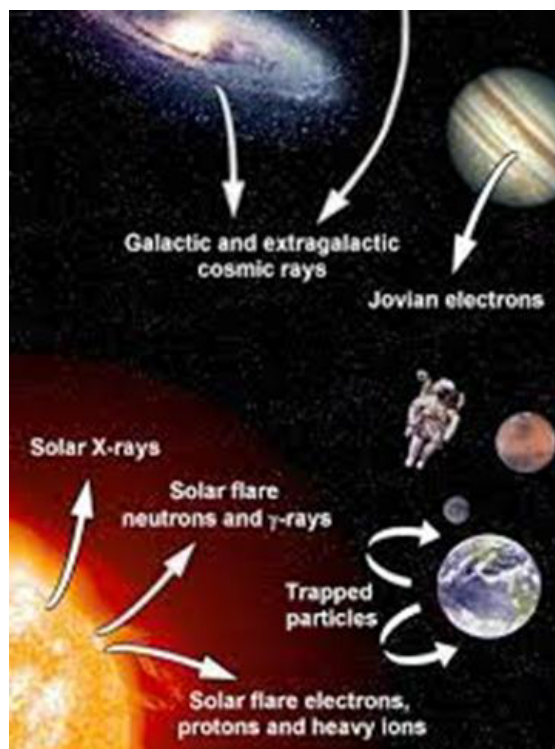


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Effect of vortex generator shape and attack angle on thermal-hydraulic performance of a finned-tube heat exchanger

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Abstract: The objective of this study is to numerically investigate the fluid flow and heat transfer performance of a finned-tube heat exchanger (FTHEX). The analysis focuses on the implementation of three vortex generator (VG) configurations: rectangular winglet (RW), delta-winglet upstream (DWU), and delta-winglet downstream (DWD) — mounted on the fin surface in a “common-flow-up” orientation. Attack angles of 15°, 30°, and 45° are considered for each VG type to evaluate their impact on the heat exchanger’s heat transfer potential and friction losses. The air-side Reynolds number, based on the outside tube diameter, was varied within the range $684 \leq Re \leq 1532$. The results indicate that among the tested configurations, the RWP setup with an attack angle of 45° achieves the highest enhancement in the air-side Nusselt number, with improvements ranging from 20% to 45% compared to the reference configuration, but at the expense of a higher pressure drop. For attack angles $\alpha_{vg} = 15^\circ$ and $\alpha_{vg} = 30^\circ$, the highest overall performance (TPF factor) is achieved with the rectangular winglet configuration across the entire Reynolds number range. At an attack angle of $\alpha_{vg} = 45^\circ$, the heat exchanger with downstream delta winglets shows higher TPF values compared to the other configurations, except at $Re = 1278$.

Keywords: HEAT EXCHANGERS, HEAT TRANSFER ENHANCEMENT, VORTEX GENERATORS, NUMERICAL ANALYSIS.

1. Introduction

Finned-tube heat exchangers (FTHEXs) are widely used across various industries, including aerospace, chemical processing, refrigeration, and electronics cooling. A key challenge in their design is achieving optimal thermal performance while operating within constraints such as limited space, minimal flow resistance, and reduced material usage. In most cases, the primary source of thermal resistance in these devices is on the gas side [1]. To enhance heat transfer efficiency, researchers have proposed a number of innovative techniques.

Longitudinal vortex generators (VGs), as a passive heat transfer enhancement technique, have been extensively studied for improving the performance of heat exchangers. These small flow-disturbing devices create longitudinal vortices that promote fluid mixing, disrupt the boundary layer, and delay flow separation. As a result, the convective heat transfer on the gas side is increased, making them an effective and energy-efficient solution for compact and high-performance heat exchanger designs [2]. The conventional shapes of vortex generators are usually in form of delta wings, rectangular wings, delta winglets, rectangular winglets, and trapezoidal winglets. Rectangular and delta winglets are preferred VG shapes, representing the most widely investigated configurations in experimental and numerical studies.

The application of VGs to improve the thermal performance of heat exchangers dates back to the mid-1970s when Edwards and Alker [3] conducted one of the first experimental investigations on the effects of delta winglets and block-shaped inserts on the average Nusselt number (Nu) in rectangular air ducts. In the initial phase, VGs were mainly installed on flat heating plates or channel walls. The first studies on their integration into FTHEXs were carried out by Fiebig et al. [4,5], who demonstrated through experimental and numerical analyses that longitudinal vortices induced by delta winglet pairs can significantly reduce thermal resistance and increase heat transfer rates.

He et al. [6] numerically identified the optimal punching arrangement for delta winglets in inline-tube FTHEXs, while Hwang et al. [7] examined the flow and heat transfer characteristics of delta winglets placed upstream of the tubes. Their results confirmed that enhanced fluid mixing and boundary-layer disruption contribute to improved thermal performance, with minimal pressure drop penalties, particularly at higher Reynolds numbers. Wu and Tao [8] further analyzed the influence of attack angle on thermo-hydraulic performance, finding that larger angles of attack generally improved heat transfer. Salviano et al. [9] employed a genetic algorithm to optimize winglet position and inclination, showing that reduced frontal area could lower pressure losses without sacrificing thermal enhancement. Modi and Rathod

[10] demonstrated that perforated rectangular winglets can both improve thermal performance and reduce pressure loss. Modifications to straight rectangular winglets, such as curved [11,12] or wavy [13] designs, have been shown to further increase efficiency. Comparative studies highlight that performance differences between delta and rectangular winglets often depend on operating conditions. Li et al. [14] reported that rectangular winglets provided slightly better overall thermo-hydraulic efficiency, while Hu et al. [15] observed that rectangular winglets were advantageous at low inlet velocities and delta winglets at high velocities, with differences in Nu and j/f generally within 5%.

In this paper, the comparative thermal-hydraulic performance of FTHEX with three VG shapes (rectangular, delta-winglet upstream and delta-winglet downstream) was systematically evaluated. All configurations have identical dimensions and are arranged in a ‘common flow up’ layout. Three angles of attack (15°, 30°, and 45°) were investigated in order to improve air-side heat transfer performance and overall FTHEX performance.

2. Mathematical model, numerical solving and validation

The study examines fluid flow and heat transfer process occurring in a crossflow air-water FTHEX. Aluminum fins are vertically attached to copper tubes to enhance air-side heat transfer, forming channels through which the air is heated. In this investigation, pairs of VGs are symmetrically positioned on the fin surface near the circular tubes and arranged in a “common-flow-up” configuration, as illustrated in Fig. 1. Three types of VGs are considered: rectangular winglet (RW), delta-winglet downstream (DWD) and delta-winglet upstream (DWU), having identical height and length but differing in the orientation of the hypotenuse of their

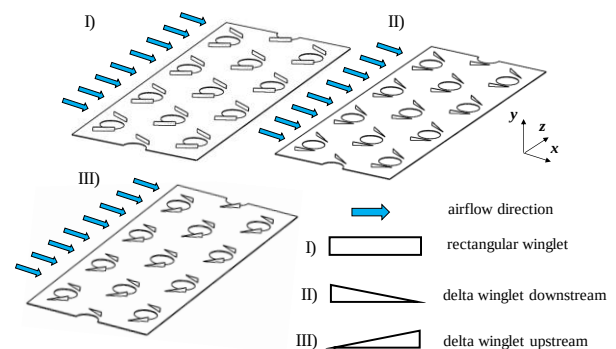


Fig. 1 Three-dimensional view of a fin segment with rectangular and delta winglet VGs.

The main dimensions of FTHEX, are as follows: longitudinal tube pitch $X_L = 30$ mm, transverse tube pitch $X_T = 60$ mm, fin pitch $F_p = 2.81$ mm, fin length $L_x = 90$ mm, fin thickness $\delta_f = 0.2$ mm, inside tube diameter $d_i = 14.8$ mm, outside tube diameter $d_o = 15.9$ mm. Winglet height equals $0.65 F_p$ ($H_{vg} = 1.827$ mm) and chord length of each winglet is $0.9 d_o$ ($L_{vg} = 14.31$ mm). The central distances between the tube and the winglet in the airflow direction and in the spanwise direction are $\Delta x = 0$ mm and $\Delta y = 13$ mm, respectively.

Computational domain consists of three subdomains: air, water and solid (fin, tubes and vortex generators). A schematic view of the computational domain has been shown in Fig. 2. The 3D numerical model was developed under the assumptions that air and water are incompressible Newtonian fluids with constant thermal-physical properties, and that viscous dissipation is negligible. Perfect thermal contact between fins and tubes was considered, while heat transfer and fluid flow are in steady state with turbulence modeled in both air and water flows.

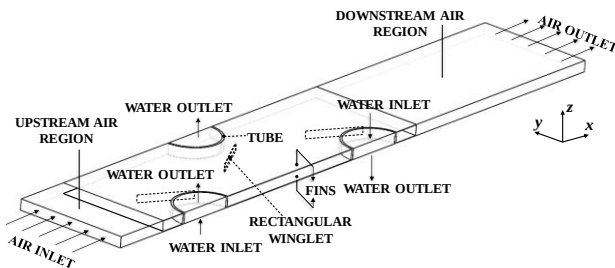


Fig. 2 The computational domain.

Based on the stated assumptions, the governing conservation equations for the air and water subdomains include the continuity equation to satisfy mass conservation and the Reynolds-averaged Navier–Stokes momentum equations for the x , y , and z directions. Energy transfer is described by the steady-state energy equation, with Reynolds stresses determined using the Boussinesq approximation. Turbulence closure is achieved via the SST $k-\omega$ model, which combines $k-\omega$ accuracy near walls with $k-\epsilon$ robustness in the free stream, solving transport equations for turbulent kinetic energy k and specific dissipation rate ω . In solid domains, steady-state heat conduction governs thermal behavior.

Suitable boundary conditions are defined at the outer boundaries of the calculation domain and at the interfaces between subdomains, appropriate boundary conditions are specified. The uniform velocity and temperature profiles are assigned to the air inlet and fully developed velocity and temperature distributions are prescribed at the water inlets. At both the air and water outlets, the flow is assumed to be fully developed, with no variation of field variables along the streamwise direction. Symmetry boundary conditions are applied to the front, back, top, and bottom planes of the domain. Heat transfer at fluid–solid interfaces is modelled by near-wall boundary layer treatment, while the no-slip condition ensures that fluid velocity at solid surfaces is zero due to viscous effects.

The governing equations and boundary conditions are solved by Fluent 18.2. The computational region is discretized with a hexahedral mesh using multi-block grid approach. To achieve good accuracy with shorter computation time, all simulations were performed with the grid size of approximately 1.6 million control volumes. The SIMPLE algorithm is applied to ensure the pressure-velocity coupling. The second order upwind scheme is used in the discretization. The least squares cell-based gradient method was used to evaluate the values of a scalar at the cell faces, secondary diffusion terms and velocity derivatives. The iteration process stops when the convergence criteria are achieved. The convergence criteria were: 10^{-5} for continuity, momentum, turbulence kinetic energy and turbulent frequency equations and 10^{-9} for energy

equation. A comparison between experimental and numerical results for the baseline air-water FTHEX with plain fins is presented in Fig. 3. The results comprise values of air-side Nusselt numbers Nu and air-side pressure drops Δp for different inlet air velocities $u_{air,in}$: 0.46 m/s, 0.65 m/s, 0.86 m/s and 1.04 m/s. The comparison between numerical predictions and experimental data shows good agreement of the analyzed variables. The agreement between experimental and numerical results demonstrates that the chosen computational domain and mathematical model, incorporating fully developed water inlet flow, together with the applied numerical procedure, can reliably simulate the flow and heat transfer behavior within the examined FTHEX.

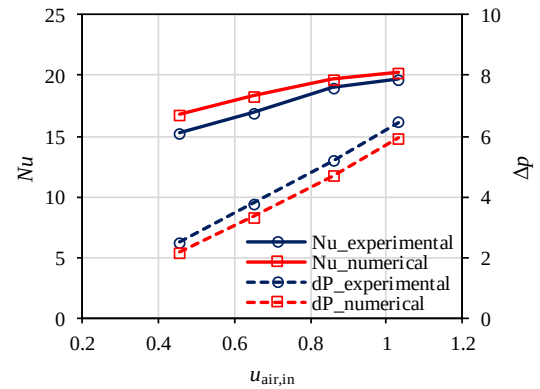


Fig. 3 Experimental validation.

3. Results and discussion

The vortex generator's angle of attack relative to the airflow streamlines (α_{vg}) is one of the parameters that most strongly influences the amount of heat exchanged in the recirculation zone and the process of forming secondary flows, i.e., vortices that further enhance convective heat transfer between the air and the fin. A comparison of results was made for three angles of attack: 15° , 30° , and 45° . Numerical simulations were carried out under the following conditions: $T_{air,in} = 295$ K, $T_{water,in} = 313$ K, $0.46 \text{ m/s} \leq u_{air,in} \leq 1.04 \text{ m/s}$, $u_{water,in} = 0.76 \text{ m/s}$. For the given inlet air velocities, the Reynolds number (Re), based on the tube's outer diameter, ranges between 684 and 1532.

From the comparison of air-side Nu for three different vortex generator configurations and three angles of attack (Fig. 4), it can be observed that the Nu is highest for the FTHEX with rectangular winglet vortex generators (RW) for the given ranges of air-side Reynolds numbers, at all analyzed angles of attack.

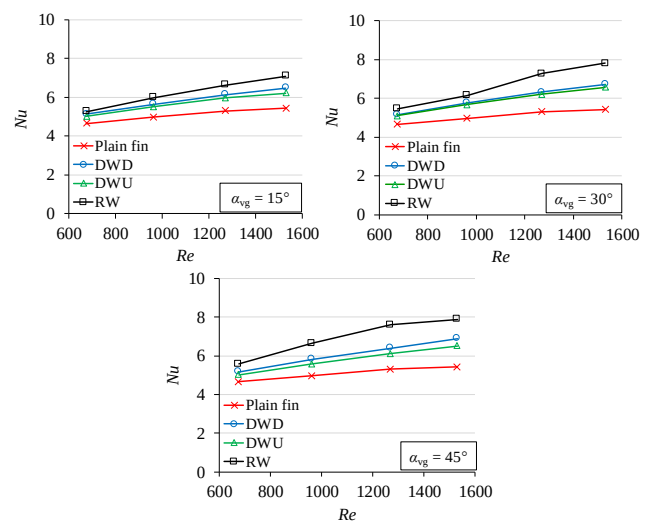


Fig. 4 The effect of winglet shape and attack angle on Nusselt number.

Compared to the reference heat exchanger with plain fins, the Nu in the heat exchanger with RW increases between 13.1% and 30.4% for an angle of attack of $\alpha_{vg} = 15^\circ$, between 17.5% and

43.7% for $\alpha_{vg} = 30^\circ$, and between 19.7% and 45.2% for $\alpha_{vg} = 45^\circ$. At higher Re , and thus higher inlet air velocities, convective heat transfer between the air and solid surfaces becomes more intense, resulting in higher Nu . The Nu is slightly higher in the heat exchanger with downstream delta winglets (DWD) compared to the upstream delta winglet configuration (DWU). The maximum relative increase in Nu for the DWD configuration is 27% at an attack angle of $\alpha_{vg} = 45^\circ$, while for the DWU configuration it is 21% at an angle of attack of $\alpha_{vg} = 30^\circ$, compared to the reference plain fin case.

Heat transfer enhancement is often associated with additional flow resistance, which results in a higher pressure drop. Fig. 5 shows the dependence of air-side pressure drops on Reynolds numbers for the considered FTHEx configurations and analyzed angles of attack. The smallest pressure drop is observed for the reference case with plain fins. The largest pressure drop occurs in the configuration with the rectangular winglets, due to their larger surface area compared to the other two shapes. As the vortex generator's angle of attack increases, a sharper rise in pressure drop is noticeable, caused by higher form drag that obstructs the airflow streamlines and induces more intense vortex formation. From the perspective of pressure drop, a comparison of the three analyzed VG shapes shows that the lowest values are obtained in the heat exchanger with the upstream delta winglets.

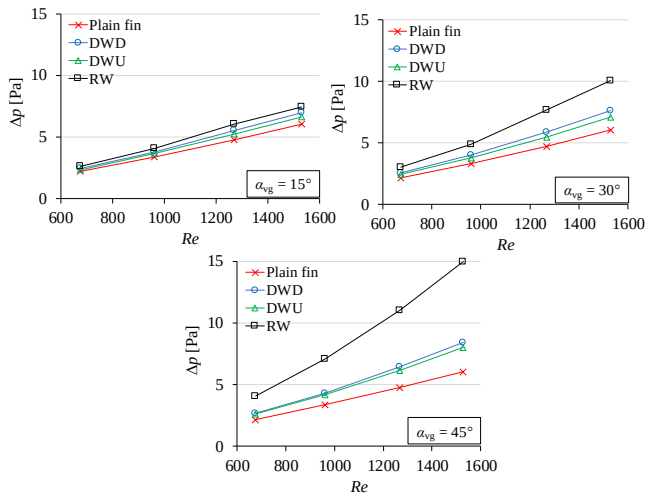


Fig. 5 The effect of winglet shape and attack angle on air-side pressure drop.

Fig. 6 shows velocity vector distributions in the central xy -plane between the fins ($z = 1.405$ mm), at $Re = 1532$. The recirculation zone behind the tube is largest for the case of the FTHEx with plain fins. This zone is a consequence of the form drag of the tube, where, due to an unfavorable pressure distribution along its surface, reverse airflow occurs in the region behind the boundary layer separation point. Heat transfer is poorest within this zone. This issue can be mitigated by installing vortex generators, which form a nozzle-like passage that directs the airflow streamlines behind the tube. The VGs with a rectangular shape contribute most to the reduction of poor heat transfer zones, which also decrease with increasing angle of attack for all three winglet configurations. The analysis of the velocity vector field in the central plane shows low velocity zones behind the VGs, particularly at $\alpha_{vg} = 45^\circ$, which indicates the presence of intense secondary flow structures.

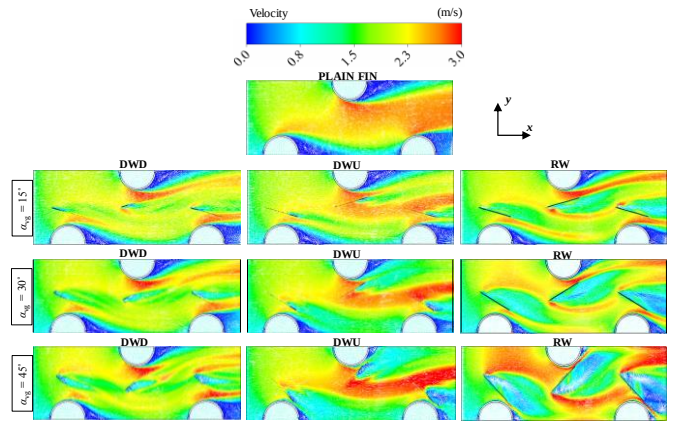


Fig. 6 Comparison of velocity vector distributions at xy mid-plane obtained numerically at $Re = 1532$.

Yun and Lee [16] defined the volume goodness factor $Nu/f^{1/3}$ as a measure for evaluating the flow and heat transfer performance on the gas side of FTHEx. Here, f refers to the Fanning friction factor, a dimensionless parameter that characterizes the pressure drop due to friction in the flow passages of the heat exchanger. A higher volume goodness factor indicates better heat transfer for the same fan power required to compensate for the air-side pressure drop, and allows for the design of a more compact heat exchanger while maintaining the same thermal-hydraulic characteristics. The comparison of the volume goodness factors of heat exchangers with vortex generators and the reference heat exchanger with plain fins is presented using the factor $TPF = Nu/Nu_{ref} \times (f_{ref}/f)^{1/3}$. The dependence of the TPF factor on the air-side Re for the VG attack angles of 15° , 30° , and 45° is shown in Fig. 7. The TPF factor increases with increasing Re , except for the case of the heat exchanger with RW at $\alpha_{vg} = 45^\circ$, where a slight decrease is observed at $Re = 1532$. From Figs. 4 and 5 (at $\alpha_{vg} = 45^\circ$), it can be concluded that both the Nusselt number and the air-side pressure drop are higher at $Re = 1532$ compared to $Re = 1278$, but the TPF decreases due to the lower value of their ratio. Furthermore, after $Re = 1278$, a sharper increase in air-side pressure drop is observed compared to the Nu , which increases only slightly. For $\alpha_{vg} = 15^\circ$ and $\alpha_{vg} = 30^\circ$, the heat exchanger with RW configuration achieves the highest TPF values over the entire range of Re . At $\alpha_{vg} = 45^\circ$, the heat exchanger with downstream delta winglets attains higher TPF compared to the other configurations, except at $Re = 1278$.

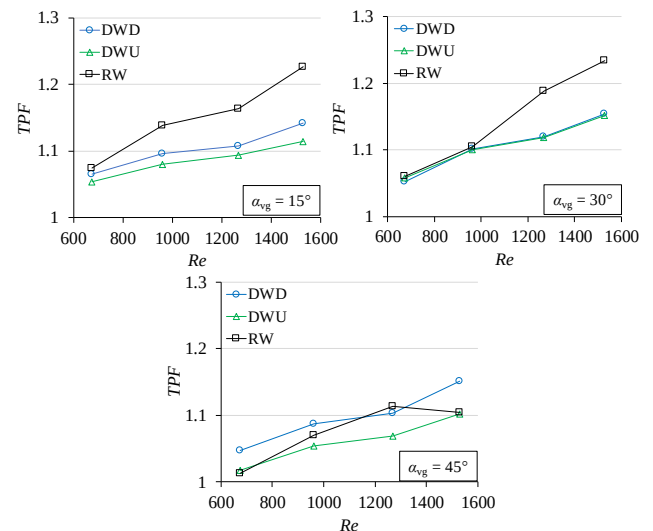


Fig. 7 The effect of winglet shape and attack angle on overall thermal-hydraulic performance.

4. Conclusion

A numerical investigation was performed to assess the effect of vortex generator (VG) shape and attack angle on the thermal-hydraulic performance of a finned-tube heat exchanger (FTHEX). Three VG configurations: rectangular winglet (RW), upstream delta winglet (DWU), and downstream delta winglet (DWD) were analyzed at attack angles of 15°, 30°, and 45° for air-side Reynolds numbers between 684 and 1532. Results showed that the RW configuration produced the highest air-side Nusselt numbers for all attack angles, with enhancements of 13.1–45.2% compared to the reference case with plain fins. However, this improvement was accompanied by higher pressure drops, which increased with attack angle due to greater form drag and more intense vortex formation. Velocity vector analysis confirmed that all VG types reduced recirculation zones behind the tubes, with the RW shape providing the largest reduction. Comparison of *TPF* values showed that heat exchanger with RW VGs provided the best overall performance at 15° and 30°. At 45°, the DWD configuration reached higher *TPF* values than the other VG types, except at $Re = 1278$, owing to a more favorable trade-off between heat transfer and flow resistance. Therefore, a separate analysis should be conducted for each FTHEX design to ensure the most suitable choice of vortex generator type and geometry, balancing thermal enhancement with acceptable flow resistance.

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5. References

1. R. K. Shah, D. P. Sekulic, Fundamentals of heat exchanger design, John Wiley & Sons, Hoboken, New Jersey, 2003.
2. A. M. Jacobi, R. K. Shah, "Heat Transfer Surface Enhancement through the Use of Longitudinal Vortices: A Review of Recent Progress," *Experimental Thermal and Fluid Science*, 11(3), 295–309 (1995).
3. F. J. Edwards, C. J. R. Alker, "The Improvement of Forced Convection Surface Heat Transfer Using Surface Protrusions in the Form of (A) Cubes and (B) Vortex Generators", *Proc. Fifth International Heat Transfer Conference 2*, 244-248 (1974).
4. M. Fiebig, N. K. Mitra, Y. Dong, "Simultaneous heat transfer enhancement and flow loss reduction of fin-tubes", *Proc. Ninth International Heat Transfer Conference 4*, 51-56 (1990).
5. G. Biswas, N. K. Mitra, M. Fiebig, "Heat transfer enhancement in fin-tube heat exchangers by winglet type vortex generators", *International Journal of Heat and Mass Transfer* 37(2), 283-291 (1994).
6. Y. L. He, H. Han, W. Q. Tao, Y. W. Zhang, "Numerical study of heat-transfer enhancement by punched winglet-type vortex generator arrays in fin-and-tube heat exchangers", *International Journal of Heat and Mass Transfer* 55(21-22), 5449-5458 (2012).
7. S. W. Hwang, D. H. Kim, J. K. Min, J. H. Jeong, "CFD analysis of fin tube heat exchanger with a pair of delta winglet vortex generators", *Journal of Mechanical Science and Technology* 26(9), 2949-2958 (2012).
8. J. M. Wu, W. Q. Tao, "Investigation on laminar convection heat transfer in fin-and-tube heat exchanger in aligned arrangement with longitudinal vortex generator from the viewpoint of field synergy principle", *Applied Thermal Engineering* 27(14-15), 2609-2617 (2007).
9. L. O. Salviano, D. J. Dezan, J. I. Yanagihara, "Optimization of winglet-type vortex generator positions and angles in plate-fin compact heat exchanger: Response Surface Methodology and Direct Optimization", *International Journal of Heat and Mass Transfer* 82, 373-387 (2015).
10. A. J. Modi, M. K. Rathod, "Experimental investigation of heat transfer enhancement and pressure drop of fin-and-circular tube heat exchangers with modified rectangular winglet vortex generator", *International Journal of Heat and Mass Transfer* 180, 122742 (2022).
11. H. Naik, S. Harikrishnan, S. Tiwari, "Numerical investigations on heat transfer characteristics of curved rectangular winglet placed in a channel", *International Journal of Thermal Sciences* 129, 489-503 (2018).
12. J. Xie, H. M. Lee, "Thermo-Hydraulic Performance of a Fin-and-Tube Heat Exchanger with Differently Configured Curved-Rectangular Vortex Generators", *Heat Transfer Engineering* 43(1), 63-82 (2020).
13. J. Wu, P. Liu, M. Yu, Z. Liu, W. Liu, "Thermo-hydraulic performance and exergy analysis of a fin-and-tube heat exchanger with sinusoidal wavy winglet type vortex generators", *International Journal of Thermal Sciences* 172, 107274 (2022).
14. L. Li, X. Du, Y. Zhang, L. Yang, Y. Yang, "Numerical simulation on flow and heat transfer of fin-and-tube heat exchanger with longitudinal vortex generators", *International Journal of Thermal Sciences* 92, 85-96 (2015).
15. W. Hu, L. Wang, Y. Guan, W. Hu, "The effect of shape of winglet vortex generator on the thermal-hydrodynamic performance of a circular tube bank fin heat exchanger", *Heat and Mass Transfer* 53, 2961-2973 (2017).
16. J. Y. Yun, K. S. Lee, "Influence of design parameters on the heat transfer and flow friction characteristics of the heat transfer with slit fins", *International Journal of Heat and Mass Transfer* 43(14), 2529-2539 (2000).

Effect of nano coating and nano fluid on photovoltaic module performance

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Abstract: Recent researches have shown that Nano-coating materials play a vital role in improving the performance of the PV cell operation, enhancing the life span and reducing its surface temperature. In addition to that, the Nano-coating can achieve many benefits such as making a smoother surface, stronger and less adhesive of externous on the surface of PV panel. In this work, the effect of nanomaterials coating using Titanium dioxide, silicon dioxide and Nano fluid Titanium dioxide on performance and temperature of PV cell when coated by these Nano particles separately with different thicknesses (0.5 μ m, 50 μ m, 100 μ m and 300 μ m). To achieve these objectives ANSYS software technology (version.1) was used. The results showed that there is a significant effect specifically when using TiO₂ Nano fluid. The maximum improvements were when using Nano coating TiO₂ and SiO₂ which are (0.62%) and (0.135%), respectively, at thickness 300 μ m and ambient temperature 16°C in case without externous particles. But the minimum improvement was with TiO₂ and SiO₂ of coating thickness 0.5 μ m which are (0.0937%) and (0.0937%), respectively, at ambient temperature 23°C in presence of dust. The results of TiO₂ Nano fluid with concentration and flow rate which are (5% and 0.01 kg/s), respectively, showed that the maximum improvement was (39.88%) in case without externous particles at ambient temperature 23°C, but the minimum improvement was (37.84%) in case with dust at ambient temperature 16°C.

KEYWORDS: PV, NAO-COATING, ANSYS, TITANIUM DIOXIDE, SILICON DIOXIDE, NANO-FLUID

Introduction:

The Nano research is concerning mainly about advance aspects of the Nano science and nanotechnology. Nano research journal has large scope as it tries to support research ideas in the field of Nano science with scientific inventions, discoveries and developments. Nano technology is modern multidisciplinary technique that includes an application that depends on the composition of molecules in Nano scale, size and range. The nanotechnology is referred to the Greek word Nano (means dwarf), Nano technology field that includes manufactured application of structure and system through controlling shape and size in nanometer scale Nano coating is a coating made by various materials which generated at the Nano scale to investigate the specific properties. The main purpose for Nano Coating on solar panels is to protect, preserve, and achieve higher energy output. The form of coating material is usually in powder state, paste, or liquid. [1-4]. The progress and the advanced imagination for human led to create new science and technology, Nanotechnology appeared in a 21st Century. It is known as understanding and controlling of things in dimensions from 1 to 100 nm, the Nano particles have largely increased due to the industrial revolution, the expression of "Nano meter" was initial proposed by Richard Zsigmondy, who he had a noble prize in 1925 in the chemistry, he put the term of nanometer to describe particle sizes. Modern nanotechnology was very important for Richard Feynman, who he had a Nobel prize in 1965 in physics and he presented the concept of handling matter at the atomic level, so he is considered the father of modern nanotechnology. After that the Japanese scientist Norio Taniguchi was the first to use nanotechnology to depiction semiconductor processes which happens because of a nanometer, he think the Nano technology is a group of processing, Consolidation, separation and deformation of materials through one atom or a molecule. Many scientists cared about nanotechnology by the beginning of 1980s. One of these scientists replaced the term of Nano technology to be known as "molecular nanotechnology". [6-8]. The Nano coatings have several types such as: Super hydrophobic coatings; scientists can make super hydrophobic Nano coating which protects equipment and solar materials from corrosion, contamination and hazardous chemicals. Due to development in technology in Nano coating led to the invention of responsive Nano coating which respond to environmental triggers such as light or heat. Since some sunlight reflected and reducing uptake a new type of Nano coating appeared that is called anti-reflective Nano coating which achieved more efficiency for solar panel. There are many types also for example: Anti-corrosion Nano coatings and tribological Nano coating which contribute in the development of the system and protection it. [9-10]. Nano coating is used for covering the surface with Atom-Thin-Nano Sheltering layer. Most surfaces have tiny holes and scratches, if these surfaces were put under microscope the hole's structure will be clear, so this shape of structure will allow water and pollution to bond on surface.

However, the Nano particles are tiny. They can fill into all those tiny holes in uniform shape that make the solar panel surface smooth and slippery off, fats, dirt, oil, water and all containment. Nano coating goes in many applications such as: solar panels, kitchen surfaces, cars mirrors, clothes, furniture and electronics

Research problem: The development of renewable energy became essential in these days because the fossil fuel emits a lot of CO₂ globally which cause the global warming phenomenon, so this thesis deals with this issue to find the best enhancement for efficiency of solar panel by Nano coating, to make renewable energy more compatible with fossil fuel. To solve that issue there are many questions and points that should be exposed as: Which Nano coating material should be chosen, what is the material phase when using it? Determining the properties of Nano coating material, thickness of Nano coating that should be limited. If this work can do as an experiment then more question will be take, how stability of Nano coating? What is the best way to coating determining the climate (nature) of the country? How much does coating cost? Does coating cost matches with stability? Diy Nano coating or readymade also will be determined, check if solar panel have been coated perfectly or not [11-13]. In this work may will obtain answers to some of these questions, especially in solar renewable energy when using Nano materials to improving the PV performance.

Research objectives: The main aim of this work is to improve the PV panel performance by using Nano coating, while the sub-objectives are studying the followings:

- The effect of Nano-coating on PV cell performance by using different materials and coating thickness.
- The effect of Nano-coating on PV thermal properties.
- The effect of Nano-coating on externous adhering on PV panel surface.
- The effect of cooling efficiency of Nano-fluid with different concentration on PV panel.
- The effect of Nano-coating of the PV performance under various ambient temperature and raining weather.

Research Methodology:

Figure (1) shows flow chart of the main steps of this work. [3] These steps of the research such as the thickness, where four values will be taken but these values are subject to iterations If they cannot achieve the required (increase and decrease in the efficiency of solar panels), the ambient temperature variable has three values in this study, the condition of the solar panels will also vary such as a layer of dust to denote the location of the dust and the area of rain is also provided as a variable here. Some variables will be taken as constant, such as: internal solar radiation, which has one value throughout the study, this value represents continuous radiation in the city of study, also any variables that are not important and far from a focused study can be considered constant.

Transmittance proprieties for SiO₂ and TiO₂:

The transmission is the main point when choose Nano coating materials to be applied in PV field, figure (2) illustrates why these materials selected and transmittance percentage when each one is alone and when combined together also.

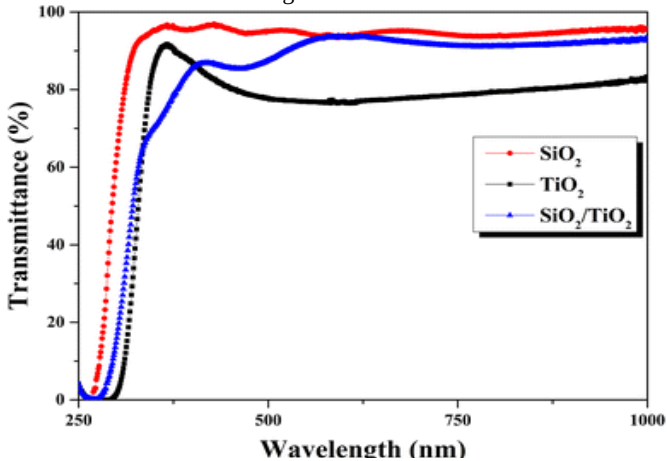


Figure (2): Transmission for SiO₂ and TiO₂ [19]

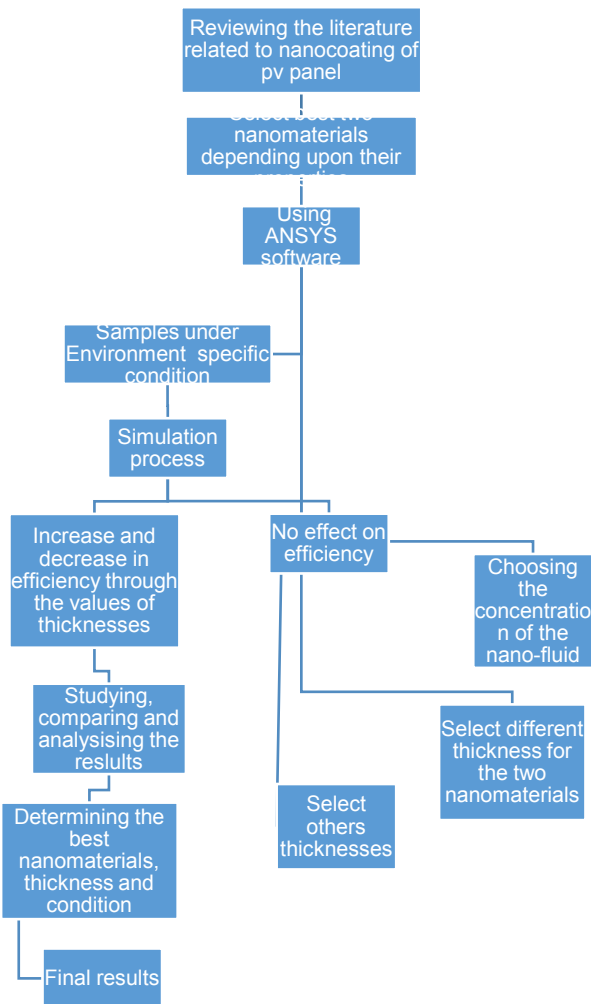


Figure (1): Flow chart of the main steps of this work

Research Design:

The solar PV system components are set of devices which are illustrated in figure (3),

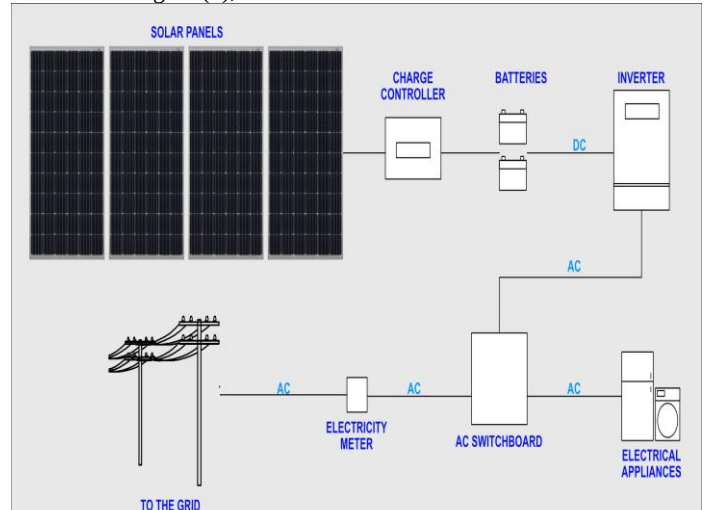


Figure (3): Components of PV system. [20]

which contains:

- **Solar Panels:** also called solar modules that consist of a number of solar cells that produce electricity, these solar panels are protected between the front glass and the back polymer plate with an aluminum frame, these solar panels are easily connected to each other, the figure (4) shows the solar panel of the following parts:

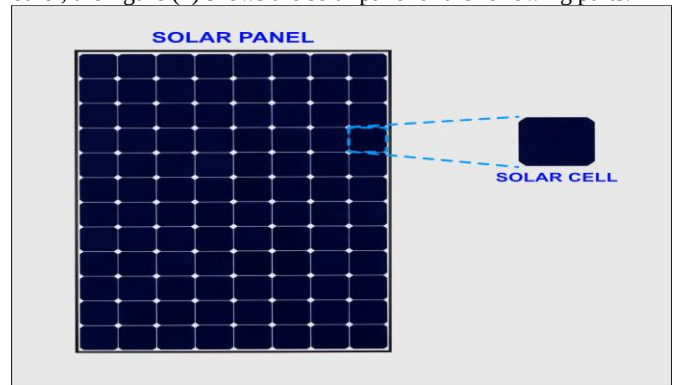


Figure (4): solar panel contains. [20]

- **Inverter:** this device in the system converts the DC current produced by the solar panels into AC current, which is usually used in homes. The main functions of the inverter are:

- Improving the power output of the solar panels.
- Battery charge control.
- Controlling the system.
- Work as a safety device.

- **Batteries:** if it is found in the PV system the power can be stored for use at sunset, it is important in an off-grid system.

- **Charge controllers:** this device is used when the system includes batteries and when there is no hybrid inverter, the important functions are:

- prevent the batteries from being overcharged as well also from overly discharged.
- Monitoring batteries and solar panels.

Geometric model: Geometric model give details about model such as dimensions, main part of model and properties of it.

(a) Dimensions of photovoltaic panel:

The main dimensions of panel are length and width, they are controlled the area which receive solar incident radiation, figure (5) show the dimension of PV panel.

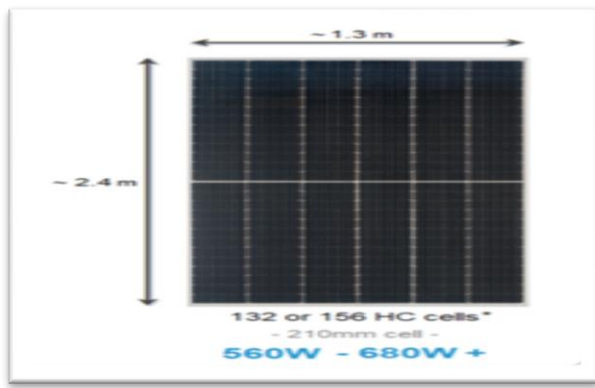


Figure (5): Dimensions of photovoltaic panel. [21,22]

(b) Layers of photovoltaic panels and their properties: photovoltaic panels have six layers, each one has a function with specific properties which enable it to do her function, figure (6) show these layers.

