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Innovation Marketing and Strategic Marketing

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Abstract: This article examines the role of innovative and strategic marketing in enhancing the competitiveness of businesses in an environment of rapid technological change. Particular attention is paid to a strategic approach to marketing planning, which involves a thorough analysis of consumer needs and market assumptions. The article emphasizes the need for continuous adaptation of product portfolios to changing market conditions and increasing fragmentation of customer segments. The concept of strategic innovation marketing is introduced as a key factor for successful product positioning, while its implementation in business strategies is considered essential for effective management of innovation processes. The final findings of the paper suggest that strategic innovation marketing not only promotes customer retention, but also enables the transformation of business models and supports the long-term growth of firms in an environment of rapidly evolving technologies.

Keywords: INNOVATION MARKETING, STRATEGIC MARKETING, INNOVATIONS, MARKETING MANAGEMENT

1. Introduction

In economic terms, innovation means the development and implementation of ideas and technologies that lead to higher quality goods and services or to their more efficient production or provision. A typical example of innovation is the development of steam engine technology in the 18th century, with the beginning of the use of steam engines leading to the start of mass production. More recently, information technology has changed the way businesses produce their goods and services, opening up new markets and introducing new business models. [1]

Product quality is clearly a determining factor for a company to position itself on the market and win the largest number of customers, which automatically implies a growth in market share and room for making the expected profit. Marketing is a stabilising factor in management, which enables enterprises to orient themselves securely in the market. It is one of the means by which an enterprise can successfully establish itself in the market. Innovative marketing is a very important tool for an enterprise. In a competitive environment, innovation of existing products and the development of new products is a necessity in order to retain customers and market share. Enterprises that do not spend on new product development or invest in the innovation of machinery and equipment and existing products expose themselves to the risk of losing regular and potential customers and, inevitably, of losing their market share. An enterprise should strive to obtain good quality and reliable information on its own activities as well as on the activities of the external environment, which provide a good starting point for the enterprise to make the right decisions and to operate successfully on the market. [2]

Marketing innovations are aimed at better meeting the needs of consumers, opening new sales markets to increase sales volumes, which are key to the successful development of the organization. In order to keep up with the rapidly changing needs of the market and to make the most of the opportunities that open up in the external environment, organisations need to continuously work on new products, technologies and relationships with the outside world. The key to solving these problems is innovative marketing activity, which in modern times has become the core of corporate competitive strategies. [3]

The production of goods, the provision of services, the provision of information and their compulsory sale in the respective markets are the basis of the cultural and economic life of the people. Services, goods and information generate utility, which economists in their own circles call utility, which enables the consumer to satisfy a certain desire. The commercial tone of the relationship between producers and buyers of products is set by four types of basic instruments: form, time, place and ownership. The commercialisation of innovations requires the use of marketing innovations. Therefore, issues related to the development of marketing innovations and the creation of mechanisms for the implementation of marketing innovations in order to increase the

potential and competitiveness of domestic enterprises are nowadays particularly important in the post-industrial stage of the country's economic development. [3, 4]

Strategic marketing involves the acquisition of theoretical knowledge by undergraduates and practical skills in the development of marketing strategies for manufacturers, taking into account the opportunities and threats existing in the external environment, as well as the available skills, capabilities and resources that contribute to the creation of a unique market offering designed for the most attractive market segments. [3] Innovation is becoming an integral part of the modern economy. The process of economic and political transformations taking place in the country has led to the need for significant changes in the activities of economic actors. Existing organisational structures, interests and, with them, behavioural mechanisms and ways of decision-making are changing. The conditions of modernity require increased attention to the management of innovative activities that ensure the efficient development of production. Innovative activity is the most progressive form of entrepreneurship in market relations. The market creates real opportunities for the development of scientific and technological progress. [5]

2. The functioning of strategic innovation marketing

The logic of development of an innovative company leads to a shift of the focus from operational tactical planning to the strategic level, to the level of forming a new type of management - innovative marketing. Innovative marketing in the modern concept represents the unity of strategies, business philosophy, functions and procedures of company management. In industrialised countries, the marketing concept of company development has been important for decades. The concept of innovative marketing is the basis for market research and the search for a competitive strategy for an enterprise. The innovative marketing complex includes the development of an innovative strategy, market analysis and operational marketing. Figure 1 shows that all phases of innovation marketing are related to strategic or operational components. [2]

Strategic innovation marketing is defined by market segmentation and product positioning. The key point of the marketing strategy is the study and forecasting of the demand for the new product, based on a thorough study of consumer perception of the innovation. During the strategic research, innovation project leaders should define what products will be offered, in what quality and to which consumers. [7] Strategic marketing therefore focuses on close contact between the company's marketing and sociological services staff and the potential consumer, through various tools such as questionnaires, telephone surveys, representative samples, etc. A general economic analysis is usually carried out in the initial market research phase. This type of analysis is closely linked to the study of the external environment of the enterprise and allows for the examination of macroeconomic factors related to the demand for

innovation, including population, growth rates, per capita income and consumption, the consumer price index, the consumer basket and the inflation rate. This includes the study of the legal conditions as well as the practice of legislation concerning the import and export of like products, quotas, restrictions on standards, obligations, taxes, subsidies, etc. At the same time, it is necessary to analyse the level of national production of such products, the presence or possibility of imports, the level of exports, data on the production of import substituting products and innovation. [3, 5]

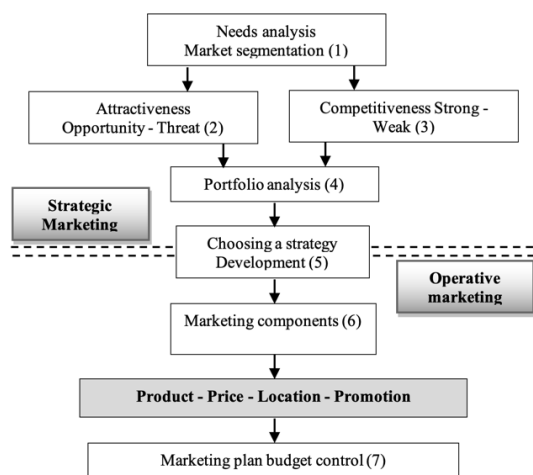


Fig. 1 Innovative marketing complex [1]

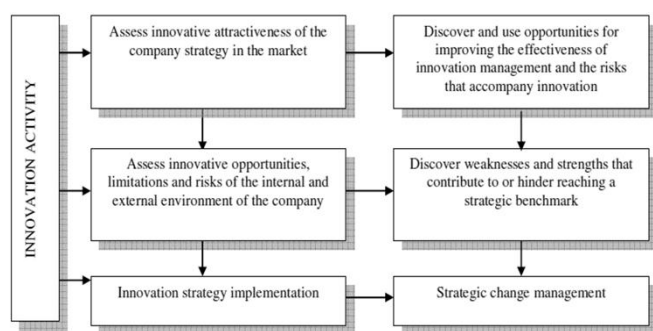


Fig. 2 Model of Formation of the Company Innovation Strategy for Activation of Market Activity [8]

3. Functions of innovative marketing

Innovative marketing involves the use of creative approaches in all areas of business, focusing on the constant search for ideas, their implementation in order to improve business technology and create competitive products. Modern researchers emphasize the possible areas of innovative marketing within both traditional thinking and non-standard practices. [1]

If the former focuses on finding ideas and creating products within the goals, target markets, and opportunities defined by the enterprise, then the latter involves search processes that are not constrained; innovative ideas are superior to the enterprise's goals. The second direction identifies the spin-off of innovation departments in large companies and the emergence of venture capital firms focused on the implementation of venture projects and the creation of fundamentally new products and technologies. [9]

F. Kotler and F. Trias de Bez, based on the type of thinking, proposed to distinguish the concepts of vertical and lateral marketing in the innovation process. Vertical marketing is based on logic and consistency of thinking. The concept of lateral thinking

was introduced by Edward de Bono and defined as "a set of processes designed to use information in a way that generates creative ideas through the ingenious restructuring of concepts accumulated in memory". Characteristics of innovative marketing: [10]

1. The strategic focus on finding and satisfying new needs suggests that innovation marketing is used not only at the "output" but also at the "input" of innovation management.
2. The organization and management of the innovative activity of the enterprise is carried out through the prism of interaction with the market, which includes the use of network theory and the study of modern forms of relations in the innovation market.
3. The object of investigation and the product on the market is not a finished product, but an idea, which determines the use of methods for the exploitation and evaluation of intellectual property. Thus, the goal of innovation marketing can be defined as the creation and implementation of an innovation strategy for the organization's activities, which includes increasing its competitiveness.

