specifications (GPS) – Length standards – Gauge blocks. 2nd ed. Geneva: ISO; 1998. This standard specifies the design and metrological characteristics of gauge blocks with rectangular cross-section and nominal length, ranging from 0.5 mm to 1000 mm.

A Hough-transform-based method is proposed to localize the final length-measure set. Using the coordinates of the found vertices, we determine the geometric dimensions of the rectangles and, with the known final length measure, we determine the image scale. Based on the scale of the images thus determined, it is possible to estimate the geometric dimensions of the structural parts in the given images. Another challenge is the contour detection of the turbine blade, which has a complex, irregular shape. A modified Canny edge detector is used in this research. This ensured the required accuracy in geometric measuring of turbine blades.

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## NEW METHOD OF MAGNETO-OPTICAL IMAGE ACQUISITION AND PROCESSING FOR MATERIAL DAMAGE TESTING

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Magneto-optical testing is a promising method for detecting local structural changes in metals under mechanical and thermal impacts; residual stresses during welding and mechanical processing; hidden defects in welded joints; and microcracks and surface corrosion, in particular, deep pitting. Its advantage is the simultaneous testing of a relatively large surface area and high spatial resolution. In addition, the use of modern algorithms for the acquisition and processing of magneto-optical images allows for increasing the reliability of defect detection and reducing the error in estimating their geometric parameters. Another significant advantage of this approach is its low dependence on the object's surface geometry.

A mock-up of an optoelectronic system was created to visualize defects in ferromagnetic materials. The system enabled effective registration of magnetic field leaks near defects and the formation of high-contrast images of hidden cracks in steel samples. The fatigue failure of compact 38XC steel samples with cracks of various sizes was studied. The length and growth of cracks after a specified number of load cycles were estimated from magneto-optical image processing results.

Steel test samples containing riveted joints with known defect sizes were also examined. A structure-adaptive method for detecting crack-like defects in magneto-optical images of construction details based on mathematical morphology was developed. The proposed registration scheme and method of magneto-optical image processing enabled the detection of hidden surface defects in openings that are typical for riveted joints.

The results of the study confirmed the potential of using the magneto-optical approach in the aviation, energy, transport, and oil and gas industries, where there is often a need to inspect complex geometric parts operating under critical loads. Its use in combination with a variable magnetic field expands the diagnostic capabilities for detecting damage in products made not only from ferromagnetic but also from paramagnetic materials.

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## NON-DESTRUCTIVE TESTING OF THE LARGE-SCALE THREADED CONNECTIONS

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Threaded connections (detachable and non-detachable) are widely used in various industries. Detachable connections allow assembly and disassembly without damaging the parts' materials. Such connections are widely used in the oil and gas industry during the drilling of oil and gas wells. At the present stage, quality evaluation of threaded connections usually involves checking compliance with dimensions, thread profile, surface cleanliness, and correct assembly of the connection. For this, a visual inspection, and strength and tightness tests are also used, depending on the purpose of the connection. However, these methods do not ensure the operational reliability of threaded connections, leading to stress corrosion cracking or separation, resulting in full connector failure or destruction of the thread profile when the optimal screwing torque is exceeded.

The features of contacts between surfaces in threaded connections were investigated as an important condition needed for safe service life. Since contact between solids occurs discretely through the protrusions of the stiffeners, the actual contact area is represented by the zones of setting and tight contact, with a width, as a rule, of 0.1 to 2 microns (see Fig. 1). It has been established that permanent deformation occurs with an increase in torque and reaching the limit of the yield point. This moment occurs when the deformation increases without an increase in load (torque), and a further increase in contact pressure does not increase the contact area. At this point, the greatest probability of stress corrosion cracking occurs.

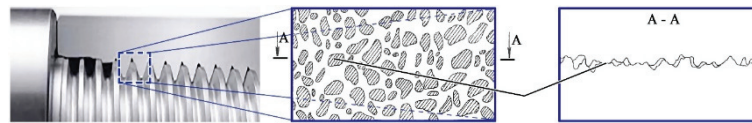


Fig. 1. The condition of the contact zone when contacting solid surfaces in threaded connections.