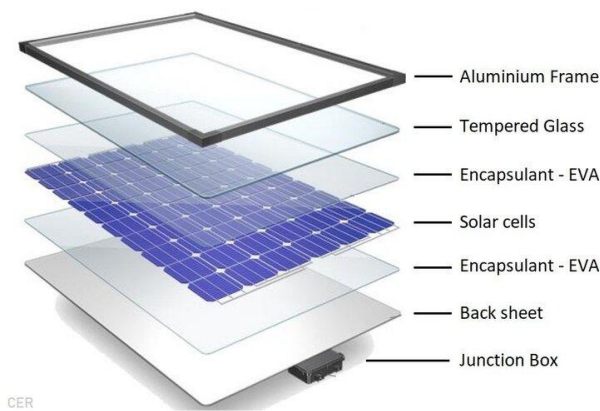


Figure (6): Layers of photovoltaic panels. [21]

- **solar PV cells:** It converts sunlight into DC electrical energy, and the base of the photovoltaic cell is a very thin plate, which is made either positive (p-type) or negative (n-type).
- **Glass:** this layer protects the cells from harsh weather conditions and hazardous pollutants, this glass has high strength, and the important suitability for high-transmittance glass.
- **Aluminum frame:** it is important for protection the edge of section house the cells and give solid structure when amount the solar panel, it is very light weight and able to stand in loading and stress.
- **EVA film:** the EVA refers to "ethylene vinyl acetate", which is a polymer layer with high transparency, it is used to encapsulate and install the cell, and this film is important in preventing inter the moisture and dirt.
- **Back Sheet:** this layer is most common in solar panels and acts as a moisture block to protect the mechanical and electrical in the solar panels.
- **Junction Box:** it is located at the back of the solar panels; it is a central point where all the cells are connected together by it. [21] There are multi layers in solar panel, so in this study these layers must be defined and determined the main properties.

Results:

In this section, the samples classification in three case (a, b and c) which different between them in precipitation (water, dust) or without precipitation, where this different follow him change in amount of solar radiation, this amount finding by using equation (1) for dust and equation (2) for water.

$$y = 4.39 X + 0.507 \quad (1)$$

Y: Solar energy reduce (%)

X: precipitation of dust or water (gr/m²)

$$y = 0.6762 X - 10.017 \quad (2)$$

y: net radiation (w/m²)
x: solar radiation (w/m²)

For each case specific solar radiating depended upon percentage of precipitation in Irbid city which is 79%. [21]

Case (a): Without precipitation of dust or water on panel:

The results of Nano coating by (TiO₂ and SiO₂) without externous dirt at two ambient temperatures and four thicknesses are show in figure (7), the solar radiation remains as it in this case. The results with thermal distribution are show in figures (8-18).

Q= 650 kW/m²

Q: solar radiation (kW/m²)

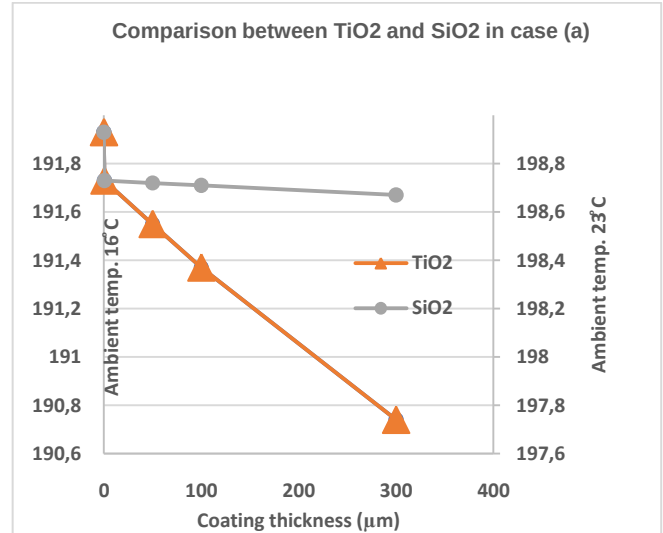


Figure (7): Comparison ambient temp. (Y—axis) at different thicknesses (μm) for TiO₂ and SiO₂ in case (a)

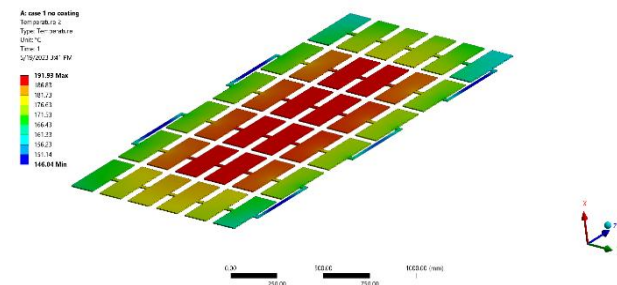


Figure (8): Thermal distribution without coating (standard) at ambient temp. (16°C).

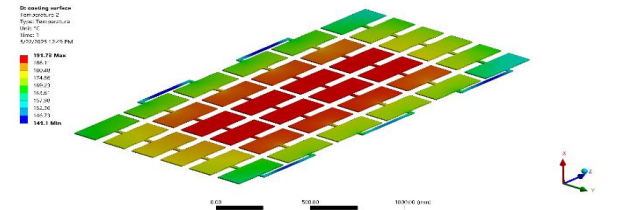


Figure (9): Thermal distribution with (0.5μm) TiO₂ coating at ambient temp. (16°C)

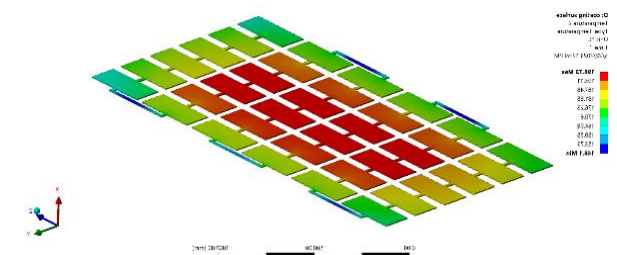


Figure (10): Thermal distribution with (0.5μm) TiO₂ coating at ambient temp. (23°C)

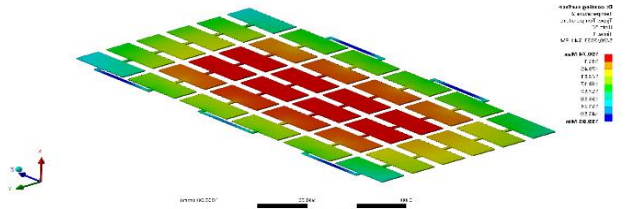


Figure (11): Thermal distribution with (300 μm) TiO_2 coating at ambient temp. (16 $^\circ\text{C}$)

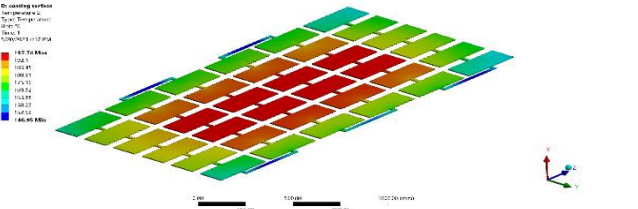


Figure (12): Thermal distribution with (300 μm) TiO_2 coating at ambient temp. (23 $^\circ\text{C}$)

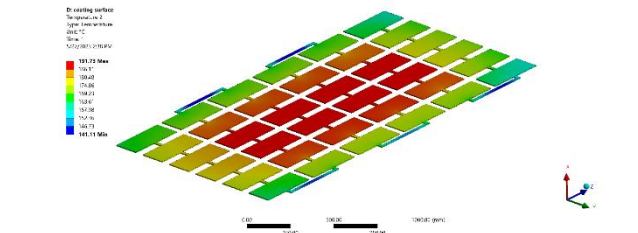


Figure (13): Thermal distribution with (0.5 μm) SiO_2 coating at ambient temp. (16 $^\circ\text{C}$)

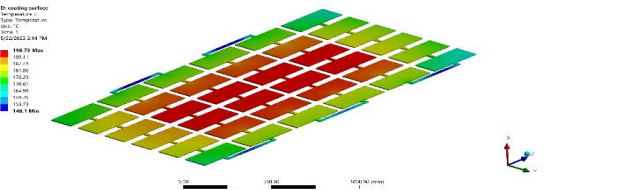


Figure (14): Thermal distribution with (0.5 μm) SiO_2 coating at ambient temp. (23 $^\circ\text{C}$).

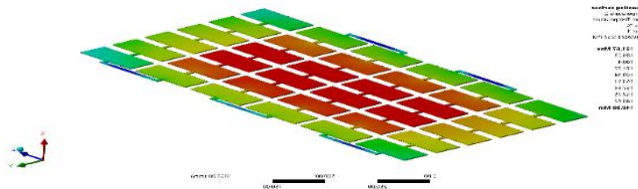


Figure (15): Thermal distribution with (300 μm) SiO_2 coating at ambient temp. (16 $^\circ\text{C}$)

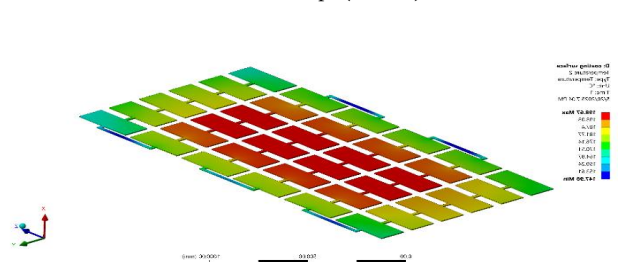


Figure (16): Thermal distribution with (300 μm) SiO_2 coating at ambient temp. (23 $^\circ\text{C}$)

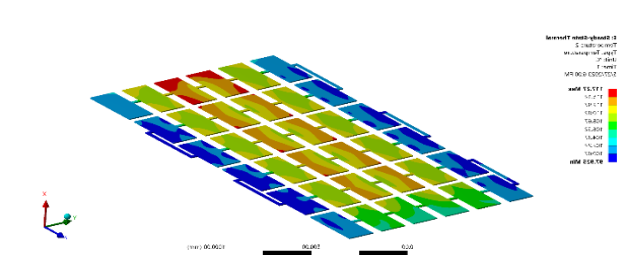


Figure (17): Thermal distribution with Nano fluid TiO_2 at ambient temp. (16 $^\circ\text{C}$)

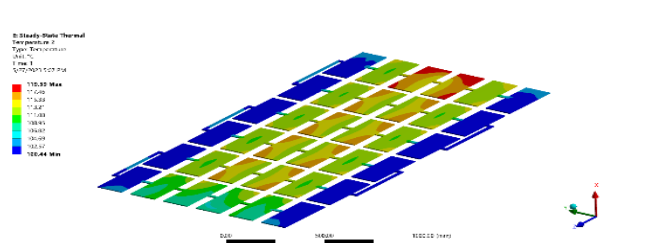


Figure (18): Thermal distribution with Nano fluid TiO_2 at ambient temp. (23 $^\circ\text{C}$)

Case (b): With precipitation of dust: The results of Nano coating by (TiO_2 and SiO_2) with precipitation dust at two ambient temperatures and four thicknesses are show in figure (19). The results with thermal distribution are show in figures (19-29), the solar radiation decrease in this case as show bellow:

$$Y = 3.97 \%$$

$$Q = 650 - 25.83 = 624.16 \text{ kW/m}^2$$

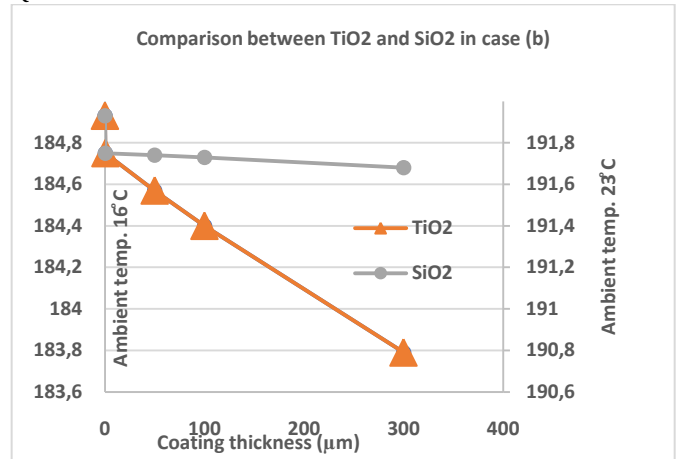


Figure (19) : Comparison ambient temp. (Y—axis) at different thicknesses (μm) for TiO_2 and SiO_2 in case (b)

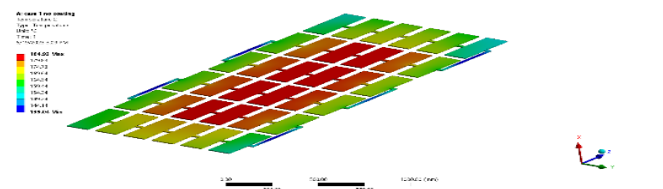


Figure (20): Thermal distribution without Nano coating at ambient temp. (16 $^\circ\text{C}$)

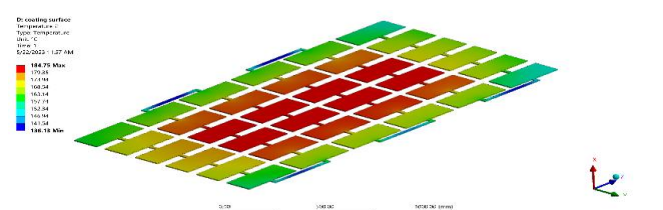


Figure (21): Thermal distribution with (0.5 μm) TiO_2 Nano coating at ambient temp. (16 $^\circ\text{C}$)

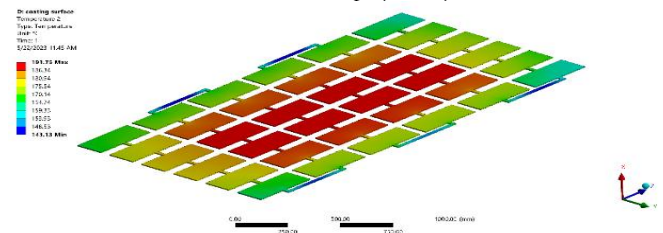


Figure (22): Thermal distribution with (0.5 μm) TiO_2 Nano coating at ambient temp. (23 $^\circ\text{C}$)

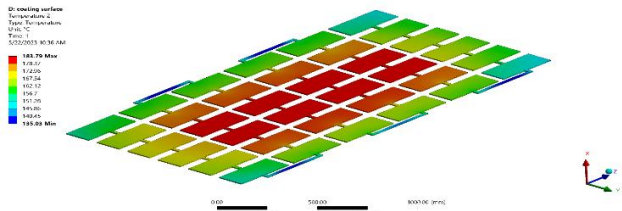


Figure (23): Thermal distribution with (300 μm) TiO_2 Nano coating at ambient temp. (16 $^{\circ}\text{C}$)

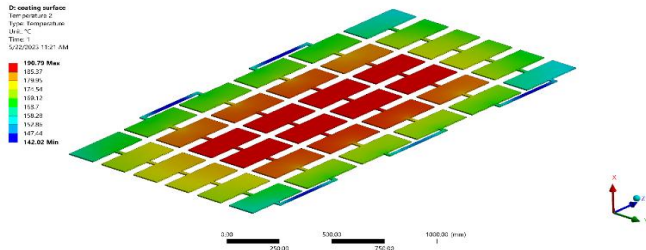


Figure (23): Thermal distribution with (300 μm) TiO_2 Nano coating at ambient tem Figure (33): p.(23 $^{\circ}\text{C}$)

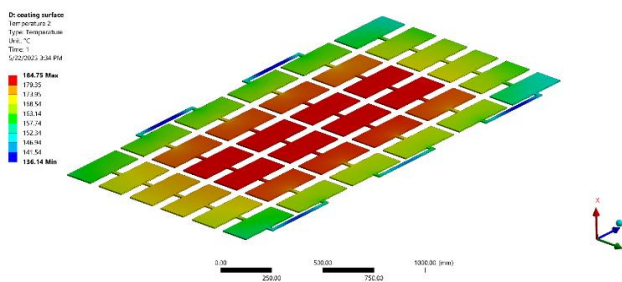


Figure (24): Thermal distribution with (0.5 μm) SiO_2 Nano coating at ambient temp. (16 $^{\circ}\text{C}$)

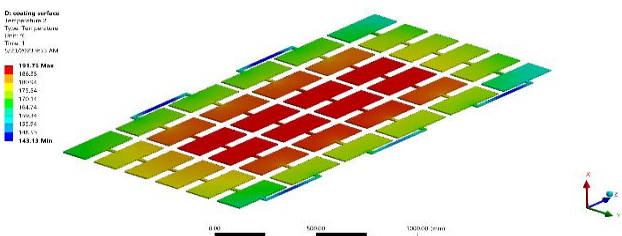


Figure (25): Thermal distribution with (0.5 μm) SiO_2 Nano coating at ambient temp. (23 $^{\circ}\text{C}$)

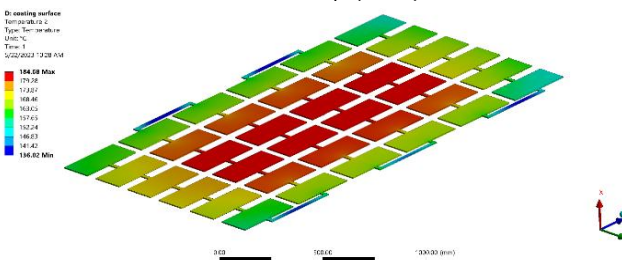


Figure (62): Thermal distribution with (300 μm) SiO_2 Nano coating at ambient temp. (16 $^{\circ}\text{C}$).

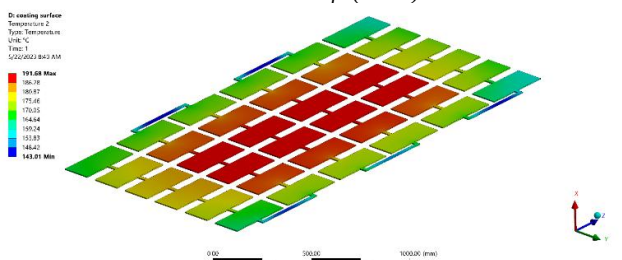


Figure (27): Thermal distribution with (300 μm) SiO_2 Nano coating at ambient temp. (23 $^{\circ}\text{C}$)

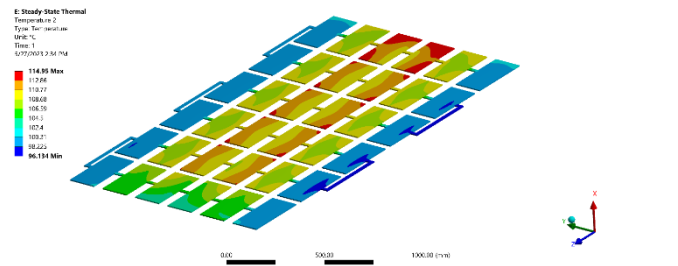


Figure (28): Thermal distribution with Nano fluid TiO_2 at ambient temp. (16 $^{\circ}\text{C}$)

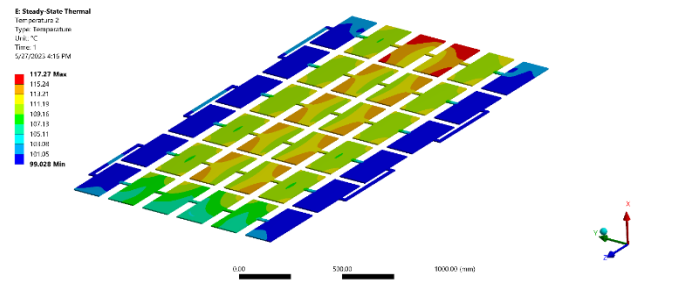


Figure (29): Thermal distribution with Nano fluid TiO_2 at ambient temp. (23 $^{\circ}\text{C}$)

Case (c): With precipitation water: The results of Nano coating by (TiO_2 and SiO_2) with precipitation water at two ambient temperature and four thicknesses are show in fig.(30). The results with thermal distribution are show in figs.(31-42), the solar radiation decrease in this case as show bellow:

$$Y_{\text{TOTAL}} = 33.9\% \quad Y = 3.05\% \\ Q = 650 - 19.82 = 630.17 \text{ kW/m}^2$$

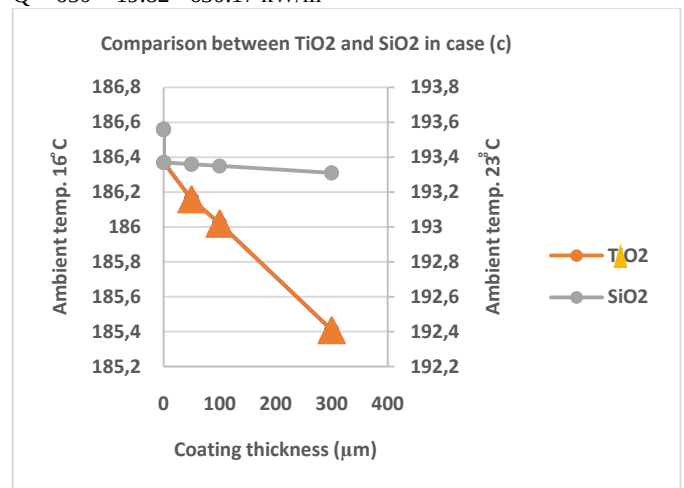


Figure (30) : Comparison ambient temp. (Y—axis) at different thicknesses (μm) for TiO_2 and SiO_2 in case (c)

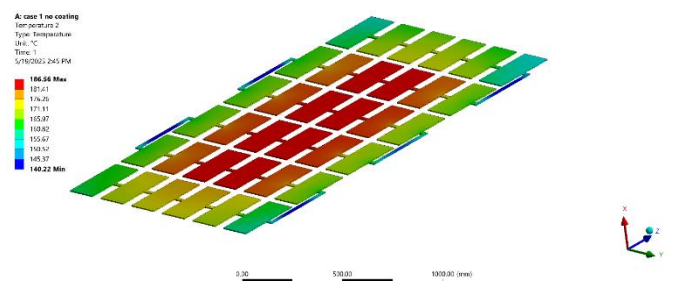


Figure (31): Thermal distribution without Nano coating at ambient temp. (16 $^{\circ}\text{C}$)

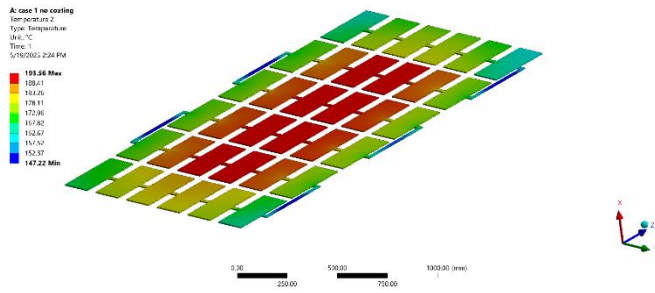


Figure (32): Thermal distribution without Nano coating at ambient temp. (23 °C)

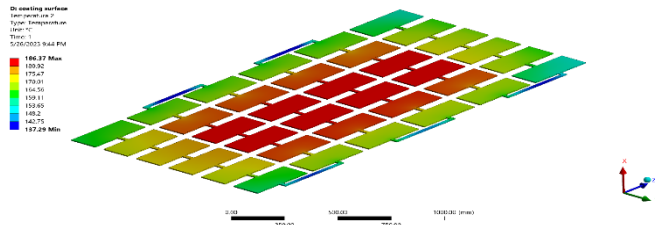


Figure (33): Thermal distribution with (0.5m) TiO_2 Nano coating at ambient temp. (16 °C)

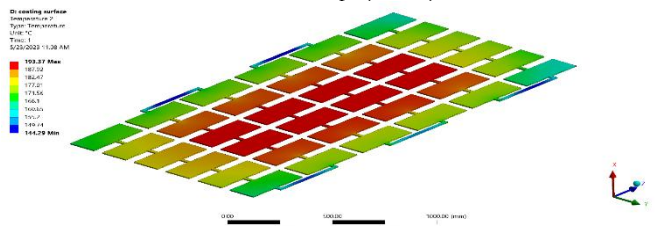


Figure (34): Thermal distribution with (0.5 μm) TiO_2 Nano coating at ambient temp. (23 °C)

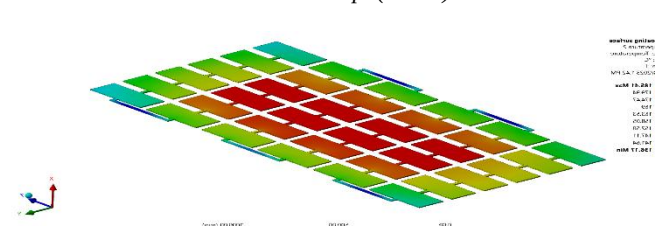


Figure (35): Thermal distribution with (300 μm) TiO_2 Nano coating at ambient temp. (16 °C).

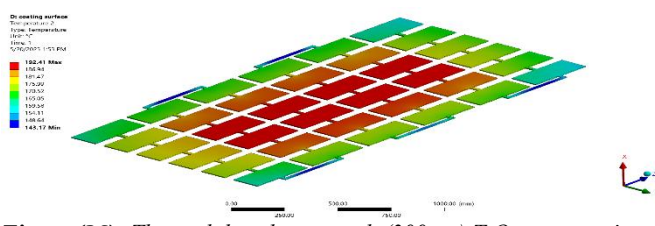


Figure (36): Thermal distribution with (300 μm) TiO_2 nanocoating at ambient temp. (23 °C)

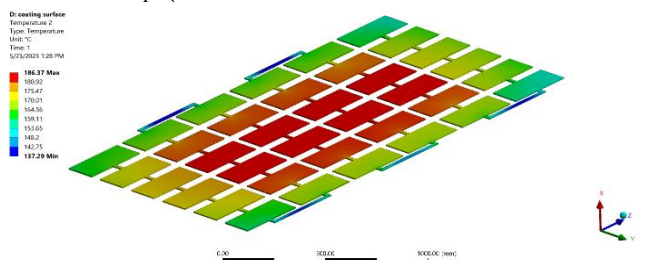


Figure (37): Thermal distribution with (0.5 μm) SiO_2 Nano coating at ambient temp.

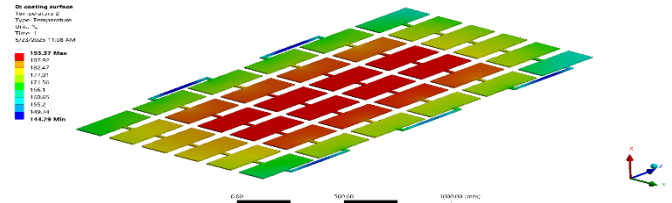


Figure (38): Thermal distribution with (0.5 μm) SiO_2 Nano coating at ambient temp. (23 °C)

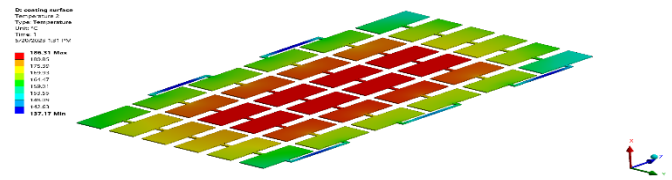


Figure (39): Thermal distribution with (300 μm) SiO_2 Nano coating at ambient temp. (16 °C)

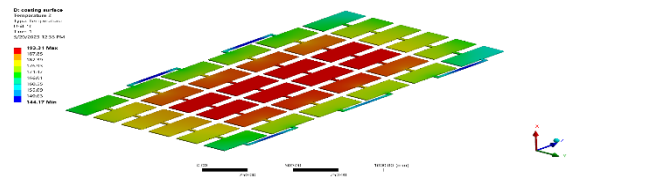


Figure (40): Thermal distribution with (300 μm) SiO_2 Nano coating at ambient temp. (23 °C)

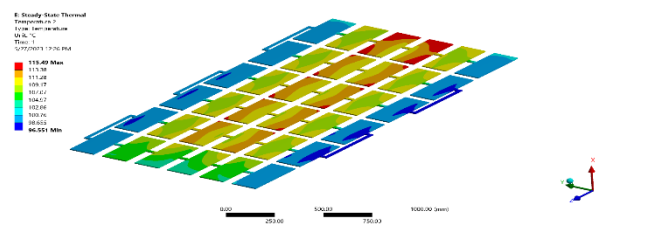


Figure (41): Thermal distribution with Nano fluid TiO_2 at ambient temp. (16 °C)

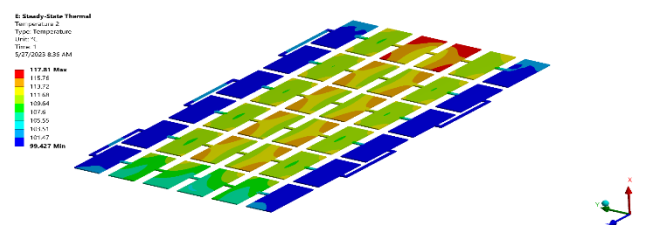


Figure (42): Thermal distribution with Nano fluid TiO_2 at ambient temp. (23 °C)

Summary of the Main Results:

From table (1), can see that the maximum improvement with TiO_2 was in case (a) at thickness 0.5 micrometer and ambient temperature 16°C, for SiO_2 the maximum improvement was in case (a) at thickness 300 micrometer and ambient temperature 16°C, but the Nano fluid gave a large improvement, where the maximum improvement was without dust or water at ambient temperature 23°C. [14]

Table (4.13): Main Results

Samples with thickness [micro]			Ambie nt temp. [16 C]	Improve ment At [16 C] %	Ambie nt temp. [23 C]	Improve ment At [23 C] %
Case(a): without dust or water	Standar d		T _{max} PV cell =191.93	0	T _{max} PV cell =198.93	0
	Ti O ₂	0.5	T _{max} PV cell =191.73	0.10420466	T _{max} PV cell =198.73	0.10053788
		300	T _{max} PV cell =190.74	0.62001771	T _{max} PV cell =197.74	0.59820037
	Si O ₂	0.5	T _{max} PV cell =191.73	0.10420466	T _{max} PV cell =198.73	0.10053788
		300	T _{max} PV cell =191.67	0.13546606	T _{max} PV cell =198.67	0.13069924
	Nano-fluid TiO ₂		T _{max} PV cell =117.27	38.8995988	T _{max} PV cell =119.59	39.8833761
Case(b): with dust	Standar d		T _{max} PV cell =184.93	0	T _{max} PV cell =191.93	0
	Ti O ₂	0.5	T _{max} PV cell =184.75	0.09733413	T _{max} PV cell =191.75	0.09378419
		300	T _{max} PV cell =183.79	0.61644947	T _{max} PV cell =190.79	0.59396655
	Si O ₂	0.5	T _{max} PV cell =184.75	0.09733413	T _{max} PV cell =191.75	0.09378419
		300	T _{max} PV cell =184.68	0.13518629	T _{max} PV cell =191.68	0.13025582
	Nano-fluid TiO ₂		T _{max} PV cell =114.95	37.8413454	T _{max} PV cell =117.27	38.8995988
Case(c): with water	Standar d		T _{max} PV cell =186.56	0	T _{max} PV cell =193.56	0
	Ti O ₂	0.5	T _{max} PV cell =186.37	0.10184391	T _{max} PV cell =193.37	0.09816078
		300	T _{max} PV cell =185.41	0.61642367	T _{max} PV cell =192.41	0.59413102
	Si O ₂	0.5	T _{max} PV cell =186.37	0.10184391	T _{max} PV cell =193.37	0.09816078

		300	T _{max} PV cell =186.31	0.13400515	T _{max} PV cell =193.31	0.12915892
	Nano-fluid TiO ₂		T _{max} PV cell =115.49	38.0949828	T _{max} PV cell =117.81	39.1351519

Conclusions:

From the above results, the following main points can be concluded:

- The maximum improvement in reduction PV temperature when using TiO₂ is (0.1042%) with coating of thickness 0.5 micrometer without externous dirt on panel.
- The maximum improvement in reduction PV temperature when using SiO₂ is (0.1354%) with coating of thickness 300nmicrometer without externous dirt on panel.
- The Nano fluid of TiO₂ in reducing the panel temperature has a better improvement in all conditions, which was a maximum improvement of (39.88%) without externous dirt on panel.
- All Nano coating thicknesses had better improvement in lower ambient temperature which was 16°C.
- Also, results showed the amount of change in ambient temperature reflects the same change in temperature of PV cell in all cases of Nano coating, but that isn't apply on Nano fluid.
- The Nano coating for both TiO₂ and SiO₂ at thickness 0.5 micrometer and any ambient temperature have the same improvements.

References:

- [1] A.W. Kandeal, Amirt, M.R. Elkadeem, Mahmoud, Zia Ullah, Ravishankar, Swellam, November (2020), Photometric Performance Improvement Using Different Cooling Methodologio, Science Direct, Vol. 273.
- [2] MHS Ahmeda, NHS Ahmida, AA Ahmeida, (2017), introduction to nanotechnology, limu, vol.2;
- [3] Emran, Innocent, waleed, Mohammed, Thaer, Harris, S.M. Muyeen, (2021), performance enhancement to self-cleaning Hydrophobic Nanocoated photovoltaic panel in Dust environment, mdpi.
- [4] Eylul, Megan, Laurent, April 2021, Effect of Dew and Rain on Photovoltaic Solar Cell Performances, Science Direct, Vol. 222.
- [5] Erdem, Tulin, Suphi, December (2011), Effect of Passive Cooling on Performance of Silicon Photovoltaic Cells, International, Vol. 6, no. 4.
- [6] Muhammad, Sishaj, Sundareswaran, Kevin, T. Sriharsha, (2022), Effects of Nano-coatings on Temperature-dependent Cell Parameters and Power Generation of Photovoltaic Panels, Springer).
- [7] Hulla, Sahu, Hayes, (2015), nanotechnology: History and future, Sage pub, vol.34, no.12.
- [8] Ravishankar Sathyamurthy, A.E. Kabeel, Ali chamkha, Alagar Karthick, A. Muthu Manokar, M.G. Sumithra, (2021), Energy Conversion and Management, Applied Nanoscience, Vol. 11.
- [9] Talib. K. Murtadha, Ali Adil Hussein, (2022), optimizatin the performance of photovoltaic panels using aluminum-oxide nanofluid as a cooling fluid at different concentrations and one-pass flow system, Vol.15.
- [10] Farzaneh and Mostafa, (2020), Nanotechnology and the environment, Mousumi sen.
- [11] Fernandez-Cerero, Dr.Fernandez-MontesA. Jakobic, (2020), Solar Panel Nanocoating, IEEE, Vol. 8.
- [12] Mozilla, (2021), solar panel nanocoating, <https://solar.techadvistor>

- [13] Junbeum, Julio, Toon, Bertrand, Sha, 2016, Review of life cycle assessment of nanomaterials in photovoltaics, *Solar Energy*, Vol. 133.
- [14] M.Z. AL-Badra, M.S. Abed-Elhady, H.A. Kandil, (2020), Anovel technique for cleaning pv panels using antistatic coating with a mechanical vibrator, *Energy*, vol.6.
- [15] Mohammad, Sishaj, Sundareswaran, Kevin, Sriharsha, March (2021), Effect of soiling on Photovoltaic Modules and its Mitigation Using Hydrophobic Nanocoatings, *IEEE Journal of Photovoltaic*, vol. 11, no.3,
- [13] Seyyed, Ali, Akbar, (2019), Experimental Study of the Dew Formation Effect on the Performance of Photovoltaic Modules, *Science Direct*, Vol. 130.
- [14] Silicon Dioxide- Structure, Properties, Uses of SiO₂ , <https://byjus.com>, 11/14/2022.
- [15] Muhamad Aziz, (2019), Exergy in photovoltaic/thermal Nano fluid-based collector system.
- [16] Talib. K. Murtadha, Ali Adil Hussein, Ahmed A.H. Alalwany, Saad S. Alrwashdeh, Alaa M. Al-Falahat, (2022), Improving the Cooling Performance of Photovoltaic Panels by Using Two Passes Circulation of Titanium Dioxide Nanofluid, *ELSEVIER*, Vol. 36.
- [18] Yousef, Septemer 24, (2022), Solar Panel: Types, working Advantages and More, *Mechanical Engineering*.
- [19] <https://www.researchgate./transmittance-spectra-thin-film>, 3/2023
- [20] <https://solar design guide.com/an Introduction-to-solar-pv-systems>, 18/11/2022.
- [21] Jason Svarc, (2020), *Clean Energy Reviews*, Solar Panel Construction.
- [23] Jason, (2022), Most Power Full Solar Panel, *Clean Energy Reviews*
- [24] <https://weatherspark.com>, 11/2022.
- [25] <https://www.clean energy reviews-info/blog/solar panel-components-construction>, 18/11/2022.
- [26] <https://www.researchgate.net/figure/Output-from-the-regionalised-solar-radiation-model>,12/2022.
- [27] Jim, Sonali, Govindasamy, Anil, Januray 2016, Study of soiling Loss on Photovoltaics modules with artificially deposited dust of different gravimetric densities and compositions collected from different locations in India, *IEEE Xplore*, Vol. 6, No. 1.
- [28] Michael, Bodo, J. Riley, Lawrence, June (2013), Comparison of PV Power Plant Soiling Measurements Extracted from PV Module Irradiance and Power Measurements, *IEEE Photovoltaic Specialists Conference*, Tampa, USA.
- [29] Muhamad, Volker, Christian, Ralph, Klemens, (2021), Mitigation of Soiling Losses by Smart Heating and Night Tilting of ASC and Standard pv Module Glass, *IEEE Photovoltaic Specialists Conference*, USA.
- [30] Munzer.S.Y.Ebaid, Ayoup. M. Ghrair, Mamdoh Al-Busoul, (2018), Experimental investigation of photovoltaic cooling photovoltaic (pv) panels using (TiO₂) nanofluid in water-polyethylene glycol mixture and (AL₂O₃) nanofluid in water- cetyltrimethylammonium bromide mixture, *Energy Conversion and Management*, vol. 155.
- [31] Pierre, H.,and J., January (2009), Study of dust removal by Standing-wave electric for application to Solar Cells on mars, *IEEE.Transactions on industry applications*,Vol.45,No. 1.
- [32] Rui Yu, Qinfeng lin, Sui—Fung Lenug, Zhiyong Fan, january (2012), *Nanomaterials and Nanostructures for efficient light absorption and photovoltaics*, *ELSEVIER*, vol.1, no.1.
- [33] V.jafari fesharaki, Majid Dehghani, J. jafari fesharaki, (2011), The Effect of temperature on photovoltaic cells efficiency, *Proceedings of the International Conference on Emerging Trend in Energy Conservation*, Tehran, Iran, Power and Water, University of Technology.

Investigation on hardness Shore D of 3D printed parts of Acrylonitrile butadiene styrene

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Abstract: In this article, hardness Shore D of 3D printed ABS samples were investigated. The experimental results were analytical and statistically processed.

Keywords: 3D PRINTING, SHORE D HARDNESS, ACRYLONITRILE BUTADIENE STYRENE

1. Introduction

3D printing technologies are constantly improving. Much research is being done on the production of machine elements using the basic 3D printing technology- FDM material deposition. In this regard, it is necessary to study the mechanical properties of 3D printing materials. One of the main materials used in FDM technology is Acrylonitrile butadiene styrene ABS. The advantages of this thermopolymer include excellent strength, good dimensional stability, good processability and chemical resistance. Figure 1 shows the technology for printing ABS using the technology FDM[1],[2],[3].