Table 1. Functions of innovative marketing [6]

Feature	Table of Contents
Marketing research	Research of innovation processes of external environment and internal innovation potential, research of innovation potential of competitors, research of potential markets of finished products, research of consumers of innovations, research of marketing mix possibilities in different stages of innovation process.
Planning policy on innovation, trade and assortment policy	Development of new products, development of measures to modify existing products (improvement of quality characteristics and competitiveness), development of the product range structure, etc.
Sales and distribution	Creation of a sales network, determination of the sales structure at different stages of the innovation process, control of physical flows in the distribution system.
Promotion	The development of advertising policy at different stages of the innovation process, the development of the trademark, the image of innovation, the development of measures to change the image, the formation of demand for innovation.
Pricing	Forecasting new product prices, developing pricing strategies, analysing prices of substitute products and similar products.
Marketing Management	Organization of the marketing management structure at different stages of the innovation process, optimization of managerial decisions in the system of marketing activities, marketing audit.

Innovative marketing involves the use of creative approaches in all areas of the enterprise, focusing on the constant search for ideas, their implementation in order to improve enterprise technology and create competitive products. Modern researchers emphasize the possible areas of innovative marketing within traditional thinking and non-standard (combinatorial) thinking. If the former focuses on the search for ideas and the creation of products within the framework of enterprise-defined goals, target markets and opportunities, then the latter assumes unrestricted processes of searching for innovative ideas and their primacy over the objectives of enterprises. The second direction determines the allocation of innovative units in large enterprises and the emergence of venture capital firms. According to the theory of innovative marketing, the

process of perception of a new product consists of the following stages: [6, 7]

1. Primary awareness. The consumer learns about the innovation but does not have enough information.
2. Product recognition. The consumer already has some information, is interested in the novelty; may seek further information about the new product.
3. New product identification. The consumer compares the novelty with his needs.
4. Evaluation of the possibilities of using the innovation. The consumer decides to test the innovation.
5. Consumer endorsement of the innovation to obtain information about the innovation and the possibility of acquiring it.
6. The decision to acquire or invest in the creation of an innovation.

The logic of development of an innovative company leads to a shift of the focus from operational tactical planning to the strategic level, to the level of forming a new type of management - innovative marketing. Innovative marketing in the modern concept represents the unity of strategies, business philosophy, functions and procedures of company management. In industrialised countries, the marketing concept of company development has been at the forefront for decades. The concept of innovative marketing is the basis for market research and the search for a competitive strategy for the enterprise. The innovative marketing complex includes the development of an innovative strategy, market analysis and operational marketing. [7]

The main objective of strategic innovation marketing is to develop a strategy for bringing innovations to the market. The basis of strategic marketing research is therefore the analysis of the market situation with the subsequent development of market segments, the organisation and shaping of demand and the modelling of purchasing behaviour. [4]

Strategic innovative marketing is determined by market segmentation, product positioning. The key point of the marketing strategy is the study and forecasting of the demand for the new product, based on a thorough study of consumer perception of the innovation. In the course of the strategic research, the leader of the innovation project must determine: what products, in what quality and for which consumers will be offered. Strategic marketing therefore focuses on close contact between the marketing and sociological services staff of the company and the consumer (through questionnaires, telephone surveys, representative samples, etc.). [8]

4. Conclusion

The rapid evolution of technology requires significant changes in the product portfolio and continuous market analysis. Due to the fragmentation of mature markets and the emergence of customer groups with specific requirements, a market segmentation strategy is only possible on the basis of detailed information. Strategic marketing comprises two parts: strategic analysis and strategic decisions. Conceptually, the concepts of brand and strategy are intrinsically linked. A brand is essentially a strategic decision that is followed across the corporate structure to achieve key objectives. When developing a brand strategy, it must be taken into account that the market structure is always dynamic, not static. If the brand strategy does not take into account strategic adaptation to market demands and has a strong connection in relation to the brand's history and standard, then the company may find itself in a situation where the brand is overwhelmed by the market and is outperformed by other brands.

The process of innovation and strategic marketing is indeed a source of information for the management of innovation activities and innovative solutions that can translate the value of innovations from product innovations conditioned by technological innovations, innovations in the organizational structure of the enterprise and in synergy with marketing innovations into changes in quantitative performance indicators and performance in monetary and non-monetary indicators.

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Photophysical properties of some phthalocyanine derivatives using ultrafast spectroscopy

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Abstract: Transient absorption spectroscopy uses short laser pulses which can be up to tens of femtoseconds. These pulses can effectively “freeze” the motion of the molecules at specific times during a reaction or a dynamic process, and by modification of the time delay between the pump and probe pulses snapshots of the molecular system can be obtained at different stages of its evolution, providing insights into the underlying dynamics. For this purpose, the nanosecond or femtosecond transient absorption techniques can be utilized.

In this presentation ultrafast spectroscopy (transient absorption) and emission (steady state and time-resolved fluorescence) spectroscopy were applied for to study and characterize the photophysical properties of some phthalocyanine derivatives. For this, new compounds (phthalocyanine derivatives) have been synthesized and the quantum yields and lifetimes of excited states were estimated. Also, to demonstrate excited-state processes from the transient absorption map, we obtained a ground state bleaching band (GBS), absorption in excited state (ESA) and at longer wavelength, stimulated emission (SE).

Keywords: TRANSIENT ABSORPTION, PHTHALOCYANINE DERIVATIVES, EXCITED STATE

1. Introduction

Phthalocyanine derivatives have been utilized extensively in biomedical applications due to their unique physico-chemical properties such as high thermal and chemical stability. The introduction of metal ions in the molecular structure of phthalocyanine as well as the peripheral substituents determines significant changes in the photophysical and photochemical behavior [1, 2]. Phthalocyanines are typically second-generation photosensitizers utilized in the photodynamic therapy (PDT) for the cancer treatment. For photodynamic therapy different components are necessary such as photosensitizer drugs that accumulate in tumor cells, light irradiation with wavelength corresponding to the absorption band of the photosensitizer, and molecular oxygen [3]. Changing the central metal atoms and the positions of the peripheral and non-peripheral substituents, a control of their optical and electrochemical characteristics can be realized and the therapeutic effect can be improved. The introduction of the hydrophilic substituents to pyrrole rings enhanced their water solubility and stability [4].

The advantages of the metallophthalocyanines are strong absorption in red and near infrared ranges, high singlet oxygen generation yield, low dark toxicity, selective accumulation in tumors, fast vanishing from healthy tissues, good solubility in aqueous solutions and high storage stability [5, 6].

The present work was centered on the combination of photosensitizers of tetra- and octa- carboxy phthalocyanine type with some nanomaterials that can improve photodynamic therapy efficiency and eliminate its side effects as well.