An ultrasonic method was proposed to monitor the actual contact area during the threaded connector screwing to optimize this process. The proposed technique for evaluating threaded connections was tested on a special setup. Experimental studies were carried out on steel casing pipes with a diameter of 245 mm. The threaded elements were checked before the study using a special calibrator. Ultrasonic piezoelectric transducers were connected in a through-transmission mode.

During the experiment, each of the three connections was screwed and unscrewed 18 times at a constant speed with a torque change from 0 to 24 kN·m (optimal torque 15.2 kN·m). The research results showed that the amplitude of the ultrasonic wave that passed through the threaded connection (the contact surface of the threaded connection) is proportional to the change in the contact pressure (contact area). Proposed new monitoring methodology and technical instruments (specialized piezo transducers and scanners) were developed and successfully implemented into an inspection practice for the evaluation of threaded connections of different types.

**Keywords:** ultrasonic quality evaluation, threaded connections, piezo transducers, permanent deformation

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## **EDDY CURRENT IN-SERVICE DETECTION OF DELAMINATIONS IN TWO-LAYER AIRCRAFT STRUCTURES COMPOSED OF CARBON FIBER REINFORCED PLASTIC AND ALUMINUM ALLOY SUBSTRATE**

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Carbon fiber reinforced plastic (CFRP) combines high load-carrying capacity with high corrosion resistance and low specific weight, making it important for aerospace structures (AS). Among the materials used in the Airbus A380, aluminum alloy (AA) accounts for 60%, and CFRP for 25%. Similar proportions for Boeing 787 are 25% and 50%, respectively. In aircraft, CFRP repair patches are applied for AS reinforcing after crack detection and removal. Under in-service mechanical loading or due to poor bonding, delamination can originate within the CFRP layer or at the “metal-CFRP” boundary. At the same time, nondestructive evaluation (NDE) methods for two-layer AS composed of CFRP and aluminum alloy (AA) have not yet been developed. In our previous study [1], we proposed measuring the thickness of the CFRP layer bonded to AA substrates using the low-frequency eddy current (EC) technique. During in-service life, the proposed EC method can be applied to detect delamination between the CFRP layer and the AA substrate, or between different CFRP layers.

In this study, the interaction of the EC probe with a two-layer AS, comprising a low-conductive CFRP layer and an AA substrate, was analyzed to elucidate the effects of CFRP layer thickness and delamination on EC probe impedance characteristics. The proposed EC NDE method was considered for application during the manufacturing of two-layer AS. It was shown that the proposed EC method can be applied to in-service structural health monitoring of two-layer structures (an AA component covered by a CFRP layer) to detect possible delamination. For this purpose, preliminary measurements of the CFRP layer thicknesses at pre-selected reference points are required. The results obtained during the preliminary evaluation can serve as reference values for subsequent comparisons during periodic in-service monitoring of the AS.

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## **MAGNETOCYCLIC METHOD FOR NON-DESTRUCTIVE TESTING OF PIPE METAL UNDER COATING**

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A new magnetocyclic method for non-contact detection of defects in a steel cylinder has been proposed, which can be used to monitor corrosion or mechanical damage to the metal of underground pipelines and process pipes under coatings.

Calculations of the influence of a steel pipe defect on the magnetic field distribution have been carried out, confirming the feasibility of implementing this method.

A procedure and electronic circuits for the excitation of a rotating magnetic field, its reception, and visualization of anomalies for defect detection have been developed. Experimental studies have shown that coatings can detect corrosive or mechanical damage to the steel pipe metal.

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## EXPERIMENTAL DETERMINATION OF DETECTION SENSITIVITY LIMITS FOR EDDY CURRENT SYSTEMS IN MULTILAYER STRUCTURE INSPECTION

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Detection of deep-seated cracks in multilayered aircraft structures is a challenging task due to the rapid attenuation of electromagnetic fields. While the standard depth of penetration  $\delta$  provides a baseline for frequency selection, the actual inspection limit is determined by the probe’s ability to resolve minimal secondary-field perturbations caused by a defect against the background of much stronger signals from air gaps between layers and from probe lift-off. This research evaluates the practical depth limits of a transformer-type double-differential probe in thick aluminum alloys, emphasizing excitation frequency optimization to enhance signal clarity at depths exceeding 15 mm.