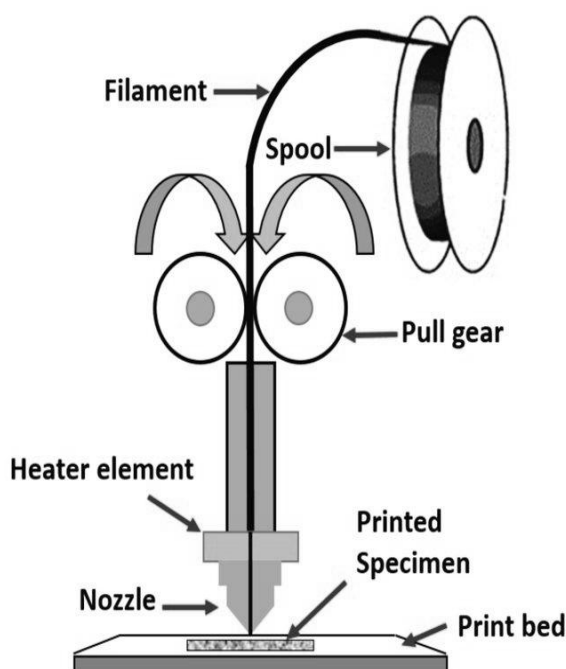


Fig. 1 Schematic of a FDM 3D printing.

In it, the material, which is in the form of a thread, also called filament, is extruded from a special extruder. It has a built-in drive, as well as a heater through which a melt is created. With the help of mechanisms driven by stepper motors, 3D printing is carried out.

Hardness is understood as the ability of the surface layer to resist elastic and plastic deformation when impacted by a harder body[4]. The method is widely used in engineering practice because the test is fast, easy and non-destructive. According to the principle of operation, hardness testing methods are classified into the following[5]:

- Scratching methods
- Indentation methods
- Rebound methods

According to the loading rate, the methods are divided into static and dynamic. For many materials, the ratio of the hardness value to that of the maximum tensile strength is known, i.e. the method can be used to obtain indirect data for other mechanical characteristics such as fatigue tests. As a mechanical characteristic,

hardness depends on a number of properties of the materials - elastic properties, plastic properties, etc. Hardness is an important mechanical characteristic because it characterizes the wear resistance of the parts

2. Materials and methods

4 samples measuring 40x40x6mm were printed from ABS polymer with the following modes:

- Material- Acrylonitrile butadiene styrene
- 3d printing speed- 350mm/s
- Extruding temperature- 235-240° C
- Bed temperature- 105° C
- Layer height- 0,2mm
- Infill- 100%
- 3D printing duration: 10 min

There are a number of standardized methods for measuring hardness - Brinell, Rockwell, Shore, Knoop, etc. The Shore method is most often used to test the hardness of rubber and plastics. The Shore method is a method of indentation testing and is standardized according to ASTM D2240 and ISO 48-4[6].

Depending on the hardness of the tested material, different scales are used - For semi-hard and hard plastics, the D scale is used. The D scale indenter is a cone with a 30 degree apex angle. and a diameter of 1.4 mm[7]. The indenter material is hardened steel, and the standardized applied force is 44.5 newtons. The standardized holding time during testing is 15 seconds. The hardness tester is calibrated using reference blocks before testing. The measurement is in dimensionless units from 0 to 100. The accuracy of the method is ± 0.05 units.

The minimum number of measurements is 5 per sample, for better precision, 10 experimental measurements were made on each sample. All standardized measurement requirements were met - the tests were made through 4 times the diameter of the indenter, the penetration depth was more than 10 times smaller than the thickness of the test samples, the samples were placed on a solid support, no measurements were made near the edges of the test plates. The hardness tester was calibrated for accuracy. The measurements were made on both sides of the test samples in order to obtain more precise experimental data. Before the test, the surface of the samples was cleaned so as not to compromise the penetration depth, and hence the experimental results. The tests were made in laboratory conditions in strict compliance with the standards for the application of the method - ASTM D2240 and ISO 48-4 - Fig. 2

ABS was chosen as the material for the hardness test. It is widely used in engineering practice due to its good mechanical strength, thermoplasticity, chemical resistance, light weight and smooth surface after processing. It is one of the most common materials used for 3D printing and is used in the automotive industry, electronics boxes, toys, packaging, housings and the construction industry[8],[9]. Its annual use exceeds 10 tons per year, which makes experimental studies of its mechanical performance very relevant. The disadvantages of ABS are low UV resistance and it is not biodegradable. ABS material is preferred for engineering applications where small force loads are required, due to its easy processing[10].



Fig. 2 Measurement of the test specimen.

3. Results and discussion

Results are presented in tab. and in fig.3.

Table 1: Measured Shore D hardness of the test specimens

Specimen 1	Specimen 2	Specimen 3	Specimen 4
76.5	77.2	78.7	77.8
77	78	78.1	76.1
77.4	77.4	77.5	77.7
76.2	76.2	78.4	78.2
79.1	79.1	77.3	78
77.9	77.9	78.4	77.3
79	79	77.8	76.8
78.3	78.3	77.7	77.7
78.4	78.4	78.7	77.8
77.3	77.3	78.7	78.9

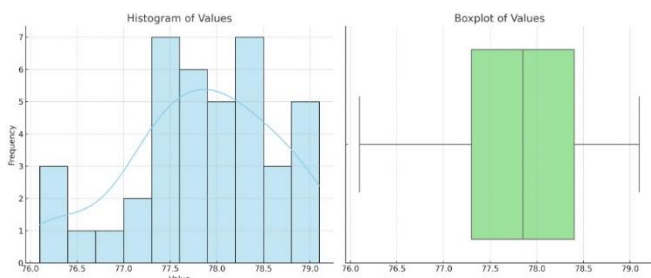


Fig. 3 Histogram of values and boxplot of values

The minimum measured value is 76.1, and the maximum is 79.1, the range is 3.0. The arithmetic mean is 77.76, the median is 77.75, and the modes are two - 77.3 and 78.4. The distribution in Figure 3 shows a symmetric distribution around the mean, with no outliers noted. The results in the box are compact and have low variance. The bimodal distribution is completely realistic in real experimental tests. The 95% confidence interval of the sample is in the range of 77.58-78.09.

4. Conclusions

Based on the 40 test tests performed using the standardized method for measuring the Shore D hardness of ABS, the following conclusions can be drawn. The results are in the range of 76.1 to 79.3, the distribution is symmetrical and compact, no anomalous results have been recorded, the variation is low, the experimental results can be used in the selection of material, as well as indirectly for strength sizing. The statistical analysis of the data validates their correctness.

5. References

1. M.N. Ahmad; M.R. Ishak; M. Mohammad Taha; F. Mustapha; Z. Leman; D.D. Anak Lukista; I. Ghazali, Application of Taguchi Method to Optimize the Parameter of Fused Deposition Modeling (FDM) Using Oil Palm Fiber Reinforced Thermoplastic Composites. *Polymers* 2022, 14, 2140. <https://doi.org/10.3390/polym14112140>
2. Fdsfds Rajendran, Sundarakannan & Palani, Geetha & Sanjeevi, Shankar & Prabu, V. & Trilaksana, Herri & Sundaram, Vickram & Marimuthu, Uthayakumar & Yang, Yo-Lun & Shanmugam, Vigneshwaran. (2025). A review on AI integration with FDM printing to enhance precision, efficiency, and process optimization. *Journal of Reinforced Plastics and Composites*. 10.1177/07316844251358587.
3. Hussam, Heba & Soliman, MEmad & Hassab-Allah, Ibraheem & Abdelrhman, Yasser. (2025). Effect of annealing on FDM-manufactured ABS parts. *The International Journal of Advanced Manufacturing Technology*. 138. 2233-2243. 10.1007/s00170-025-15455-5.
4. Pham, Gia Khanh & Domes, Ruth & Mavis, Ümit & Ernstberger, Johannes & Seidel, Christian & Eulenkamp, Constanze & Hausner-Henzel, Christine & Nguyen, Anh & Vu, Pham. (2025). Indentation hardness of 3D-printed metals. *Rakenteiden Mekaniikka*. 58. 86-109. 10.23998/rm.148552.
5. Song, Enpeng & Jin, Quan & Cai, Ke. (2025). Research on the hardness testing method of ceramicsite proppants. *Journal of Physics: Conference Series*. 3021. 012009. 10.1088/1742-6596/3021/1/012009.
6. Schmeiser, Felix & Schramm, Wolfgang & Mayinger, Felicitas & Baumert, Uwe & Stawarczyk, Bogna. (2025). Effect of Filler Type, Content, and Silanization on the Flexural Strength, Elastic Modulus, Shore D Hardness, and Two-Body Wear of PAEK Compounds. *Materials*. 18. 2736. 10.3390/ma18122736.
7. Ganapathi, Chethan & K C, Sunil & Maddani, Mahagundappa & Narayana, Y.. (2023). A Study on Shore D Hardness of Areca Husk Fibre Reinforced Polyester Resin Composite: Impact of Fibre Maturity. *Materials Science Forum*. 1111. 83-88. 10.4028/p-inPOp0.
8. Kuleyin, Hamdi & Budak, Selahattin & Yasan, Ömer & Gümrük, Recep. (2025). Characterization of thermal, chemical, mechanical, and fatigue behavior of 3D printed ABS-based elastomeric blends: ABS/EVA and ABS/TPU. *Polymer Testing*. 145. 108763. 10.1016/j.polymertesting.2025.108763.
9. Liu, Yujia & He, Hui & Zhang, Cheng & Zhai, Hongyu & Han, Luyun & Yang, Chuangbiao. (2025). Enhancing the Properties of ABS/PET Blends for 3D Printing by Functionalized Janus Nanosheets. *Polymer Engineering & Science*. n/a-n/a. 10.1002/pen.70045.
10. Karupiah, Vigneshwaran & Narayanan, Venkateshwaran & Nagarajan, Rajini & Ismail, Sikiru & Mohammad, Faruq & Al-Lohedan, Hamad & Krishnan, Associate Prof. Dr. Kumar. (2024). Performance evaluation of 3D-printed ABS and carbon fiber-reinforced ABS polymeric spur gears. *BioResources*. 19. 2796-2810. 10.15376/biores.19.2.2796-2810.

Options of applying manual laser welding for thin sheets

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Abstract: Manual laser welding has become one of the progressive technologies in recent years for processing of metallic materials, showing particular advantages in the welding of different metals. By the high energy concentration and precise focus of the laser beam, it is possible to produce joints with minimal heat-affected zones, significantly reducing the risk of deformation, cracking and other types of defects. This technology enables high-quality and aesthetically welds without the need of post-processing, while also increasing productivity and process repeatability.

This article examines the main principles, parameters and modes of laser beam welding itself, analyzes practical parameters of device LW-2000W, designed for manual laser welding. The final section summarizes practical part focusing on welding of sheet metals at different values of parameters such as power, welding speed, wire feed and beam oscillation.

Keywords: LASER, QUALITY, SHEETS, PARAMETERS, MANUAL WELDING.

1. Introduction

Welding technologies are in many cases a key focus of research due to the diversity of materials involved, whether they are filler or base materials. The selection of the appropriate welding method largely depends on the properties of these input materials. These may include chemical composition and properties, physical characteristics, or dimensional specifications. Once this data is known, a suitable welding technology is chosen, with the expectation of achieving the most satisfactory results. One of the main factors is also the complexity of the welding technique itself, especially in cases where the process is not automated and the welder's skills directly influence the final weld quality. Lastly, the selection and adjustment of suitable parameters serve as important indicators of the quality that will ultimately be achieved.[1][3]

2. Methodology of work

Advancements in the research and development of modern power sources, optical components, and electronics have enabled the creation of devices that are significantly more compact than their counterparts from two decades ago. Today, manual laser welding machines are available on the market, allowing for manual welding with filler materials mainly in the form of wires. These devices, are priced between 7,000 and 15,000 euros, pose serious competition to MIG/MAG welders. Their main advantages include high welding speed and minimal thermal impact on the weld. However, compared to arc welding methods, optimizing the welding parameters requires significantly deeper technical knowledge. [1][5]

A laser is a special type of light source that differs from conventional ones by precisely defined properties. The light produced by a laser is unique due to its **coherence** – the individual light waves are synchronized in phase. Another characteristic is **monochromaticity**, meaning it consists mainly of a single wavelength. Additionally, a laser beam has very low **divergence** (it spreads out very little) and features a high concentration of energy in a small space. These unique properties result from a specific process of radiation generation known as stimulated emission. [2]

The main component of every laser device is the active medium, which can exist in different states:

- solid (e.g., crystals like Nd:YAG),
- liquid (such as in dye lasers),
- gas (e.g., CO₂ lasers).

Stimulated emission occurs when an atom or molecule in an excited state is triggered by an incoming photon to release another photon with identical energy, phase, and direction. This process results in a pair of identical photons, which further amplify the light beam [4].

Laser welding systems can be categorized according to the degree of operator involvement [7][2]:

- **Manual welding** – The laser head is guided by the operator's hand. This approach demands a high degree of skill and accuracy, and is typically used for repairs, prototyping, or low-volume production.
- **Semi-automatic and CNC-controlled systems** – Laser optic head movement is governed by computer control, allowing for greater consistency, precision, and improved weld quality.
- **Robotic laser welding** – By integrating lasers into multi-axis robotic arms, this method offers high-speed, highly adaptable production, making it ideal for sectors like automotive manufacturing and mechanical engineering.

Advanced automated systems often feature sensors to detect joint positions, adaptive control of laser power, and real-time quality monitoring. These technologies help reduce defects and maintain consistently high weld quality [7][8].

Parameters of continuous laser welding process

The basic parameters of continuous mode laser welding are:

- **Laser beam power,**
- **Welding speed,**
- **Focusing system parameters.**

Laser beam power represents the thermal influence of the laser beam on the material during the welding process. In laser technology, power is defined as the radiation directed into the focusing system. The relevance and specification of this parameter are meaningful only when the characteristics of the beam such as mode, polarization, and divergence are known. Laser beam power significantly affects both the penetration capability and the overall quality of the weld [1][4].

Welding speed refers to the distance the heat source travels across the material per unit of time. It's important to emphasize that, when laser power is held constant, the welding speed directly influences the amount of energy delivered to the material. Research has shown that welding speed affects the temperature distribution within the material. According to thermal process theory, increasing the welding speed results in smaller areas near the heat source reaching specific temperatures. These factors must be carefully considered, as they influence the weld geometry, microstructure, material properties, and chemical composition in the heat-affected zone [1].

Focusing system parameters include the diameter of the focused laser beam, the configuration of the lens or objective, the design of the focusing system, and the beam divergence.

An optimal beam diameter typically ranges between 0.5 and 1 mm. This is because, at spot sizes smaller than 0.5 mm, the delivered energy becomes excessive, leading to overheating of the metal and a higher likelihood of weld defects. Conversely, when the beam diameter exceeds 1 mm, the efficiency of the laser as a concentrated heat source decreases. Thus, maintaining the beam diameter within this optimal range is essential for ensuring stable and high-quality welds [8][9].

Delivered energy – represents the energy applied per unit length $Q=P/v$,

Power density – the power of the beam applied on area $I [W.cm^{-2}]$,

Type of shielding gas, shielding gas flow rate [l-min],

3. Experimental stand of work

Information about LW-2000W device

The LW handheld laser welding system is classified as a Class 4 laser device, posing significant hazards when directly exposed to the laser beam or when the beam contacts the skin. Furthermore, diffuse reflections and scattered beams present additional safety risks. The system architecture includes a controller unit paired with a touchscreen interface, through which operators can configure welding parameters, engage control functionalities, toggle between operating modes, monitor system alerts, and execute various operational commands. The controller functions as a supplementary component integrating laser control, wire feeding, and welding torch management. [6]



Fig.1 LW-2000W with feeding system MARS9000P



Fig.2 Working screen of LW-2000W

Base materials

Surface-treated steel sheets were used for the laser welding process. The welding was performed with butt joints in the PA position, with zero gap between the base sheets. Welds were made using combinations of different steel grades. **All sheets had a thickness of 0.8 mm.** Except for the DC04 sheet, all steel grades were micro-alloyed and surface-treated on both sides with hot-dip galvanizing. The chemical composition of the welded sheets, determined by the Belec Compact Port spectral analyzer, is presented in Tables 1. The mechanical properties of the steel sheets used are summarized in Table 2.

Table 1. Chem. Composition of sheets samples A (% , Fe bal.)

	C	Si	Mn	P	S	Cu	Al	Cr	Mo	Ni	Nb	Co
HCT600X+Z	0,068	0,238	1,589	0,016	<0,002	0,03	0,044	0,206	0,074	0,039	0,026	0,063
DC04	0,03	0,034	0,228	0,015	<0,002	0,035	0,088	0,042	0,027	0,023	0,026	0,074

Table 2. Mechanical features of based materials (supplier info)

	Re [MPa]	Rm [MPa]	A80 [%]
HCT600X+Z	346	654	23,5
DC04	197	327	39,0

Chemical features of filler material in a form of wire with the mark G 42 4 M21 3 Si1 - EN ISO 14341 (MAGMA weld ø 1,0mm) are described in Table 3.

Tab 3 . Chem. Composition of filler material in wire form

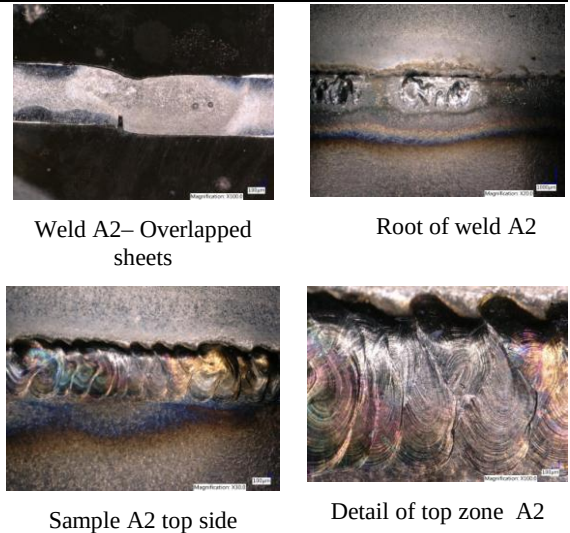
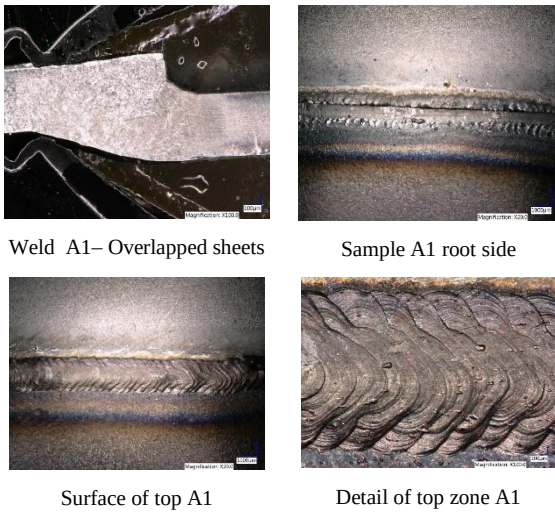
Wire	C	Si	Mn	P	S	Re [MPa]	Rm [MPa]	A80 [%]
G 42 4 M21 3 Si1	0,09	0,9	1,53	<0,002	<0,002	440	540	26

Process was done by pWPS (Fig. 3). During welding was secured zero gap between sheets, with prethreated edges by mechanical process. Length of sample : 300x120 mm. At this length were done 3 welds with different used parameters.

PREDBEŽNÉ STANOVENÝ POSTUP ZVÁRANIA PRELIMINARY WELDING PROCEDURE SPECIFICATION pWPS (STN EN ISO 15 608-1)										Číslo / No. : KTMaPPV-A1-25		
Strojnícka fakulta Projekt : Zváranie plechov Názov : Laserové zváranie Objekt : Laser welding Typ spoja : Tuhý spoj Joint type : Butt joint					Číslo výkresu : Drawing num ber : Materiál : 1+0.8 mm - HCT600X+Z; 1.1 CR 10 1088 1+0.8 mm - DC04; 1.1 CR 10 1088 Materiál : Skúšky postupu : WPAR-IV - Tests							
Príprava zvárových hrán / Joint Design 					Vyhodnotenie zvaru / Weld sequence 							
Poznámky: Notes:												
Weld Layer	Metoda Process	Ličba zvaru Right side	Ličba zvaru Left side	Poloha zvaru Weld Pos/for	Prídavný materiál Filler material	Ø mm	Zvárací prúd Current	Napätie Voltage	Polarita Polarity	Rýchlosť Speed (mm/s)	Rýchlosť zvárania Travel speed (mm/min)	Teplotný príkon Heat input (kJ/mm²)
1	52	1	-	PA	MO 2	1.0	-	-	-	-	-	-
Ovládanie lasera / Laser Control Výkon / Power : 600W Frekvencia / Frequency : 1000 Hz Prázdny cyklus / Duty Cycle : 100%												
Ovládanie podkova / Arcer Control Modus / Mode : Frekvencia / Frequency : 30 Hz Šírka / Width : 3.0 mm												
Asistované ovládanie Rýchlosť drži / speed wire : 12 mm/s Predfúz / pre-purge : 200 ms Dotuk / post-purge : 200 ms												
Predhriev : Predhriev temp. : Ochranný plyn : Shielding gas : Nedešť skúšky : NDT :												
Medzistúžia teplota : Rozpáza temp. : Prerok plynu : Flow rate : RTG : X-Ray test :												
Dohrev : Poohrev temp. : Sekund. ochl. : Backing gas : Pevnosť skúšky : PT :												
Tep. spracovanie : Heat treat ent. : Prerok plynu : Flow rate : Ultrazvuk : UT :												
Prídavné materiály / Filler materials Typ / Type : G 42 4 M21 3 Si1 Normoznačka / Classification : EN ISO 14341 Výrobca / Producer : MAGMAWELD Obchodné označenie / Trade name : MO 2												
Vypracoval / Issued by : Datum / Date : Pečiatka, podpis / Stamp, Signature :												

Fig. 3 pWPS (Sample A – first weld)

Tab. 4 Sample A (weld zone in A1)



Tab. 6 Sample A (weld zone in A3)

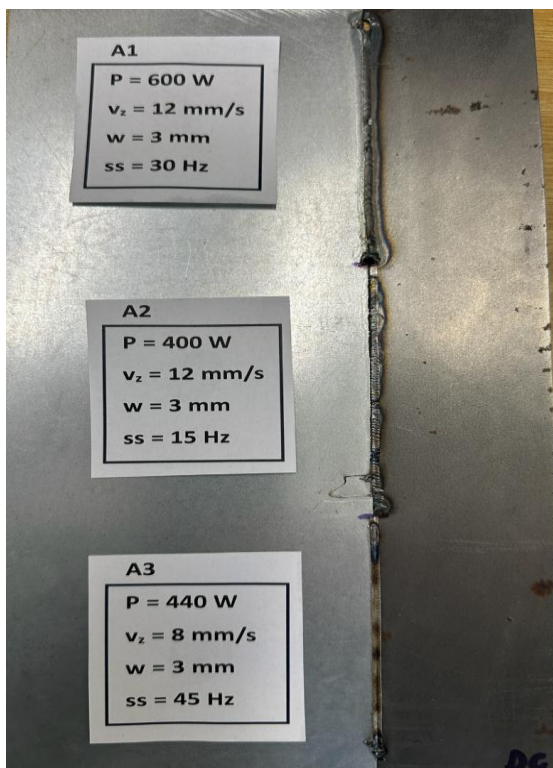
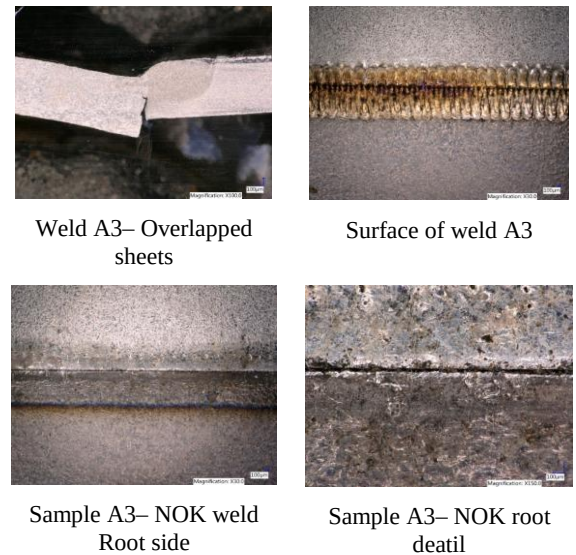


Fig. 4 Sample A (with 3 different welds A1, A2, A3)

Three different welds were made along a single sheet length, with the following designations and parameter which are described at **Fig. 4**.

- P – Laser power [W]
- v_z – welding speed [mm/s]
- w – width of oscillation [mm]
- ss – frequency [Hz]

Weld spatter was present in several areas. Some weld surfaces appeared darkened due to the use of a shielding atmosphere. Surface characteristics of the welds, including the root areas, were documented with a Keyence VHX-5000 digital microscope. Microstructures were analyzed on cross-sectional metallographic samples. The microstructures were revealed by etching with a 2% HNO_3 solution.

Tab. 5 Sample A (weld zone in A2)

4. Conclusion

Based on the presented results of the metallographic analysis of welded joints made by manual laser welding device, it can be concluded that the selected welding parameters were not suitable for the given type of joints. Despite the welders' experience and the relatively good visual appearance of the samples under non-destructive testing methods, none of the samples would pass the evaluation.

The optimization of process parameters and the application of multiple types of base materials are essential to achieve results that meet the required quality standards upon subsequent testing. Therefore, continued optimization efforts are necessary to ensure compliance with performance and reliability criteria. From the perspective of overall process complexity, this welding method can be considered relatively simple. Compared to arc welding technology, it offers a more appropriate welding speed, lower heat input, and significantly simpler operational technique. However, the input parameters that influence the process itself are much broader and more complex. All these factors must be taken into account in order to establish proper working conditions and training for the welding operator both in terms of the welding technique itself and safety during operation.

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5. References

1. UNIVERSAL LASER SYSTEMS. Laser system education [online]. Available at: <https://www.ulsinc.com/ru/%D0%BE%D0%B1%D1%83%D1%87%D0%B5%D0%BD%D0%B8%D0%B5> [cit. 18. 7. 2025]
2. SHANTHOS KUMAR, G., RAGHUKANDAN, K., SARAVANAN, S., SIVAGURUMANIKANDAN, N. Optimization of parameters to attain higher tensile strength in pulsed Nd:YAG laser welded Hastelloy C-276–Monel 400 sheets. *Infrared Physics & Technology*, 2019, vol. 100, s. 1–10. ISSN 1350-4495.
3. Stavridis J, Papacharalampopoulos A, Stavropoulos P. Quality assessment in laser welding: A critical review. *International Journal of Advanced Manufacturing Technology*. 2018;94:1-23
4. Milonni PW, Eberly JH. *Laser Physics*. Hoboken, New Jersey: John Wiley & Sons, Inc.; 2010
5. DAWES, C. T. *Laser welding: a practical guide*. Cambridge: Woodhead Publishing, 1992.
6. ASKOZVAR s.r.o., Návod na použitie ručného laserového zariadenia LW 2000W. Košice. 35 s.
7. Katayama S. *Handbook of Laser Welding Technologies*. Elsevier Science, Woodhead Publishing; 2013
8. Xinju L. *Laser Technology*. CRC Press; 2010. ISBN: 9781138372764
9. YANG, Y., GAO, Z., CAO, L. Identifying optimal process parameters in deep penetration laser welding by adopting Hierarchical-Kriging model. *Infrared Physics & Technology*, 2018, vol. 92, s. 443–453. ISSN 1350-4495.
10. FRACTORY. *Laser Welding Explained* [online]. Available at: <https://fractory.com/laser-welding-explained/> [cit. 21. 07. 2025].

Plasma technologies for the synthesis of wear-resistant multifunctional metal matrix composites of the Al–TiC System

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Abstract A novel two-stage approach for obtaining wear-resistant multifunctional powder composites based on metal powders with high-modulus Ti–TiC system fillers is proposed. The method combines high-voltage electric discharge (HVED) treatment and spark plasma sintering (SPS), offering a promising alternative to conventional techniques for producing Al–Ti–C system composites. This approach enables the development of a unified route for material synthesis using high-energy-density processing.

HVED treatment prevents oxidation of metal particles, reduces contamination by tool materials, and initiates the synthesis of additional dispersed strengthening phases. For example, HVED treatment of titanium powder in a hydrocarbon liquid promotes the in situ formation of titanium carbide (TiC) particles.

The present work investigates the influence of adding Ti–TiC powder—synthesized via HVED in ethanol under reverse polarity mode with a specific energy input of 20 MJ/kg—on the structure, phase composition, and properties of Al–Ti–C metal matrix composites (MMCs).

It was shown that the addition of 2 wt% of Ti–TiC powder synthesized via HVED in ethanol to aluminum powder results in an MMC with an electrical resistivity of 0.5 $\Omega\cdot\text{mm}^2/\text{m}$ and a hardness of 31 HRB. However, the heat resistance of this composite is 2.5 times lower than that of consolidated pure aluminum powder. Increasing the Ti–TiC content to 10 wt% leads to the formation of a wear-resistant Al–Ti–C composite, whose structure includes Al, Ti, TiC, the intermetallic compound Al_3Ti , MAX phases Ti_2AlC and Ti_3AlC_2 , and free carbon. For the MMC sample with the addition of 10% Ti–TiC, the mass gain per cycle during the heat resistance test is 0.23%/cycle, whereas for samples made from consolidated Al powder it is 0.18%/cycle, indicating that their heat resistance is approximately the same. The wear resistance of this composite is more than three times higher than that of the consolidated base aluminum powder, with wear rates of 0.003 g/km and 0.010 g/km, respectively. This material also demonstrates a hardness of 43 HRB and relatively low electrical resistivity at the level of 0.3 $\Omega\cdot\text{mm}^2/\text{m}$.

KEYWORDS: TITANIUM, TITANIUM CARBIDE, METAL MATRIX COMPOSITES, HIGH-VOLTAGE ELECTRICAL DISCHARGE, PLASMA TECHNOLOGIES, SPARK PLASMA SINTERING, MAX PHASES

1. Introduction

Metal matrix composites (MMCs) based on the Al–TiC system are characterized by high strength while maintaining considerable plasticity. For example, the introduction of 10 wt.% TiC reduces the relative elongation of aluminum by only ~10%. The use of titanium carbide as a reinforcing phase also enhances corrosion resistance, impact toughness, and heat resistance. This effect is attributed to the strong modifying influence of TiC on aluminum, which results from the close match of their crystal lattices: the face-centered cubic lattice of TiC is nearly identical to that of $\alpha\text{-Al}$, with a mismatch of only about 7%. During the fabrication of Al–TiC composites, titanium carbide particles can react to form intermediate phases such as Al_4C_3 , Al_3Ti , AlTi , and AlTi_3 . At elevated temperatures up to 1000 °C, the formation of ternary titanium carbides such as Ti_3AlC , Ti_2AlC , and Ti_2AlC_2 is also possible [1–3].

However, conventional methods for producing such materials have nearly exhausted their potential. Mechanical techniques for powder preparation prior to consolidation are associated with oxidation and contamination of powder particles, as well as high specific energy consumption. Furthermore, traditional consolidation methods such as isothermal sintering involve prolonged exposure to high temperatures, which leads to grain coarsening in the consolidated specimens and results in reduced strength and hardness.

In recent years, a novel two-stage approach has been developed at the Institute of Pulse Processes and Technologies of the National Academy of Sciences of Ukraine for the synthesis of wear-resistant multifunctional powder composites based on aluminum with high-modulus TiC–Ti reinforcements. This method combines high-voltage electrical discharge (HVED) treatment of initial powders and subsequent spark plasma sintering (SPS), offering a viable alternative to conventional fabrication techniques for Al–Ti–C composites [4–6].

In the first stage, HVED treatment of the initial Al–Ti powder mixture in a hydrocarbon liquid facilitates surface activation of the powders, synthesis of nanocarbon in various allotropic forms, and in situ formation of TiC from titanium powder. In the second stage,

SPS is used to synthesize multifunctional powder composites with high-modulus reinforcements, preserving the fine structure of the material components.

The findings from previous studies, which form the basis of this work, demonstrate that the proposed approach can be adapted for the fabrication of high-wear-resistant MMCs of other compositions within the Al–TiC system under conditions of high-energy powder treatment and extreme ultrafast thermal and pressure loading during SPS consolidation.

However, earlier studies investigated only the scenario in which the Al–Ti powder mixture was subjected to joint HVED treatment followed by SPS consolidation. For certain MMC compositions, a different approach may be more promising. This alternative involves pre-treatment of titanium powder by HVED to produce a sufficient amount of TiC, followed by the addition of aluminum powder in the required proportion and subsequent SPS consolidation. The advantage of this method lies in the ability to generate the desired amount of titanium carbide required for effective reinforcement.

Therefore, the goal of this work is to investigate the effect of the concentration of HVED-processed Ti–TiC powder on the properties of Al–Ti–C composites.

2. Methodology

The study utilized aluminum powder of PA1 (IIA1) grade (according to GOST 6058-73) with an average particle diameter of $d_0 = 21\ \mu\text{m}$, as well as Ti + 23 wt.% TiC composite powder obtained by high-voltage electrical discharge treatment of titanium powder in the mode of volume-distributed multi-spark discharge (VMD). The treatment was carried out in ethanol with a specific treatment energy of 20 MJ/kg. The average particle diameter of the used Ti + 23 wt.% TiC powder was $d_0 = 10\ \mu\text{m}$.

Consolidation of MMC specimens was performed using the "HEFEST-10" («ГЕФЕСТ-10») universal experimental setup [4] under vacuum conditions. Spark plasma sintering (SPS) was carried out in dies made of MPG-6 (MIIT 6) grade graphite. The inner diameter of the die was 10 mm, and the powder charge mass was

3 g. The SPS temperature regime was selected based on the melting point T_m of the most fusible component; the isothermal holding temperature was set to $0.8 \cdot T_m = 528^\circ\text{C}$ [7]. The duration of the isothermal holding stage during SPS was 3 minutes.

The obtained MMCs were analyzed in terms of structure, phase composition, and properties, including Rockwell hardness, wear resistance, thermal stability, and specific electrical resistivity. Microstructural investigations were carried out using the BIOLAM-I optical microscope with a maximum magnification of $\times 1350$ and a Canon digital camera.

X-Ray diffraction (XRD) patterns were recorded using the Rigaku Ultima IV diffractometer (at the E.O. Paton Institute of Materials Science and Welding of NAS of Ukraine) and the Bruker D8 DISCOVER diffractometer (at the Center for Microelectronics and Nanotechnology, University of Rzeszów) under $\text{Cu}_{K\alpha}$ radiation. A nickel β -filter was applied to reduce background noise and suppress β -lines. Phase identification was conducted using the POW_COD database and Bruker EVA software. Quantitative phase composition was determined by the reference intensity ratio (RIR) method [8] using the QualX software and full-profile analysis with the Maud software package. A quartz reference sample was used to determine the instrument function.

Rockwell hardness (HRB scale) was measured in accordance with ISO 6507-4:2008 using the TK-2 hardness tester, which records the difference in indentation depth between preliminary and main loads. A steel ball indenter with a diameter of 1.588 mm was used under a total load of 60 kg. At least 10 measurements were performed for each experimental point.

The specific electrical resistivity of the samples was determined using a custom-built test stand. The design and methodology of this setup are described in detail in [9].

Wear resistance of consolidated MMC samples was evaluated by gravimetric method on a friction testing machine. The description of the setup and methodology is provided in [10].

The heat resistance of the samples was assessed by their mass gain during exposure in air inside the SNOL («CHOJI») 7.2/1300 furnace, according to GOST 6130–71. Prior to testing, the specimens were weighed in crucibles using analytical scales with an accuracy of 0.1 mg. The samples were then heated to 600°C and held for 5 hours, followed by furnace cooling for 16 hours to a temperature of approximately 115°C . Thus, each cycle of high-temperature exposure lasted 21 hours. After each cycle, the specimens were weighed again along with the crucibles. This procedure was repeated for five cycles. The total duration of exposure per sample at elevated temperature was 105 hours, with a total holding time at 600°C of 25 hours.

Heat resistance was evaluated as the mass difference of the sample before and after each cycle. Additionally, the average mass gain per cycle k_h , expressed in %/cycle, was calculated as the ratio of total mass increase to the number of test cycles.

3. Results and discussion

The material obtained by consolidating the initial Al powder, used as a reference sample, exhibited a uniform microstructure (see Fig. 1, a).

The addition of 2 wt.% of the Ti–TiC mixture (obtained via HVED treatment) to the initial aluminum powder influenced both the structure and properties of the resulting material. Microstructural analysis revealed a homogeneous distribution of reinforcing particles within the matrix, with particle sizes ranging from $50\ \mu\text{m}$ to $100\ \mu\text{m}$ (see Fig. 1, b). The specific electrical resistivity of the material increased nearly fivefold, from $0.106\ \Omega\cdot\text{mm}^2/\text{m}$ to $0.504\ \Omega\cdot\text{mm}^2/\text{m}$. The hardness of the consolidated material increased by 53%, rising from 20 HRB to 31 HRB (see Fig. 2).

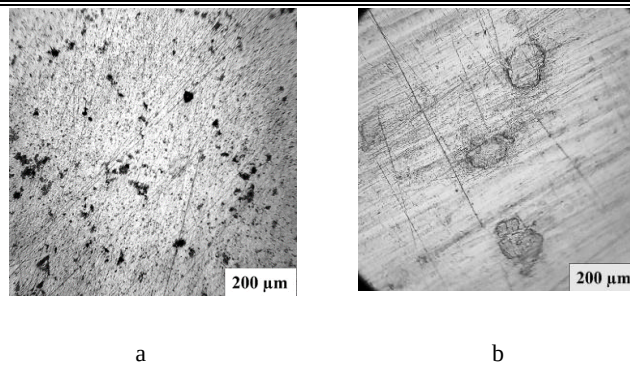


Figure 1: Microstructures of the consolidated materials: a – Al; b – Al + 2 % Ti–TiC

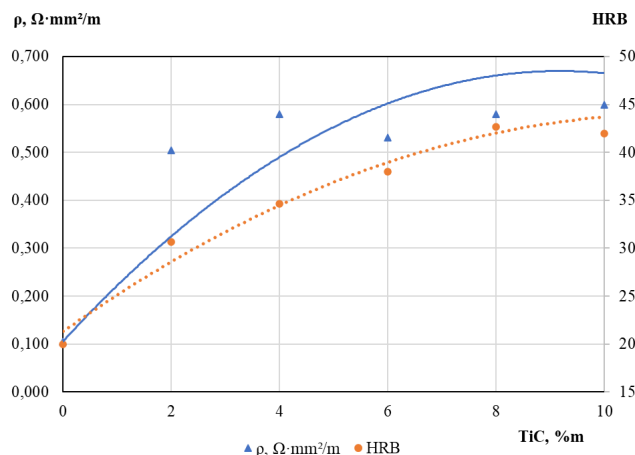


Figure 2: Properties of consolidated materials of the Al + Ti–TiC system

An increase in the Ti–TiC content (after HVED treatment) in the initial aluminum powder from 2 wt.% to 4 wt.% led to a higher number of visible particles in the range of $50\ \mu\text{m}$ to $100\ \mu\text{m}$ (see Fig. 3, a), a 14% increase in the material's specific electrical resistivity—from $0.504\ \Omega\cdot\text{mm}^2/\text{m}$ to $0.576\ \Omega\cdot\text{mm}^2/\text{m}$ —and a 13% increase in hardness, from 31 HRB to 35 HRB (see Fig. 2).