2. Materials and methods

All solvents were purchased from Sigma-Aldrich and were of spectrophotometric grade, being used as received. The synthesized materials were characterized by nuclear magnetic resonance spectroscopy, electronic absorption and emission spectra. The electronic absorption spectra of all the solutions were collected on a SPECORD 210Plus spectrometer (Analytik Jena, Germany). An Edinburgh FS5 spectrometer (Edinburgh, Ltd., England) and a Perkin Elmer LS55 luminescence spectrometer were applied to determine the steady-state fluorescence spectra. Time-correlation single photon counting system (FLS 980, Edinburgh Instruments, England) was used to conduct the time-resolved photoluminescence analysis by using a nanosecond diode laser at 375 nm as excitation source. Experiments were carried out at room temperature in 10 nm quartz cells. The absolute fluorescence quantum yield (Φ) was determined by FLS980 integrated sphere using solutions having the absorbance value bellow 0.1 and excitation wavelengths corresponding to the absorption band maxima.

The “Long” setup for ultrafast transient absorption spectra offers an average temporal resolution of 100 fs, an amplified Ti:Sapph laser emitting 100 fs pulses at 800nm, with a repetition rate of 2 kHz (fig. 1). It can be turned into several layouts across ultrabroad bandwidths and ultralong temporal windows, ranging from few hundreds of fs to 2 ns. We can use the fundamental laser beam at 800 nm, we can frequency double the fundamental, second harmonic generation (SHG) at 400nm or we can exploit a frequency tunable NOPA with the excitation beam that can continuously cover all the wavelengths from 480 nm to 1.6 μm , with a bandwidth of 10-20nm.

Also, for the broadband probe, obtained by White Light Generation (WLG) onto thin highly nonlinear plates. 800 nm pumped Sapphire plate generates light in the range of 430-780 nm (Visible) and 840-1200 nm (Near IR). In 800 nm pumped CaF₂ crystals the WL can be extended to the UV region, down to 340 nm.

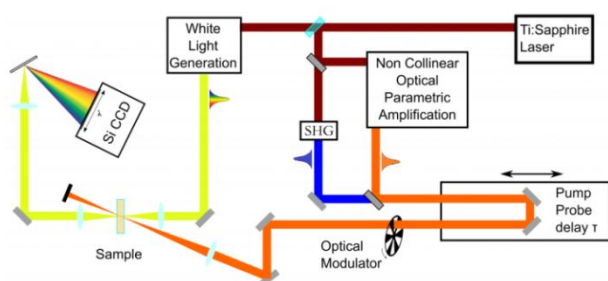


Figure 1. Setup of ultrafast transient absorption spectroscopy

General chemical formulae of ZnPc derivatives are presented below.

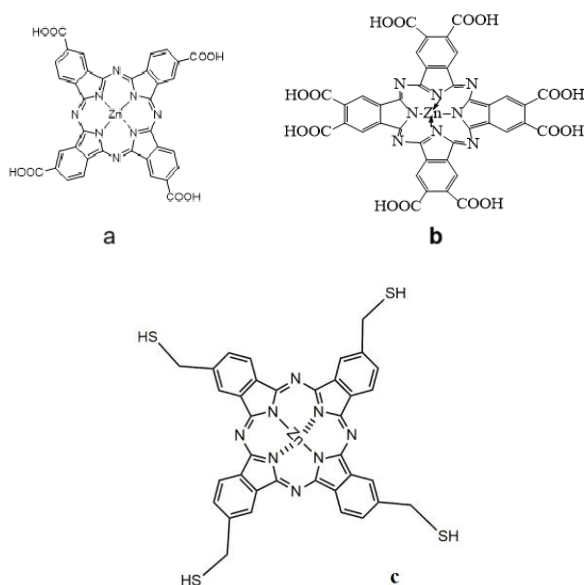


Figure 2. General chemical structures of ZnPc (COOH)₄ (a), ZnPc (COOH)₈ (b) and ZnPc(SH)₄ (c)

The synthesis of ZnPc(COOH)₄ was performed from a mixture consisting of trimellitic anhydride; Zn(CH₃COOH)₂·2H₂O; (NH₄)₆Mo₇O₂₄·4H₂O; anhydrous Na₂SO₄; urea and 1-bromonaphthalene, heated at (200-205) °C for 8 h under continuous stirring. After 8 hours, the reaction mixture is cooled and treated with methanol. The obtained suspension is filtered. The solid reaction product is washed on the filter with methanol, chloroform and finally with acetone. Further after drying, it was refluxed for one hour in 5% HCl solution. After drying, the same procedure was carried out with 5% NaOH solution for one hour at 90°C. The basic solution is acidified with HCl until a pH of 2 and finally a precipitate product is reached. This product settles, filters and dries in the open air. A quantity of 0.68 g of ZnPc(COOH)₄ product is obtained, with a yield of 70%. The following characteristic vibrations (cm⁻¹) were observed in the FTIR spectra: 3300 (νO-H); 3103, 3078, 3042 (νC-H); 1710 (νC=O); 1654, 1590 (νC-C); 1484, 1446, 1284, 1173 (νC-O); 1228, 1088 (νC-H); 1004, 880, 770, 705, 570, 499, 435.

3. Results and discussion

Transient absorption (TA) spectroscopy, steady state, and time-resolved fluorescence spectroscopy were used to investigate and characterize the tetra- and octa- carboxy zinc phthalocyanine derivatives with applications in medicine. For this purpose, the new compounds were been synthesized in order to have a good emission, stability and sensitivity. We choose the investigation of some phthalocyanine derivatives for the theoretical information and applications resulting from this study, and to develop new technological innovations for the health sciences, a new pathway for the treatment of cancer.

In this paper, the synthesis, photophysical and biological characterization of ZnPc(COOH)₄, ZnPc(COOH)₈ and ZnPc(SH)₄ are displayed. The unsubstituted metallphthalocyanines (MPcs) have very low solubility in the majority of organic solvents, and the formation of substituted ZnPc is necessary to improve solubility in the manufacturing process.

The optical properties of the compounds under study were assessed by absorption and emission spectra (figs. 3-5), fluorescence lifetimes (fig. 6) and fluorescence quantum yield determinations.

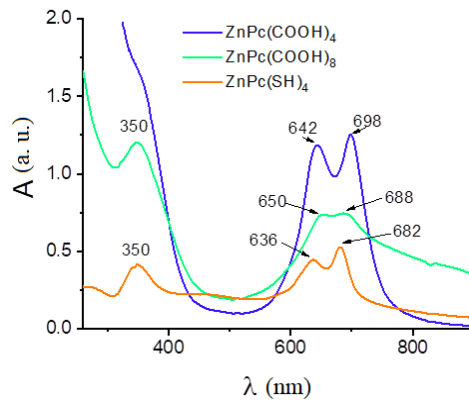


Figure 3. Absorption spectra of $\text{ZnPc}(\text{COOH})_4$, $\text{ZnPc}(\text{COOH})_8$ and $\text{ZnPc}(\text{SH})_4$

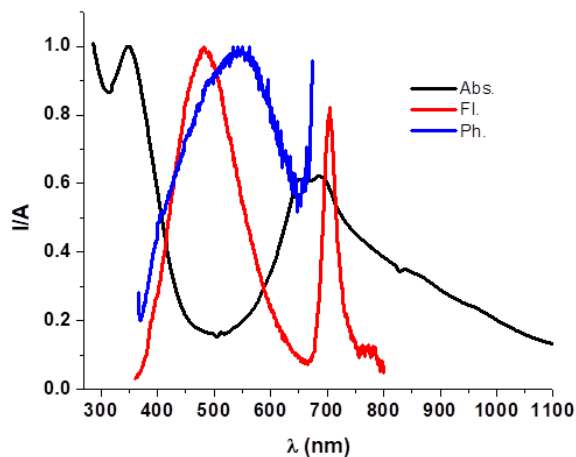


Figure 4. Absorption and emission spectra of $\text{ZnPc}(\text{COOH})_8$

In order to demonstrate the excited-state processes and the involvement of the higher energy electronic states ($S_n > 1$), transient absorption spectroscopy (TA) was used. In the transient absorption map at ns, for $\text{ZnPc}(\text{COOH})_8$ in $\text{H}_2\text{O}/\text{DMSO}$ at pump pulse 355 nm, it can be noticed ground state bleaching bands (**GBS**) at 270, 290 nm, absorption in the excited state (**ESA**) at 260, 290, and 320 nm, respectively and more than one excited state ($S_n > 1$). At longer wavelengths, such as 460 nm, 500 nm, 530 nm, stimulated emission (SE) occurs, and at wavelengths of 640 nm and 680 nm, other stimulated emissions appear, attributed to the triplet manifold, confirmed by time-resolved fluorescence experiments, such as phosphorescence. Also, at 510 nm, the triplet excited state absorption is found (fig. 7).