The experimental setup used a double-differential eddy current probe (MDF-1501M) and a NORTEC 600 defectoscope. The test object was a D16T aluminum alloy structure with an electrical conductivity of approximately 18.5 MS/m. To simulate a subsurface defect at varying depths, a base specimen with an “infinite” crack was covered by a sequence of 0.9 mm thick plates, reaching a total inspection depth of 15.3 mm across 17 layers. The research focused on identifying the optimal excitation frequency at each depth to maximize the informative component of the complex impedance signal while accounting for localized conductivity perturbations, as analyzed through FEM modeling.

Experimental analysis reveals a distinct non-linear shift in the optimal excitation frequency toward lower frequencies as the defect depth increases. For the maximum tested depth of 15.3 mm, the peak signal-to-noise ratio was achieved at an excitation frequency of 50 Hz. Numerical simulations correlate with these findings, demonstrating a system sensitivity of 40  $\mu\text{V}$  per 1 MS/m change in local conductivity. The double-differential configuration effectively compensated for the high-amplitude primary field, allowing for a 6 dB gain increase per step to maintain signal clarity. The results confirm that the combined analytical-numerical approach provides reliable subsurface crack detection at depths significantly exceeding standard industrial expectations for aircraft materials.

**Keywords:** eddy current testing, signal modeling, double-differential probe, subsurface defects, defect depth, aluminum alloys, structural health monitoring

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## **DETERMINATION OF RESIDUAL AND OPERATION STRESSES IN WELDED STRUCTURES BY THE MAGNETO-ANISOTROPY METHOD**

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Fusion welding is the primary technological process for joining components in metallic structures. However, the non-uniform thermal cycles inescapable in fusion welding are inevitable and result in significant residual welding stresses. These stresses can lead to a reduction in structural load-bearing capacity, shortened fatigue life, geometric instability, and increased susceptibility to stress-corrosion cracking.

As most welded structures consist of ferromagnetic low-carbon and low-alloy steels, magnetic-based NDT methods provide an effective means of control. In particular, the magneto-anisotropic method (MAM) proves extremely effective for express control.

The MAM method uses a surface double-differential eddy-current probe designed to minimize sensitivity to the "lift-off" effect (non-magnetic gaps). This enables inspection of structures protected by non-metallic coatings (e.g., paint) without surface preparation. The MAM method provides high scanning performance (several meters per minute).

This express assessment capability enables real-time evaluation of stress-reduction techniques during production and prediction of dimensional stability. During the operational phase, MAM facilitates monitoring of both residual and operational stresses, identifying critical "danger zones" to optimize maintenance and unloading procedures, thereby enhancing the overall structural integrity.

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**SECTION VI:**  
**APPLIED ASPECTS OF FRACTURE**  
**MECHANICS**

## DEVELOPMENT OF WELDING TECHNOLOGY FOR MEDIUM-CARBON ALLOYED HEAT-TRAINED HIGH-HARDNESS STEELS

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The conditions of a full-scale war necessitated the use of medium-carbon alloyed heat-strengthened high-hardness steels of foreign production in Ukraine, whose chemical composition and behavior during welding differ significantly from those of previously used domestic analogues. This requires a scientifically sound approach to the development of their welding technologies, capable of ensuring high technological and operational strength of welded joints.

The aim of the work is to establish the patterns of the influence of thermal cycles of arc welding on the structure, mechanical, and operational properties of the metal of the heat-affected zone (HAZ) of butt joints of medium-carbon alloyed high-hardness steels with a thickness of 6–20 mm, and to develop a technology for their mechanized welding in protective gases.

The influence of welding modes, energy input, welding speed, and preheating temperature on the conditions of heating and cooling of the HAZ metal, the width of the seam, and individual high-temperature and low-temperature sections of the HAZ was studied. It was found that increasing the energy input and decreasing the cooling rate expand the HAZ and reduce cooling intensity, significantly affecting the formation of structural components.

It was shown that in the HAZ overheating zone at cooling rates of more than 5 °C/s, a predominantly martensitic structure is formed in the studied steels, which causes an increase in hardness and strength with a simultaneous decrease in plasticity. The metal’s impact toughness in this zone decreases slightly but remains within regulatory requirements. The presence of weakening areas in the low-temperature HAZ region (350–780 °C) was also established, where a decrease in hardness and strength is observed, which is critical for special-purpose products.