Further addition of HVED-treated Ti–TiC to the initial aluminum powder from 4 wt.% to 6 wt.% resulted in an even greater number of visible particles sized $50\ \mu\text{m}$ to $100\ \mu\text{m}$ in the structure of the SPS-consolidated material (see Fig. 3, b). The specific electrical resistivity of the material remained nearly unchanged at $\rho = 0.57\ \Omega\cdot\text{mm}^2/\text{m}$, while the hardness increased by

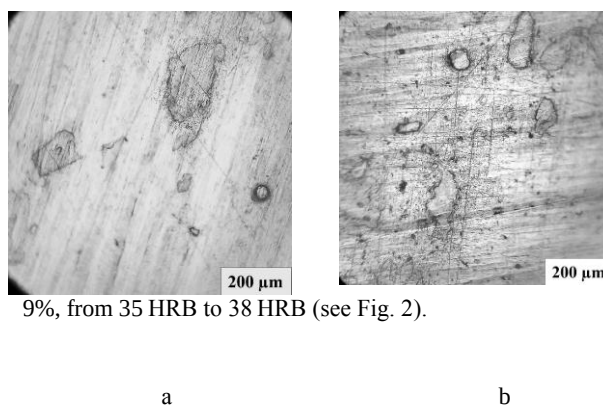


Figure 3: Microstructures of the consolidated materials: a – Al + 4 % Ti–TiC; b – Al + 6 % Ti–TiC

When the Ti–TiC content (after HVED treatment) was increased from 6 wt.% to 8 wt.%, the number of visible particles sized 50 μm to 100 μm increased, along with the amount of dark carbon-containing phase at their boundaries in the structure of the consolidated material (see Fig. 4, a). The specific electrical resistivity of the consolidated material increased by 9%, from 0.57 $\Omega \cdot \text{mm}^2/\text{m}$ to 0.58 $\Omega \cdot \text{mm}^2/\text{m}$, and the hardness increased by 12%, from 38 HRB to 43 HRB (see Fig. 2).

A further increase in the Ti–TiC content in the powder mixture from 8 wt.% to 10 wt.% did not result in a higher number of visible particles sized 50 μm to 100 μm , nor in an increase in the dark carbon-containing phase at their boundaries in the compact's structure (see Fig. 4, b). However, the specific electrical resistivity increased from 0.58 $\Omega \cdot \text{mm}^2/\text{m}$ to 0.6 $\Omega \cdot \text{mm}^2/\text{m}$, while the hardness remained unchanged at 43 HRB (see Fig. 2).

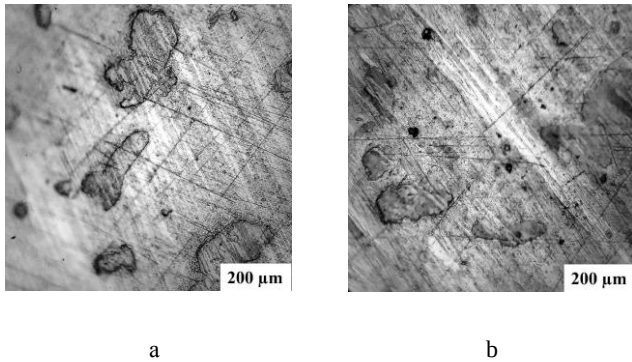


Figure 4: Microstructures of the consolidated materials: a – Al + 8 % Ti–TiC; b – Al + 10 % Ti–TiC

The X-Ray phase analysis results presented in Fig. 5 for the MMC sample obtained from the Al + 10 wt.% Ti–TiC powder mixture indicate that, in addition to Al (88 wt.%), Ti (9 wt.%), and titanium carbides TiC (<1 wt.%) and Ti₃C₂ (<1 wt.%), the material's structure also contains high-modulus reinforcements synthesized during HVED treatment and subsequent SPS. These include the intermetallic phase Al₃Ti (<1 wt.%), MAX phases such as Ti₅Al₂C₃ (<1 wt.%), Ti₂AlC (<1 wt.%), Ti₃AlC₂ (<1 wt.%), and the ternary carbide Ti₃AlC (<1 wt.%) with a perovskite-like structure. This XRD pattern also shows peaks indicating the presence of free carbon in the MMC structure in an amount of approximately 2 wt.%.

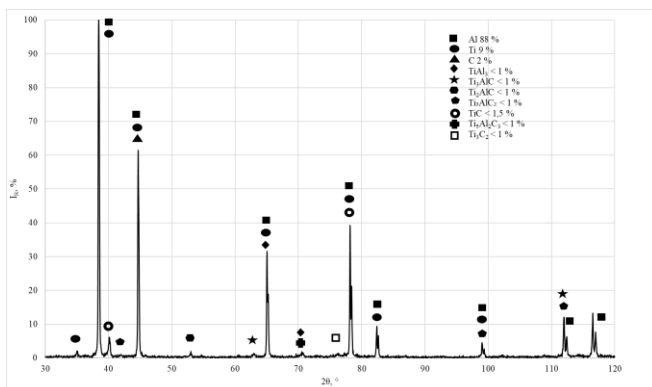


Figure 5: XRD pattern of the consolidated material based on the Al + 10 wt.% Ti–TiC powder system

Wear resistance testing was conducted for the consolidated material sample of the Al + 10 wt.% Ti–TiC system (see Fig. 6). The determined wear coefficient for this material is 0.003 g/km.

The wear curve for this sample is characterized by a nearly constant wear rate, with a small segment of relatively slower wear observed between a wear distance (l_w) of 3.5 km and 6 km.

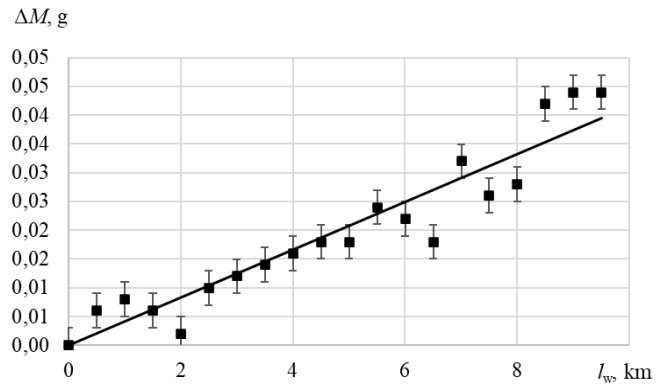


Figure 6: Wear curve of the consolidated material sample based on the Al + 10 wt.% Ti–TiC system

For comparison, wear resistance testing was performed on a consolidated initial Al powder sample (see Fig. 7), which exhibited a wear coefficient of 0.008 g/km. Thus, the addition of 10 wt.% Ti–TiC powder obtained via high-voltage electrical discharge treatment to the powder mixture resulted in nearly a threefold increase in the wear resistance of the consolidated material. This improvement can be explained, in particular, by the increase in hardness from 20 HRB to 43 HRB (see Fig. 2).

The wear curve for the consolidated Al powder sample, shown in Fig. 7, is characterized by a small segment of relatively rapid wear from 0 to 1.5 km, which may be attributed to additional surface run-in between the sample and the friction machine roller. From 1.5 km to 10 km of the wear path, the wear rate is practically uniform.

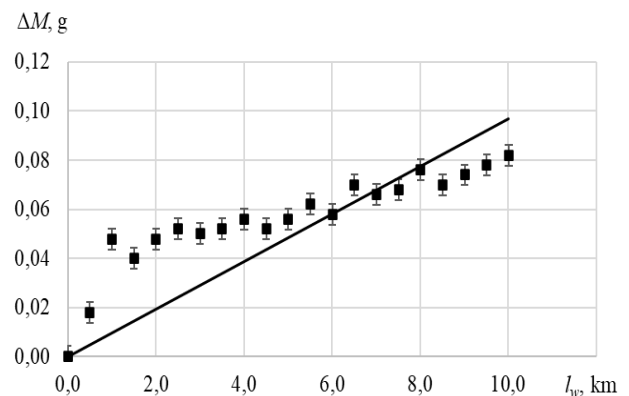


Figure 7: Wear curve of the consolidated Al powder sample

The results of the heat resistance study revealed that adding Ti–TiC powder to the Al-based composite in concentrations from 2% to 6% leads to a slight decrease in heat resistance (see Fig. 8). In contrast, the heat resistance of the Al + 8% Ti–TiC composite is somewhat higher than that of the consolidated Al powder. The heat resistance of the Al + 10% Ti–TiC MMC is significantly greater than that of the consolidated Al powder sample.

Thus, the curve illustrating the dependence of the mass change per heat resistance test cycle coefficient on the Ti–TiC content in the initial powder for Al + Ti–TiC composites exhibits an extremal behavior. The highest value of this coefficient (and correspondingly the lowest heat resistance) is characteristic of the Al + 2% Ti–TiC

MMC, amounting to 0.46 %/cycle, whereas for the Al + 10% Ti–TiC MMC this value is minimal at 0.025 %/cycle (see Fig. 9).

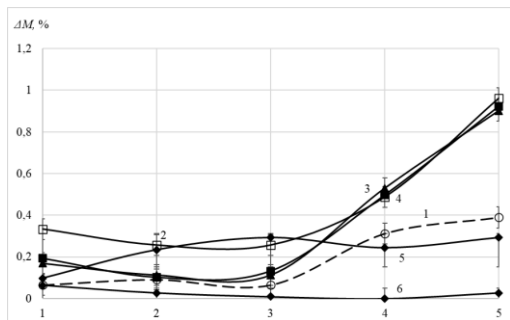


Figure 8: Mass change of consolidated samples during heat resistance testing: 1 – consolidated Al powder, 2 – Al + 2% Ti–TiC, 3 – Al + 4% Ti–TiC, 4 – Al + 6% Ti–TiC, 5 – Al + 8% Ti–TiC, 6 – Al + 10% Ti–TiC

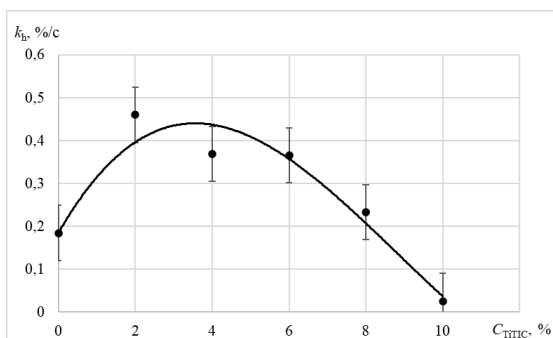


Figure 9: Dependence of the mass change per cycle coefficient during heat resistance tests on the Ti–TiC content in the initial powder used to produce the consolidated material

4. Conclusions

1. The influence of Ti–TiC filler concentration (ranging from 2 % to 10 %), synthesized via high-voltage electrical discharge treatment, on the structure and properties of aluminum-based metal matrix composites was found.

2. It was shown that the addition of 2 % Ti–TiC after HVED processing in ethanol under volume-distributed multi-spark discharge mode with a specific treatment energy of 20 MJ/kg allows obtaining an MMC with a specific electrical resistivity of $0.184 \Omega \cdot \text{mm}^2/\text{m}$ and a hardness of 43 HRB.

3. Increasing the Ti–TiC content up to 10 % led to a hardness increase up to 68 HRB, with a corresponding rise in specific resistivity to $\rho = 0.3 \Omega \cdot \text{mm}^2/\text{m}$. The composite structure contains phases such as titanium carbide TiC and free carbon.

4. Increasing the Ti–TiC content from 2 % to 8 % results in improved heat resistance — for the MMC sample with 8 % Ti–TiC addition, the mass gain coefficient per heat resistance test cycle is 0.23 %/cycle, while for consolidated pure aluminum powder samples it is 0.18 %/cycle.

5. References

1. J. C. Viala, M. Peronnet, F. Bosselet, J. Bouix, *Chemical compatibility between aluminium base matrices and light refractory carbide reinforcements*, Int. Committee on Composite Material, ICCM-12 Paris (1999), 9 p.
2. V. H. López, A. R. Kennedy, *J. Colloid Interface Sci.* **4**, 356–362 (2006).
3. X. H. Wang, Y. C. Zhou, *Z. Metallkd.* **93**, 66–71 (2002).
4. M. Prystash, S. Prystash, A. Torpakov, Y. Lypian, O. Syzonenko, R. K. Janutienė, *Machines. Technol. Mater.* **16**(8), 267–269 (2022).
5. O. M. Syzonenko, P. I. Loboda, A. D. Zaichenko, Ye. V. Solodkyi, A. S. Torpakov, M. S. Prystash, V. O. Trehub, *J. Superhard Mater.* **39**, 243–250 (2017).
6. O. M. Syzonenko, M. S. Prystash, E. I. Taftai, A. S. Torpakov, Ye. V. Lypian, *Mater. Sci.* **57**, 209–214 (2021).
7. A. Stepanchuk, I. Bilyk, P. Boiko, *Tekhnologiya poroshkovoy metallurgii* (Vyshcha Shkola, Kyiv, 1989), 415 p. (In Russian).
8. S. J. Chipera, D. L. Bish, *Multireflection RIR and intensity normalizations for quantitative analyses: Applications to feldspars and zeolites*, *Powder Diff.* **10**, 47–55 (1995).
9. D. Gričius, R. K. Janutienė, D. Mažeika, R. Šertvytis, O. Syzonenko, A. Torpakov, *Mechanika* **29**(2), 168–173 (2023).
10. O. M. Syzonenko, P. Tashev, M. S. Prystash, A. S. Torpakov, Y. V. Lypian, *Eng. Sci.* **58**, 79–94 (2021).

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Amortization systems for objects with discrete switching of parts of a viscoelastic element in a duffing type oscillator

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Abstract: In order to enhance the efficiency of oscillation damping, the viscoelastic element in a Duffing-type system is divided into parts, with discrete commutation occurring four times per period between them. It has been demonstrated that the enhancement of oscillation energy dissipation is achieved through mass transfer between the parts. The influence on the equivalent coefficients of the solution parameters has been analyzed. 3D surfaces of the dissipated energy and equivalent coefficients have been constructed as functions of amplitude, mass ratio of the parts, and tension. It has been shown that discrete commutation allows for obtaining a hyperbolic type of frequency dependence of the aperiodicity coefficient, reaching values of 0.4..0.6 in the resonance zone.

KEYWORDS: DUFFING-TYPE SYSTEM, DISCRETE SWITCHING, DISPLACEMENT OF THE STATE OF STATIC EQUILIBRIUM, MASS TRANSFER, POSITIONAL FORCE, NON-CONSERVATIVITY, DISSIPATION, EQUIVALENT COEFFICIENTS, INITIAL TENSION.

1. Introduction and problem statement

In order to protect a number of modern technology objects, it is advisable to have a hyperbolic type of frequency dependence of the relative attenuation coefficient in the shock-absorbing systems (SAS). In this case, an increase in this coefficient in the low-frequency resonance zone to a value of (0.45..0.5) should be achieved [1]. This type of dependence can be ensured by very quickly applying and removing a rigid connection to a part of the viscoelastic element (discrete switching) in the Duffing oscillator (OD with DS), carried out 4 times per oscillation period [2, 3] (Fig. 1).

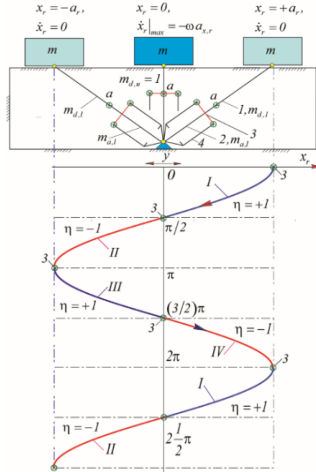


Fig. 1. OD with DS of parts of a viscoelastic element:
1 – deformable part; 2– accumulating part;
3 – connection (switch); 5 – absolutely rigid shell

In the OD with the DS, when connection 3 is removed, tension is introduced $s \equiv s/l_{d,0}$. At rest and at the end of loading and unloading quarters, after the DK parts, the dimensionless total mass of the viscoelastic element $m_{\Sigma} = m_{d,0} + m_{a,0} = 1 + \mu$ (Fig. 2).

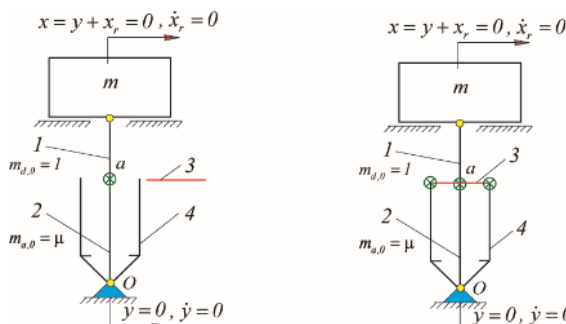


Fig. 2 The imposition of the constraint 3 in the state of equilibrium; point a divides the spring into parts; at DS a does not fall below the edge of the shell 4

is distributed between the parts in some ratio $\mu = m_{a,0}/m_{d,0} \equiv l_2/l_{d,0}$: the mass of the deformable part becomes $m_{d,u} = 1$, accumulating – $m_{a,u} = \mu$.

The masses of the parts change abruptly at the moments of the DS, i.e. $m_d = \text{var}$, $m_d \neq m_{d,0}$ и $m_a = \text{var}$, $m_a \neq m_{a,0}$.

At the end of the DS in the right and left amplitude positions of the object $m_{d,l} > 1$, $m_{a,l} < \mu$ (Fig. 3a, b).

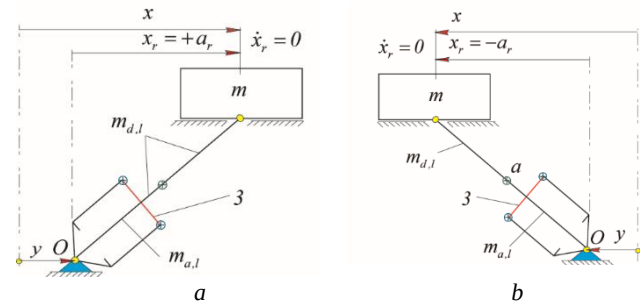


Fig. 3 Connection 3 imposition and switching termination

The processes of equalization of forces in the OD with the DS of parts are typically irreversible processes, therefore they are accompanied by the production of entropy due to mass exchange between the parts [4]. Despite the fact that the equation of state of the viscoelastic element is Hooke's linear law, the ambiguous characteristic of the positional force of the OD with the DS of parts is piecewise nonlinear (Fig. 4).

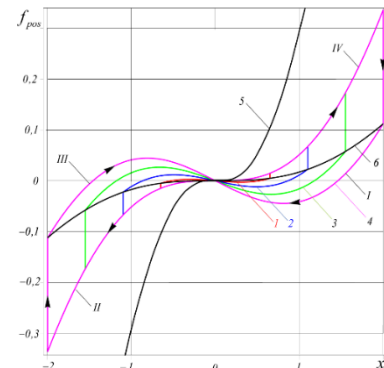


Fig. 4. Curves 1 and 2 are the characteristics of the restoring force of the deformable part and the element after removing the connection 3

Based on the proposed model of the OD with the DK parts (Fig. 2, Fig. 3), the problem of ensuring a hyperbolic type of frequency dependence of the relative attenuation coefficient with its achievement in resonance of values close to the limit is solved $\frac{2}{\pi}$.

2. Theoretical foundations

2.1. Displacement of the equilibrium state of an object

A sudden change in the mass of a deformable part m_d viscoelastic element, occurring at the moments of its commutation with the accumulating part, regardless of the quarter period of oscillations is described by the expression

$$m_d = \left(\frac{m_{d,I} + m_{d,II}}{2} + \eta \frac{m_{d,I} - m_{d,II}}{2} \right), \quad (1)$$

where $m_{d,I}$ – mass of the deformable part when it is loaded in parts I and III of the period, $m_{d,II}$ during its unloading in the II and IV parts of the period, η – Heaviside function, which takes values on the phase segments of relative oscillations $\psi_I = \left[0, \frac{\pi}{2} \right]$,

$\psi_{III} = \left[\pi, \frac{3\pi}{2} \right]$ and -1 on segments $\psi_{II} = \left[\frac{\pi}{2}, \pi \right]$, $\psi_{IV} = \left[\frac{3\pi}{2}, 2\pi \right]$.

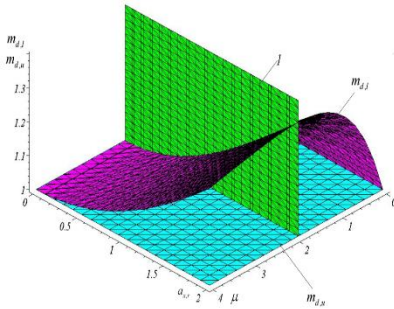
An approximate dimensionless periodic solution with respect to the generalized coordinate can be written as [5]

$$x_r = m_{x,r} + a_{x,r} \cos \omega t,$$

where is the displacement of the center of oscillation $m_{x,r} = 0$;

$a_{x,r} \equiv a_{x,r}/l_{d,0}$ – amplitude, ω – excitation frequency γ (Fig. 1).

Using $a_{x,r}$ (1) the expression takes the form



$$m_d = \frac{\mu+1}{2} \left\{ \left[1 - \frac{\mu}{\sqrt{a_{x,r}^2 + (\mu+1)^2}} \right] + \eta \left[1 - \frac{\mu}{\sqrt{a_{x,r}^2 + (\mu+1)^2}} \right] \right\}$$

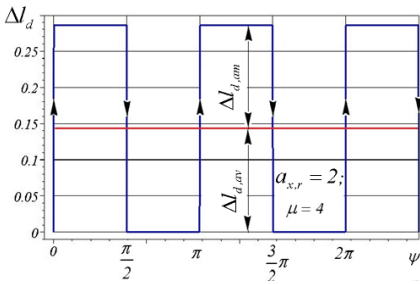
or $m_d = m_{d,av} + \eta m_{d,am}$ – the sum of its average $m_{d,av}$ and amplitude $m_{d,am}$ values (Fig. 5).

Fig. 5. Masses $m_{d,I}$,

$m_{d,II}$ – when loading in

I, III and when unloading in II, IV quarters;

1 – plane $\mu \approx 1,95$, plane passing through the maximum of the surface section $m_{d,I}$ by the plane $a_{x,r} = 2$



in the initial length Δl_d (Fig. 6).

Fig.6. Equality of the average and amplitude values of the initial length of the deformable part $\Delta l_{d,av} = \Delta l_{d,am}$

The dimensionless rigidities of the parts of a pre-deformed viscoelastic element in the intervals between switching moments are found using the expressions [6]

$$c_d = \frac{1}{1 + \Delta l_d} \text{ и } c_a = \frac{1}{\mu - \Delta l_d}.$$

Substituting into them Δl_d , get

$$c_{d,I} = \frac{1}{(\mu+1) \left[1 - \frac{\mu}{\sqrt{a_{x,r}^2 + (\mu+1)^2}} \right]}, \quad c_{d,II} = 1 \quad (\text{Fig. 7}),$$

$$c_{a,I} = \frac{1}{(\mu+1) \left[1 - \left(1 - \frac{\mu}{\sqrt{a_{x,r}^2 + (\mu+1)^2}} \right) \right]}, \quad c_{a,II} = \frac{1}{\mu}.$$

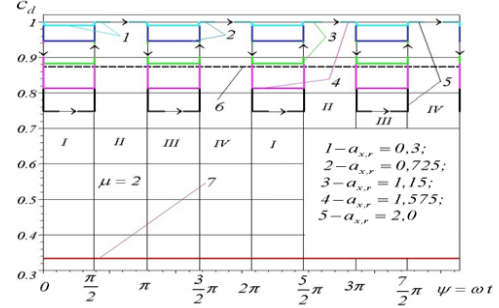


Fig. 7. Graphs of changes in the rigidity of the deformable part: 1..5 – in intervals between moments of DS;

6 – average value of rigidity at amplitude $a_{x,r} = 2$;

7 – rigidity of the element as a whole at moments of DS

Taking these rigidities into account, the coefficient determining the share of s , falling on the deformable part, will be written in the form

$$k_d = \frac{(2+\mu) \sqrt{a_{x,r}^2 + (\mu+1)^2} - \mu(\mu+1)}{2(\mu+1) \sqrt{a_{x,r}^2 + (\mu+1)^2}} + \eta \frac{\mu \sqrt{a_{x,r}^2 + (\mu+1)^2} - \mu(\mu+1)}{2(\mu+1) \sqrt{a_{x,r}^2 + (\mu+1)^2}}. \quad (2)$$

The periodic change in the length of the deformable part that occurs during the oscillations of the object Δl_d leads to a periodic shift Δx_r of its equilibrium state, in which the positional force is equal to zero (Fig. 8).

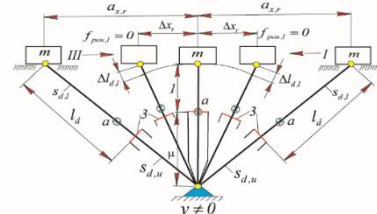


Fig. 8. To determine the displacement of the state of static equilibrium of an object Δx_r in quarters I and III

Solving the equation

$$\sqrt{\Delta x_r^2 + (\mu+1)^2} - (\mu+1) - \Delta l_d + k_d s = 0,$$

we obtain an expression for the periodic displacement of the equilibrium state of the object in quarters I and III

$$\Delta x_r^{I,III} = \pm \sqrt{2\mu\Delta l_d - 2\mu k_d s + 2\Delta l_d - 2k_d s + \Delta l_d^2 - 2\Delta l_d k_d s + k_d^2 s^2} \quad (\text{Fig. 9}).$$

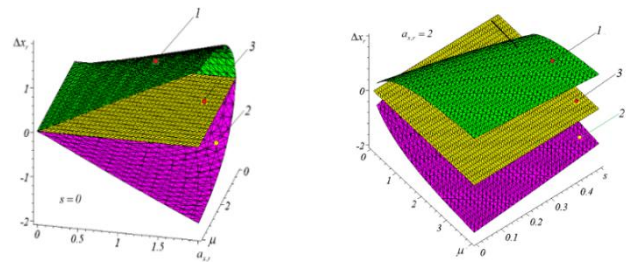


Fig. 9. Surfaces of periodic displacement of the equilibrium state Δx_r in quarters of the oscillation period

$a - x_r = f(a, \mu)$ at $s = 0$; $b - x_r = f(\mu, s)$ at $a_{x,r} = 2$;

$$1 - \Delta x_r^I, 2 - \Delta x_r^{III}, 3 - \Delta x_r^{II} = \Delta x_r^{IV} = 0$$

2.2. Equivalent linearization of the positional force characteristic

We obtain the characteristic of the positional force as the first derivative of the expressions for the potential energy of the deformable part in quarters I, III and II, IV of the oscillation period

$$V_d = \frac{1}{2} c_d \left[\sqrt{x_r^2 + (\mu + 1)^2} - (\mu + 1) - \Delta l_d + k_d s \right]^2. \quad (3)$$

At the moments of the DC, the parts are connected in series, so the potential energy is written as

$$V_{d+a} = \frac{1}{2} c_{sp} \left[\sqrt{x_r^2 + (\mu + 1)^2} - (\mu + 1) + s \right]^2, \quad c_{sp} = \frac{1}{\mu + 1} \quad (\text{Fig. 10}).$$

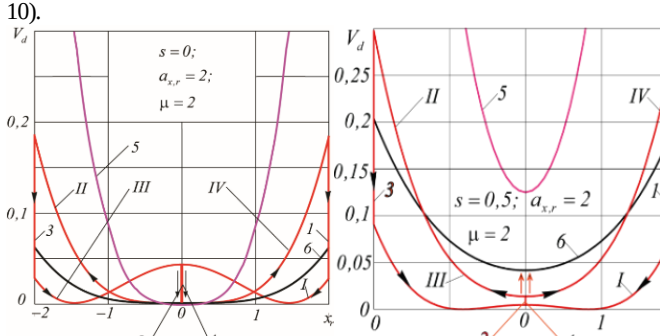


Fig. 10. Potential energy of the deformable part as a function of tension s , ratio μ and amplitude $a_{x,r}$:

1, 3 – vertical switching in amplitude positions;

2, 4 in states of static equilibrium $x_r = 0$;

5 – deformable part; 6 both parts at moments of DS

Differentiating (3) with respect to x_r , we obtain expressions for the

characteristics of the positional force in loading quarters I, III

$$f_{pos,l} = \frac{\left(\sqrt{x_r^2 + (\mu + 1)^2} - 2\mu - 1 + s \right) \sqrt{a_{x,r}^2 + (\mu + 1)^2} - \mu(-\mu - 1 + s)}{(\mu + 1) \left(\sqrt{a_{x,r}^2 + (\mu + 1)^2} - \mu \right) \sqrt{x_r^2 + (\mu + 1)^2}} x_r \quad (4)$$

and unloading II, IV

$$f_{pos,\mu} = \left(1 - \frac{\mu + 1 - s}{\sqrt{x_r^2 + (\mu + 1)^2}} \right) x_r. \quad (5)$$

The area of the loops during the DS of the viscoelastic element is significantly larger than during its normal use. The increase leads to a decrease in the displacement Δx_r .

Substituting into (4) and (5) the dimensionless relative displacement $x_r = a_{x,r} \cos \psi$, $\psi = \omega t$, we obtain

$$f_{pos,l}(\psi) = \frac{\left(\sqrt{a_{x,r}^2 \cos^2 \psi + (\mu + 1)^2} - 2\mu - 1 + s \right) \sqrt{a_{x,r}^2 + (\mu + 1)^2} - \mu(-\mu - 1 + s)}{(\mu + 1) \left(\sqrt{a_{x,r}^2 + (\mu + 1)^2} - \mu \right) \sqrt{a_{x,r}^2 \cos^2 \psi + (\mu + 1)^2}} a_{x,r} \cos \psi, \quad (6)$$

$$f_{pos,\mu}(\psi) = \left(1 - \frac{\mu + 1 - s}{\sqrt{a_{x,r}^2 \cos^2 \psi + (\mu + 1)^2}} \right) a_{x,r} \cos \psi. \quad (7)$$

During the oscillation process, at a certain phase value, the positional force becomes equal to zero. This occurs at a value $x = \Delta x_r$ – a shift in the state of equilibrium, which depends on the ratio μ , amplitude $a_{x,r}$ and tension s . By setting μ and $a_{x,r}$, we can determine the tension s_0 , at which $\Delta x_r = 0$. For example, for $\mu = 1$, $a_{x,r} = 2$ $\Delta x_r = 0$ at $s_0 \cong 0,453$, and when increasing, the "shortfall" of the object to the state of equilibrium is always equal to zero (Fig 11).

Substituting (6) and (7) for the positional force $f_{pos,l}(\psi)$ и $f_{pos,\mu}(\psi)$ into expressions for the coefficients of its harmonically linearized approximation [5],

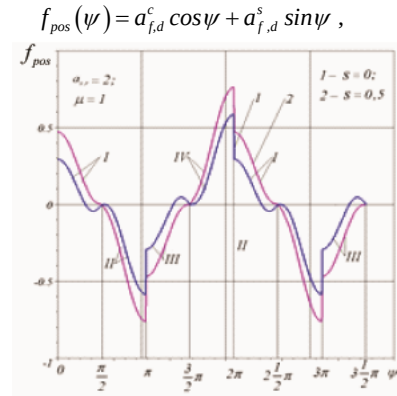


Fig. 11. The effect of tension on the positional force according to (4) and (5); vertical lines indicate the DS of the parts

integrating over quarters and summing the results, we obtain the expression for the amplitude of the potential component of this force:

$$a_{f,d}^c = f \left(\mu, a_{x,r}, s, K \left(\sqrt{-\frac{a_{x,r}^2}{(\mu + 1)^2}} \right), E \left(\sqrt{-\frac{a_{x,r}^2}{(\mu + 1)^2}} \right) \right), \quad (8)$$

in which

$K \left(\sqrt{-\frac{a_{x,r}^2}{(\mu + 1)^2}} \right)$ и $E \left(\sqrt{-\frac{a_{x,r}^2}{(\mu + 1)^2}} \right)$ – complete elliptic integrals of the first and second kind [7], respectively, we obtain (Fig. 12).

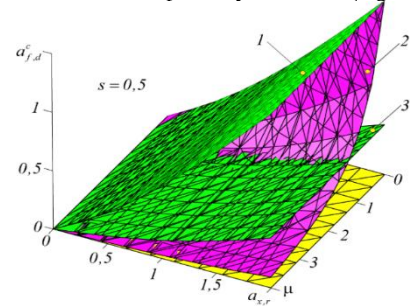


Fig. 12. Surface amplitude of the potential component of positional force: 1 – one deformable part ($\mu = 0$); 2 – OD with DS parts; 3 – when removing the connection and the total length of the parts ($\mu + 1) = 2$

The amplitude of the dissipative component of the positional force, found by

$$a_{f,d}^s = \frac{1}{\pi} \int_0^{2\pi} f_{pos}(\psi, \mu) \sin \psi d\psi,$$

has the form

$$a_{f,d}^s = \frac{2\mu \left[\left(\mu + \frac{1}{4} a_{x,r}^2 + \mu^2 \right) \sqrt{a_{x,r}^2 + (\mu + 1)^2} - \mu^3 - 2\mu^2 \right]}{\pi (\mu + 1) a_{x,r} \left(\sqrt{a_{x,r}^2 + (\mu + 1)^2} - \mu \right)} \rightarrow \frac{- \left(1 + \frac{3}{4} a_{x,r}^2 \right) \mu - \frac{a_{x,r}^2}{4}}{\rightarrow}. \quad (9)$$

Maximum surface $a_{f,d}^s(a_{x,r}, \mu)$ on amplitude $a_{x,r} = 2$ achieved with a lower value of the ratio μ , than on the one on which m_d maximum (Fig. 5, Fig.13).

The harmonically linearized positional force is found from the expression

$$f_{pos} = a_{f,d} \cos(\psi + \delta), \quad (10)$$

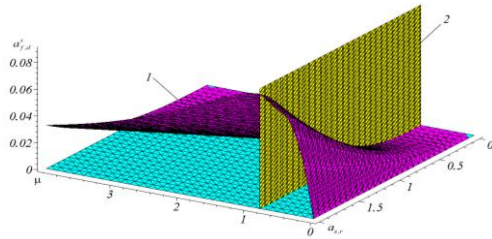


Fig. 13. Surface 1 is independent of tension s ;
2 – plane passing through the maximum of the cross-section of the surface by the plane $a_{x,r} = 2$

in which its amplitude $a_{f,d}$ is as

$$a_{f,d} = \sqrt{(a_{f,d}^c)^2 + (a_{f,d}^s)^2}, \quad (11)$$

and the tangent of the angle of mechanical losses [6] –

$$\operatorname{tg} \delta = \frac{a_{f,d}^s}{a_{f,d}^c}. \quad (12)$$

Substituting the expressions for the amplitudes of the potential (8) and dissipative components (9) into (11) and (12), we obtain expressions for $a_{f,d}$ and the tangent of the angle of mechanical losses δ (Fig. 14).

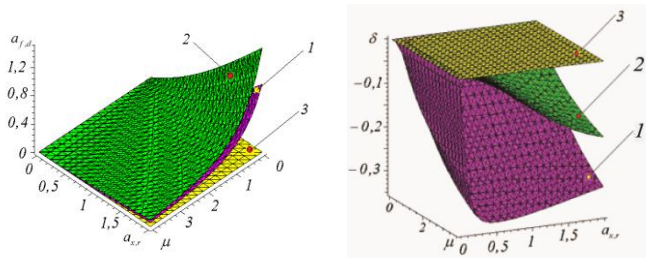


Fig. 14. Dependence of the amplitude of the positional force and the angle of mechanical losses δ on tension s :

1 – $s = 0$, 2 – $s = 0,5$;

3 – in a state of static equilibrium $a_{f,d} = 0$ and corner $\delta = 0$

The equivalent stiffness can be obtained from the expression

$$c_{eq}(a_{x,r}, \mu, s) = a_{f,d}^c / a_{x,r}, \quad (13)$$

which is significantly influenced by tension s (Fig. 15).

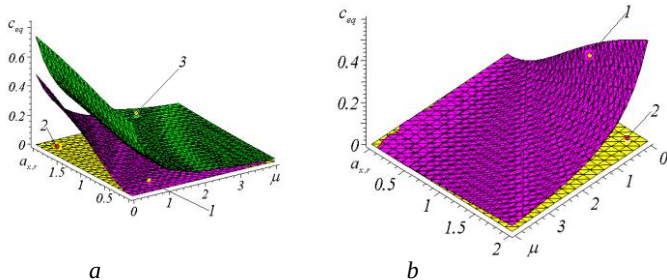


Fig. 15. Dynamic stiffness versus initial tension s : 1 – $s = 0$; 3 – $s = 0,5$; (on b surface 3 is not shown in order to show surface 1 for small μ and large $a_{x,r}$)

In the limit (13) gives an expression for the rigidity of the system linearized in the small

$$c_{eq}|_{a_{x,r}=0} = \lim_{a_{x,r} \rightarrow 0} \frac{a_{f,d}^c}{a_{x,r}} = \frac{s}{(\mu + 1)^2}. \quad (14)$$

When tensioned the dynamic stiffness surface (13) is located above the surface at $s = 0$, and the plane linearized in small rigidity turns into a cylindrical surface, which means its independence from the amplitude $a_{x,r}$ (Fig. 16).

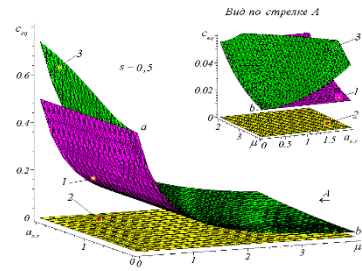


Fig. 16. Dynamic stiffness surfaces:

1 – stiffness of the system linearized in the small (14); 3 – according to (13)

Dynamic stiffness versus amplitude $c_{eq}(a_{x,r})$ is a projection of the surface sections 3 $c_{eq}(a_{x,r}, \mu, s)$ in Fig. 16 planes $\mu = \text{const}$ on the plane $\mu = 0$ at two tension values s (Fig. 17).

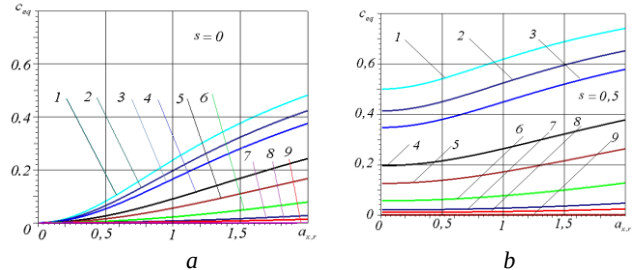


Fig. 17. Dynamic stiffness versus amplitude $a_{x,r}$ and relationships

μ at different tension values s :

$a - s = 0$; $b - s = 0,5$;

1 – $\mu = 0$; 2 – $\mu = 0,1$; 3 – $\mu = 0,2$; 4 – $\mu = 0,6$;

5 – $\mu = 1$; 6 – $\mu = 2$; 7 – $\mu = 4$; 8 – $\mu = 6$; 9 – $\mu = \infty$

Sections of the dynamic stiffness surface $c_{eq}(\mu, s)|_{a_{x,r}=2}$ at a fixed amplitude $a_{x,r} = 2$ in the function of the relation μ and tension s show its decrease with growth μ and increase with growth s (Fig. 18).

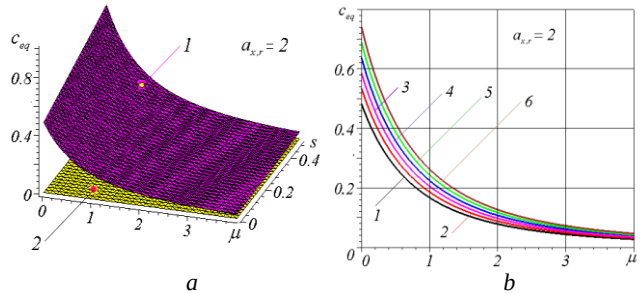


Fig. 18. a – Dynamic stiffness surface $c_{eq}(\mu, s)|_{a_{x,r}=2}$;

b – sections of the surface in Fig. a by planes:

1 – $s = 0$; 2 – $s = 0,1$; 3 – $s = 0,2$;

4 – $s = 0,3$; 5 – $s = 0,4$; 6 – $s = 0,5$

The expression for the dimensionless coefficient of inelastic resistance is [6]

$$\beta_{eq}(a_{x,r}, \mu) = \frac{a_{f,d}^s}{\nu \eta a_{x,r}}, \quad (14)$$

when $a_{f,d}^s$ – amplitude of the dissipative component of force (9);

$\nu = \sqrt{c_{eq}(a_{x,r}, \mu, s)}$ – frequency of free oscillations of an object;

$\eta = \frac{\omega}{\omega_{fr}(a_{x,r})} = \frac{\omega}{\omega_n \sqrt{c_{eq}(a_{x,r}, \mu, s)}} = \frac{\omega}{\omega_n \nu(a_{x,r})}$ – dimensionless frequency of kinematic excitation y (Fig.1);

$\omega_n = \sqrt{\frac{c_{eq}|_{a_{x,r}=0} c_{d,0}}{m}}$ – natural frequency of oscillations of OD with DS;
 $c_{d,0}$ – dimensional rigidity of the deformable part.