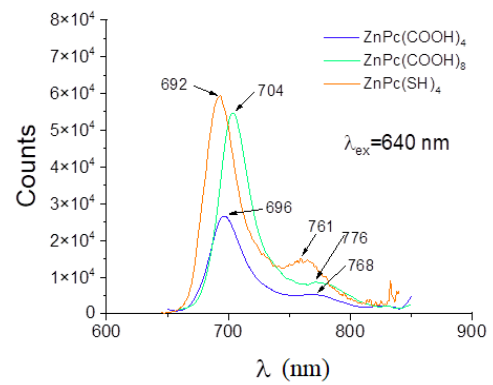


Figure 5. Fluorescence spectra of $\text{ZnPc}(\text{COOH})_4$, $\text{ZnPc}(\text{COOH})_8$ and $\text{ZnPc}(\text{SH})_4$

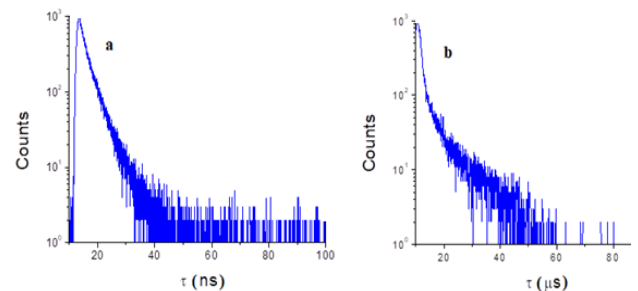


Figure 6. Fluorescence (a) and phosphorescence (b) decay of $\text{ZnPc}(\text{COOH})_4$

The values of the fluorescence lifetimes vary between 1.46 and 10.21 ns, whereas the phosphorescence lifetimes are in the range of 1.07 to 9.33 μs . Also, emission quantum yields under 15% were determined [2].

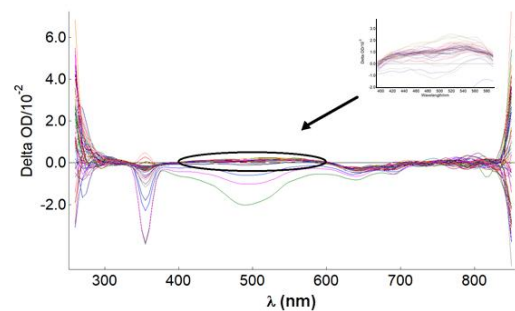


Figure 7. Transient absorption of $\text{ZnPc}(\text{COOH})_4$ in $\text{H}_2\text{O}/\text{DMSO}$

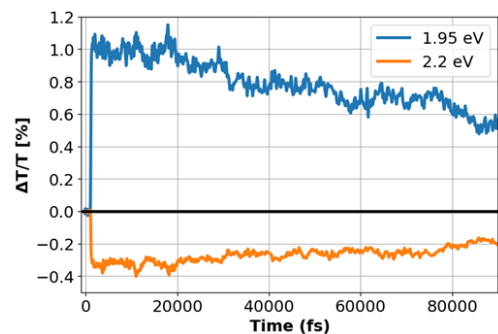


Figure 8. Ultrafast dynamics of $\text{ZnPc}(\text{SH})_4$ in DMSO

By using ultrafast spectroscopy, transient absorption at fs, for $\text{ZnPc}(\text{SH})_4$ at pump pulse 680 nm it can be observed photoinduced absorption (PA) at 2.2 eV and stimulated emission (SE) at 1.95 eV (figs. 8, 9).

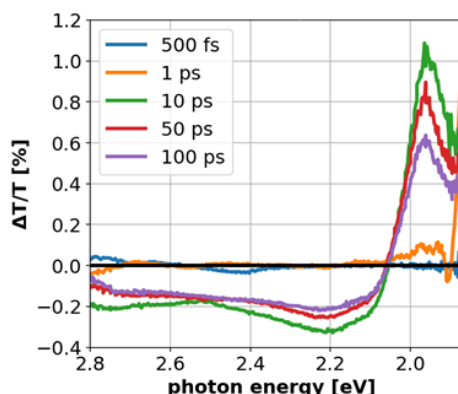


Figure 9. Transient absorption of $\text{ZnPc}(\text{SH})_4$ in DMSO

The antimicrobial activity of the synthesized $\text{ZnPc}(\text{COOH})_4$ and $\text{ZnPc}(\text{COOH})_8$ in $\text{H}_2\text{O}/\text{DMSO}$ compounds was studied in vitro by the serial dilution method. The results of the bactericidal tests are present in Table 1. For clarity, they have been compared with well-known bactericidal drug, such as chlorhexidine. As can be seen from the table, the bactericidal activity of $\text{ZnPc}(\text{COOH})_4$ is much lower than that of $\text{ZnPc}(\text{COOH})_8$ and chlorhexidine.

Table 1. Bacterial tests

Samples	Microorganisms, (μg/mL)				
	<i>S. aureus</i> (t. 209)	<i>E. faecalis</i> (t. ATCC 19433)	<i>E. coli</i> (t. ATCC 25922)	<i>Ps. Aerugi-nosa</i> (t. ATCC 27853)	<i>Pr. Vulgaris</i> (t. HX 19222)
$\text{ZnPc}(\text{COOH})_8$	300	75	110	75	80
$\text{ZnPc}(\text{COOH})_4$	38	89	58	>300	>300
chlorhexidine	125	115	230	>300	>300

4. Conclusion

From the transient absorption map of the phthalocyanine derivatives, it can be observed ground state bleaching bands (GBS), absorption in excited state (ESA) and more than one excited state ($S_n > 1$). At longer wavelengths stimulated emission (SE), and other stimulated emissions can appear ascribed to the triplet manifold, confirmed by time-resolved experiments to be phosphorescence. Also, the triplet excited state absorption can occur.

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Effect of thermal drilling strategy on the geometrical characteristics of metal – composite joints

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Abstract: This paper deals with the change of joint geometry of non-ferrous metal sheets and composite plates reinforced with bi-directional glass and carbon fiber by thermal drilling due to the effect of different drilling strategy. Joints formed by direct and sequential drilling were tested. Sequential drilling represents a convenient way to minimize delamination of layered composites during joining.

Keywords: METAL-COMPOSITE JOINING, THERMAL DRILLING, DRILLING STRATEGY, DIRECT DRILLING, SEQUENTIAL DRILLING, BUSHING GEOMETRY

1. Introduction

Thermal drilling is one way of joining materials through bushing forming. Nowadays, the challenges of joining materials with completely different properties such as metallic and composite thin-walled materials are being overcome [1-6]. Such material combinations occur in the construction of ultralight structures in the automotive or aerospace industries. Joints of metals and composites are found, for example, in the construction of A-pillars, engine covers, load plates or front stretchers.