Special attention was paid to assessing the technological strength of welded joints. It has been proven that the use of high-alloy welding materials provides a minimal risk of cold and hot cracks without the need for significant preheating. The influence of the chemical composition of the deposited metal and the content of diffuse hydrogen on the resistance to cold cracks has been established, which is confirmed by tests of the “Implant” type and technological tests of “hard welding”.

It has been shown that the operational strength of welded joints, particularly their resistance to fatigue fracture, is largely determined by the choice of welding materials and post-welding treatments. The highest fatigue durability is achieved with joints made from high-alloy wires, and additional mechanical treatment of the seams increases fatigue resistance by almost three times.

Based on the complex of conducted research, technological recommendations and technologies for welding medium-carbon alloyed heat-hardened steels of high hardness have been developed, ensuring high technological and operational reliability of welded structures and implemented in the production of special-purpose machines.

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## **FRACTURE MECHANICS APPROACHES FOR ADVANCED REPAIR TECHNOLOGIES OF DAMAGED HYDROGEN COOLED TURBOGENERATOR ROTORS**

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The use of fracture mechanics approaches to assess materials' suitability for long-term operation (accounting for degradation) is needed for planned and emergency repairs of turbine hall equipment in fossil and nuclear power plants. Examples of types of emergency hydrogen-cooled turbogenerator damage demonstrate the need to analyze defect size and type using fracture mechanics criteria and to assess the degree of degradation. Based on these preliminary assessments, decisions are made to apply established repair techniques or propose innovative ones.

Seriously damaged rotor rings and copper bars (when critical defects are detected on their surfaces) are typically replaced. However, in the case of the rotor, for the first time in the world, Alstom Power (Wrocław) installed an insert (sealing) to fill the material loss (rotor steel). The weight of the inserted material (up to 20 kg) indicates the seriousness of the damage. Before this, hardness measurements were taken at the damaged areas, and the central rotor bore (up to 11 m long) was checked for cracks.

An advanced rotor-machining technology was proposed for the turbine hall or repair shop, using eco-friendly cooling and lubricating fluids. Additionally, a special locking technology was used, and the insert design at the damaged rotor shaft, the mounting method, and the compatibility of the sealing characteristics with the base rotor metal's properties were analyzed. Analysis of the chemical composition, strength testing, and other properties under significant centrifugal forces (generated at 50 Hz rotor rotation) enabled the implementation of a well-thought-out, proven, innovative technology at the Khmelnytska Nuclear Power Plant.

Advanced technology of hydrogen cooling of a flow turbogenerator and its general overhaul by sealing (including and using advanced additive 3D printing technologies) the damaged "rotor-retaining ring" assembly and planned overhaul (cutting the degraded metal) using ecological lubricating and cooling liquids directly in the turbine hall has been adopted for implementation in numerous power units.

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## FAILURE MECHANISMS AND CRITICAL STRUCTURAL COMPONENTS OF OWC SYSTEMS: MILESTONE ASSESSMENT BASED ON METHODOLOGICAL TYPES

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Oscillating water column (OWC) is one of the most mature wave energy conversion concepts, with deployments ranging from laboratory prototypes to nearshore demonstrators and commercial-scale installations. However, field experience indicates that the long-term viability of OWC devices is often constrained not only by energy-capture efficiency but also by reliability issues and recurring structural damage. Reported incidents such as cracking and fatigue in steel or concrete members, local buckling of thin plates, corrosion-assisted degradation, joint and weld failures, and damage around openings, chambers, and turbine/duct interfaces can progressively reduce pneumatic performance, increase maintenance downtime, and in severe cases force partial or complete shutdown of the system. Accordingly, this paper reviews documented structural failure events in OWC installations by mapping the observed damage modes to their associated operational states and marine loading conditions, thereby clarifying the practical pathways from environmental forcing to structural response and failure. The review also discusses the structural failure criteria commonly adopted for OWC components (covering fatigue, fracture, yielding, buckling, and serviceability limits) and explains the physical mechanisms that make each criterion relevant under wave loading and internal air-pressure dynamics. Furthermore, analytical formulations, numerical modeling approaches (e.g., coupled CFD–FEA and simplified hydro-structural models), and experimental methods (scaled tests, instrumentation, and monitoring strategies) are synthesized to improve understanding of OWC responses and to highlight gaps between controlled testing and real-sea conditions. Beyond the technical contribution, this agenda directly aligns with SDG 17 (Partnerships for the Goals), i.e., environmentally sound technologies, global partnership for sustainable development, and international cooperation, because improving OWC reliability is inherently a multi-stakeholder challenge: robust integrity assessment and design optimization require coordinated collaboration among universities (methods and validation), industry and developers (design and manufacturing feedback), utilities and investors (risk and lifecycle requirements), testing facilities (standardized benchmarking), and regulators/standards bodies (harmonized criteria and certification pathways).