Surface coefficient $\beta_{eq}(a_{x,r}, \mu, s)$ at different tensions s and its sections by vertical planes $\mu = const$, are given on Fig. 19, Fig. 20.

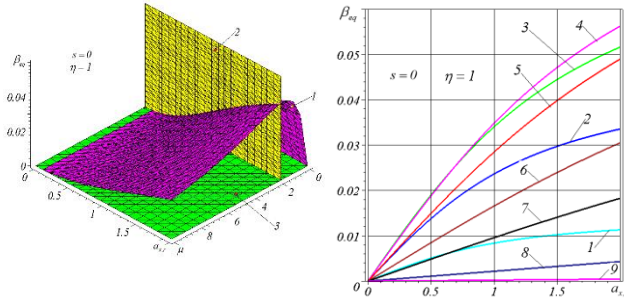


Fig. 19. a – 3D dependence of the equivalent coefficient of inelastic resistance as a function of amplitude $a_{x,r}$ and ratio μ (no3. 1) under tension $s=0$ on frequency $\eta=1$,
 2 – vertical plane $\mu \approx 1,95$;
 3 – zero damping plane;
 b – sections of surface 1 by vertical planes:
 1 – $\mu=0,1$; 2 – $\mu=0,4$; 3 – $\mu=1$; 4 – $\mu=2$; 5 – $\mu=4$;
 6 – $\mu=10$; 7 – $\mu=20$; 8 – $\mu=100$; 9 – $\mu=1000$

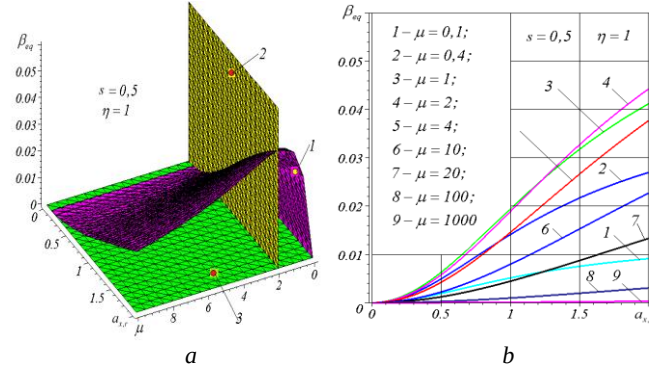


Fig. 20. a – 3D dependence of the equivalent resistance coefficient on the amplitude $a_{x,r}$ and relationships μ (surface 1) under tension $s=0,5$ on frequency $\eta=1$;
 2 – vertical plane $\mu \approx 1,95$;
 3 – zero damping plane;
 b – sections of surface $\beta_{eq}(a_{x,r}, \mu, s)$ planes $\mu = const$

Substituting into the expression for the amount of energy dissipated during the period $\Delta w = \pi \beta_{eq}(a_{x,r}, \mu) a_{f,d}^s a_{x,r}$ [6] expression for the amplitude of the dissipative component $a_{f,d}^s$ (9), independent of s , we will receive

$$\Delta w = 4\mu \frac{\left[\left(-\mu - \mu^2 - \frac{1}{4} a_{x,r}^2 \right) \sqrt{a_{x,r}^2 + (\mu+1)^2} + \mu^2 (\mu+2) + \mu \left(\frac{3}{4} a_{x,r}^2 + 1 \right) + \frac{a_{x,r}^2}{4} \right]}{(\mu+1) \left(\mu - \sqrt{a_{x,r}^2 + (\mu+1)^2} \right)}. \quad (16)$$

The amount of energy dissipated during a period can also be found as twice the area of the hysteresis loop (Fig. 4)

$$\Delta w' = 2 \left(\int_0^{a_{x,r}} f_{pos,\mu} dx_r - \int_0^{a_{x,r}} f_{pos,l} dx_r \right). \quad (17)$$

Substituting into (17) expression (4) for the positional force of the deformable part $f_{pos,l}$ in quarters I, III when it is loaded and (5) for $f_{pos,\mu}$ in quarters II, IV when unloading it, we get (16), i.e. $\Delta w' \equiv \Delta w$.

From the equation $\frac{d(\Delta w)}{d\mu} = 0$ let's find the ratio μ^{extr} , at which the amplitude $a_{x,r} = 2$ the maximum is reached: $\mu^{extr}|_{a_{x,r}=2} \approx 0,81$ (Fig. 21).

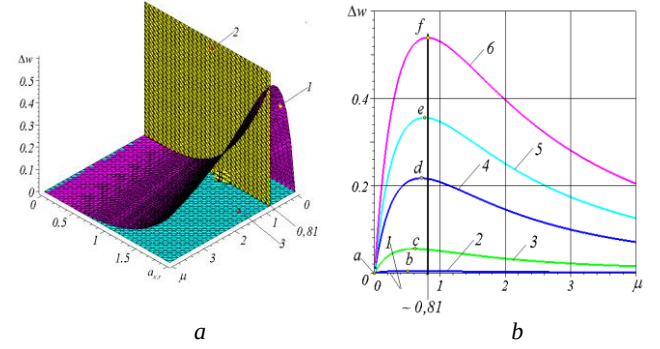


Fig. 21. a – Scattered energy surface 1; 2 – vertical plane $\mu^{extr} \approx 0,81$,
 3 – zero damping plane for $\mu = 0$;
 b – sections of surface 1 planes $a_{x,r} = const$:
 1 – $a_{x,r} = 0,01$; 2 – $a_{x,r} = 0,5$; 3 – $a_{x,r} = 1$;
 4 – $a_{x,r} = 1,5$; 5 – $a_{x,r} = 1,75$; 6 – $a_{x,r} = 2$

The line passing through the maxima of the surface of dissipated energy is a spatial curve. Points a, b, c, d, e, f in Fig. 21b are projections of these maxima onto the plane $a_{x,r} = 0$.

Equating, in accordance with the principle of energy balance [5], the amount of energy dissipated over a period in a linear system, the expression for which is transformed to the form [6]

$$\Delta w^{lin} = 2\pi\psi(a_{x,r}, \mu, s) a_{x,r}^2 \eta c_{eq}(a_{x,r}, \mu, s)$$

when $\eta = \frac{\omega}{\omega_n \sqrt{c_{eq}(a_{x,r}, \mu, s)}}$ – kinematic excitation frequency; c_{eq} –

dynamic stiffness (13) the amount of energy dissipated in the linearized OD with the DS parts (16), we obtain for the equivalent coefficient of relative attenuation the expression

$$\psi(a_{x,r}, \mu, s) = \frac{\Delta w}{2\pi\eta a_{x,r}^2 c_{eq}(a_{x,r}, \mu, s)}. \quad (18)$$

Otherwise, this coefficient can be obtained using the formula [6]

$$\psi(a_{x,r}, \mu, s) = \frac{a_{f,d}^s}{2\eta a_{x,r} c_{eq}(a_{x,r}, \mu, s)}, \quad (19)$$

in which the dissipative component of the positional force $a_{f,d}^s$ is located at (9).

The nature of the change in surfaces in the ranges of change in the ratio $\Delta\mu = 0..20$ and amplitudes $\Delta a_{x,r} = 0..2$ indicates a fundamentally different effect of tension on the relative attenuation coefficient ψ (Fig. 22).

Difference in relations dependences of the relative attenuation coefficient on some relations μ and limiting tension values s due to different changes in dynamic stiffness (Fig. 17, Fig. 23).

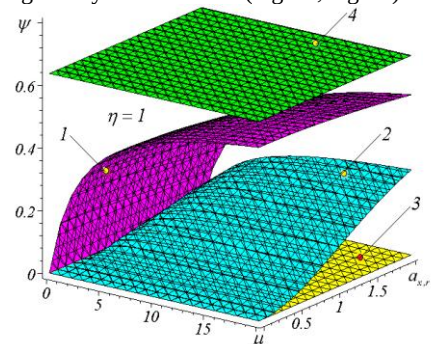


Fig. 22. Dependence of coefficient surfaces ψ from the amplitude $a_{x,r}$ and ratio μ at the excitation frequency $\eta = 1$ at tension values s : 1 – $s = 0$; 2 – $s = 0,5$; 3 – plane of zero damping at $\mu = 0$; 4 – maximum level $\psi^{lim} = \lim_{\mu \rightarrow \infty} \psi = \frac{2}{\pi} \cong 0,6366$

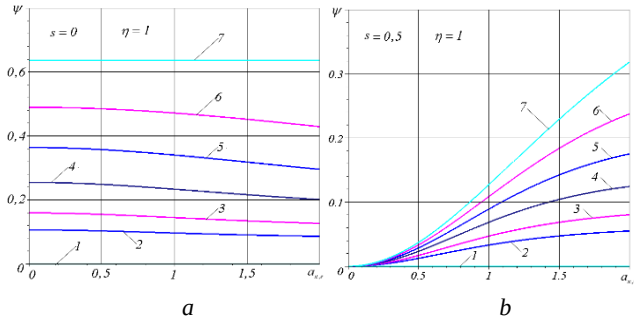


Fig. 23. Amplitude dependence of the coefficient at the excitation frequency $\eta = 1$: a – at tension $s = 0$; b – at $s = 0,5$; 1 – $\mu = 0$; 2 – $\mu = 0,6$; 3 – $\mu = 1$; 4 – $\mu = 2$; 5 – $\mu = 4$; 6 – $\mu = 10$; 7 – $\mu = 1E + 20$

Laws of change of the coefficient of relative attenuation $\psi(a_{x,r}, \mu, s)$ in the Fig. 22, Fig. 23a and Fig. 23b differ significantly. If at $s = 0$ (Fig. 22, Fig. 23a) the amplitude dependence is decreasing ψ in the range of relations $\Delta\mu = 0..20$ we can neglect it and accept for it the expression (19), the analytical limit of which is $\psi^{lim}|_{a_{x,r}=0}$ cannot be obtained, although the dependence graphs $\psi(a_{x,r})$ (Fig. 22, plane 1; Fig. 23a), build possible, avoiding meaning $a_{x,r} = 0$.

However, even with a very small deviation s from zero in the direction of increase, the curves of the coefficient ψ for the same μ become increasing from zero and approximately twice as small at each amplitude $a_{x,r}$. Moreover, the curves in Fig. 23b, obtained by sectioning the surface 2 by vertical planes $\mu = const$ (Fig. 22) at any μ do not depend on the value s .

To obtain a simple expression $\psi(\mu, \eta)$ for the dependence of the relative attenuation coefficient on the mass ratio μ and excitation frequency η under tension $s = 0$ we calculate a series of values ψ with amplitude $a_{x,r} = 1E - 10$ (Table 1).

Table 1. Values of the relative attenuation coefficient ψ as a function of the ratio μ at $s = 0$ the excitation frequency $\eta = 1$ (diamonds in Fig. 24)

μ	0	1	2	3	4	5	6	7	8	9	10
ψ	0	0,159	0,255	0,318	0,364	0,398	0,424	0,446	0,463	0,477	0,490

Continuation of Table 1

μ	11	12	13	14	15	16	17	18	19	20	∞
ψ	0,500	0,509	0,517	0,524	0,531	0,536	0,541	0,546	0,550	0,554	0,6366

Approximating the data in Table 1 with a nonlinear function μ :

$$\psi = \frac{2}{\pi\eta} \cdot \frac{k\mu}{k\mu + 1}, \quad (20)$$

we will receive $k = \frac{1}{3}$

In two limits the coefficient ψ has values

$$\psi^{lim}|_{\mu=0} = 0 \text{ и}$$

$$\psi^{lim}|_{\mu=\infty} = \frac{2}{\pi} \cong 0,6366 \text{ (Fig. 24 pos.4).}$$

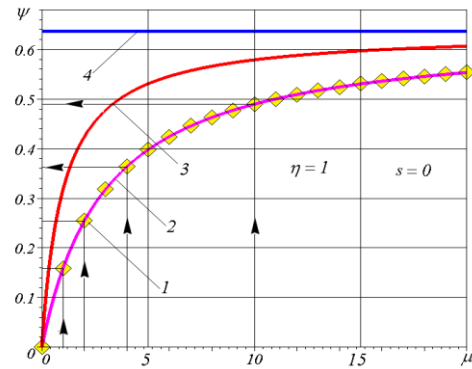


Fig. 24. Dependence of the coefficient ψ on the ratio μ at tension $s = 0$ at the excitation frequency $\eta = 1$:

1 – numerical values ψ at amplitude $a_{x,r} = 1E - 10$; 2 – approximation of these values; 3 – limit analytical dependence ψ for SA with DS of pneumatic element parts and solid deformable bodies [6]; 4 – limit value

$$\psi^{lim}|_{\mu=\infty} = \frac{2}{\pi} \cong 0,6366$$

From a similar expression for the SA with the DS of parts of elastic elements [6],

$$\psi^{lim}|_{\substack{a_{x,r} \rightarrow 0 \\ m_{x,r} \rightarrow 1}} \cong \frac{2}{\pi\eta} \cdot \frac{\mu}{\mu + 1}, \quad (20)$$

for OD with DS it differs by a multiplier $k = 0,333$, shifting curve 2 downwards, but the limiting values of the coefficient ψ at $\mu = \infty$ coincide (Fig. 24), i.e. in both cases

$$\psi^{lim}|_{\mu=\infty} = \frac{2}{\pi} \cong 0,6366.$$

Regardless of the amplitude, $a_{x,r}$ reducing the tension s to zero with a simultaneous increase in the ratio μ to infinity changes the coefficient ψ at the resonant frequency $\eta = 1$ of the limit $\frac{2}{\pi}$ (Fig. 25).

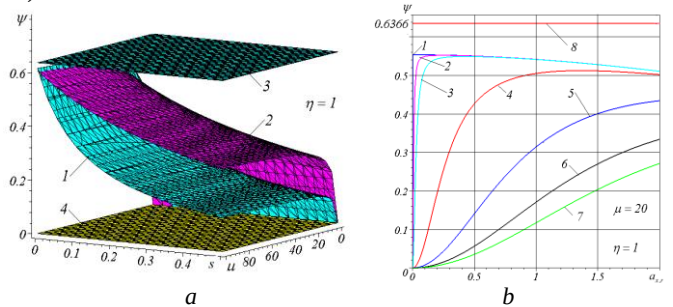


Fig. 25. a – Dependence of the coefficient ψ on the ratio μ at tension s at the excitation frequency $\eta = 1$:

1 – $a_{x,r} = 1$; 2 – $a_{x,r} = 2$;

b – Dependence of the coefficient ψ on the amplitude $a_{x,r}$:

1 – $s = 1E - 10$; 2 – $s = 1E - 5$; 3 – $s = 1E - 4$; 4 – $s = 0,01$; 5 – $s = 0,1$;

6 – $s = 0,3$; 7 – $s = 0,5$; 8 – $s = 0$.

2.3. Frequency characteristics of the relative attenuation coefficient

Equation of motion of an object (Fig. 1) when a non-conservative positional force acts on it $f_{pos}(x_r, \mu, s)$, determined by formulas (4) and (5), is written in the form

$$a\ddot{x} + c_{d,0}c_d x_r \left(1 - \frac{(\mu+1) + \Delta l_d - k_d s}{\sqrt{x_r^2 + (\mu+1)^2}} \right) = 0, \quad (21)$$

when $a = m$ – coefficient of inertia, $c_{d,0}$ – dimensional rigidity of the deformable part in a state of static equilibrium.

Replacing in (21) the positional force its harmonically linearized approximation [5], we obtain

$$a\ddot{x}_r + c_{d,0}(a_{f,d}^c - a_{f,d}^s) = -\ddot{y}. \quad (22)$$

Let us transform (22) to the form [6]

$$a\ddot{x}_r + c_{d,0} \left[\beta_{eq}(a_{x,r}, \mu) \frac{\dot{x}_r}{\omega_n} + c_{eq}(a_{x,r}, \mu, s) x_r \right] = -a\ddot{y}, \quad (23)$$

in which the damping coefficient $\beta_{eq}(a_{x,r}, \mu)$ (14) does not depend on tension s .

Using the system's own time $\tau = \omega_n \nu(a_{x,r}, \mu, s)t$ the derivatives included in (23) are written in the form

$$\dot{x}_r = \omega_n \nu(a_{x,r}, \mu, s) x_r'; \quad \ddot{x}_r = \omega_n^2 \nu^2(a_{x,r}, \mu, s) x_r'';$$

$$\ddot{y} = \omega_n^2 \nu^2(a_{x,r}, \mu, s) y''.$$

Substituting them into (23), we obtain it in the form

$$x_r'' + 2\nu(a_{x,r}, \mu, s) x_r' + x_r = -y'', \quad (24)$$

in which the relative attenuation coefficient $\nu(a_{x,r}, \mu, s)$ is determined by (17) or (18).

Having found from the equation for the frequency response

$$W_{x_r-y}(\eta) = \frac{a_{x,r}}{y_0} = \frac{\eta^2}{\sqrt{(1-\eta^2)^2 + 4\nu^2(a_{x,r}, \mu, s)\eta^2}},$$

obtained from (24), the amplitude and substituting it into (18), we obtain the frequency characteristics of the relative attenuation coefficient (Fig. 26) (solid curves).

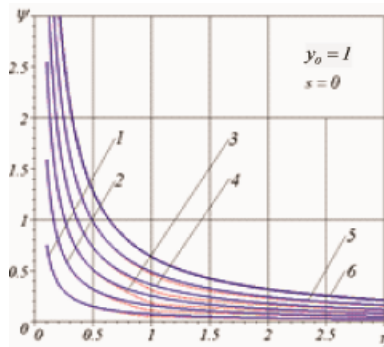


Fig. 26. Frequency characteristics of the relative attenuation coefficient of the OD with the DS parts:

1 – $\mu = 0,4$; 2 – $\mu = 1$; 3 – $\mu = 2$; 4 – $\mu = 4$; 5 – $\mu = 10$; 6 – $\mu = \infty$

Approximate characteristics are constructed according to (20) (dashed curves).

Discussion of results

1. Unlike the SA with DS, investigated earlier, in the Duffing-type oscillator with discrete commutation of its parts, the resulting shift of the equilibrium state does not coincide with the change in the initial length of the deformable part. The inequality of these quantities depends on the value of the initial tension of the viscoelastic element and becomes equal to zero with its increase. The tension increases the potential component of the positional force, but does not affect its dissipative component. This is due to the fact that the amount of energy dissipated during the period does not depend on this tension. An increase in the dynamic rigidity and a decrease in the equivalent coefficient of inelastic resistance, occurring with an increase in tension, result in a decrease in the relative attenuation coefficient. However, with an increase in the mass ratio, this decrease tends to zero.

2. The almost linear dependence of the shift of the static equilibrium state on the oscillation amplitude leads to a quadratic dependence of the amount of dissipated energy on it. The nonlinear dependence of the static equilibrium displacement on the mass ratio of the parts causes the appearance of maxima of the amount of dissipated energy depending on this ratio at a specific amplitude of relative oscillations.

3. With a horizontal arrangement of the viscoelastic element, its four-fold DS turns into a two-fold one. The change in the length of the deformable part coincides with a similar value [6], and the difference between it and the displacement of the static equilibrium state disappears.

4. The considered dynamic model of the OD with the DS of the viscoelastic element can be used in constructing models of the MS type of Duffing two- and four-chamber pneumatic elements with the DS of their parts. Intensification of the processes of flow and mixing of gases of the parts will also lead to an increase in the dissipative properties of such SA.

Conclusion

1. Fourfold discrete switching of the deformable and accumulating parts of the viscoelastic element in the Duffing oscillator in states of static equilibrium and in amplitude positions creates a periodic change in the initial length of this element, as a consequence, a shift in the state of equilibrium, giving the system non-conservative properties, allowing one to obtain a value of the relative attenuation coefficient in the resonance zone close to the limiting value. $\frac{2}{\pi}$ in the range of the mass ratio of the parts 4..10.

2. The hyperbolic type of frequency characteristics of the relative attenuation coefficient is due to the frequency independence of the amount of energy dissipated over a period. This type is in satisfactory agreement with the bell-shaped nature of the change in amplitude-frequency characteristics.

3. Zero initial tension of the viscoelastic element allows one to obtain an amplitude-independent expression for the tangent of the angle of mechanical losses and, thanks to this, to construct a simple engineering technique for selecting the main parameters.

4. Positive tension of the viscoelastic element, increasing the dynamic rigidity and decreasing the equivalent coefficient of viscous friction, reduces the relative attenuation coefficient, giving it a virtually linear dependence on the amplitude, regardless of the ratio of the masses of the parts.

References

1. Kalashnikov B. Systems of amortization with discrete switching of elastic elements. - In the proceedings of MOTAU-TO'12. 20th International Scientific and Technical Conference on Transport, Road-Building, Agricultural, Hoisting & Hauling, and Military Techniques and Technologies. June 27-29, 2012. Varna, Bulgaria, pp. 105-111.
2. Rasskazova N.N. Improving the efficiency of damping in Duffing-type systems with discrete switching of parts of elastic elements. - In Dynamics of Systems, Mechanisms, and Machines. No. 1, 2016, Vol. 1. Omsk, OmSTU, pp. 80-85.
3. Kalashnikov B.A., Rasskazova N.N., Sorokin V.N. Discrete switching of elastic elements as a means of ensuring damping in a Duffing oscillator. 2018, Vol. 6, No. 1. Omsk, OmSTU, pp. 56-74.
4. Rumers Y.B., Rvkin M.Sh. Thermodynamics, Statistical Physics, and Kinetics: Textbook. - 3rd ed., stereotype. - Novosibirsk: NSU - Siberian University Press, 2001. - 608 p.
5. Babitsky V.I. Theory of Vibro-Impact Systems (Approximate Methods). - M.: Nauka, 1978. - 352 p.
6. Kalashnikov B.A. Systems of objects with discrete switching of elastic elements: monograph. B.A. Kalashnikov. - Omsk: OmSTU Publishing House, 2008. - 344 p.
7. Yanke E., Emde F., Lösch F. Special Functions: Formulas, Graphs, Tables. Translated from German. Nauka Publishing House. Chief Editor of Physical and Mathematical Literature. M.: 1977. 344 p.

Measurements of electromagnetic fields emitted in urban environments

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Abstract: The paper presents an analysis of the results of measurements of electromagnetic radiation from a base station installed on the roof of a site located in an area with a higher degree of urbanization, an extended center of the capital of Bulgaria, Sofia. Using mobile measuring equipment Narda AMB-8057-03, the dynamics of electromagnetic radiation in the frequency range from 100 kHz to 7 GHz was monitored over a period of eight days (weekdays and weekends). The obtained values for the levels of electromagnetic fields comply with the current national legislation and European standards. They are $\leq 10 \mu\text{W}/\text{cm}^2$. However, there remains a need for monitoring, tracking and control of the emitting EMF sources, because the susceptibility of an individual person is individual and the possible health effects are different, which in some cases manifests itself as "hypersensitivity" to electromagnetic radiation.

Keywords: ELECTROMAGNETIC RADIATION, ELECTROMAGNETIC POLLUTION, ENVIRONMENTAL LEGISLATION, EMF MONITORING

1. Introduction

Modern wireless communication systems (GSM) and networks (GSM base stations) are an integral part of telecommunications infrastructure. They provide continuous connectivity for billions of users worldwide and offer a vast range of capabilities. However, this has also led to the saturation of the environment, especially urban areas, with technical sources of electromagnetic emissions. Electromagnetic pollution is caused by the ever-increasing demands of mobile users for high-quality service, high data speeds, and ultra-reliable communication between devices. The new 5G mobile networks meet all these requirements, but also result in increased electromagnetic radiation. As is known, mobile phones (GSM) operate by communicating with a fixed infrastructure called a base station, generating radio frequencies between them. 5G telecommunications networks operate at high frequencies up to 8 GHz. To ensure reliable communication between devices, small cells with a large number of transmitters are used to cover smaller areas. In urban environments, more and more base stations (BS) are mounted on walls and rooftops of buildings where people work or live. Such a system with multiple antennas can generate very large electromagnetic radiation emissions, higher concentrations of electromagnetic energy, closer to the general public. As a result, the level of exposure to electromagnetic fields (EMF) can lead to an increase in radiation exposure for users.

Electromagnetic pollution is becoming increasingly serious with each passing day in the modern urban environment, raising growing concerns about the impact of electromagnetic radiation (EMF) on human health. As a result, maximum permissible exposure limits for non-ionizing radiation have been established, regulating the conditions for human exposure to electromagnetic fields. These standards have been adopted and published in various international and national laws and regulations [1-6].

Although everyone is aware of the benefits provided by electromagnetic systems and devices, only a few users understand the real dangers associated with them. EMFs are biologically active and can have adverse effects on the environment, plants, and animals, as well as on human health [7-11]. Many research teams are increasingly focused on studying the influence of EMFs on the biological effects triggered in human and animal physiology. EMFs negatively affect the nervous system and the brain due to the electrical nature of nerve impulses [11-13]. Using mobile phones before bed delays and reduces sleep, causes depression, leads to mood changes, and affects brain physiology, resulting in poor concentration [14]. It can also lead to changes in cellular structure and DNA, as well as impact the immune, hormonal, and reproductive systems [15-17]. Other studies report headaches, a warming sensation in the ear, and a burning feeling on the facial skin [18].

The present study was conducted at the request of citizens due to concerns about exposure to electromagnetic radiation from a base station installed near the facility where they reside permanently.

2. Characterization methods

Measurements were conducted using a Narda AMB-8057-03

mobile measurement kit equipped with an isotropic antenna to assess the characteristics of electromagnetic fields propagating in the environment and reaching the antenna from all spatial directions (360°), including points that are difficult to observe.

This type of equipment is used for monitoring electromagnetic fields. The device measures and records data from continuous measurements of the E (electric) and H (magnetic) components of electromagnetic fields within the frequency range of 100 kHz to 7 GHz, transmitting the data once every 24 hours to a storage server.

Mobile equipment Narda AMB-8057-03 provides the ability to visualize and review measurement information for a selected time interval, date, week or day, for the entire frequency range (110 kHz – 7 GHz) or for a selected sub-range. The electric field measurement data is averaged for consecutive intervals every 6 minutes for both the average value (RMS) and peak values (Peak) for a given frequency.

3. Results and Discussion

Measurements of electromagnetic fields were conducted in object located in the extended downtown area of Sofia, Bulgaria's capital. The measured object is an apartment on the eighth (top) floor of a residential building. A mobile operator's base station antennas are installed on the roof of an adjacent building positioned at a right angle to the studied object (Fig. 1). The distance between the object and the antennas is approximately 50 meters in a straight line with direct visibility to the antennas.

The measurements were conducted continuously over 24-hour periods for eight consecutive days (including both weekdays and weekend days), with the objective of studying the temporal distribution characteristics of EMF in two frequency bands: 1842 MHz and 2140 MHz. These frequency bands encompass the operational frequencies of all mobile network operators functioning within Bulgaria's territory.

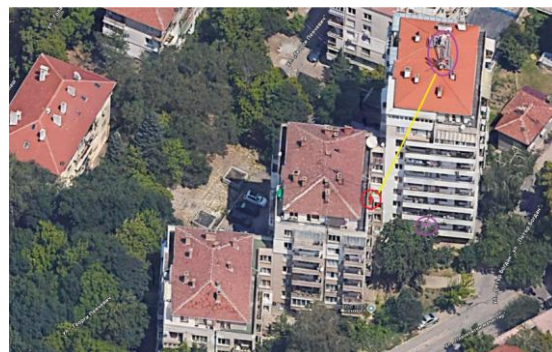


Fig.1 Location of measuring equipment and arrangement of base stations around the research object [19]

In Figure 2 and Figure 3, the daily results of the conducted measurements are graphically displayed, visualized, and recorded by the Narda AMB 8057-03 mobile equipment. The average value (RMS) and peak value (Peak) for the respective frequency ranges of 1842 MHz and 2140 MHz are presented in different colors. The

data was obtained and visualized in V/m, with the maximum permissible value of 6 V/m outlined on the graphs (Limit - white line). During the measurement, data on the ambient temperature in degrees is accumulated, visualized, and recorded.

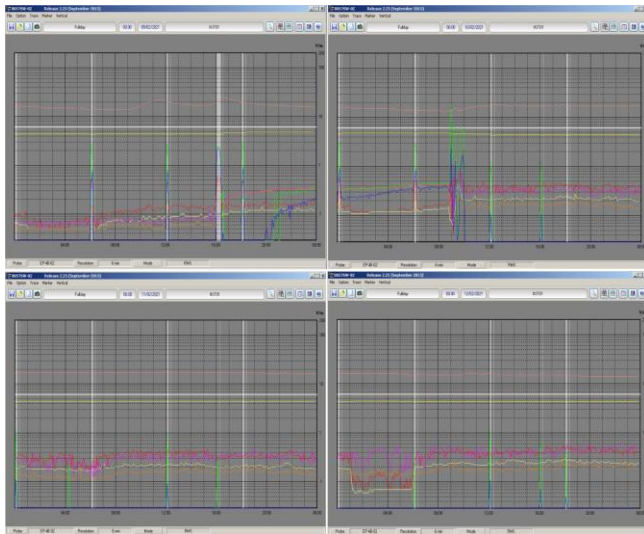


Fig.2 Measured electromagnetic field values in the studied object over four consecutive days

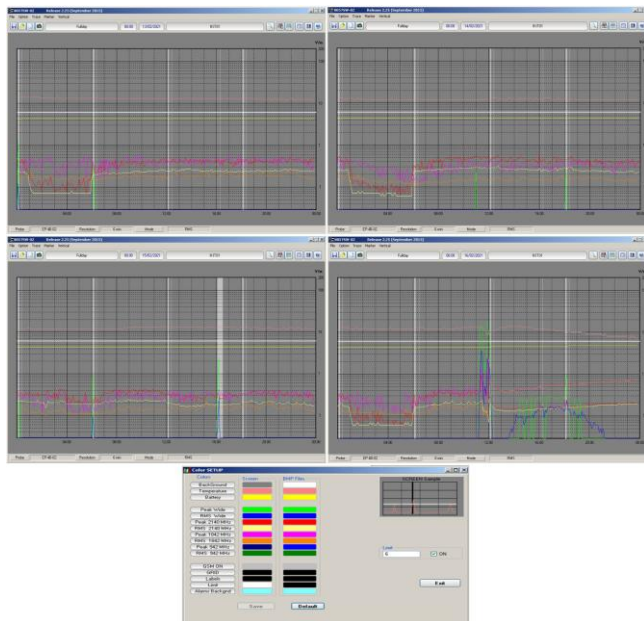


Fig.3 Measured electromagnetic field levels in the study object over four consecutive days, including legend

The accepted maximum permissible levels of electromagnetic radiation in Bulgaria, ensuring adequate protection of public health, are set at $10 \mu\text{W}/\text{cm}^2$. The mobile measurement equipment NARDA AMB 8057-03 measures, records in digital files, and visualizes the results in V/m. For comparison with the permissible limits according to BDS (Bulgarian National Standards), national, and international standards, the measured values are converted from V/m to $\mu\text{W}/\text{cm}^2$ using a standardized formula.

Figure 4 and figure 5 display the maximum averaged values (RMS) from continuous 24-hour measurements of electromagnetic fields in two frequency ranges - 1842 MHz and 2140 MHz - for each day in the studied object.

The maximum averaged values (RMS) of the measured electromagnetic radiation power density for the 1842 MHz frequency range during the study period ranged from 0.01 to $0.06 \mu\text{W}/\text{cm}^2$, while for the 2140 MHz frequency range, they ranged from 0.015 to $0.075 \mu\text{W}/\text{cm}^2$.

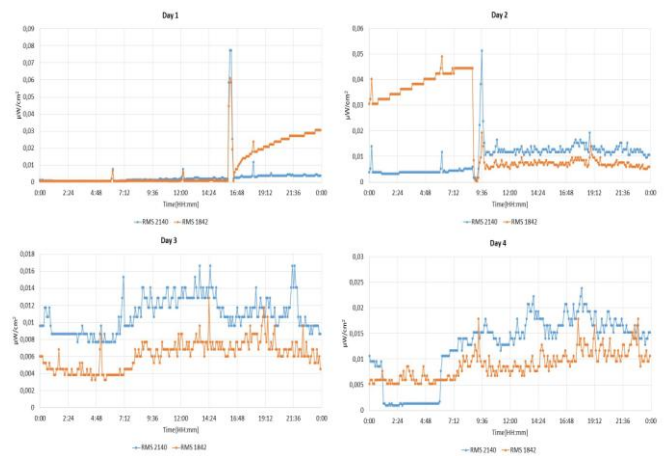


Fig. 4 Maximum average values RMS at frequency range 1842 MHz and frequency range 2140 MHz from measurements of electromagnetic fields in a research object four consecutive days

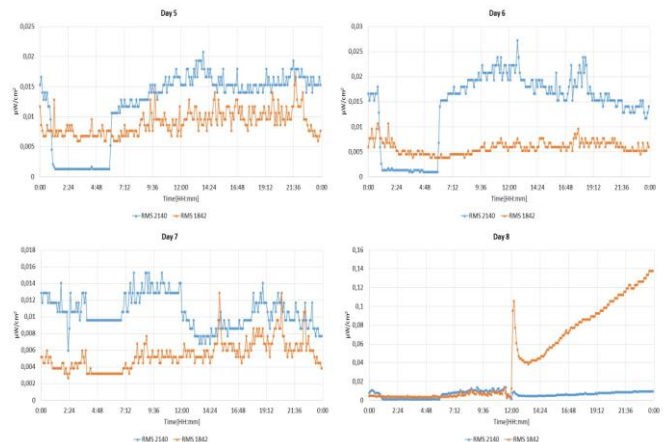


Fig. 5 Maximum average values RMS at frequency range 1842 MHz and frequency range 2140 MHz from measurements of electromagnetic fields in a research object four consecutive days

From the graphs shown in Figure 4 and Figure 5, the maximum averaged values for each time period remain well below the permissible limit of $10 \mu\text{W}/\text{cm}^2$ as per the standard. Quantitatively, the EMF levels in the study area are quite stable, although slightly greater variations are observed in the recorded maximum peak values (figure 6 and figure 7) compared to the maximum averaged values.

The maximum peak values (Peak) of measured EMF range from 0.045 to $0.10 \mu\text{W}/\text{cm}^2$ for the 1842 MHz frequency band, and from 0.05 to $0.17 \mu\text{W}/\text{cm}^2$ for the 2140 MHz frequency band - significantly lower than the permissible exposure standard.

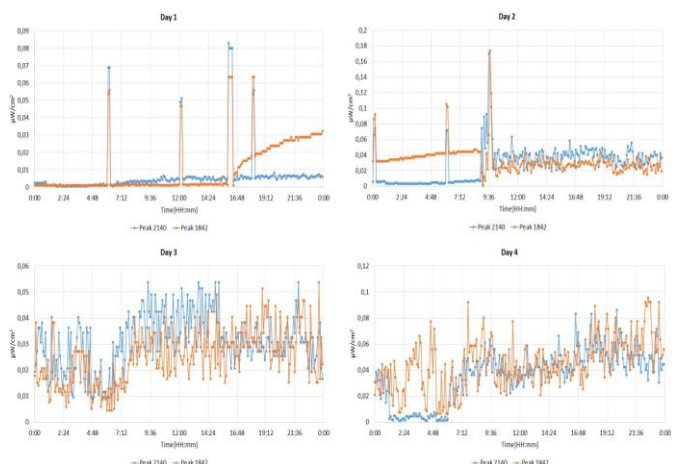


Fig. 6 Maximum peak values RMS at frequency range 1842 MHz and frequency range 2140 MHz from measurements of electromagnetic fields in a research object four consecutive days

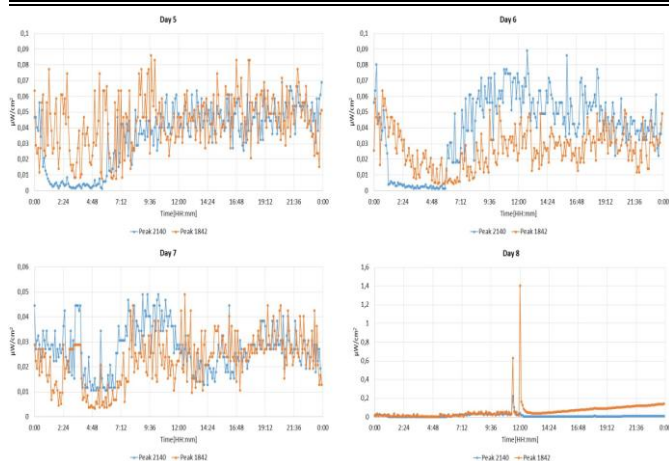


Fig. 7 Maximum peak values RMS at frequency range 1842 MHz and frequency range 2140 MHz from measurements of electromagnetic fields in a research object four consecutive days

4. Conclusions

The purpose of this study was to monitor the dynamics of electromagnetic radiation in object (an apartment on the eighth/top floor of a building) located approximately 50 meters in direct line of sight from installed mobile operator base station antennas. Following analysis of data from continuous 24-hour measurements conducted over eight days (including weekdays and weekend), the following was established:

All measured values were significantly below the accepted maximum permissible limit of $\leq 10 \mu\text{W}/\text{cm}^2$, which ensures adequate protection of public health in Bulgaria.

- The maximum average values (RMS) of the measured power density of electromagnetic radiation:

- ☐ For the frequency range of 1842 MHz, $\text{RMS}_{\text{max}} - 0.06 \mu\text{W}/\text{cm}^2$.
- ☐ For the frequency range of 2140 MHz, $\text{RMS}_{\text{max}} - 0.075 \mu\text{W}/\text{cm}^2$.

- The maximum peak values (Peak) of the measured power density of electromagnetic radiation:

- ☐ For the frequency range of 1842 MHz, $\text{Peak}_{\text{max}} - 0.10 \mu\text{W}/\text{cm}^2$.
- ☐ For the frequency range of 2140 MHz, $\text{Peak}_{\text{max}} - 0.17 \mu\text{W}/\text{cm}^2$.

The antennas from the nearby base station do not pose a health risk to the surrounding population. Although the measured EMF values are generally safe and well below the norm, the need for monitoring and control of the Base Station remains, because the susceptibility of an individual is individual and some people may experience negative health effects from prolonged exposure.