Some specific applications of composites in car bodies are shown in Fig. 1.

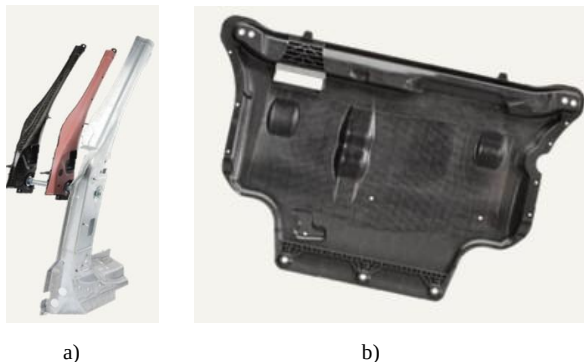


Fig. 1 Examples of the application of composite materials: a) Porsche A-pillar, b) MQB platform engine cover

Thermal drilling provides a way to create a bond between a metal sheet and a continuous fiber-reinforced composite with two significant advantages: no fastener and therefore no added weight, and no disruption to the continuity of the fibers. Making joints without disturbing the continuity of the fibres in the composite is possible only if the matrix of the composite is thermosoftening polymer. It heats up when drilled, softens and the fibres are deflected out of position without breaking when the tool penetrates and the bushing is formed, Fig. 2.

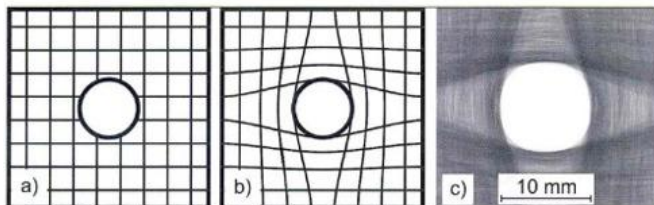


Fig. 2 Comparison of a hole in a fibre composite formed by a) conventional drilling, b) and c) thermal drilling of a fibre composite with a thermosoftening matrix, adapted from [4,6]

The mechanical joining of the metal sheet and the composite plate formed by thermal drilling can then look like this, Fig. 3:

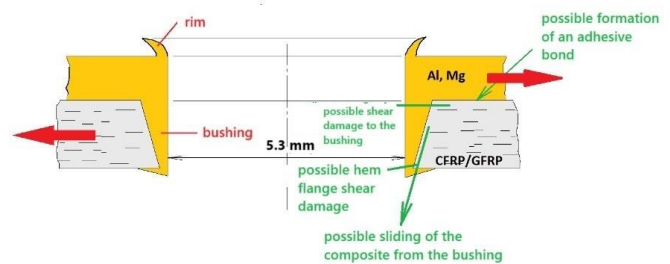


Fig. 3 Schematic diagram of metal sheet and fibre composite joint made by thermal drilling

The aim of this paper is to present the differences in shaping the bushing when drilling the metal plate alone, and also when drilling the metal-composite pair by direct and sequential thermal drilling. The objective is to create a bushing with sufficient thickness and length to penetrate through the full thickness of the composite plate to form a mechanical joint and to determine which of the strategies investigated is the most appropriate.

2. Materials and Methods

Materials used in the automotive industry were chosen for the metal – composite joints formation using thermal drilling. Composite materials are progressively replacing conventional metals in automotive construction. They compete with them in terms of comparable mechanical properties and low specific weight - i.e. an advantageous strength-to-weight ratio, also called specific strength.

Characteristics and identification of selected materials:

- Aluminium alloy EN AW-6082 T6 (AlSi1MgMn) – Al alloy supplied in a precipitation-hardened state with relatively high mechanical properties. The alloy was supplied in the form of a 1 mm thick rolled sheet. Hereinfter Al.
- AZ 91 magnesium alloy with the main alloying elements Al and Zn. The alloy was supplied in the form of a 2 mm thick rolled sheet. Hereinfter Mg.
- Composite with polypropylene (PP) matrix reinforced with continuous glass fibres in two perpendicular directions. The thickness of the consolidated composite organosheet is 1.55 mm, which is the result of the compaction of three layers of preregs. Hereinfter GF.
- Composite with polypropylene matrix (PP) reinforced with continuous carbon fibres in two perpendicular directions. The thickness of the consolidated composite organosheet is 1.55 mm, the result of the compaction of seven layers of preregs. Hereinfter CF.

The basic characteristics of the materials are shown in Tab. 1-3.

Tab. 1 Chemical composition of alloys in wt.%

alloy	Si	Mg	Mn	Fe	Zn	Cu	Al
Al	1.0	0.7	0.44	0.4	0.08	0.06	balance
Mg	0.09	balance	0.14	0.004	0.93	0.02	8.9

Tab. 2 Mechanical and physical properties of alloys

alloy	Re [MPa]	Rm [MPa]	A ₅₀ [%]	density [g·cm ⁻³]
Al	295	340	15	2.71
Mg	280	200	24	1.81

Tab. 3 Properties of composite organosheets

Composite	PP CF50 T200 OS	PP GF45 T600 OS
Matrix	polypropylene	
Reinforcement	Carbon fibre	Glass fibre
Type of fibre	Carbon HT	E glass
Weaving	Twill 2/2	Twill 2/2
Surface mass. mats	200 g·m ⁻²	600 g·m ⁻²
Density of weaving	3K	1200 tex
Fibre content by weight	50%/50%	50%/50%
Fibre content in the composite	51%	47%
Surface weight of finished product	301 g·m ⁻²	887 g·m ⁻²
Prepreg thickness	0.22 mm	0.5 mm
Specific weight of composite	1.46 g·cm ⁻³	1.68 g·cm ⁻³
Melting temperature	165°C	165°C
Operating temperature (short-term)	140°C	161°C
Operating temperature (long-term)	100°C	100°C
CTE (23-80°C)	3.2×10 ⁻⁶ K ⁻¹	11×10 ⁻⁶ K ⁻¹

The geometry of the test joints as well as the shape and dimensions of the test specimens, determined in accordance with STN EN ISO 12996:2014 using a 5.3 mm diameter tool (Flowdrill Long 5.3 mm), are shown in Fig. 4. The opening (joint) is located in the centre of the overlapped area.

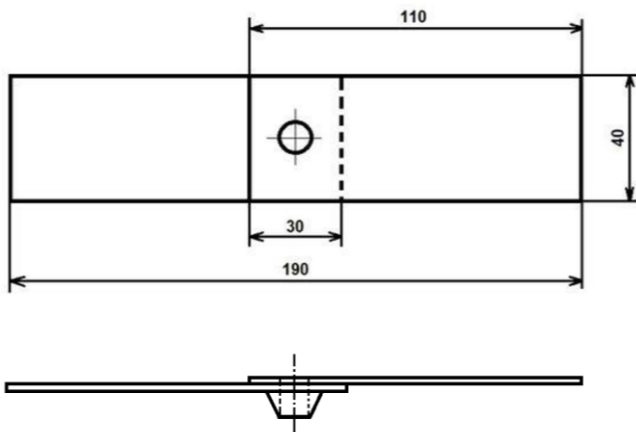


Fig. 4 Shape and dimensions of test specimens and joint for the tool Ø5.3 mm.

The parameters tested in thermal drilling were: rotational speed 2400 min⁻¹ and 4800 min⁻¹, feed rate 60 mm·min⁻¹ and 240 mm·min⁻¹. Thermal drilling was carried out on a bench drill, the materials were heated and clamped in the fixture. The fixture for setting and securing the relative position of the materials during thermal drilling is shown in Fig. 5.