**Keywords:** oscillating water column, structural failure, environmentally sound technologies, global partnership for sustainable development, international cooperation

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## SAFETY - RISK OF CCUS TECHNOLOGY: INDUSTRIAL REGULATION AND POLICY ASSESSMENT AGAINST STRUCTURAL FAILURE AND DAMAGED COMPONENTS

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Global pressure to reduce greenhouse gas emissions has positioned Carbon Capture, Utilization, and Storage (CCUS) as a strategic pillar in many energy-transition pathways, particularly for hard-to-abate sectors such as cement, steel, refining, and chemicals, where a substantial fraction of emissions arises from process chemistry and high-temperature heat that cannot be eliminated through electrification in the near term. In this context, CCUS functions not only as a climate mitigation option by capturing CO<sub>2</sub> at point sources or from the atmosphere and ensuring long-term containment, but also as a pragmatic mechanism to sustain industrial productivity and energy security while avoiding the premature retirement of existing assets that still provide economic value. Across decarbonization scenarios, CCUS is frequently framed as a “bridging and enabling” technology: it can reduce emissions from fossil-based generation and industrial facilities during transition periods, support low-carbon fuels (e.g., hydrogen with captured CO<sub>2</sub>), and potentially deliver net-negative outcomes when paired with biogenic CO<sub>2</sub> streams. Given the importance of CCUS implementation, safety and risk assessment of the state-of-the-art technology is required. This aims to investigate the industrial regulation and policy factors that may influence the technical performance of the CCUS during operations. Safety and risk under catastrophic conditions are considered to ensure synchronization of safety and risk regulations with structural failure and damaged mechanisms. This agenda is closely aligned with SDG 17 (Partnerships for the Goals) because CCUS at scale is rarely achievable through single-actor efforts. Effective deployment requires coordinated partnerships across governments (policy, permitting, liability frameworks), industry (capture projects and CO<sub>2</sub> supply), infrastructure operators (shared transport and storage hubs), research institutions (monitoring, verification, and risk assessment), and finance stakeholders (bankable business models and risk-sharing). Harmonized standards for measurement, reporting, and verification, cross-border cooperation for regional storage resources, and collaborative “cluster” development around industrial zones are all partnership-driven levers that determine whether CCUS becomes a reliable, scalable contributor to emissions reduction rather than a set of isolated pilot projects.

**Keywords:** carbon capture, structural failure, environmentally sound technologies, global partnership for sustainable development, international cooperation, industrial regulations, damaged component

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## EFFECT OF STIFFENER GEOMETRY ON THE STRUCTURAL RESPONSE OF STIFFENED PLATES SUBJECTED TO UNDERWATER EXPLOSION LOADS