5. References

1. 1999/519/EC: Council Recommendation of 12 July 1999 on the limitation of exposure of the general public to electromagnetic fields (0Hz to 300GHz), 199, 59-70, 1999. <http://data.europa.eu/eli/reco/1999/519/oj> (June 29, 2025)
2. Ordinance No. 9 on maximum permissible levels of electromagnetic fields in populated areas and determination of hygienic protection zones around radiating objects, of the Ministry of Health and the Ministry of Environment and Water (SG 35/1991, amended and supplemented, SG 8/2002, published in SG 42/07.09.2022), 1991. <https://lex.bg/laws/ldoc/-551794688> (June 29, 2025), (in Bulgarian)

3. Health Act, published in SG 70/2004. 2004. <https://lex.bg/laws/ldoc/2135489147> (June 29, 2025), (in Bulgarian)
4. Ordinance No. 36 on the conditions and procedure for exercising state health control, promulgated, SG 63/2009. 2009. <https://lex.bg/laws/ldoc/2135642508> (June 29, 2025), (in Bulgarian)
5. Human exposure to radio frequency fields from hand-held and body-mounted wireless communication devices – Human models, instrumentation, and procedures – Part 1: Procedure to determine the specific absorption rate (SAR) for hand-held devices used in close proximity to the ear (frequency range of 300 MHz to 3 GHz). 2005. <https://webstore.iec.ch/publication/6588> (June 29, 2025)
6. Guidelines for limiting exposure to time-varying electric, magnetic and electromagnetic fields (up to 300 GHz), International Commission on Non-Ionizing Radiation Protection (ICNRP), non-governmental organization, 74(4), 494-522, 1998. <https://pubmed.ncbi.nlm.nih.gov/9525427/> (June 29, 2025)
7. D. Austin, Health and electromagnetic fields, West J Med, 156(5), 538-539 (1992)
8. P. Gajsek, P. Ravazzani, J. Wiart, J. Grelier, T. Samaras, G. Thuroczy, Electromagnetic field (EMF) exposure assessment in Europe—Radio frequency fields (10 MHz–6 GHz), J. Expo. Sci. Environ. Epidemiol, 25, 37–44 (2015) doi: 10.1038/jes.2013.40
9. S. Rafiqi, S. Kumar, R. Chaudhary, U. Farooq, P. Kirthika, Mobile phone radiations and its impact on Birds, Animals and Human Beings, Int J Vet Sci, 3, 25-28 (2016) IJAVS_7
10. K. Rothman, Health effects of mobile telephones. Epidemiology, 20(5), 653-655 (2009) doi: 10.1097/EDE.0b013e3181aff1f7
11. A. Aly, S. Deris, N. Zaki, Research review on the biological effect of cell phone radiation on human. International Conference on Innovations in Information Technology, 140-144 (2008) <https://doi.org/10.1109/INNOVATIONS.2008.4781774>
12. E. Cardis, I. Deltour, S. Mann, M. Moissonnier, M. Taki, N. Varsier, K. Wake, J. Wiart, Distribution of RF energy emitted by mobile phones in anatomical structures of the brain, Phys. Med. Biol., 53(11), 2771–2783 (2008) doi: 10.1088/0031-9155/53/11/001
13. K. Sri, Mobile Phone Radiation: Physiological & Pathophysiological Considerations, Indian J Physiol Pharmacol, 59(2), 125-35 (2015)
14. A. Sharma, O. Lamba, A review: Source and effect of mobile communication radiation on human health, Advances in Wireless and Mobile Communications, 10(3), 423-435 (2017)
15. R. Aitken, L. Bennetts, D. Sawyer, A. Wiklendt, B. King, Impact of radio frequency electromagnetic radiation on DNA integrity in the male germline, Int J Androl, 28(3), 171-179 (2005) doi: 10.1111/j.1365-2605.2005.00531.x
16. R. Aitken, G. De Iuliis, On the possible origins of DNA damage in human spermatozoa, Mol Hum Reprod, 16(1), 3-13 (2009) doi: 10.1093/molehr/gap059
17. G. Altun, Ø. Deniz, K. Yurt, D. Davis, S. Kaplan, Effects of mobile phone exposure on metabolomics in the male and female reproductive systems, Environ. Res., 167, 700-707 (2018) DOI: 10.1016/j.envres.2018.02.031
18. N. Falzone, C. Huyser, P. Becker, D. Leszczynski, D. Franken, The effect of pulsed 900-MHz GSM mobile phone radiation on the acrosome reaction, head morphometry and zona binding of human spermatozoa, Int. J. Androl., 34, 20-26 (2011) DOI: 10.1111/j.1365-2605.2010.01054.x
19. <https://publicemp.ncpha.government.bg/Geolocation/ViewBaseStationsOnMap.aspx>

Effects of gamma irradiation technology on biodeteriorated paper materials determined by thermogravimetry

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Abstract: The present manuscript describes some of the results obtained as part of a research contract investigating the effects of gamma irradiation on leather and library materials. Six samples of books and magazines, produced in Germany, the USA, and the former USSR between 1896 and 1962, were selected. All paper materials showed visible signs of biodeterioration and environmental damage. The samples were gamma-irradiated with a dose of 20 kGy using BULGAMMA radiation facility, based on the JS-850 ⁶⁰Co gamma irradiator at Sopharma AD, Bulgaria. The applied dose rate was 0.47 kGy/h. The effects of gamma irradiation were studied using thermogravimetric analysis. The results showed a 13% reduction in residual mass at 700 °C in the 1962 Soviet Union Newsletter, accompanied by a 3.6% decrease in the temperature (T_{max}) at maximum weight loss rate. An 8.7% increase in residual mass at 700 °C was observed in the 1952 Reference Journal, and a 6.6% increase was measured in a German monograph from 1923. The study revealed that the effects of gamma radiation on paper structure depend on both the degree of prior damage and the type and composition of the paper.

Keywords: PAPERS, GAMMA IRRADIATION, DISINFESTATION, SIDE EFFECTS, THERMAL GRAVIMETRIC ANALYSIS

1. Introduction

Gamma irradiation is a widely recognized effective method for preserving and disinfecting biologically contaminated paper materials that have been affected by insects, fungi, and bacteria [1-3]. Historically, library and archival documents have suffered from biological degradation and adverse environmental conditions (high temperature and humidity etc), leading to different degree of damage of paper. However, the application of gamma radiation must be carefully controlled, as radiation can also cause chemical changes such as oxidation, depolymerization, and discoloration of paper cellulose. Despite the studies conducted so far, intensive research on the effects of radiation on paper materials continues in order to optimize the parameters of irradiation [4-7].

This article presents some of the results obtained under the Research Contract № 80-10-66/27.05.2025 "Study of radiation-induced structural changes in leather and paper after high-dose gamma irradiation with the aim of preserving cultural and historical heritage," funded by Sofia University. Thermograms of papers from library materials before and after irradiation with 20 kGy gamma radiation are shown and discussed.

2. Materials and Methods

2.1. Samples

Six samples of books and magazines, produced in Germany, USA and USSR (former Soviet Union) in the period 1896 – 1962 y were selected. Description of the papers is given in Table 1.

Table 1. Description of the investigated archives

Sample №	Description of the paper	Year/country of publishing
1	Periodical (Izvestija vuzov USSR)	1962/USSR
2	Periodical (Chemical Abstracts)	1962/USA
3	Reference book (Beilstein)	1942/Germany
4	Periodical (Referativnij Zhurnal Khimija)	1952/USSR
5	Monography	1923/Germany
6	Periodical (Chemische Berichte)	1896/Germany

All the paper materials described above had visible traces of damage of micro-organisms, as well as darkening and yellowing

due to contact with moisture, exposure to sunlight, and oxygen in the air.

Images of the selected samples are presented on Figure 1.

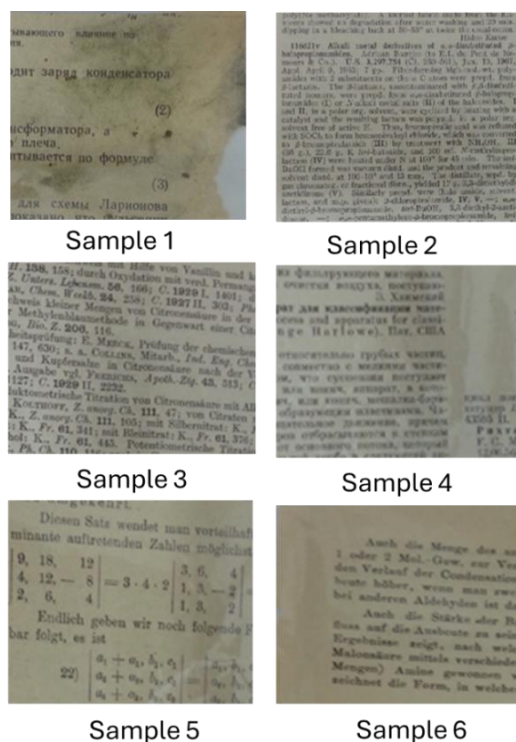


Fig.1. Images of the studied paper materials.

2.2. Gamma irradiation

The samples were individually packed in polypropylene bags. Each sample was gamma-irradiated with 20 kGy, using radiation facility BULGAMMA based on JS-850 ⁶⁰Co type gamma irradiator of Sopharma AD, Bulgaria. Dose rate of 0.47 kGy/h at temperature of 20 °C was applied. The absorbed dose distributions were measured with ethanol chlorobenzene routing dosimeters.

2.3. Instrumentation

The thermal properties of the samples were studied by thermogravimetry (TG/DTG) in pure argon, at the temperature range from 20 °C to 700 °C, with heating rate of 10 °C/min, using Perkin-Elmer TGS-2.

3. Results and Discussion

The results of the TG and DTG analysis are presented on Figs.2-19. The changes in % of the residual mass at 700 °C and the temperature of maximum weight loss as a result of irradiation with 20 kGy were calculated in order to quantitatively assess the radiation effects (Fig. 20). The following areas on the TG diagrams can be distinguished:

1. A dehydration area (about 100 °C) where a slight decrease in the mass of the samples is observed;
2. Depolymerization and aging area (at about 250 °C) where a constant mass of samples is observed;
3. Area of thermal decomposition (between 320 °C and 345 °C) followed by carbonization of samples (above 400 °C).

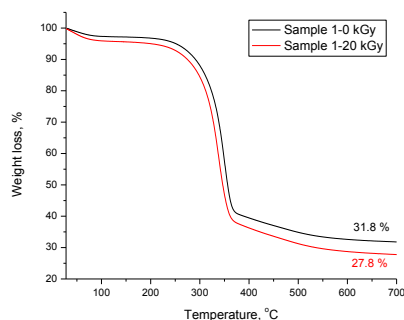


Fig. 2. TG diagram of sample 1 before and after gamma-irradiation with 20 kGy.

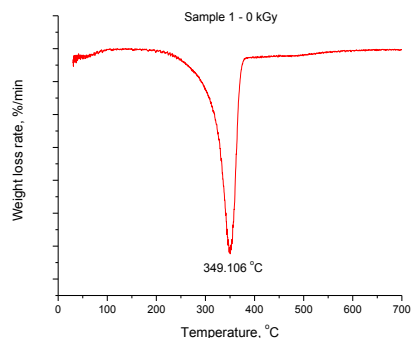


Fig. 3. DTG diagram of sample 1 before irradiation.

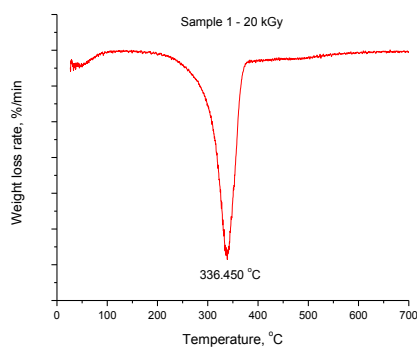


Fig. 4. DTG diagram of sample 1 after irradiation with 20 kGy.

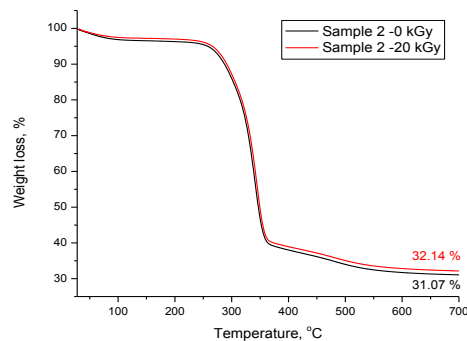


Fig. 5. TG diagram of sample 2 before and after gamma-irradiation with 20 kGy.

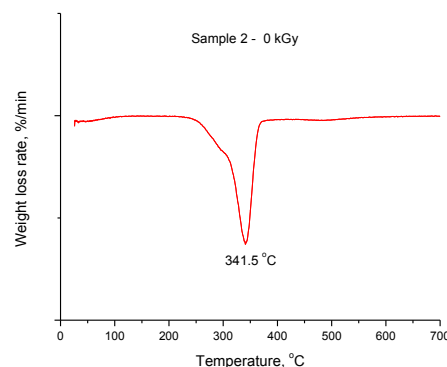


Fig. 6. DTG diagram of sample 2 before irradiation.

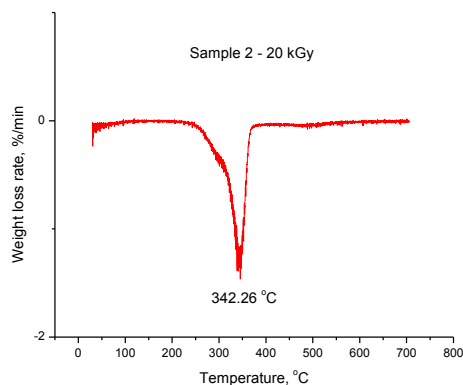


Fig. 7. DTG diagram of sample 2 after irradiation with 20 kGy.

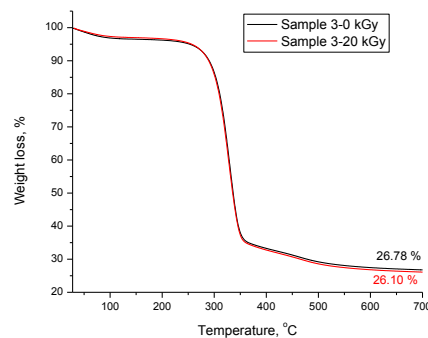


Fig. 8. TG diagram of sample 3 before and after gamma-irradiation with 20 kGy.

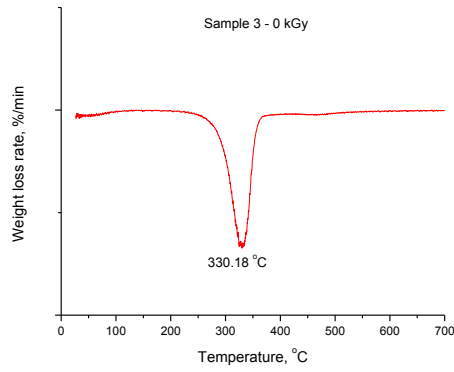


Fig. 9. DTG diagram of sample 3 before irradiation.

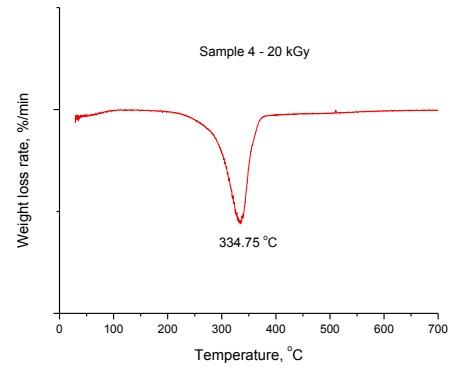


Fig. 13. DTG diagram of sample 4 after irradiation with 20 kGy.

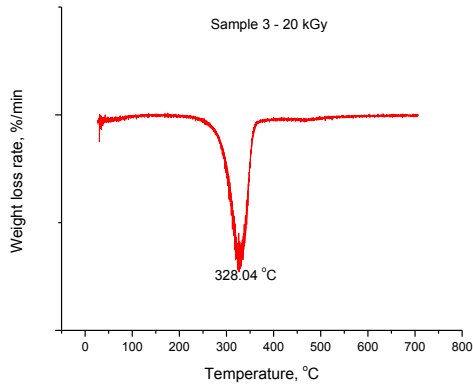


Fig. 10. DTG diagram of sample 3 after irradiation with 20 kGy.

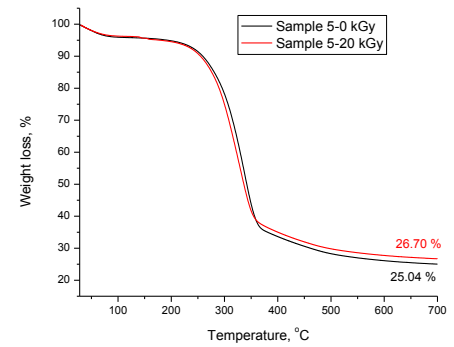


Fig. 14. TG diagram of sample 5 before and after gamma-irradiation with 20 kGy

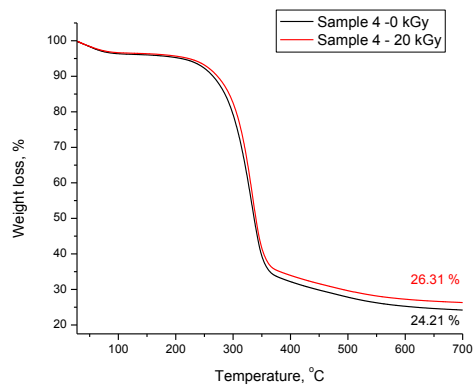


Fig. 11. TG diagram of sample 4 before and after gamma-irradiation with 20 kGy.

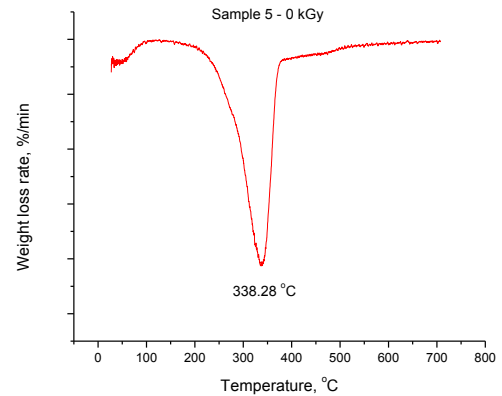


Fig. 15. DTG diagram of sample 5 before irradiation.

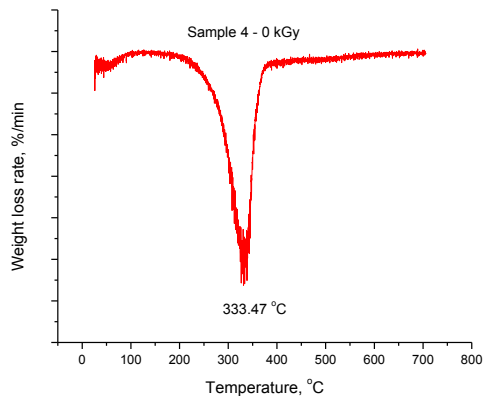


Fig. 12. DTG diagram of sample 4 before irradiation.

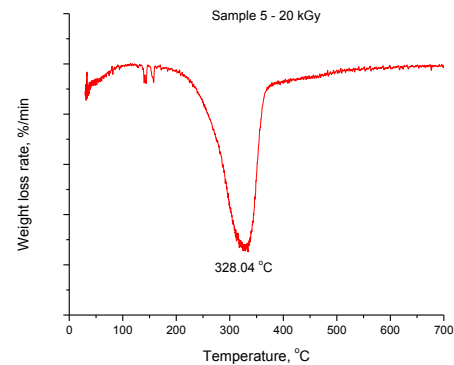


Fig. 16. DTG diagram of sample 5 after irradiation with 20 kGy.

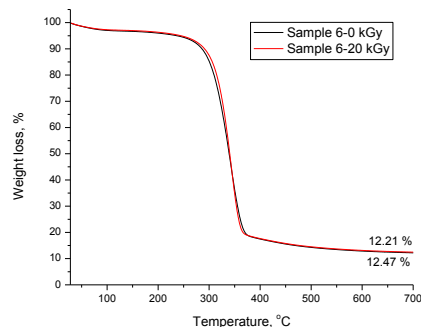


Fig. 17. TG diagram of sample 6 before and after gamma-irradiation with 20 kGy.

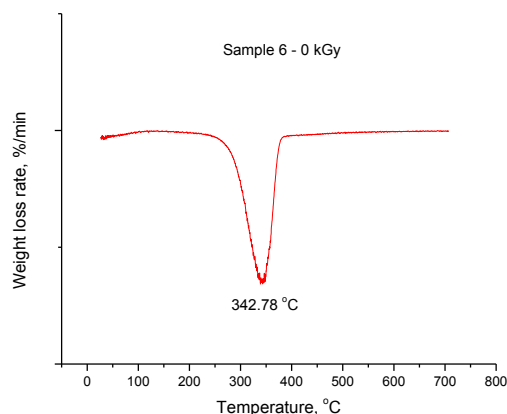


Fig. 18. DTG diagram of sample 6 before irradiation.

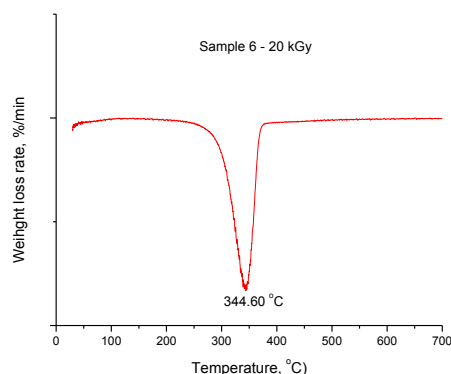


Fig. 19. DTG diagram of sample 6 after irradiation with 20 kGy.

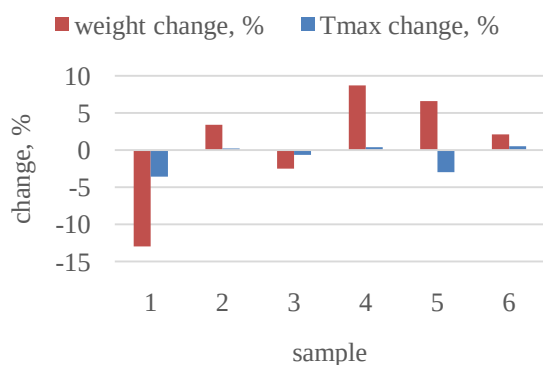


Fig. 20. Relative changes in % residual mass (weight change) and temperature (Tmax) at maximum mass loss as a result of irradiation with 20 kGy.

The results showed that irradiation with 20 kGy causes the following effects:

- A 13% reduction in residual mass at 700 °C in the 1962 Soviet Union Newsletter (Sample 1), accompanied by a 3.6% decrease in the temperature (T_{max}) at the maximum mass loss rate. This effect is primarily due to gamma radiation causing cellulose chain breakage and chemical oxidation, leading to more complete or altered thermal degradation of paper components and thus reducing the residual mass at high temperature.
- An 8.7% increase in residual mass at 700 °C in the 1952 Reference Journal (Sample 4) and a 6.6% increase in residual mass in the German monograph from 1923 (Sample 5). This can be explained by radiation-induced chemical oxidation and modification of cellulose and other paper constituents, which promotes the formation of stable char residues upon heating. The increased residual mass during thermal decomposition may result from the formation of additional chemical bonds that hinder depolymerization and thermal degradation.

For the remaining paper samples, the radiation-induced changes (%) range from 2 to 3%, which fall within the experimental uncertainty.

4. Conclusions

The results obtained in this study showed that the greatest negative impact on the studied characteristics of library materials was found in sample 1 (News of Higher Education Institutions of the former Soviet Union, 1962), which was the most severely biologically damaged. Thermogravimetric analysis did not reveal any significant negative effects of radiation in the other five samples.

Therefore, it can be concluded that the effects of gamma radiation exposure on the thermal properties of library materials depend both on the degree of damage and the type and composition of the paper. The effects of gamma irradiation on radical formation and the structure of the selected paper materials, studied using EPR, FT-IR, and DSC, will be published separately.

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References

1. Cortella L., Tran K.Q., Gluszewski W.J., Moise I.V., Ponta C.C., Nuclear techniques for preservation of cultural heritage artefacts; IAEA technical cooperation project – RER 8015, Using nuclear techniques for the characterization and preservation of cultural heritage artefacts in European region, 2011, p 44
2. Adamo A. M., Magaudo G. G., Zappala M. P., Rocchetti F., Rossi G., Effect of gamma rays on pure cellulose paper Restaurator, 19, 1998, 41 – 59
3. IAEA, Uses of ionizing radiation for tangible cultural heritage conservation, International Atomic Energy Agency, Vienna, Series: IAEA radiation technology № 6, 2017.
4. Gonzalez M.E., Calvo A.M., Kairiyama E., Gamma radiation for preservation of biologically damaged paper, Radiat. Phys. Chem., 63(3–6), 2002, 263-265
5. Area M. C., Calvo A. M., Felissia F. E., Docters A., Miranda M. V., Influence of dose and dose rate on the physical properties of commercial papers commonly used in libraries and archives, Radiat. Phys. Chem., 96, 2014, 217-222
6. Cemmi A., Di Sarcina I., D'Orsi B., Gamma radiation-induced effects on paper irradiated at absorbed doses common for cultural heritage preservation, Radiat. Phys. Chem., 202, 2023, 2023
7. Marušić K., Klarić M. S., Sinčić L., Pucić I., Mihaljević B., Combined effects of gamma-irradiation, dose rate and mycobiota activity on cultural heritage – Study on model paper, Radiat. Phys. Chem., 170, 2020, 108641

Analysis of shell-and-tube latent thermal energy storage tube diameter on charging and discharging performance

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Abstract: The study reports on a series of numerical simulations conducted to assess how tube diameter affects charging (melting) and discharging (solidification) performance in a shell-and-tube latent thermal energy storage (LTES) with longitudinal fins. In the investigated LTES, water flows through the tubes and serves as the heat transfer fluid (HTF), while paraffin is used as the phase change material (PCM) and fills the shell side. Employing an experimentally validated mathematical model and numerical procedure, LTES charging and discharging performances were investigated for three tube diameters: 28/24, 38/34 and 48/44 mm. LTES performance for different tube diameters was assessed by comparing melting and solidification times, as well as stored and released thermal energies in 8, 9 and 10 h of charging and 12, 13 and 14 h of discharging for each configuration. Results show that larger tube diameters accelerate melting and solidification processes due to increased conductive surface area, but also decrease LTES energy storing capacity as the amount of the PCM reduces as a result of increased tube diameter. The results indicate that tube diameter greatly influences LTES thermal performance and must be chosen carefully for the LTES to be effective.

Keywords: LATENT THERMAL ENERGY STORAGE, CHARGING AND DISCHARGING, TUBE DIAMETER, NUMERICAL ANALYSIS.

1. Introduction

Thermal energy storage (TES) plays a pivotal role in stabilizing solar- driven thermal systems by storing excess heat during peak irradiance and releasing it when the sun is unavailable, thereby smoothing the mismatch between energy supply and demand. Among TES technologies, latent thermal energy storage (LTES) stands out for its high energy density and narrow operating temperature window afforded by phase change materials (PCMs) [1]. In LTES, a heat transfer fluid (HTF) transfers thermal energy into the PCM during charging (melting) and retrieves it during discharging (solidification).

Shell- and- tube configurations, where HTF flows through tubes surrounded by PCM, account for roughly 70% [2] of LTES research due to their superior heat- transfer rates and exergy efficiencies compared to rectangular blocks [3]. Within these, concentric- tube units, comprising an inner HTF tube and an outer PCM annulus, serve as fundamental elements. A key geometry parameter is the outer- to- inner tube diameter ratio. Ismail and Melo [4] showed that reducing outer- to- inner tube diameter ratio thins the PCM layer, shortening melting times but at the expense of total storage mass. Seddegh et al. [5] experimentally confirmed that larger ratios markedly prolong melting with negligible gains in stored energy.

Beyond diameter ratios, tube layout parameters, such as tube pitch, number of tubes, and aspect ratio (height to tube pitch ratio), critically influence performance. Denser tube arrays raise surface area but limit PCM volume; taller, narrower assemblies enhance natural- convection effectiveness during melting. Optimal pitch and aspect ratios balance these trade- offs, guiding design toward maximal thermal power without undue capacity loss.

Enhanced configurations embed fins onto the HTF tubes to further boost heat- transfer area. Longitudinal fins have been shown to cut melting times by 25–52 % and solidification by up to 44 % in vertical modules [6]. Radial fins achieve melting- time reductions as high as 65 %, though overly numerous or thick fins can impede natural convection and shrink PCM volume [7]. Spiral fins on concentric tubes improve mid- and lower- tank performance, reducing charge/discharge times by 41 % and 22 % respectively [8]. In horizontal configurations, elliptical fins in the annular space elevate convective transfer across top and bottom regions, delivering charging/discharging improvements up to 16.9 %/13.8 % over baseline designs [9].

Tube diameter, tube count, pitch, and fin geometry collectively determine the balance between charging power (through high surface area and thin PCM layers) and storage capacity (through PCM volume). Excessive tube sizing or fin addition can reduce

PCM mass, capping total energy. Therefore, systematic optimization, via response- surface methods or experimental designs, identifies the most favorable combinations of diameters, pitch, aspect ratio, and fin parameters for given HTF conditions and PCM types. While HTF conditions offer marginal gains, tube geometry, i.e. diameters, spacing, and fin enhancements, provides the most effective route to high- performance LTES.

In this paper, a numerical study on how LTES tube diameter affects charging and discharging processes in a vertically oriented, longitudinally finned shell-and-tube LTES has been performed. LTES thermal performance has been assessed by comparing stored and released thermal energies in multiple charging and discharging times, as well as melting and solidification times for different tube diameters. This analysis offers guidelines for selecting the favorable tube diameters for the described LTES configuration in order to enhance its thermal performance.

2. Physical problem, mathematical model and numerical solving

A numerical study examined PCM melting and solidification within a vertically oriented shell-and-tube LTES tank during charging and discharging processes. Water, as the HTF, enters from the top and flows through the tubes, while technical-grade paraffin fills the shell side. During charging (daytime), hot HTF melts the PCM, storing heat, while during discharging (nighttime), solidifying PCM releases heat back to cooler HTF. The LTES unit is 1.5 m high and it consists of an aluminum HTF tube with 10 equidistant longitudinal fins, 40 mm wide and 2 mm thick, and a corresponding PCM annulus, as shown in Fig. 1. Three different tube diameters were tested: 28/24, 38/34 and 48/44 mm.

Experimental data for low-temperature organic PCMs show non-isothermal melting over a narrow range and near-isothermal solidification. This has been taken into account in the present investigation, with melting process beginning at a solidus temperature of 18 °C and is completed at a liquidus temperature of 25 °C, while during solidification both the solidus and liquidus occur at 25 °C. The PCM has a specific latent heat of 170 kJ/kg. Its thermal expansion coefficient is 0.001 K^{-1} , dynamic viscosity is $0.0036 \text{ Pa}\cdot\text{s}$, density is 820 kg/m^3 , and its specific heat capacity is $2 \text{ kJ/(kg}\cdot\text{K)}$. Finally, the PCM thermal conductivity is $0.2 \text{ W/(m}\cdot\text{K)}$.

To minimize computational cost, symmetry and geometric repetition allow modeling just one-eighth of a single tube and its PCM annulus. In multi-tube LTES units, each tube's "region of influence" is a circle whose diameter equals the tube pitch; thus, simulating one tube with its surrounding PCM segment suffices [10]. The computational domain is divided into HTF, tube wall/fins, and PCM subdomains (also shown in Fig. 1).

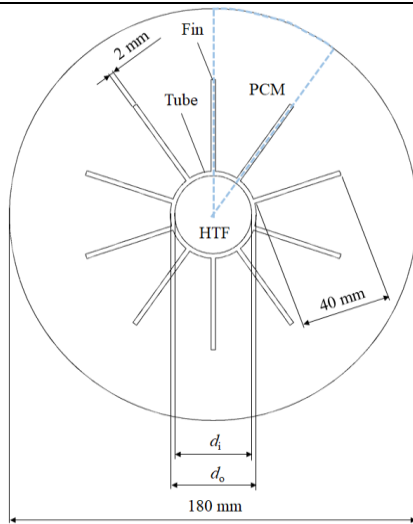


Fig. 1 Top view of the LTES unit with selected domain and denoted subdomains.

A three-dimensional model was developed to simulate the transient, conjugate heat transfer problem; combining forced convection, conduction, phase change, and natural convection in the liquid PCM. An enthalpy-based formulation [11] governs melting and solidification, using specific enthalpy rather than temperature in the PCM energy equation. Natural convection markedly enhances heat transfer during melting but has minimal effect during solidification, as previous works suggest, so neglecting it during solidification introduces only minor errors while greatly reducing computational cost [12]. Accordingly, the present study includes natural convection in the PCM only during melting.

Both liquid PCM and HTF are treated as incompressible, Newtonian fluids, with laminar flow, and all materials are isotropic, with constant and homogeneous thermophysical properties. Natural convection in the molten PCM is modeled via the Boussinesq approximation.

For HTF and PCM subdomains, continuity and momentum equations are applied. Continuity equation is the mass conservation equation, while three momentum equations are the Navier-Stokes equations, which in the PCM subdomain during charging investigations are expanded with buoyancy terms defined through the Boussinesq approximation, as well as momentum sinks that account for the lack of motion in fully solid or melting PCM. Finally, energy equation is applied to all three subdomains. For the HTF subdomain, it is a convection-diffusion equation for temperature, while for the wall (tube and fins) subdomain, it is a diffusion equation for temperature, describing pure conduction. In the PCM subdomain, enthalpy is used as variable and temperatures are obtained indirectly. In charging investigations, the PCM energy equation is a convection-diffusion equation, while in discharging investigations, it is a diffusion equation.

Inlet and outlet conditions are imposed on the HTF: the inlet specifies temperature and velocity, while the outlet assumes fully developed flow (no downstream gradients). The tank's top and bottom walls are treated as adiabatic and, during melting, enforce a no-slip condition (zero fluid velocity). At all HTF-wall and wall-PCM interfaces, conductive heat transfer and no-slip conditions apply (for the PCM side only during melting). All remaining outer faces of the HTF, wall, and PCM subdomains use symmetry conditions, reflecting identical flow and temperature profiles across these boundaries.

Numerical solving was performed using the finite volume method [13] and ANSYS Fluent numerical solver. SIMPLE algorithm was used for pressure-velocity coupling and the PRESTO! scheme for pressure correction. Coupling of temperatures and enthalpies at the wall-PCM interface was done through self-

written user-defined functions. Convective terms in the momentum and energy equations were discretized with the QUICK scheme, and time stepping was fully implicit with a timestep of 0.1 s. Under-relaxation factors of 0.6 (momentum), 0.3 (pressure), and 1.0 (energy) ensured stability, and each timestep was deemed converged when residuals fell below 10^{-3} (continuity) and 10^{-6} (momentum and energy). Mesh independency has been performed and the most suitable mesh has been selected.

3. Experimental validation and numerical analysis results

Validation of the model and numerical procedure was performed by comparing numerically obtained time-wise temperature variations of the PCM with those obtained experimentally by Longeon et al. [14] and the comparison is shown in Fig. 2. From Fig. 2, it can be observed that time-wise temperature variations of the PCM obtained numerically are in good agreement with those compared from the literature, thus indicating that the defined mathematical model and numerical procedure can be used to accurately simulate phase change behavior in shell-and-tube LTES.

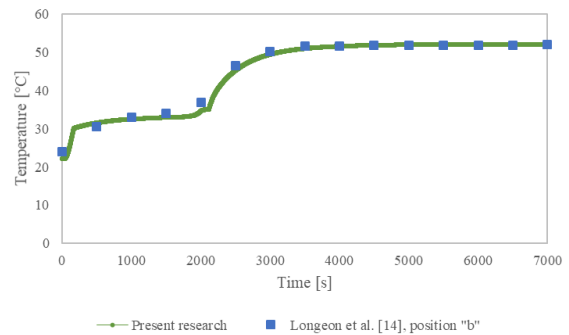


Fig. 2 Experimental validation.

The effect of tube diameter ratio (d_o/d_i) on heat transfer during PCM melting and solidification was examined by comparing three LTES configurations with d_o/d_i values of 28/24, 38/34 and 48/44 mm. All simulations used an HTF inlet velocity of 0.02 m/s; the HTF inlet temperature was 42 °C for melting and 7 °C for solidification, with a uniform initial PCM temperature of 13 °C and 42 °C, respectively. The slightly larger initial ΔT in the solidification runs yields about 5% higher discharging capacity.

Performance metrics included melting and solidification rates, evaluated via temperature and liquid fraction contours, graphical representations of melting and solidification times and amounts of thermal energy stored or released over charging times of 8, 9 and 10 h and discharging times of 12, 13 and 14 h.

Contours of temperatures and liquid fractions in the computational domain middle section, i.e. equidistant from HTF inlet and outlet, at calculation time of 4 h during charging and 6 h during discharging calculations for different tube diameters have been shown in Figs 3 and 4.

A comparison of temperature and liquid fraction contours at selected simulation times shows that both melting and solidification rates are most intense with the largest tube diameter (48/44 mm) and least intense with the smallest (28/24 mm). The liquid fraction contours reveal that the phase change front advances more rapidly in the large- diameter case.

Melting and solidification times for each configuration have been shown in Fig. 5. Additionally, for the single LTES unit (as shown in Fig. 1), the amounts of thermal energy stored in 8, 9 and 10 h, as well as released thermal energy in 12, 13 and 14 h for different tube diameters have been shown in Figs. 6 and 7.

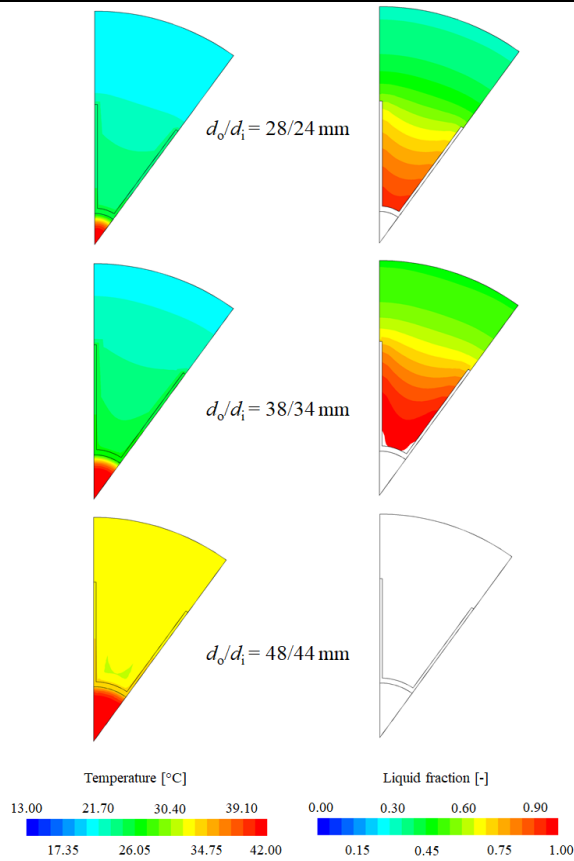


Fig. 3 Contours of temperature and liquid fraction during charging in the computational domain middle section at calculation time of 4 h for different tube diameters.

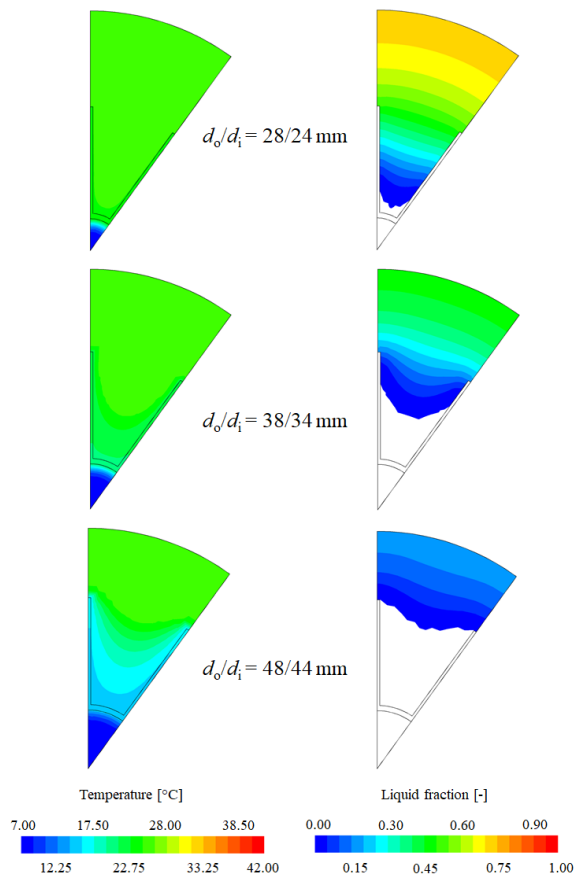


Fig. 4 Contours of temperature and liquid fraction during discharging in the computational domain middle section at calculation time of 6 h for different tube diameters.