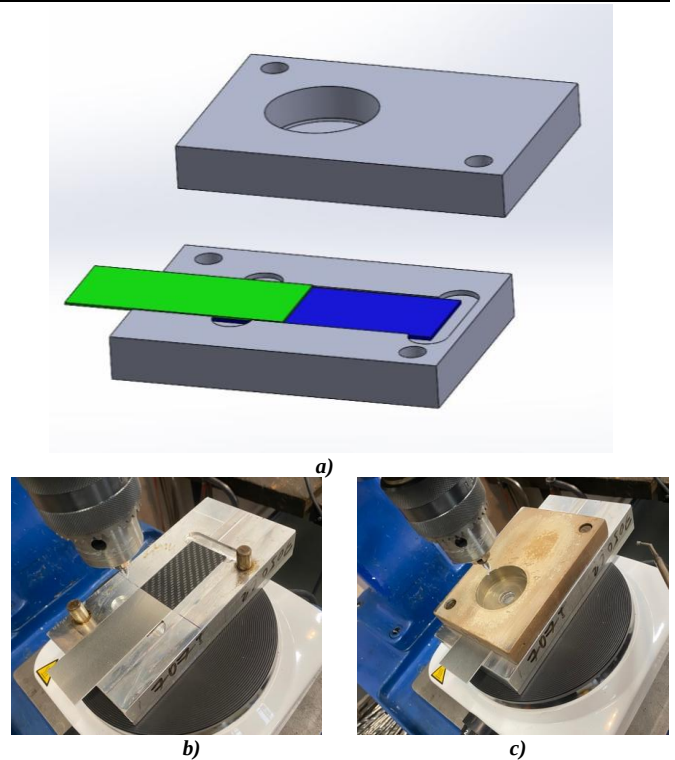


Fig. 5 Fixture for joining production: a) CAD model, b) open fixture, inserted materials, c) closed fixture, ready for thermal drilling

The dimensions of the resulting bushing were determined when the metal plates only were drilled in the fixture, as well as when metal plate is placed on the composite sheet in direct and sequential drilling. Direct drilling means the drilling of overlapped metal-composite materials heated and 165°C at once, Fig. 6. Sequential drilling means that in the first step a opening is made with a tool in the preheated composite, which is overlapped with a metal plate in the second step and drilled again, assuming easier forming the metal bushing in the pre-prepared opening in the composite and less delamination, Fig. 7.

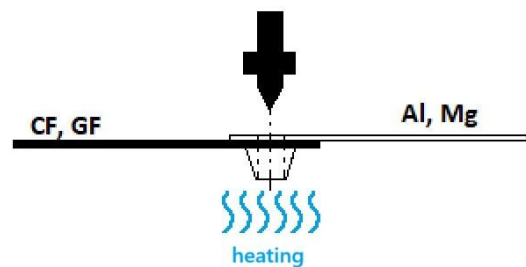


Fig. 6 Direct drilling

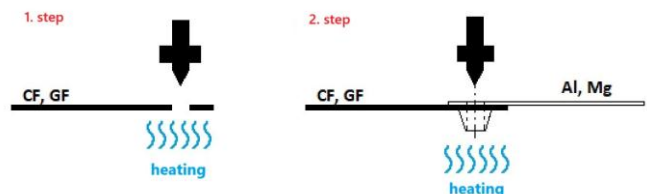


Fig. 7 Sequence drilling

After forming the bushings in the metal sheets separately, as well as after forming the joints with the composites, the bushing characteristics - thickness and length - were monitored, Fig. 8. The overall suitability of the shape of the resulting bushing was also assessed - it should have a sharp end, conical shape to be able to penetrate the composite without much delamination of the layers.

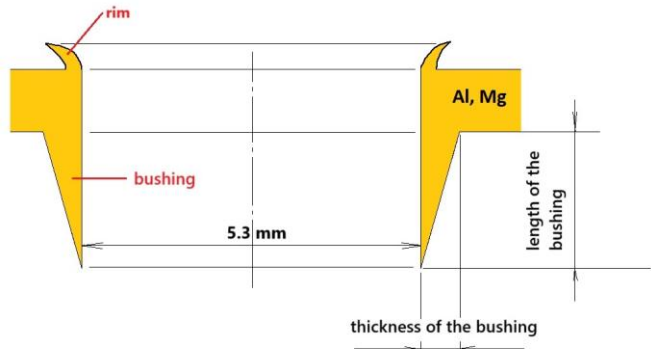


Fig. 8 Basic bushing characteristics monitored

Results

The metallographic study of the bushings was carried out on Al, Mg metal sheets at all process parameters tested, and also for Al and Mg joints with CF and GF composites at all process parameters (two levels of rotational tool speed, two levels of feed rate) and direct and sequential drilling strategies. Example metallographic sections for Al and Mg and their joints with CF are shown in Tab. 4 and 5.

Tab. 4 Al-CF joints

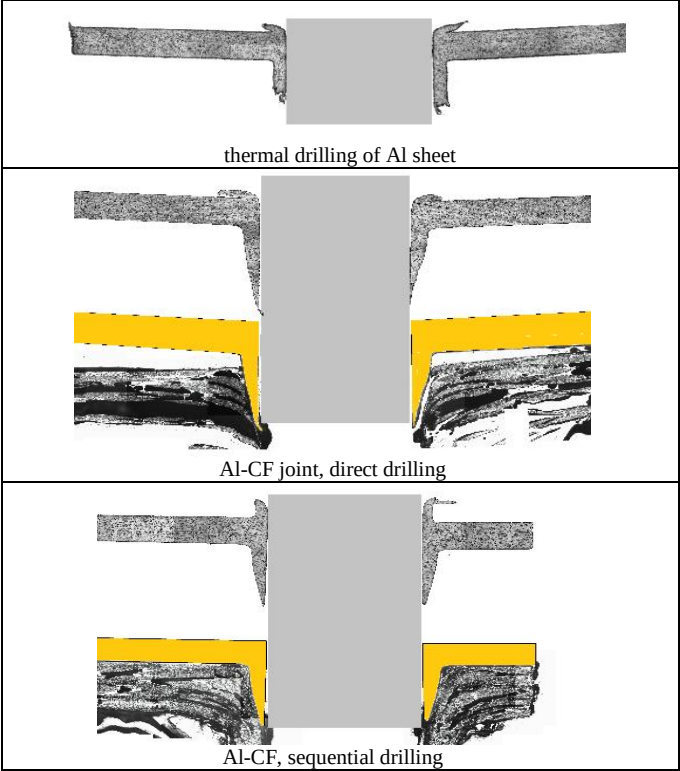
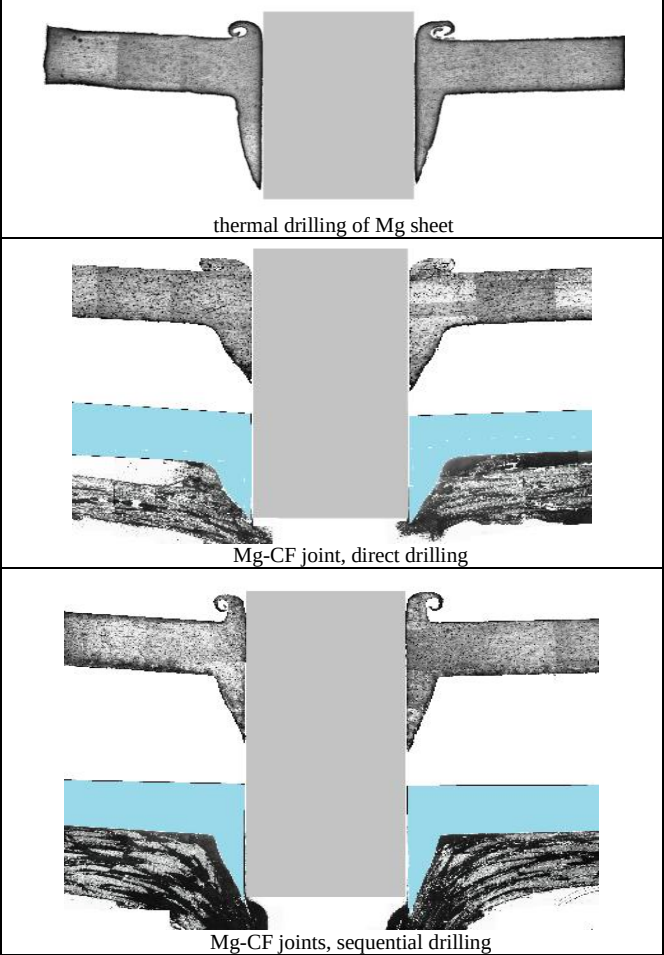