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Maritime structures operating in hostile or high-risk environments (particularly naval platforms such as warships and submarines) are highly vulnerable to Underwater Explosions (UNDEX), which impose short-duration, high-intensity loads that differ fundamentally from conventional wave or impact events. For stiffened plates, which are widely used in hull and internal deck/shell arrangements due to their high strength-to-weight ratio, the stiffener geometry becomes a governing factor in load redistribution. Despite extensive work on stiffened panels under mechanical impact and quasi-static loading, the specific role of stiffener shape (beyond spacing and height) in mitigating UNDEX-driven damage remains insufficiently resolved, especially when designers must balance survivability improvements with strict constraints on mass, manufacturability, and integration with the surrounding structure. To address this gap, the present study examines the influence of stiffener shape variation on the dynamic response of a stiffened plate subjected to UNDEX loading via finite element analysis. A scaled stiffened plate fabricated from Aluminium Alloy 2024-T35 is numerically modeled and placed within a hemispherical water domain to represent the surrounding fluid medium, incorporating the acoustic behavior of water and a representative transient blast load. Several stiffener configurations, including flat bar, T-shaped, and hat-shaped, are systematically evaluated while keeping material properties and overall structural mass constant, enabling a fair comparison that isolates the geometric contribution of each stiffener type. This research also connects directly to SDG 17 (Partnerships for the Goals) because credible UNDEX survivability assessment and blast-resistant design are inherently partnership-driven: advancing the state of practice requires coordinated collaboration between academia (model development and validation), shipyards and industry (manufacturing constraints and scalable implementation), classification/standards bodies (harmonized acceptance criteria and verification pathways), and end users/regulators (risk-informed requirements and safety frameworks). Shared experimental benchmarks, cross-institutional data repositories, and joint verification programs are essential to reducing uncertainty in simulation-based design, accelerating technology transfer, and ensuring that survivability improvements can be adopted across the maritime sector through transparent, multi-stakeholder cooperation.

**Keywords:** stiffened panel, underwater explosion, stiffener variation, environmentally sound technologies, global partnership for sustainable development, international cooperation, finite element method

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**ISSUES OF PHYSICOCHEMICAL MECHANICS OF MATERIALS IN THE EDUCATION  
OF SPECIALISTS IN THE FIELD OF PORT, FLEET, AND OFFSHORE FACILITY  
OPERATION MANAGEMENT**

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In the operating conditions of ships, port facilities, and offshore structures, interactions occur between the materials used to construct the means of transport and infrastructure and the marine and coastal environment. Knowledge of the basics of these phenomena and relationships significantly impacts the operational quality of this class of structures. Research projects carried out as part of the activities of the Faculty of Transport Engineering and Economics included, among others, mutual relations in cargo-means of transport systems, research on the occurrence of complex wear processes in maritime transport technology, and research on the impact of improper operating practices on the accelerated degradation of facilities. Over nearly 40 years of professional practice, it has been found that limited knowledge of these phenomena among management staff leads to decisions focused solely on business results, without accounting for the realities of the technical environment.

The results of research in this field have been implemented in teaching practice as elements of an integrated block covering the subjects of "Materials Science," "Mechanics and Strength of Materials," and "Fundamentals of Technical Operation," totaling over 120 teaching hours and 15 ECTS credits. Cooperation with part-time second-cycle students working professionally in technical and maintenance services has proven to be highly educational. The professional practice of these students provides interesting case studies of degradation and damage to objects.

Over twenty years of cooperation with the Karpenko Institute have been particularly valuable for the teaching process. Employees of this Institute stayed and taught at the Faculty as visiting professors under direct agreements and as part of the "New Horizons" teaching exchange project. The topics of the classes conducted by visiting professors allowed students to learn about the latest research on operational processes in aggressive environments. The latest teaching project is the preparation of a block of courses on the management of facilities and installations for hydrogen energy and hydrogen-powered means of transport.

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**ROUND TABLE**  
**on Research Projects Supported**  
**by the National Research Foundation of Ukraine**

## ROUND TABLE

### on Research Projects Supported by the National Research Foundation of Ukraine (NRFU)

The Round table, focused on the dissemination of research results, project implementation perspectives, and expected outcomes, was held within the framework of the 7th International Conference “Fracture Mechanics of Materials and Structural Integrity”, which took place on March 3–5, 2026, in Lviv, Ukraine.



Project’s Leaders after the Round table (*from left to right*):

DSci Andriy Syrotyuk (Project No. 2025.07/0154); Prof. Ihor Zavaliiy (Project No. 2025.07/0315);  
Prof. Olha Zvirko (Project No. 2025.07/0337); DSci Sergiy Korniy (Project No. 2025.07/0048);  
Prof. Iryna Pohrelyuk (Project No. 2025.07/0035).