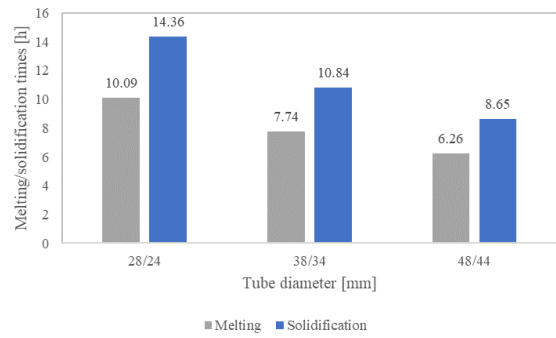


Fig. 5 Comparison of melting and solidification times for different tube diameters.

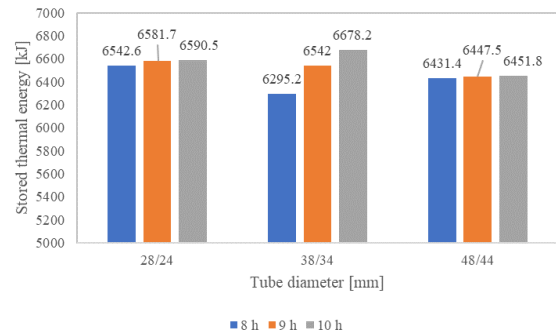


Fig. 6 Comparison of stored thermal energies for different tube diameters in charging times of 8, 9 and 10 h

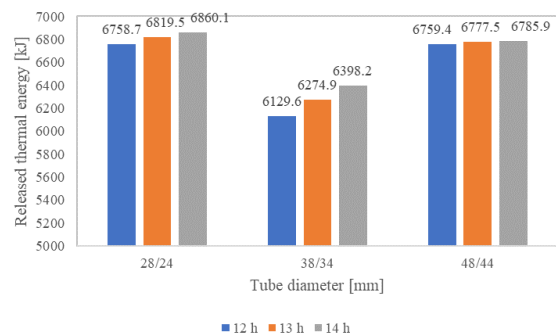


Fig. 7 Comparison of released thermal energies for different tube diameters in discharging times of 12, 13 and 14 h

As can be seen from Fig. 5, melting times for LTES configurations with 28/24, 38/34 and 48/44 mm tube diameter, melting times are 10.1, 7.74 and 6.26 h, respectively. Solidification times for LTES configuration featuring different tube diameters are 14.36, 10.84 and 8.65 h for tube diameters of 28/24, 38/34 and 48/44 mm, respectively. It can be observed that both melting and solidification times are shorter for larger tube diameters as increasing the tube diameter increases heat transfer surface area of the tube. It also reduces the amount of the PCM in radial direction, effectively reducing its thermal resistance. Both of these features are beneficial for promoting heat transfer.

From Figs. 6 and 7, it can be observed that the amount of stored and released thermal energy increases with the duration of charging and discharging time. However, the rate of energy storing and release varies depending on the configuration.

In 8 h of charging, LTES configurations with tube diameters of 28/24, 38/34 and 48/44 mm store 6542.6, 6295.2 and 6431.4 kJ of thermal energy, respectively. In 9 h of charging, 6581.7, 6542 and 6447.5 kJ of thermal energy is stored in LTES configurations with tube diameters of 28/24, 38/34 and 48/44 mm, respectively. In 10 h

of charging, LTES variations with tube diameters of 28/24, 38/34 and 48/44 mm store 6590.5, 6678.2 and 6451.8 kJ of thermal energy, respectively.

In 12 h of discharging, LTES variations with tube diameters of 28/24, 38/34 and 48/44 mm release 6758.7, 6129.6 and 6759.4 kJ of thermal energy, respectively. In 13 h of discharging, LTES configurations with tube diameters of 28/24, 38/34 and 48/44 mm release 6819.5, 6274.9 and 6777.5 kJ of thermal energy, respectively. In 14 h of discharging, 6860.1, 6398.2 and 6785.9 kJ of thermal energy is released in LTES configurations with tube diameters of 28/24, 38/34 and 48/44 mm, respectively.

The results for both charging and discharging processes are analogous; the amount of stored and released thermal energy for the configuration with tube diameter of 28/24 mm does not increase much with time as the heat transfer is not intense because of its reduced heat transfer surface area and increased PCM radial thickness. For the configuration with tube diameter of 38/34 mm, a steady increase in both stored and released thermal energy can be observed with time. For the configuration with tube diameter of 48/44 mm, the variation in stored and released energy is not significant for different charging and discharging times as the LTES thermal energy storing capacity is nearly reached. Even though increased heat transfer surface area benefits heat transfer, it also reduces the amount of the PCM that can be stored inside the LTES so selection of this parameter is significant for efficient LTES operation.

4. Conclusion

In this paper, the influence of tube diameter on charging and discharging performance in a vertically oriented, longitudinally finned shell-and-tube LTES unit has been numerically quantified. Three tube configurations (28/24 mm, 38/34 mm, and 48/44 mm) were evaluated via a validated, transient 3D enthalpy- based model that incorporates natural convection during melting and neglects it during solidification. Results indicate that increasing tube diameter reduces both melting and solidification times by enlarging the heat- transfer surface area and thinning the PCM layer. However, increasing the tube diameter beyond the 38/34 mm was shown to be ineffective as the LTES energy storing capacity was significantly reduced. The 38/34 mm tube configuration thus represents the most favorable balance between stored/released thermal energy and melting/solidification rate. However, in order to find the optimum value of tube diameter, as well as other geometry parameters, an optimization procedure should be undertaken for desired objective or a set of objectives. Nevertheless, the findings of this investigation offer practical guidance for selecting tube diameters to optimize LTES heat transfer rate and usable energy in shell- and- tube LTES systems.

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5. References

1. Z. Khan, Z.A. Khan, A. Ghafoor, "A review of performance enhancement of PCM based latent heat storage system within the context of materials, thermal stability and compatibility," *Energy Conversion and Management* 115, 132–158 (2016).
2. A.A. Al-Abidi, S. Mat, K. Sopian, M.Y. Sulaiman, C.H. Lim, A. Th, "Review of thermal energy storage for air conditioning systems," *Renewable and Sustainable Energy Reviews* 16, 5802–5819 (2012).
3. C. Ding, J. Pei, S. Wang, Y. Wang, "Evaluation and comparison of thermal performance of latent heat storage units with shell-and-tube, rectangular, and cylindrical configurations," *Applied Thermal Engineering* 218, 119364 (2023).
4. K.A.R. Ismail, C.A. Melo, "Convection-based model for a PCM vertical storage unit," *International Journal of Energy Research* 22, 1249–1265 (1998).
5. S. Seddegh, X. Wang, M.M. Joybari, F. Haghighat, "Investigation of the effect of geometric and operating parameters on thermal behavior of vertical shell-and-tube latent heat energy storage systems," *Energy* 137, 69–82 (2017).
6. M.K. Rathod, J. Banerjee, "Thermal performance enhancement of shell and tube latent heat storage unit using longitudinal fins," *Applied Thermal Engineering* 75, 1084–1092 (2015).
7. X. Yang, Z. Lu, Q. Bai, Q. Zhang, L. Jin, J. Yan, "Thermal performance of a shell-and-tube latent heat thermal energy storage unit: Role of annular fins," *Applied Energy* 202, 558–570 (2017).
8. D.S. Mehta, B. Vaghela, M.K. Rathod, J. Banerjee, "Thermal performance augmentation in latent heat storage unit using spiral fin: An experimental analysis," *Journal of Energy Storage* 31, 101776 (2020).
9. L. Wang, Y. Lei, B. Du, Y. Li, J. Sun, "Performance enhancement of a horizontal latent thermal energy storage unit with elliptical fins," *Applied Thermal Engineering* 225, 120191 (2023).
10. L.-L. Wang, L.-B. Wang, K. Zhang, Y. Wang, W.-W. Wang, "Prediction of the main characteristics of the shell-and-tube bundle latent heat thermal energy storage unit using a shell and single-tube unit," *Applied Energy* 323, 119633 (2022).
11. A.D. Brent, V.R. Voller, K.J. Reid, "Enthalpy-porosity technique for modeling convection-diffusion phase change: application to the melting of a pure metal," *Numerical Heat Transfer* 13, 297–318 (1988).
12. Z. Khan, Z.A. Khan, "An experimental investigation of discharge/solidification cycle of paraffin in novel shell and tube with longitudinal fins based latent heat storage system," *Energy Conversion and Management* 154, 157–167 (2017).
13. H.K. Versteeg, W. Malalasekera, *An Introduction to Computational Fluid Dynamics: The Finite Volume Method* (Longman Scientific and Technical, Essex, England, 1995).
14. M. Longeon, A. Soupart, J.-F. Fourmigué, A. Bruch, P. Marty, "Experimental and numerical study of annular PCM storage in the presence of natural convection," *Applied Energy* 112, 175–184 (2013).

Solid State Contact Interaction Between Metal Matrix Composite Based on Ti64 with the Composite Based on B₄C

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Abstract: The contact interaction between the metal matrix composite based on Ti64 and the B₄C-based composite was investigated. It is shown that the interaction process is influenced by the annealing temperature and holding time. The phase that formed independently of the contact pair is TiB. However, the thickness of the products formed at the boundary depends on the contact pair. In case of the Ti64-B₄C pair the thickness is 70 μm, while for (Ti64-40 wt% TiC)-B₄C it becomes 10 μm. This significant difference in the thickness is due to the presence of refractory particles (TiC) in (Ti64-40 wt% TiC)-B₄C couple, because the TiC phase reduces the diffusion of Ti into the contact zone.

Keywords: CONTACT INTERACTION, METAL-MATRIX COMPOSITES, TITANIUM CARBIDE, TITANIUM BORIDE, MICROSTRUCTURE, BORON CARBIDE.

Introduction.

Titanium alloys are widely used in automotive, aerospace and advanced military applications because of their unique set of properties such as high specific weight, great strength and ductility, good corrosion resistance [1-2]. However, as technology evolves, homogeneous titanium materials may not always satisfy operating requirements. First of all, it is not possible to achieve a combination of high strength values without decreasing toughness and ductility of the material.

Boron carbide has a unique combination of high hardness (~32 GPa) and low density (2.5 g/cm³) and attracts more and more attention every year. However, this material has one main disadvantage. It is the covalent type of chemical bond, resulting in a high melting point (2350°C, [3]) and a hot pressing (HP) temperature above 2100°C [4]. The addition of the metal disilide like TiSi₂, significantly decreases the temperature of densification to 1900°C [5]. On the other hand, the B₄C-TiSi₂ composite had the highest mechanical properties than pure B₄C.

Our previous research [6] on the *liquid phase* interaction between Ti and B₄C showed multi-step mechanism of these reactions, which include solid state interaction with formation of TiB and TiC as well as further contact melting at the temperature close to the melting point of Ti. Because in the liquid phase interaction boron and carbon diffuse into titanium, and titanium does not diffuse into boron carbide, a weak and porous layer of TiB/TiC is formed.

The *aim of this work* was to investigate the contact interaction between MMC based on Ti and composite based on B₄C to find out the optimal regime for obtaining a dense and uniform connection between them

Materials and experimental procedure.

Hydrogenated titanium (TiH₂) powder (3.5 % H, wt.) and TiC was used as raw powder for obtaining MMC. The B₄C and TiSi₂ were used for fabrication ceramic composite.

Powder of hydrogenated titanium was blended with 60%Al-40%V master alloy powder (particles size < 63 μm) to form blend of total Ti-6Al-4V composition. Whenever inclusions of the second phase, such as TiC were needed to form MMC their powders were added at required amounts to the blends and mixed before the pressing. TiC powder with the size 1-30 μm was used to make MMC 40 % (vol.) of reinforcement particles. A smaller size samples, disk with dimension 40 mm and thickness 5 mm, at 150 and 640 MPa. Sintering of Ti-6Al-4V and Ti-6Al-4V-40% TiC was conducted in vacuum furnace (1250°C, 4h) followed by the slow furnace cooling. That provided dehydrogenation of titanium and formation of the bulk samples.

Powders of boron carbide were mixed with 30 vol. % TiSi₂ in a planetary mill in an acetone medium, using grinding beds with B₄C-20 vol % TiB₂. Disks with a diameter of 40 mm and a thickness of 6 mm were hot-pressed in a graphite mold, which was previously coated with boron nitride. Hot pressing was carried out

at temperature 1900°C, pressure 32 MPa with holding time 30 min. After hot pressing, the materials were ground, polished, and finally treated with a diamond suspension with a grain size of ~1 μm.

The well-polished disk of MMC composite on the one side and B₄C composite with the other side, placed in the graphite die and heat to the temperature of 1500°C, under a pressure 32 MPa with holding time 15 min. The addition pressure was applied to create a strong contact between MMC and B₄C composite.

Microstructure of the samples was studied by scanning electron microscopy (SEM). Scanning electron microscopy was performed on VEGA 3 (Tescan). Local chemical compositions were determined by Energy-dispersive X-ray (EDX) spectroscopy with Oxford Instruments (UK) or Bruker (Germany) analyzers. Phase content was determined by areal analysis using image analysis software ImageJ. The grain size was estimated by the line intercept method, the data reported for each phase are the average of at least 100–150 grains using ImageJ software.

Results and discussion.

The microstructure of the as sintered materials are shown on the Fig.1. The Ti-6Al-4V had a homogeneous microstructure, Fig. 1 a. The addition of TiC into Ti-6Al-4V led to the formation of large particles TiC while the size of α-Ti and β-Ti remained unchanged, Fig. 1 b.

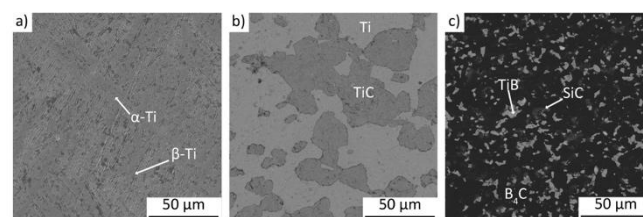


Fig.1. The microstructure of the initial materials: Ti-6Al-4V (a) and Ti-6Al-4V-40 vol% TiC (b) and B₄C-30 vol% TiSi₂ (c)

The microstructure of the hot pressed B₄C-30 vol% TiSi₂ is shown on the Fig. 1 c. As a result of the *in-situ* reaction between B₄C and TiSi₂, a final composite is formed with following phase composition: TiB, SiC and B₄C, Fig. 1 c. The introduction of an activating additive in B₄C is necessary, because the pure B₄C has a density of no more than 80% even at a temperature of hot pressing is 2100°C.

The cross section of the B₄C-30 vol% TiSi₂/ Ti-6Al-4V couple after annealing at 1500°C shown on the Fig.2.

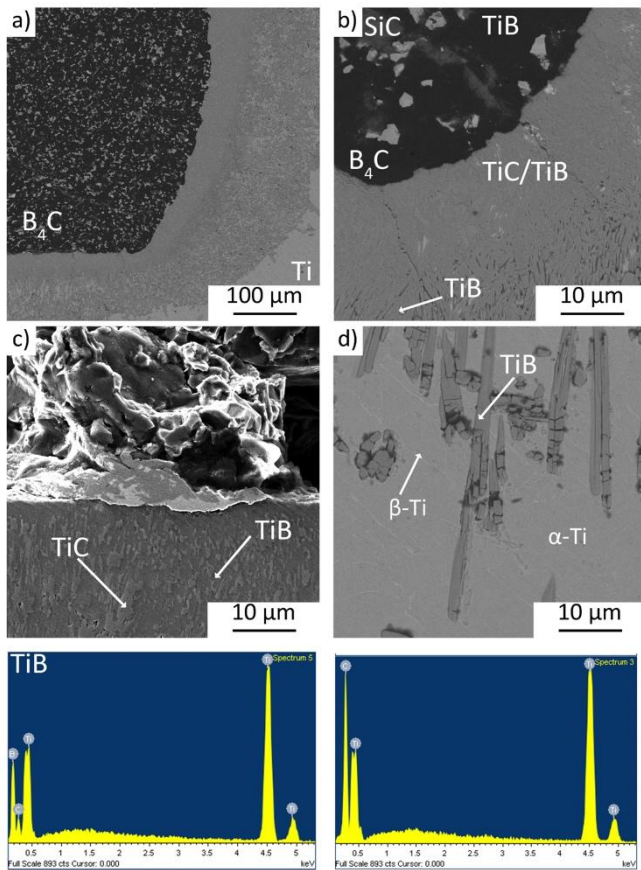
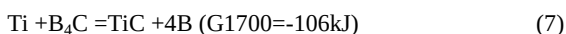
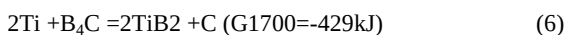
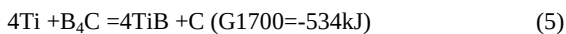
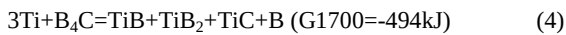
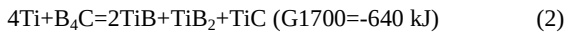
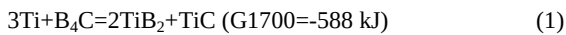


Fig.2. The cross section of the B_4C -30 vol% $TiSi_2$ / Ti-6Al-4V couple after annealing at $1500^\circ C$ for 15 min: general view (a), general view at high magnification (b), microstructure at the grain boundary between B_4C -30 vol% $TiSi_2$ / Ti-6Al-4V (c), microstructure at the boundary between formed products and Ti-6Al-4V (d).

The contact zone can be divided into several sections: first section is B_4C composite (Fig. 2 a), second section is the dense layer consisted from TiC and TiB phase (Fig. 2 b ,c), the third section of the TiB needle and α -Ti and β -Ti phase (Fig. 2 d), the last section is pure α -Ti and β -Ti. The thickness of the second section is 20-30 μm and has cracks. The crack was formed due to the mismatch between the ceramics and newly formed brittle region. The third section had the thickness of 100 μm and consisted from needle like crystal without trace of TiC.

These phases in section 2 and 3 were formed as a result of solid-phase interaction:



According to calculations, the most probable formation of titanium boride among all possible phases is, then titanium diboride and finally titanium carbide. Thus, at the initial stages, titanium boride is formed first as the most stable phase

The C has a lower diffusion coefficient than B and firstly formed TiC at the interaction region, Fig. 2 c. It should be noted

that Yang [7] and Liang [8] using the differential thermal analysis in Ti- B_4C system observed exothermic effect with maximum at $\sim 1093^\circ C$. Therefore, the temperature of formation of TiC and TiB by contact interaction between B_4C and Ti are very close. Appreciably at the same time B react and formed TiB needle crystal. Since the amount of boron in boron carbide is 4 times higher than carbon, the number of needle like crystals is also significantly higher.

The cross section of the B_4C -30 vol% $TiSi_2$ / Ti-6Al-4V-40 vol%TiC couple after annealing at $1500^\circ C$ shown on the Fig.3. Only a few zones can be observed. The first zone is adjacent to the boron carbide and consists of dense TiB layer. The thickness of this zone is 5 μm . Below this zone there is a thick layer of TiC. The thickness of this layer is 20 μm . It should be noted that TiC will play a role of a barrier.

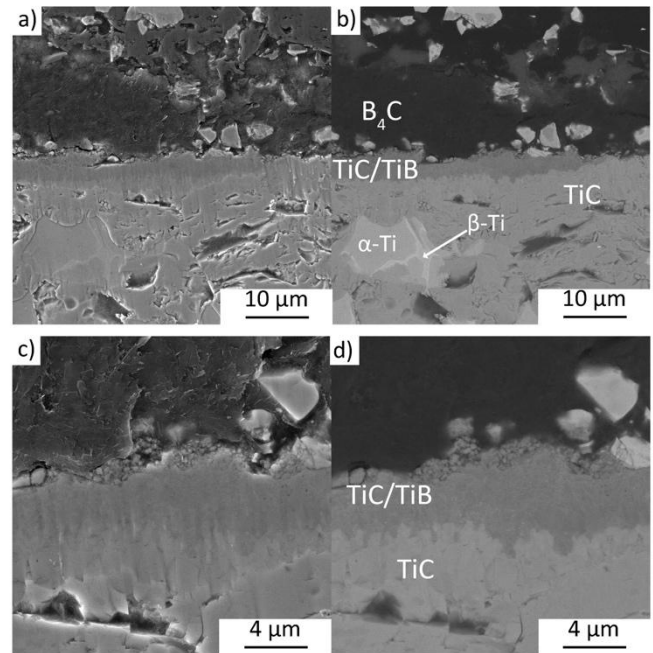


Fig.3. The cross section of the B_4C -30 vol% $TiSi_2$ / Ti-6Al-4V-40 vol%TiC couple after annealing at $1500^\circ C$ for 15 min: general view (a,b), microstructure at the grain boundary between B_4C -30 vol% $TiSi_2$ / Ti-6Al-4V-40 vol%TiC (b,c); a,c-SE;b,d-BSE mode

Because the diffusion of B to TiC is significantly low as well as self-diffusion of C into TiC. On the other hand, the reaction between B_4C and TiC is not favorable, because the Gibbs free energy is +100 kJ/mol:



The formation of a layer at the grain boundary between two materials by formation the new and dense phases increases the adhesion between them. Good adhesion between B_4C and TiC brings several critical advantages, especially when they are used together in composite materials or multilayer structures. These advantages impact the mechanical, thermal, and chemical behavior of the material.

Conclusions

- During the interaction of B_4C -30 vol% $TiSi_2$ / Ti-6Al-4V, a two-stage interaction zone is formed. The total thickness of the interaction products becomes more than 150 μm . The first layer is two-phase and consists of TiB and TiC. The other layer consists of needle-like crystals of TiB that permeate the Ti matrix.

- Addition of TiC to Ti-6Al-4V significantly reduces the thickness of the interaction region to 20 μm by reducing the diffusion of B and C into the interaction region.

- The formation of layers at the boundaries between composites by co-annealing can be used to obtain layered materials.

References.

1. A.P. Mouritz. Metal matrix, fibre-metal and ceramic matrix composites for aerospace applications, in: *Introduction to Aerospace Materials*, Woodhead Publishing, 2012: pp. 394–410. <https://doi.org/https://doi.org/10.1533/9780857095152.394>.
2. M.D. Hayat, H. Singh, Z. He, P. Cao, Titanium metal matrix composites: an overview, *Compos. Part A Appl. Sci. Manuf.* 121 (2019) 418–438, <https://doi.org/10.1016/j.compositesa.2019.04.005>.
3. Domnich, V., Reynaud, S., Haber, R.A., and Chhowalla, M., Boron carbide: structure, properties, and stability under stress, *J. Am. Cer. Soc.*, 2011, vol. 94, pp. 3605–3628.
4. Zhang, W., Yamashita, S., and Kita, H., Progress in pressureless sintering of boron carbide ceramics—A review, *Adv. Appl. Ceram.*, 2019, vol. 118, pp. 222–239.
5. Mazur, P.V., Grigoriev, O.M., Melakh, L.M. et al. Effect of B3Si on the Structure and Properties of B4C Ceramics. *J. Superhard Mater.* 45, 175–185 (2023). <https://doi.org/10.3103/S1063457623030176>
6. Dmytro Vedel, Oleksandr Stasiuk, Dmytro Kovalchuk, Dmytro Savvakina, Vasyl Tkachuk, Serhii Akhonin, Serhiy Schwab, Pavlo Markovsky Formation of the gradient metal matrix Ti-TiB-TiC composite by 3D-printing with coaxial electron-beam technology and cored wire *Journal of Alloys and Compounds* 2025/4/24 <https://doi.org/10.1016/j.jallcom.2025.180617>
7. Y.F. Yang, H.Y. Wang, Y.H. Liang, R.Y. Zhao, Q.C. Jiang, Effect of nickel addition on the exothermic reaction of titanium and boron carbide, *J. Mater. Res.* 22 (2007) 169–174, <https://doi.org/10.1557/jmr.2007.0010>.
8. Y.H. Liang, H.Y. Wang, Y.F. Yang, Y.L. Du, Q.C. Jiang, Reaction path of the synthesis of TiC–TiB2 in Cu–Ti–B4C system, *Int. J. Refract Met. Hard Mater.* 26 (2008) 383–388, <https://doi.org/10.1016/j.jrmhm.2007.09.002>.

Effect of electromagnetic radiation in space on aluminum alloy AA7075

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Abstract: Electromagnetic radiation in space presents a significant challenge to the durability of aluminum alloys used in spacecraft construction. This study analyzes the effects of ionizing radiation (gamma rays, cosmic rays, solar particles), ultraviolet and solar radiation, electromagnetic pulses (EMP), and extreme temperature fluctuations on a novel composite material based on AA7075 (B95) aluminum alloy. The results demonstrate that prolonged exposure of the material in outer space (28 months) leads to structural changes and alterations in mechanical properties. To ensure the reliability of the results, the space-exposed samples were compared with reference samples stored under terrestrial conditions.

Keywords: ALUMINUM ALLOYS, AA7075, ELECTROMAGNETIC RADIATION, SPACE

1. Introduction

Aluminum alloys are among the most widely used materials in the space industry due to their combination of high physical-mechanical properties and specific characteristics such as strength, hardness, and more. The vast variety of aluminum alloys, each with its own unique combination of material properties and chemical composition, along with the need for lightweight, stress-resistant, fatigue-resistant, and deformation-resistant materials, makes them a primary choice for constructing spacecraft structures, hulls and supporting elements, rocket nose cones, launch vehicle fuel tanks, fastening elements, and more. These alloys allow for a reduction in the mass of structures and components without compromising their reliability and operational lifespan. Additionally, they are heat-resistant, making them ideal for use under high loads and extreme temperatures—a critical requirement for spacecraft. The versatility of aluminum enables it to be formed into necessary shapes, sheets, plates, extrusions, and castings, along with heat treatments, each tailored for specific aerospace applications [1-5].

For example, the International Space Station (ISS) extensively uses aluminum in its trusses, station modules, solar panels, and other components. The frames and panels of satellites are predominantly made of aluminum alloys. They are also an integral part of the construction of antennas and communication systems for satellites and the ISS [6].

Aluminum alloy AA7075 is one of the most widely used high-strength alloys in space missions. It belongs to the Al-Zn-Mg-Cu system and is characterized by exceptional strength, good fatigue resistance, and relatively low weight, making it an ideal material for manufacturing critical space components where reliability and performance are of vital importance.

Satellite and probe housings require lightweight yet robust load-bearing structures capable of withstanding the mechanical stresses of launch, resisting thermal expansion and contraction in space, and supporting various payloads. Rocket stages are also subjected to extreme mechanical loads. Solar panel frames and antennas demand high stability and low weight.

Thanks to its high tensile strength (~500–570 MPa), AA7075 is also used to produce fastening elements such as bolts and nuts. Modern aluminum alloys like 7075-T6 and 7050-T7451 have been developed to provide even higher tensile strength and improved fatigue resistance, which are crucial for components exposed to repeated stress and harsh environments [7-9].

Space exploration and the study of the Solar System represent the most demanding environment for materials used in space missions. They must withstand extreme vibrations and mechanical stresses, vacuum conditions, severe temperature fluctuations, and electromagnetic radiation.

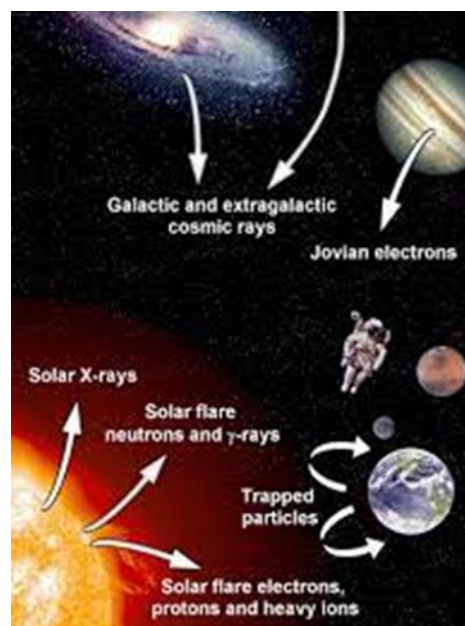


Fig. 1 Sources of radiation in the Solar System [10].

Electromagnetic radiation in space is intense and originates from various sources – both natural (stars(sun), galaxies, black holes) and artificial (satellites, spacecraft). It is a form of energy that propagates as waves across different spectral ranges from low-energy radio waves to high-energy gamma rays or particles (photons) in the vacuum of space. Solar radiation and Galactic Cosmic Rays include: ultraviolet, X-ray, and infrared radiation, ionizing radiation (gamma rays, cosmic rays, solar particles), and electromagnetic fields from the solar wind [11-12]. All these forms of electromagnetic radiation affect the mechanical and physicochemical properties of aluminum alloys, particularly under long-term exposure.

Due to the exceptional importance of issues related to the development of new materials for space applications and the characterization of their structures and physico-mechanical properties, a new material was created in the “Space Materials Science” section at the Institute of Space Research and Technology - Bulgarian Academy of Sciences (BAS). Based on an extensive literature review, the aluminum alloy AA7075 (7075 by USA standards and B95 by Russian classification) was selected with the potential to upgrade its basic properties. A method was chosen to achieve this enhancement through the addition of ultra-dispersed nanodiamond powder and tungsten alloying, along with the application of an appropriate heat treatment process.

The newly developed composite material was exposed to space mounted on the exterior of the Russian module Zvezda of the International Space Station (ISS) between 2013-2015. This marked Bulgaria's first technological experiment in open space, where the SRTI-BAS participated with a device called the “DP-PM” block, forming part of the international space project “Obstanovka (1-step)” [13].

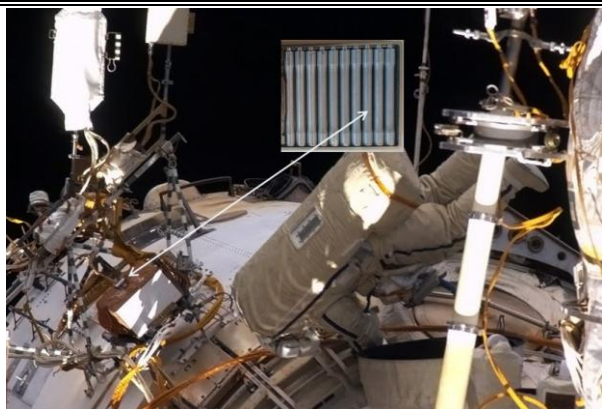


Fig. 2 DP-PM block with Samples of aluminum alloy 7075 (B95) with quantitative addition of ultradisperse diamond powder and tungsten mounted on a plasma-wave complex (PWC) on the ISS, Zvezda module

The objective of the experiment was to study the material's resistance to long-term radiation and thermal exposure, its reliability in extreme environments, and the changes that occurred in its physicochemical, particularly mechanical properties. To ensure the validity of the results, the space exposed samples were compared with reference samples stored under Earth conditions.

2. Effect of electromagnetic radiation in space on aluminum composite AA7075

Effects of Ionizing Radiation Exposure (Cosmic Rays and Solar Particle Radiation)

Structural Changes:

High-energy particles induced alterations in the material's microstructure:

- Transformation in the crystal lattice. Increasing the size of Al and $MgZn_2$ crystallites on the surface of the samples;
- Transformation in the distribution of precipitates. Decomposition and formation of new unstable phases [14];
- Vacancy generation and interstitial atom clustering.

These microstructural transformations consequently degraded mechanical performance.

Mechanical Properties:

- Reduced tensile strength;
- Increased material embrittlement.

Effects of Ultraviolet (UV) and Solar Radiation

Ultraviolet (UV) and solar radiation in space exert surface effects on AA7075, primarily through photochemical degradation and alterations in corrosion properties.

- High-energy UV radiation induced surface oxidation of the samples, leading to the formation of a thicker and more brittle aluminum oxide (Al_2O_3) layer;
- UV exposure caused microcracks on the surface of some specimens;
- In combination with the space vacuum, UV photons broke chemical bonds in surface oxides [14].

Thermal Effects (Heating/Cooling) from Solar Radiation

The extreme temperature fluctuations caused by solar radiation in space significantly impact the structural integrity of materials. The tested material underwent cyclic thermal stress from alternating

heating (up to $+150^\circ C$ in sunlight) and cooling ($-150^\circ C$ in shadow) every two hours. This led to additional thermal aging of the material on the surface and had an impact on the microstructure and mechanical properties of the material.

- Due to the different thermal expansion coefficient of the different phases, deformation of the crystal lattice on the surface of the studied samples was found. Loss of dimensional stability.

Electromagnetic fields (solar storms)

- High-energy particles from solar storms induce variable magnetic fields, which generate eddy currents, leading to localized heating of the material. Strong magnetic fields can cause minor deformation of the crystal lattice, but in combination with thermal cycles from solar radiation, they have resulted in thermal stress in the material's structure.

- Electrostatic discharges (ESD), accumulated from the solar wind in combination with radiation, have caused microcracks on the surface of some samples.

The combined effects of ionizing radiation, vacuum, thermal cycling, and electromagnetic fields have altered the structure of the AA7075 (B95) alloy-based composite reinforced with nanodiamond and tungsten exposed to open space. Consequently, this has led to changes in the composite's mechanical properties.

Alteration in the composite's mechanical properties

- The introduced radiation defects in the crystal lattice outweigh the effects of thermal stress and make the material (space-exposed samples) harder and more elastic than the reference samples [15-16].

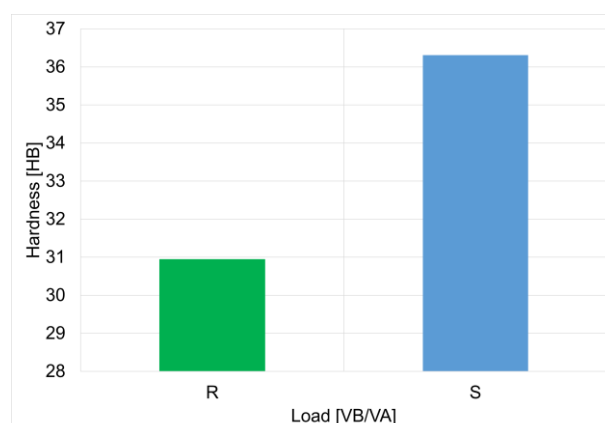


Fig. 3 Average results of Leeb hardness measurements for "reference" (R) and "space" samples (S)

Figure 3 presents averaged results from Leeb hardness measurements for reference (R) and space exposed (S) samples. The experimental studies on penetration resistance were conducted using a universal digital hardness tester in accordance with the Leeb/AI-150A standard. This approach was necessary because the investigated space samples have a diameter of $d = 5$ mm and a length of 70 mm, making them unsuitable for testing on standard hardness testers.

Both the space exposed and reference samples were shaped as cylindrical samples to facilitate their use in subsequent experiments. The dimensions and weight of the samples were designed in compliance with the strict specific requirements for space experiment implementation [13].

Following the conducted Leeb hardness (HL) tests, it was determined that the absorbed radiation dose (~ 425 kGy [17-19]) and temperature fluctuations ($-150^\circ C$ in shadow to $+150^\circ C$) induce modifications in the crystal lattice, particularly in the specimen's surface layer. A specific elemental redistribution is observed - migration of elements leading to the formation of new intermetallic phases that alter the base material's properties, consequently resulting in increased hardness.

Figure 4 displays tensile testing data comparing three reference (R) and three space exposed (S) samples. Testing was performed on a Tira Test 2300 universal testing machine featuring automated test diagram recording capabilities.

A comprehensive pre test inspection was conducted for each samples to identify surface defects including cracks and swelling. Geometrical parameters including 90° cross-section (S_0), initial gauge length (L_0), and diameter (d) were precisely measured for all cylindrical specimens prior to testing.

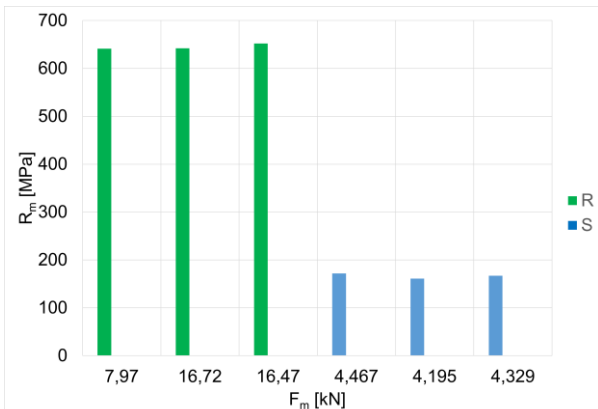


Fig. 4 Tensile test results for three reference (R) and three space exposed (S) samples

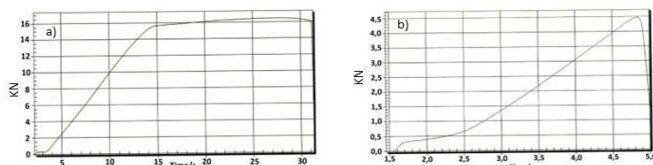


Fig. 5 Tensile diagrams: a) reference sample and b) space sample

Following tensile testing of cylindrical specimens made from AA7075-based composite (UDDP+W), it was established that:

- A substantial strength degradation in space exposed samples relative to reference samples
- Mean tensile strength values:
Reference samples: $R_m = 645$ MPa
Space exposed samples: $R_m = 167$ MPa (74% reduction)
- Space exposed samples exhibit low fracture resistance (Fig. 5b). The material is brittle with low plasticity. No yield strength $R_{p0,2}$ is observed.
- The reference samples exhibit a clearly defined yield plateau $R_{p0,2}$, characteristic of ductile materials.

4. Conclusions

Electromagnetic radiation in space poses a significant challenge to the durability of the newly developed AA7075 aluminum composite. The material shows sensitivity to ionizing radiation, particularly during prolonged space exposure (28 months).

The observed changes in material properties result from:

- The intensity of the radiation environment
- The accumulated radiation dose during exposure (~425 kGy)
- The thermal energy from temperature fluctuations during exposure

These factors led to improvements in certain mechanical properties (hardness and elasticity) in the space exposed samples. However, the accumulated radiation dose simultaneously caused degradation in other mechanical characteristics.