Table 4 shows that thermal drilling of Al sheet only leads to inappropriate bushing ends, often resulting in bushing fragmentation. When drilling with the composite, either by direct or sequential drilling, the geometry of the bushing was improved. It can be concluded that Al shaping that is constrained by other material or a pre-drilled hole improves the bushing shaping process.

Tab. 5 Joints Mg-composite CF



In Mg alloy, on the other hand, a bushing of suitable shape is formed when the Mg sheet is drilled separately, whereas when drilling with the composite by direct drilling, the flow of Mg material into the bushing area is significantly impeded. On the contrary, sequential drilling improves the shaping of the bushing by pre-drilling an opening in the composite, which allowed a sharper and longer bushing to be formed than in direct drilling. The overall results of the bushing characteristics for all material combinations and drilling strategies are shown in Tab. 6 and Fig. 9 and 10.

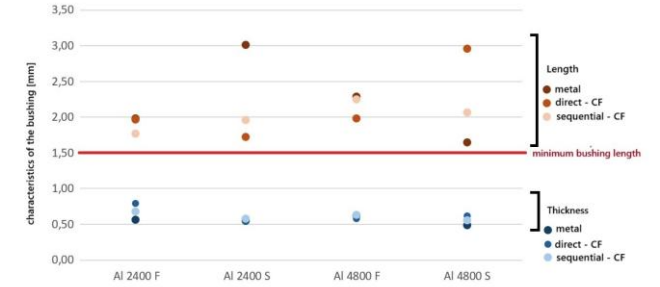


Fig. 9 Bushings characteristics for Al-CF

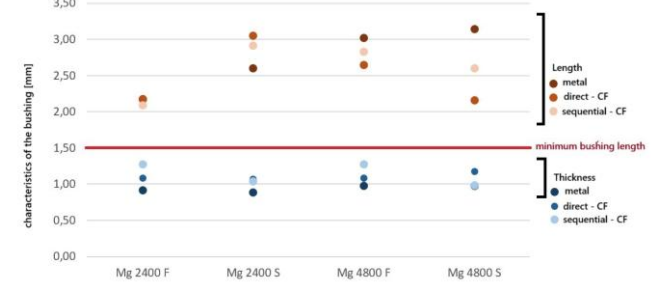


Fig. 10 Bushings characteristics for Mg-CF

Tab. 6 Geometric characteristics of the bushing in metal drilling and direct and sequential joining

Mat.	Process parameters		Thermal drilling of metallic sheets only		Direct drilling				Sequential drilling			
					CF		GF		CF		GF	
	RPM [min ⁻¹]	Feed rate [mm·min ⁻¹]	thickness [mm]	length [mm]	thickness [mm]	length [mm]	thickness [mm]	length [mm]	thickness [mm]	length [mm]	thickness [mm]	length [mm]
Al	2400	240	0.57	1.99	0.80	1.98	0.86	2.05	0.68	1.77	0.69	1.85
		60	0.55	3.02	0.56	1.73	0.59	0.80	0.59	1.96	0.59	2.90
	4800	240	0.63	2.29	0.58	1.98	0.67	2.10	0.64	2.25	0.66	2.20
		60	0.49	1.65	0.62	2.96	0.61	2.60	0.56	2.07	0.56	2.46
Mg	2400	240	0.92	2.18	1.09	2.18	1.10	2.29	1.28	2.09	1.33	2.43
		60	0.89	2.61	1.07	3.06	1.17	2.60	1.04	2.92	1.04	3.07
	4800	240	0.98	3.03	1.09	2.65	1.23	2.38	1.28	2.84	1.19	3.02
		60	0.98	3.15	1.18	2.16	1.07	2.74	0.99	2.60	1.01	3.44

Notes:

Inappropriate bushing shape	Rather inappropriate bushing shape	Rather suitable bushing shape	Suitable bushing shape
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From Tab. 6 and Fig. 9 and 10, the following observations can be made:

- the thickness of the bushings is not significantly affected by the process parameters of thermal drilling
- a greater thickness of bushings is achieved for Mg alloy (0.89–1.33 mm), which is due to a larger material volume available in drilling area with respect to the 2 mm plate thickness
- for Al alloy, the thickness of the bushings varies from 0.49 to 0.86 mm, which corresponds to a smaller sheet thickness compared to Mg
- the length of the bushings was greater than the thickness of the composite for both Al and Mg, except in one case (Al 2400/60 - GF), i.e. satisfactory
- bushing length is more sensitive to the variation of thermal drilling process parameters, with the feed rate having a more pronounced effect on the bushing length than the RPM. The effect of feed rate on bushing length is clear - slower feed rate (especially when combined with higher speed) allows longer bushing lengths to be shaped, both for Al and Mg.
- The length of the bushings is around 2 mm for Al-CF, between 2 and 3 mm for Al-GF, the length of the bushings is between 2 and 3 mm for Mg-CF, between 2.5 and 3.5 mm for Mg-GF. This can be justified by the less dense weave of the GF fabric, the thicker fibres and the lower number of glass fibre layers in GF compared to CF. This implies that the glass fibres have less resistance to penetration of the bushing.

If we consider not only the dimensions of the bushing but also their shape visually, and mark the cases of suitable shape in green in Table 6, we can determine the appropriate process parameters for the formation of the joints easier. Suitable process parameters for joining Al and Mg sheets with CF and GF composites are following: rotational tool speed 4800 min⁻¹ and slower feed rate 60 mm·min⁻¹. A suitable joining strategy is sequential drilling.

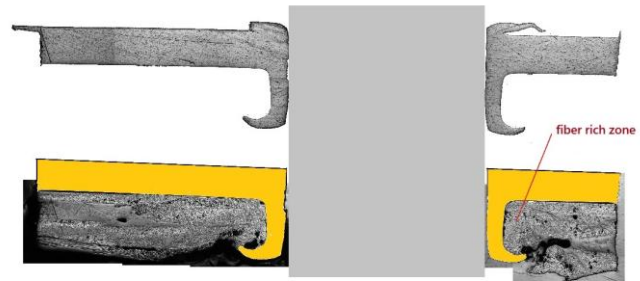
If a joint is formed with the above mentioned suitable process parameters with sufficient thickness and length of the bushing, the joint can be secured against opening by hemming flange, Fig. 11.

The fibres are closed under the formed hem flange, which in addition to closing the joint also prevents delamination of the composite.

Conclusion

Thermal drilling technology can be used for creation efficient joints of non-ferrous metal alloys and fibre composites with thermosoftening matrix at suitable process parameters. Good joining is also supported by a suitable two-step drilling strategy, but this means an extra operation and an increase in joining time when

applied under industrial practice conditions. Therefore, the load carrying capacity of joints formed by these drilling strategies still needs to be mapped.