Participants of the round table included the project leaders and key performers of five projects funded under the call “Excellent Science in Ukraine 2026–2028” of the NRFU. All these projects carry out at the Karpenko Physico-Mechanical Institute of the National Academy of Sciences of Ukraine. The discussion focused on the current status of project implementation, preliminary results, and prospects for further research.

The participants presented the projects currently underway, outlined their main objectives, and highlighted preliminary results. The projects cover fields such as materials science, corrosion, fracture mechanics, and sustainable energy. In particular, the following projects were discussed:

Prof. Ihor Zavaliiy (PI of the project No. 2025.07/0315 “Development of efficient processes and devices for decarbonization and hydrogen generation by catalytic hydrolysis of  $\text{NaBH}_4$ ”) described in detail the use of mechanical and mechanochemical milling methods for the synthesis of new materials. New functional composites based on  $\text{MgH}_2$  were synthesized at the Karpenko Physico-Mechanical Institute of the National Academy of Sciences of Ukraine for the effective accumulation and hydrolysis generation of hydrogen. In particular, it was done using high-energy ball milling in a hydrogen atmosphere due to the formation of finely dispersed material with a high concentration of defects and the addition of catalysts. Prof. Zavaliiy also noted the advantages of using mechanical milling for the synthesis of new nanostructured catalysts that can be used for hydrogen generation by hydrolysis of sodium borohydride.

The project No. 2025.07/0337 “Entropic model of degradation of pearlitic steels of hydrogen infrastructure” (PI – Prof. Olha Zvirko) is focused on creation of a new approach to investigate the mechanisms of hydrogen interaction with steels of a ferritic-pearlite structure and develop an entropic model of their hydrogen-induced degradation based on establishing the influence of the parameters of interfacial interaction and hydrogen mobility in the metal on resistance to local fracture.

Project No. 2025.07/0048 “Development of New Environmentally Friendly Inhibitory Compositions for Protection Against Tribocorrosion and Corrosion Fatigue of Aluminum Alloy Structures” (PI – DSci Sergiy Korniy), focuses on the development of environmentally safe inhibitory systems to protect aluminum alloys under mechanical stress. The preliminary results obtained include initial screening of potential inhibitor compositions. These compositions are expected to serve as effective alternatives to toxic inhibitors and to enhance the performance of aluminum alloy structures operating under tribocorrosion and corrosion-fatigue conditions. The project results are anticipated to contribute to the circular economy by extending material durability and implementing environmentally friendly solutions.

Project No. 2025.07/0154 “Experimental and Theoretical Substantiation of a New Physico-Mechanical Approach to Creating Effective Barriers to Hydrogen Penetration into Structural Low-Alloyed Steels Subjected to Mechanical Loading” (PI – DSci Andriy Syrotyuk) aims to develop and substantiate the experimental and theoretical foundations of a new approach for creating effective barriers against molecular hydrogen penetration into structural low-alloyed steels through physico-mechanical modification of their near-surface layers.

Project No. 2025.07/0035 “Development of a Concept for Forming Functional Nitride Layers on Titanium Alloys Produced by Additive Manufacturing” (PI – Prof. Iryna Pohrelyuk) aims to develop a concept for creating functional nitride surface layers on titanium alloys fabricated using additive manufacturing technologies. The project focuses on investigating the formation mechanisms of nitride layers, their structural and mechanical properties, and potential enhancement of corrosion resistance and surface functionality. Preliminary results obtained include initial characterization of additive-manufactured titanium samples and the first experiments on nitride layer deposition, providing a basis for further optimization and validation of the proposed approach.

Particular attention was paid to the effective dissemination of results, including the publication of scientific and popular-science materials, as well as the presentation of preliminary results at international scientific conferences and popularization events (Science Days, science picnics, etc.).

The participants emphasized the importance of promoting scientific achievements to a broad audience to increase public awareness, foster scientific culture, and integrate Ukrainian research into the global scientific community.

The round table participants express their gratitude to the National Research Foundation of Ukraine for the financial support provided for the implementation of projects, which facilitates the advancement of cutting-edge research and the development of national scientific capacity. This research has been supported by the National Research Foundation of Ukraine under Projects Nos. 2025.07/0315, 2025.07/0337, 2025.07/0048, 2025.07/0154, and 2025.07/0035.



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