Space exposed samples under cosmic environmental effects exhibited:

- Reduced strength parameters
- Defects in the crystalline structure

5. References

1. J. Davis, Aluminum and aluminum alloys, ASM Speciality Handbook, ASM International, Materials Park, OH, USA (1994)
2. J. Hatch, Aluminum: Properties and Physical Metallurgy, ASM international: Metals Park, OH, USA (1984)
3. C. Kammer, Aluminum and Aluminum Alloys, In: Springer Handbook of Materials Data, Springer Nature Switzerland AG, 157-193 (2018)
4. C-H Ng, S. Yahaya, A. Majid, Reviews on aluminum alloy series and its applications, Acad. J. Sci. Res., **5(12)** (2017) <https://doi.org/10.15413/ajsr.2017.0724>
5. S-S Li, X. Yue, Q.-Y. Li, He-Li Peng, B-X Dong, T-S Liu, H-Y Yang, J. Fan, S-L Shu, F. Qiu, Q-Ch. Jiang, Development and applications of aluminum alloys for aerospace industry, J. Mater. Res. Technol., **27**, 944-983 (2023) <https://doi.org/10.1016/j.jmrt.2023.09.274>
6. E. Kimiya, Aluminum in Space: Pushing the Limits of Aerospace Technology
7. L. Mondolfo, Aluminum Alloys: Structure and Properties; Butterworths: London, UK (1976)
8. I. Fridlyander, Generating aerospace and nuclear energy technologies from aluminum alloys, M.: Nauka, 286 (2006) ISBN 5-02-035750-2 (in Russian) https://elbib.biblioatom.ru/text/fridlyander_vospominaniya_2006/p2/
9. V. Antipov, O. Senatorova, E. Tkachenko, High-strength aluminum alloys, J., Non-ferrous metals, **9** (2013) (in Russian)
10. C. Hellweg, C. Baumstark-Khan, Getting ready for the manned mission to Mars: the astronauts' risk from space radiation, Naturwissenschaften, **94(7)**, 517-526 (2007) DOI: 10.1007/s00114-006-0204-0
11. Nasa Science, Chapter 6: Electromagnetics (2024) <https://science.nasa.gov/learn/basics-of-space-flight/chapter6-1/>
12. G. Badhwar, F. Cucinotta, P. O'Neill, Depth-dose relationships for cosmic rays at various solar minima, Radiat. Res., **134(1)**, 9-15 (1993)
13. A. Bouzekova-Penkova, S. Klimov, V. Grushin, O. Lapshinova, D. Novikov, D. Teodosiev, Space Experiment "Obstanovka (1 - step)", block DP - PM of the Russian segment of the International Space Station (ISS), Aerospace Research in Bulgaria, **35**, 156-164, (2023) DOI: <https://doi.org/10.3897/arb.v35.e15>
14. A. Bouzekova-Penkova, P. Tzvetkov, Investigation of outer space influence on structural properties of strengthened 7075 aluminum alloy. Experiments onboard the international space station (ISS), C. R. Acad. Bulg. Sci., **72(7)**, 939-946 (2019) DOI: 10.7546/CRABS.2019.07.12
15. A. Bouzekova-Penkova, K. Grigorov, M. Datcheva, C. Cunha, Influence of the outer space on Nanohardness properties of Al-based alloy, C. R. Acad. Bulg. Sci., **69(10)**, 1351-1354 (2016)
16. A. Bouzekova-Penkova, M. Datcheva, R. Iankov, Mechanical properties of the enhanced with nanodiamond and tungsten strengthened aluminium alloy being exposed in the Outer space, International Journal "NDT Days", **II (4)**, 396-401 (2019)
17. Ts. Dachev, G. Horneck, D.-P. Hader, M. Lebert, Expose-R cosmic radiation time profile, Intern. J. Astrobiol., **14(1)**, 17-25 (2015)
18. J. Semkova, R. Koleva, Overview on the radiation quantities observed by Liulin-5 instrument in a human phantom on International Space Station during the minimum of 23rd solar cycle, C. R. Acad. Bulg. Sci., **63(10)**, 1533-1542 (2010)
19. <https://cosmicrays.oulu.fi/>

Comparative study of hardness evolution in 5754 aluminum welds under AC and DC welding currents

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Abstract: This study examines how thermal and mechanical effects influence hardness distribution in 4, 6, and 8 mm AA5754 aluminum plates welded using TIG with AC and DC currents. Vickers hardness (HV0.01) was measured alongside tensile tests to evaluate weld performance. Results show that AC welding produces higher but more variable hardness, while DC welding yields more stable profiles. Notably, thinner plates (4 mm) showed minimal hardness differences between current types due to faster cooling. Strain hardening increased hardness up to 125 HV and reduced variation. The extent of hardness stabilization and heat-affected zone size depended on plate thickness. Although current type influenced hardness distribution, it had little effect on fracture toughness.

Keywords: TIG WELDING, AC VS DC, ALUMINIUM, STRAIN HARDENING, THERMAL EFFECT

1. Introduction

Low density, high strength-to-weight ratio, good plasticity, and high corrosion resistance all are Al-alloys advantages over other structural materials making these alloys very suitable for use in aircraft, automotive, marine and offshore applications and other transportation industries where reduction of the structural weight of components and fuel economy plays a major role [1]. To produce different structures in these areas welding remains a very popular and important technological process [2]. Therefore, aluminium welding solutions are widely studied and discussed by scientists all over the world because welding is mainly chosen for the installation of large metal structures such as ships, bridges, construction machinery and aircraft. The gas metal arc welding (GMAW) process, gas tungsten arc welding (GTAW/TIG), friction stir welding (FSW), and electron-beam welding (EBW) are the most widely used for aluminium welding because they are suitable for various applications. Of all the possible processes, arc welding, i.e. GMAW and TIG welding are more cost-effective due to lower energy consumption and greater flexibility [3]. There are a lot of published works on the influence of controlling the quality of the welds by monitoring welding speed, welding current and its polarity, heat input, and shielding gas [4-6].

Although standard welding processes exist, attempts are made to combine the processes to achieve good penetration, reduce porosity and obtain all the mechanical characteristics required for use. It has been shown that full penetration and low macro-porosity can be achieved in a 3 mm thick AA5754-aluminum alloy using a fibre laser arc hybrid welding process with filler wire [7]. Laser-arc and MIG with the CO₂ heat source combined welding of 5754 magnesium aluminium alloy lead to increased hardness of fusion zone possibly caused by strain and magnesium hardening and no cracks formed on bending over 120° [8].

Based on the results of tensile tests of joints welded by the TIG method, the influence of welding imperfections on the values of strength parameters of the seams has been confirmed by calculating *r* Pearson coefficient [9]. It was demonstrated that the biggest negative impact of the welding non-conformities such as lack of penetration and solid inclusions their type and shape in the weld leads to lower hardness values, which can result in further low tensile performance [10].

The 5754 series alloys are aluminium-magnesium (Al-Mg) widely used in marine vehicles, pressure vessels, fuel tanks, and the manufacturing of welded chemical and nuclear buildings due to their lightweight and excellent corrosion resistance in the atmosphere [2]. 5754-H111 is a non-heat-treatable high-strength aluminium alloy usually supplied in an annealed condition [11]. Different amounts of Fe as an alloying element in the alloy of this grade affect failure modes: when a high Fe amount alloy fails by void sheeting, low Fe shows a ductile type of failure. Different levels of Fe are caused by the formation of relatively coarse Fe-Mn-Al intermetallic compounds during casting [12].

It is clear from the literature that other authors analyse the influence of GMAW, FSW, EBW or hybrid laser arc, robotic, fibre laser assisted or double pulsed GMAW welding on the mechanical behaviour of the AA5754 weld, but there is a lack of published works using pure TIG welding for this grade of alloy. Therefore, the focus of this research is to assess the role of the plate thickness of AA5754-H111 on the mechanical performance of pure TIG welded joints. AC current flow is traditionally used for aluminium alloys welding and all the studies mentioned above used AC, there are no scientific results on the use of DC, only welding manuals give some advantages of DC. In order to determine the influence of both current flows on the welding process, this study is accomplished through the tensile and bending behaviour of different thickness joints. The ductility of plates is demonstrated and compared.

2. Materials and Methods

The study was concentrated on a commercial 5754 (EN 573-3:2009) aluminium alloy of 4 mm, 6 mm, and 8 mm thick plates. Samples for welding were prepared using 150 mm long and 50 mm wide plates of the aforementioned thickness. Five samples were prepared for each thickness and current flow and all measurements and tests values were averaged. A single V-groove at 60° was selected for the AC current flow welds, while no groove is required for the DC flow [13], so butt welding was performed on the DC-welded samples.

Weld pool geometry plays an important role in the performance and mechanical properties of AC welded joints [14]. It is reported that groove angle should be as small as possible to minimize the loss of alloying elements in the base metal (BM) [15]. Therefore, for AC samples, each plate with 2.4 mm root opening and 1.5 mm root face thickness was formed with one bevelled groove with an angle of 30° to ensure reasonable use of the filler rod and increase the strength of the weld.

A 2.4 mm diameter Al 5356 magnesium-based filler rod (according to ISO 18273:2015) was used in the welding process. The nominal chemical composition of the test base alloy and filler rod are shown in Table 1.

Table 1: Chemical composition

	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
Al 5754-H111	0.40	0.40	0.10	0.50	2.6-3.6	0.30	0.20	< 0.15	The rest
Al 5356	0.25	0.40	0.10	0.05-0.20	4.5-5.5	0.05-0.2	0.10	0.06-0.20	The rest

Pre-weld surface cleaning of AC welds was performed to remove grease, oxidation and moisture within 20-30 mm of the weld groove on both sides. V-milling debris was removed with a hand file from the edges of the weld groove, and the base metal oxide layer was cleaned with a stainless-steel hand brush. Equal attention was paid to the aluminium plates and filler rod, and they were cleaned with isopropyl alcohol and dried. After joining the plates for AC welding, the V-groove was cleaned again with a

stainless-steel hand brush and degreased with isopropyl alcohol. Re-degreasing was also performed on the filler rod to avoid contamination of the weld. Meanwhile, only the aluminium oxide layer was removed from the joint edges of the prepared DC-welded samples [13, 14].

The TIG technique using Sherman DIGITIG 200 AC/DC Multipro (Poland) TIG inverter type of power source was chosen for the comparative analysis of AC and DC welds, as it allows obtaining a high-quality weld joint. A large gas lens and a number 11 cup (manufactured by TBI, Germany) ensured optimal gas shielding of the weld pool. To maintain a stable arc and protect the pool from contamination, a 2.4 mm diameter non-consumable tungsten electrode WL20 (TBI, Germany) with 30° tapered conical tip and flat end diameter of 0.1 mm and an electrode protrusion of 20 mm was chosen. As the electrode tip slowly loses the required arc, it is necessary to maintain the contour of the hemispherical tip from time to time. It should be noted that in all practical cases the tungsten electrode does not transfer metal to the weld pool under normal operating conditions. The same torch travel angle (80-85°) for both current flows, and an operating angle of 80-100° was used for AC, since DC does not require an operating angle [13]. The welding parameters were confirmed based on the experimental testing of the samples and are presented in Table 2. Plates of all thicknesses were welded using both AC and DC current flows using ~100% argon or helium as shield gas, respectively, supplied from a coaxial TIG torch tip.

Table 2: TIG welding parameters

Current	Plate thickness, mm	Welding current, A	Voltage, V	Travel speed, mm/s	Shielding gas	Gas flow rate ² , l/min
AC	4	100	17 – 20	1.6	Argon ¹ 99.99%	14
	6	120		1.5		
	8	160		1.4		
DC	4	75	20 – 25	1.7	Helium ¹ 99.99%	14
	6	120		1.6		
	8	180		1.4		

¹ Gaschema (Lithuania), 200 bar, supplied in 50 l cylinders

² The flow rate is monitored by a Hercules (Germany) pressure regulator suitable for Ar or CO₂ (200 bar max. pressure and 30.32 l/min max. flow rate)

Vickers hardness measurements were performed to determine the mechanical properties of base metal, the AC and DC weld joints, and hardness of samples after the failure. A Mitutoyo HM-200 (Mitutoyo Corporation, Japan) universal tester was used to perform the hardness test with a standard load of 0.098 N and a dwell time of 10 s. Schemes for measuring the hardness of the samples after the tensile test are shown in Fig. 1. All samples were measured at room temperature five times – average values were considered for evaluation.

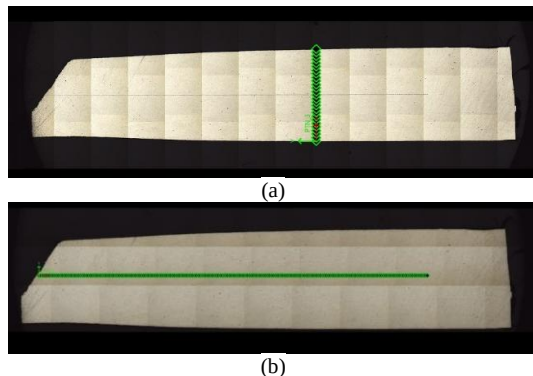


Fig. 1 Schemes of Vickers hardness measurement of transverse (a) and longitudinal (b) 6 mm thick sample

Flat tensile specimens from base metal and AC and DC welded plates of different thickness were taken according to EN ISO 4136:2012. For welded plates, it was taken transversally the welded joint so that after machining the welding axis remained in the

middle of the parallel length of the specimen. The geometric parameters of the tensile specimen with gauge length of 70 mm are presented in Fig. 2.

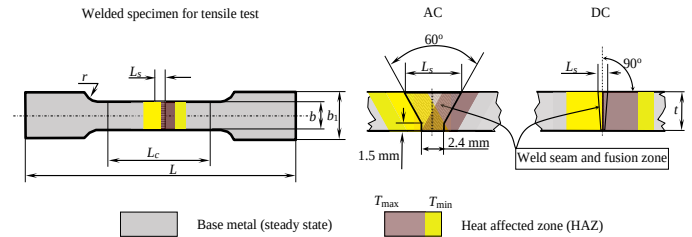


Fig. 2 Specimen geometry for tensile tests: $t_s = 4/6/8$ mm; $b = 25$ mm; $b_1 = 37$ mm; $L_c = 70$ mm; $L = 300$ mm; $r = 25$ mm; AC: $L_s = 5.3/7.6/9.9$ mm; DC: $L_s = 4-6$ mm

Destructive tensile testing at ambient temperature was performed to determine the behaviour of various thickness samples under tensile loading. The experiment was carried out using a universal testing machine 50 kN “Amsler” equipped with HBM testing device at a crosshead speed of 2 mm/min (force measurement sensor U5-100 kN (HBM); displacement sensor WA-50mm±0,1 mm; catman Express V4.5: catModule for data collection) [16]. Here, the specimens of the thickness to be tested are placed between two plates that hold the test object firmly, and then a tensile force is applied through the upper jaw, while the lower part firmly holds the tensile specimen. As a result, the sample deforms and possess fracture at some point due to various behaviour parameters such as elastic stress $\sigma_{0.05}$, ultimate stress σ_u , stress at fracture σ_{fr} , relative reduction of cross section at ultimate point Z_u , relative reduction of cross section after fracture Z_{fr} , maximum elongation A_5 (see Table 3). This determines the force required to break the welded sample and the extent to which the weld stretches or elongates to the breaking point. Three sets of samples: base metal, AC and DC welded samples underwent tensile testing according to EN ISO 4136:2012.

Table 3: Mechanical properties of the studied samples

No	Sample	$\sigma_{0.05}$	σ_u	σ_{fr}	Z_u	Z_{fr}	A_5
		MPa			%		
1	4BM	115	229	199	19	27	31.3
2	4AC	60	198	185	13	25	20.1
3	4DC	60	197	183	6	16	17.0
4	6BM	81	196	171	24	46	32.8
5	6AC	76	170	165	8	11	13.4
6	6DC	67	203	193	15	23	26
7	8BM	80	217	197	16	37	35.6
8	8AC	53	203	202	13	13	30.8
9	8DC	45	189	182	10	16	20.0

3. Experimental results

Generally, during deformation of the specimen, the microstructural non-homogeneity of weld seam which appears in sample material is also accompanied by different rate of deformation processes, which affect the tensile properties. In addition, the mechanical effect during stretching changes the hardness and its distribution in the weld and in the base metal, depending on what stage of deformation is reached, including normal elasticity (range $0 - \sigma_{0.05}$), strain hardening (range $\sigma_{0.05} - \sigma_u$) and neck formation (range $\sigma_u - \sigma_{fr}$) that is discussed as the object of the next topic.

Residual stresses σ_{res} are generated during welding. Technological parameters and welding methods influence on the characterization of their distribution and definitely influence the elastic stresses of the base material $\sigma_{BM/0.05}$. The residual stress σ_{res} is obtained by accepting that the value of the reference elastic stresses $\sigma_{BM/0.05}$ is the value of the unwelded specimen, and the elastic stresses of the welded specimen is $\sigma_{w/0.05}$. Therefore, the residual stresses σ_{res} can be written as the difference of the stresses determined for samples of different quality:

$$\sigma_{res} = \Delta\sigma_{0.05} = \sigma_{w/0.05} - \sigma_{BM/0.05} \quad (1)$$

Numerical values of residual stresses along with mechanical properties are presented in Fig. 3(d).

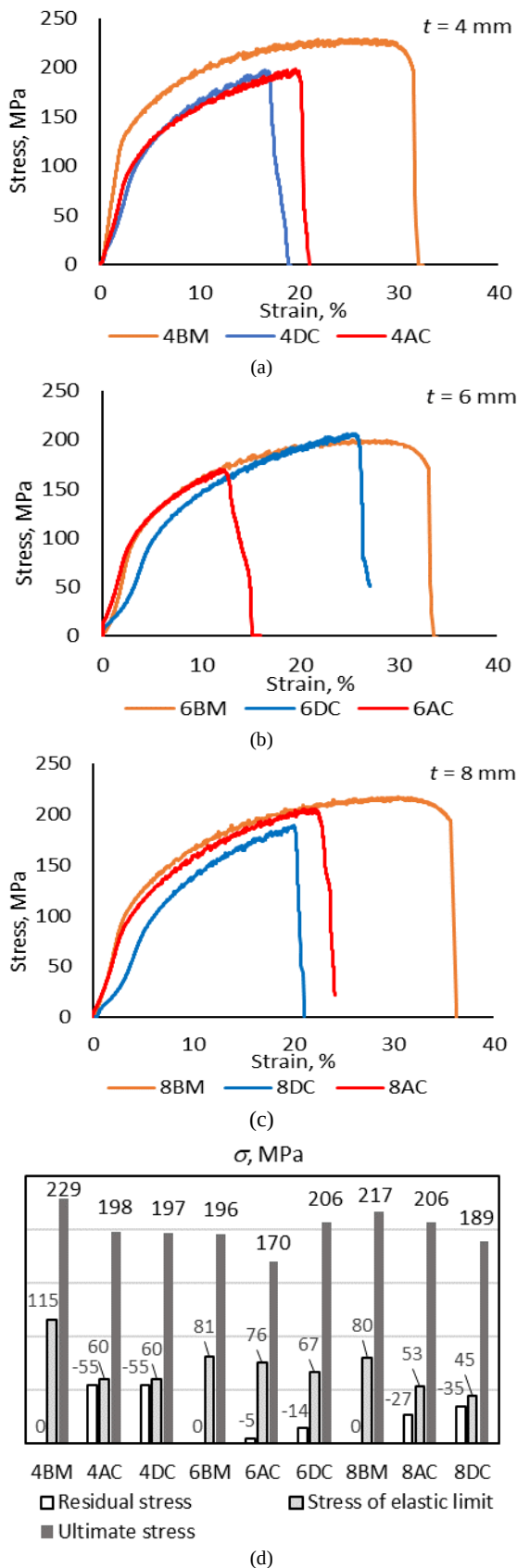


Fig. 3 Graphical comparison of tensile curves and mechanical properties of 4/6/8BM, 4/6/8AC and 4/6/8DC samples of various thicknesses t : (a) 4 mm, (b) 6 mm, (c) 8 mm, (d) determined mechanical properties and residual stresses with their numerical values

A negative sign indicates that the stresses are compressive, which would mean that the part of the residual stress resources is more likely to deform plastically and does not accumulate an increase in elasticity. Therefore, unlike the case of the Bauschinger effect, the elastic stresses of all welded specimens are lower than those of unwelded ones (see Fig. 3(a), (b), (c)).

The hardness of the AC and DC current flow welded samples was measured by evaluating two factors: 1) the thermal effect experienced after welding and 2) the influence of deformation after tensile test (straining). To ensure the reliability of the hardness measurement, it was measured along the z -axis (length) and perpendicularly along the x -axis (thickness). The hardness measurement diagram is presented in Fig. 4.

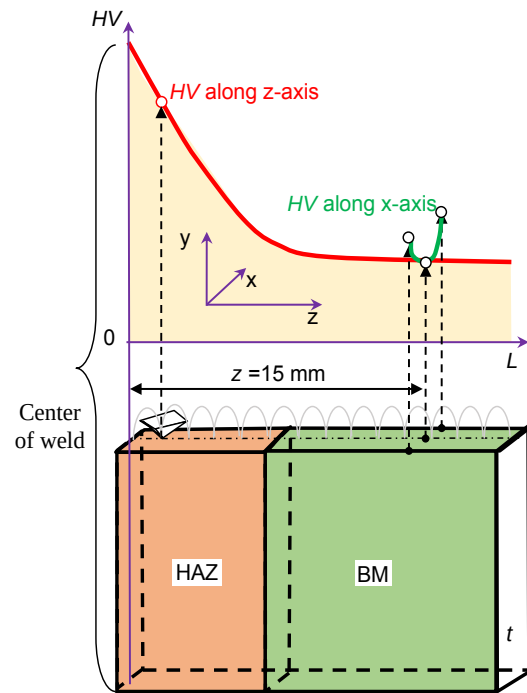


Fig. 4 Hardness measurement diagram of sample areas. HAZ is the heat affected zone and BM is the base metal

The hardness $HV_{0.01}$ of the unwelded sample (blank) or so-called base metal (BM-0) at the plate surface is about 80 $HV_{0.01}$ in all samples, and in the centre, it drops to 70 $HV_{0.01}$ in samples 4BM-0 and 6BM-0 and even to 60 $HV_{0.01}$ in sample 8BM-0. This is influenced by the rolling of the aluminium blanks from which the samples are cut. As a result, the surface layer is hardened during rolling, while the central part of the sample remains at its original hardness. The hardness values of the unwelded samples are presented by the green curves in Fig. 5.

In the AC flow welded samples, the hardness of 90-95 $HV_{0.01}$ dominates in the centre of the weld. With DC current, some regularity is seen: as the thickness of the sample increases, the hardness in the centre of the weld decreases accordingly: 4DC-T to 90 $HV_{0.01}$, 6DC-T to 80 $HV_{0.01}$ and 8DC-T to 75 $HV_{0.01}$. This is determined by the intensity of endothermic processes and the greater inertia of thermal phenomena occurring in larger volume samples, which most likely explains the reason for the lower cooling. The measurement results are presented in Fig. 5 and Fig. 6.

In addition, the hardness measurement results are approximated by polynomial expressions: along the x -axis by using a second-order polynomial, and along the z -axis by using a third-order polynomial. All polynomials corresponding to the initial (0), thermal (T) and strain (S) states of the specimen are presented in Table 4.

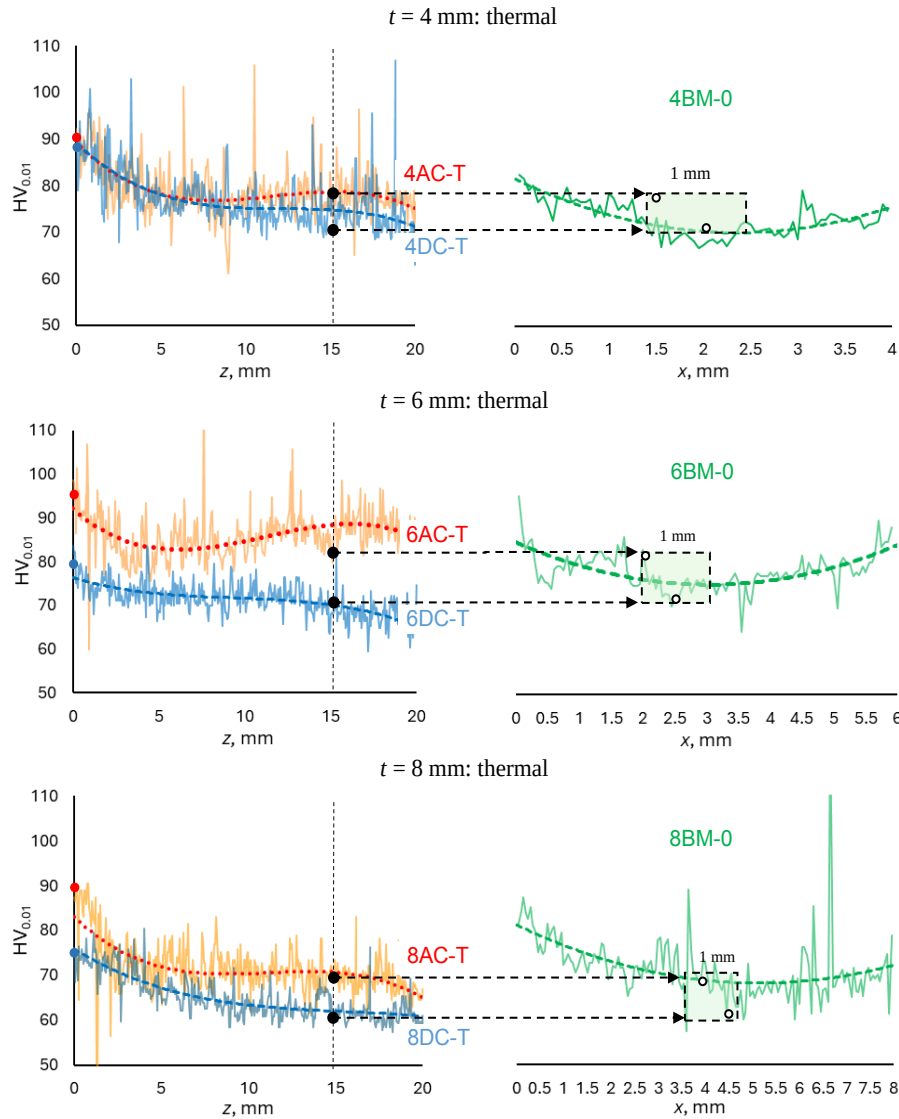


Fig. 5 Distribution of hardness values $HV_{0.01}$ due to thermal effects in 4/6/8AC-T and 4/6/8DC-T samples of various thicknesses t what shows a diminution of hardness in z -axis (figures on the left) while reaching a steady state; on the right, a light green 1 mm area (approximately in the middle of the t thickness) is used to determine the hardness correspondence of initial state 4/6/8BM-0 samples in the x direction with 4/6/8AC-T and 4/6/8DC-T samples in the z direction taken at 15 mm from the weld centre

Table 4: Empirical equations for the distribution of hardening due to thermal and straining effects

Sample	State	Sample number	$t = 4 \text{ mm: } HV_{x/z}$	
			x	z
BM	Initial	4BM-0	$2.0802x^2 - 9.818x + 81.607$	70-75
	Strained	4BM-S	$1.2195x^2 - 4.4062x + 100.41$	$-0.0024z^3 + 0.1166z^2 - 2.094z + 105.61$
AC	Thermal	4AC-T	$2.0802x^2 - 9.818x + 81.607^*$	$-0.0077z^3 + 0.282z^2 - 3.4557z + 89.223$
	Strained	4AC-S	$0.534x^2 - 1.5495x + 89.1$	$-0.0124z^3 + 0.4952z^2 - 6.4263z + 120.3$
DC	Thermal	4DC-T	$2.0802x^2 - 9.818x + 81.607^*$	$-0.0103z^3 + 0.3591z^2 - 3.7917z + 89.416$
	Strained	4DC-S	$0.6221x^2 - 2.5538x + 89.56$	$-0.0017z^3 + 0.135z^2 - 3.2685z + 112.23$
$t = 6 \text{ mm: } HV_{x/z}$				
BM	Initial	6BM-0	$1.0237x^2 - 6.2368x + 84.17$	70-75
	Strained	6BM-S	$0.4701x^2 - 2.1515x + 103.21$	$-0.004z^3 + 0.1535z^2 - 2.023z + 108.13$
AC	Thermal	6AC-T	$1.0237x^2 - 6.2368x + 84.17^*$	$-0.0117z^3 + 0.3908z^2 - 3.4768z + 92.084$
	Strained	6AC-S	$0.4965x^2 - 2.3734x + 93.312$	$-0.0144z^3 + 0.6012z^2 - 8.3245z + 125.16$
DC	Thermal	6DC-T	$1.0237x^2 - 6.2368x + 84.17^*$	$-0.0041z^3 + 0.1138z^2 - 1.2011z + 76.327$
	Strained	6DC-S	$0.8002x^2 - 5.1576x + 104.71$	$8E-05z^3 + 0.0622z^2 - 2.0961z + 109.43$
$t = 8 \text{ mm: } HV_{x/z}$				
BM	Initial	8BM-0	$0.4929x^2 - 5.0642x + 81.157$	65-70
	Strained	8BM-S	$0.3604x^2 - 2.3964x + 104.9$	$0.0003z^3 - 0.0168z^2 - 0.0796z + 102.39$
AC	Thermal	8AC-T	$0.4929x^2 - 5.0642x + 81.157^*$	$-0.0105z^3 + 0.3497z^2 - 3.7185z + 83.055$
	Strained	8AC-S	$0.3267x^2 - 2.5892x + 93.715$	$-0.0109z^3 + 0.4724z^2 - 6.3009z + 113.25$
DC	Thermal	8DC-T	$0.4929x^2 - 5.0642x + 81.157^*$	$-0.0031z^3 + 0.143z^2 - 2.3752z + 75.877$
	Strained	8DC-S	$0.3537x^2 - 2.487x + 89.403$	$-0.0027z^3 + 0.1832z^2 - 3.617z + 105.58$

* indicates a similarity of hardness distribution between base metal and DC-/AC-welded specimens when the hardness was measured on the line of x axis moved by 15 mm from the centre of unwelded specimens

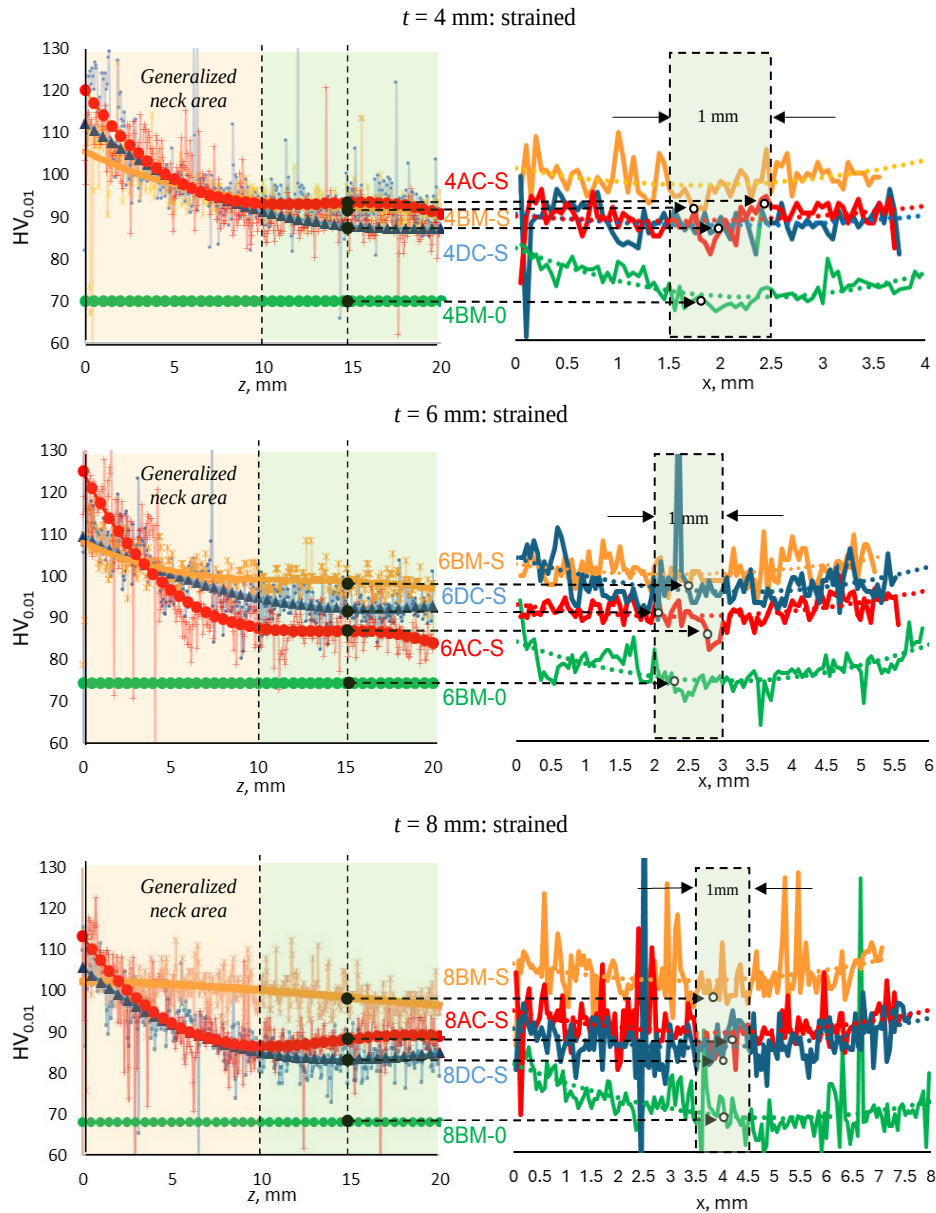


Fig. 6 Distribution of hardness values $HV_{0.01}$ due to straining effects in 4/6/8AC-S and 4/6/8DC-S samples of various thicknesses t that shows an increase of hardness HV in x and z axes; figures on the left show hardness HV on the z -axis and graphs on the right on the x -axis; on the right, a light green 1 mm area (approximately in the middle of the t thickness) is used to determine the hardness correspondence in the x and z directions at 15 mm taken from the fracture edge along the z axis

In Fig. 5 and Fig. 6, a distance of 15 mm from the edge of failure of the sample in the transverse direction with respect to the x -axis was chosen in such a way that the strain hardening is obtained outside the neck formation area, because, when it is reached, the ultimate stresses increase, hardening processes are accompanied by large plastic deformations in the neck formation zone. In addition, when measuring the hardness before and after straining, it was observed that the hardness variation of the DC-specimen is more uniform than that of the AC-specimen.

4. Discussion

The mechanical properties of the unwelded samples show that the maximum ultimate stress is in 4 mm specimen, followed by the 6- and 8 mm samples in the direction of decreasing stress (see Fig. 3). Their values are affected by the hardened layer on the surface obtained during production, where the hardness is higher than in the middle of the thickness of the sample. This can be seen in Fig. 5 of the measured hardness along the x -axis on the right. The percentage of deformed part in thick AC and DC welded samples has almost no effect on the mechanical properties. The elastic stresses are

influenced by residual stresses, and the stresses of ultimate strength are similar. Both AC and DC samples were observed to shift the deformation process from the BM to a weaker location, i.e., the HAZ. Based on the experimental results and what has been said above, two hypothetical statements are made to evaluate the hardness variation patterns.

Summarizing the achieved results, it can be stated that as the distance z increases from the AC and DC weld centre, it is simply thermally affected, the change in hardness is more stable in DC samples and wavier in AC samples until base metal HV values are reached. The hardness of the AC samples is higher than that of the samples prepared by the DC method. The strain hardening process affects both the increase of HV and the decrease of the so-called waviness. The hardness invariance distance z depends on the thickness of the specimen, which influences the distance L_s and the HAZ associated with the latter. If the welded sample breaks a little earlier than the statistical average, it means that the strain hardening process also stops earlier. In this work, the case was also chosen when the material of the base metal does not have time to deform and the strain hardening process moves to the fracture area at the

weld seam much more intensively compared to the base metal. This is related to 6 mm AC welded sample. The consequences of this case we observe when comparing 6 mm AC and DC welded strained samples at $z = 3...20$ mm what allows us to conclude that for the given z range, the 6AC-S sample hardness is less than 6DC-S sample. The evolution of the hardness HV is on average more reflective of its increase due to possible microscopic changes occurring in the material due to deformation, starting with elasticity (Range I), then strain hardening (Range II) and finally necking (Range III), when the hardness is the highest. Another interesting fact is that the micro-hardness HV_{0.01} of the samples that were cut from samples 4AC-S, 6AC-S and 8AC-S after their fracture showed the highest values compared to the other samples of the same thickness. The current flow showed no appreciable difference in hardness HV_{0.01} values for samples of the same thickness after fracture.

5. Conclusions

1. DC-welded samples have a more stable hardness distribution with increasing distance from the weld centre, while AC-welded samples have a wavier hardness profile until base metal hardness values are reached.
2. The AC-welded samples consistently show higher hardness compared to the DC-welded samples, indicating that the AC welding method increases the hardness of the material.
3. The strain hardening process not only increases the hardness, but also reduces the waviness in the hardness distribution, resulting in a more uniform hardness profile of the welded specimens.
4. The distance at which hardness stabilizes (the invariance distance, z) depends on the thickness of the specimen, which in turn affects the size of the heat affected zone (HAZ).
5. Hardness (HV) evolution is influenced by microstructural changes during deformation, AC welded specimens show faster microstructural processes leading to an increase in hardness, especially with increasing distance from the weld centre. However, no significant difference in hardness between AC and DC welding methods was observed for samples of uniform thickness after fracture.

6. References

1. Cheng J, Song G, Zhang Z, et al (2022) Improving heat-affected zone softening of aluminum alloys by in-situ cooling and post-weld rolling. *J Mater Process Technol* 306:117639. <https://doi.org/10.1016/J.JMATPROTEC.2022.117639>
2. Yürük A, Çevik B, Kahraman N (2021) Analysis of mechanical and microstructural properties of gas metal arc welded dissimilar aluminum alloys (AA5754/AA6013). *Mater Chem Phys* 273:125117. <https://doi.org/10.1016/J.MATCHEMPHYS.2021.125117>
3. Samiuddin M, Li J long, Taimoor M, et al (2021) Investigation on the process parameters of TIG-welded aluminum alloy through mechanical and microstructural characterization. *Defence Technology* 17:1234–1248. <https://doi.org/10.1016/J.DT.2020.06.012>
4. Troise M, Krichel T, Olschok S, Reisgen U (2024) Investigation of the influence of pulse parameters on the resulting weld seam quality in pulsed electron beam welding of AW 6061. *Journal of Advanced Joining Processes* 9:100183. <https://doi.org/10.1016/J.JAJP.2023.100183>
5. Abolusoro OP, Khoathane MC, Mhike W, et al (2024) Influence of welding parameters and post weld heat treatment on mechanical, microstructures and corrosion behaviour of friction stir welded aluminium alloys. *Journal of Materials Research and Technology* 32:634–648. <https://doi.org/10.1016/J.JMRT.2024.07.175>
6. Sabry I, Hewidy AM, Naseri M, Mourad AHI (2024) Optimization of process parameters of metal inert gas welding process on aluminum alloy 6063 pipes using Taguchi-TOPSIS approach. *Journal of Alloys and Metallurgical Systems* 7:100085. <https://doi.org/10.1016/J.JALMES.2024.100085>
7. Casalino G, Mortello M, Leo P, et al (2014) Study on arc and laser powers in the hybrid welding of AA5754 Al-alloy. *Mater Des* 61:191–198. <https://doi.org/10.1016/J.MATDES.2014.04.060>
8. Casalino G, Mortello M (2021) Laser-arc combined welding of aa5754 alloy. *Mater Lett* 284:128946. <https://doi.org/10.1016/J.MATLET.2020.128946>
9. Woźny P, Błachnio J, Dragan K (2019) Correlation between Strength, Hardness and the Share of Welding Imperfections in an AW 5754 Aluminium Alloy Weld Executed with the TIG Method. *Journal of KONBiN* 49:383–400. <https://doi.org/10.2478/jok-2019-0092>
10. Woźny P, Błachnio J (2018) The impact of microstructural non-conformities on microhardness of EN AW 5754 aluminium alloy welded joints made with the use of the TIG method. *Journal of KONBiN* 48:253–262. <https://doi.org/10.2478/jok-2018-0055>
11. Casalino G, Campanelli SL, Maso UD, Ludovico AD (2013) Arc Leading Versus Laser Leading in the Hybrid Welding of Aluminium Alloy Using a Fiber Laser. *Procedia CIRP* 12:151–156. <https://doi.org/10.1016/J.PROCIR.2013.09.027>
12. Sarkar J, Kutty TRG, Conlon KT, et al (2001) Tensile and bending properties of AA5754 aluminum alloys. *Materials Science and Engineering: A* 316:52–59. [https://doi.org/10.1016/S0921-5093\(01\)01226-6](https://doi.org/10.1016/S0921-5093(01)01226-6)
13. Bendikiene R, Sertvytis R, Ciuplys A (2023) Comparative evaluation of AC and DC TIG-welded 5083 aluminium plates of different thickness. *The International Journal of Advanced Manufacturing Technology* 127:3789–3800. <https://doi.org/10.1007/s00170-023-11779-2>
14. Syed Thasthagir M, Sajitha Banu A, Muthu kumaran A, et al (2024) Comparison of V groove design on mechanical performance and fracture behaviour in TIG welding of 5754-H111 aluminium alloy. *Mater Today Proc.* <https://doi.org/10.1016/J.MATPR.2024.03.031>
15. Baskutis S, Baskutiene J, Bendikiene R, Ciuplys A (2019) Effect of weld parameters on mechanical properties and tensile behavior of tungsten inert gas welded AW6082-T6 aluminium alloy. *Journal of Mechanical Science and Technology* 33:765–772. <https://doi.org/10.1007/s12206-019-0131-6>
16. Baskutis S, Baskutiene J, Bendikiene R, et al (2021) Comparative Research of Microstructure and Mechanical Properties of Stainless and Structural Steel Dissimilar Welds. *Materials* 14:6180. <https://doi.org/10.3390/ma14206180>