**Fig. 11** Al-GF joint with hem flange

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Investigation of the local permeability of filter materials by methods with the opposite direction of local air flows

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Abstract: The results of investigations of local permeability of filter materials (PFM) made of powders of tin-phosphor bronze, titanium and nickel of various fractions are presented by two methods: by one method the local flow was directed to the sample from the measuring head, and by another method the local flow entered the measuring head after passing through the sample. It is established that both methods display the uniformity of the distribution of local permeability over the surface of the filter material (filtration surface) and can be used to assess the permeability of the filter material. The advantages and disadvantages of these methods are described.

KEYWORDS: POWDER FILTER MATERIALS, UNIFORMITY OF LOCAL PERMEABILITY DISTRIBUTION, MEASUREMENT OF OPPOSITELY DIRECTED LOCAL FLOWS.

1. Introduction

The peculiarity of powder metallurgy is the possibility of creating powder filter materials (PFM), the operability and application area of which are determined by the presence of an interconnected pore system. This pore structure provides them with such properties as permeability to gases and liquids, filtering ability, ability to capillary transport of liquid, its retention in the pores, ability to interfacial interaction, etc. [1]. A significant characteristic of PFMs, especially when their application is not associated with the capture of impurities during operation, but is aimed at ensuring a uniform supply of a certain amount of gas or liquid from the working surface of the product, is the uniformity of the local permeability distribution over the filtration area [2]. The scientific and technical literature describes quite a large number of methods for estimating the uniformity of local permeability distribution over the filtration area, based on cutting out control samples from separate PFM sections [3, 4] or scanning the surface of samples using thermoanemometers or special measuring heads [5-10]. However, these methods either require the destruction of the sample (product), or are complex in hardware design, require additional calibration and adjustment work, and cannot be operated in draughts and in the open air, or have significant methodological limitations [2].

In research works [2, 11] a device for local permeability determination, simple in construction and hardware design, devoid of the noted disadvantages, is proposed; the scheme of this device is shown in Figure 1, a). This device differs from the device described in the work [9] (Figure 1, b) by the direction of air flow relative to the measured local area: in the proposed device, the air flow is directed through the measuring head to the sample, and in the device (fig. 1, a) – through the sample to the measuring head. The proposed device allows to significantly simplify the design and expand technological capabilities when using, allowing you to study large-sized tubular, flat products and samples, due to the absence of the need to seal their ends. It should also be noted the reduction of gas consumption during measuring process and their possibility of their carrying out not only in the laboratory, but also in production conditions.

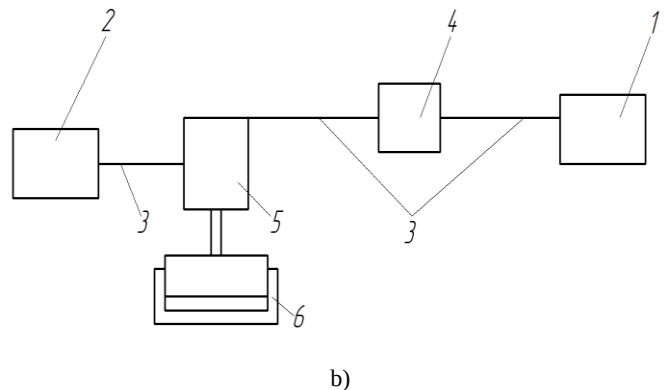
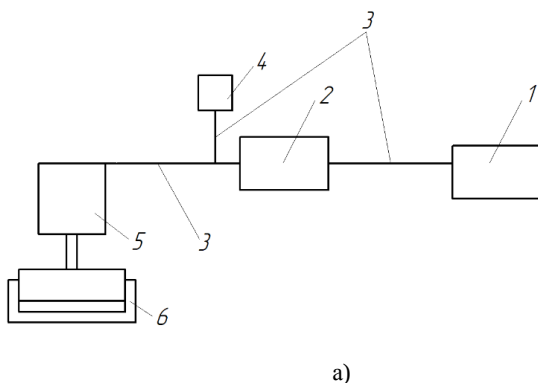


Fig. 1. Schemes of devices for determination of local permeability according to [2, 11] (a) and [9] (b): 1-pressure vessel, 2-flow meter, 3-flexible hoses, 4-pressure gauge, 5-measuring head, 6-device for fixing samples or products.

The aim of this work is to compare the results of studies of the uniform distribution of permeability over the filtration area of samples with different pore structures, carried out using the devices schematically presented in Figure 1.

2. Materials and methods of the research

The studies were performed using the measuring head described in [2], (Figure 2): the measuring head was made using 3-D printing on a Z-BOLT S300 printer (country of manufacture – Russia); a PET – G UMKA polymer (country of manufacture – Belarus) was used to make the head body, the tip – a polymer of the TRU FLEX brand (the country of origin is Russia) [2].



Fig. 2. Measuring head.

The scheme of the measurable sections on the samples also corresponded to the scheme given in the work in [2] (Figure 3).

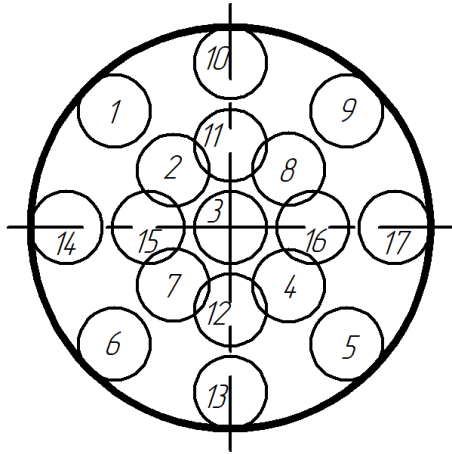


Fig. 3. Scheme of the location of the studied samples sites.

To conduct the research, there were used one-layer samples in the form of a disk with a diameter of 30 mm and a thickness of 3 mm, made of air-sprayed tin-phosphorous bronze and titanium powders of different fractions obtained by milling a titanium sponge, a mixture of electrolytic nickel powder with different content of a pore-forming agent (carbamide), and two-layer samples of the same dimensions made of finely dispersed aluminum oxide powder (a thin filter layer 0.3–0.4 mm thick) and a mixture of electrolytic nickel powder with a pore-forming agent (substrate). It should be noted that the consolidation of aluminum oxide particles among themselves and with nickel powder particles during samples fabrication was provided by using a binder based on sodium liquid glass.

Permeability coefficients were determined in accordance with the recommendations of the research work [12], and mathematical processing of the results of local permeability coefficients measurements (determination of the coefficient of variation) was performed according to the accepted method [13].

3. Experimental results and their discussion

The final results of calculations of the measurement results performed in the sample sections according to the scheme shown in Figure 3 are presented in the Table 1. Since the intermediate values of the permeability coefficients in local sections are unsystematic and uninformative, they are not shown in the table.

Table 1. Results of studies of the uniformity of the permeability distribution over the sample area

One-layer samples made of tin-phosphor bronze powder CuSn10P1				
Defined parameters		Powder particle sizes, mm		
		minus 0.4+0.315	minus 0.2+0.1	minus 0.1+0.063
Local permeability coefficient $\times 10^{-13}, m^2$	By the method of [2]	1446.7	228.0	99.0
	By the method of [9]	892.8	147.7	66.6
Mean square deviation	By the method of [2]	75.40	27.67	11.51
	By the method of [9]	62.49	14.77	7.2
Coefficient of variation	By the method of [2]	0.05	0.12	0.12
	By the method of [9]	0,07	0,10	0,11
Permeability coefficient of the sample, $\times 10^{-13}, m^2$		1147.78	140.00	62.45

One-layer titanium powder samples				
Defined parameters		Powder particle sizes, mm		
		minus 0.63+0.306	minus 0.306+0.16	minus 0.16
Local permeability coefficient $\times 10^{-13}, m^2$	By the method of [2]	203.4	74.8	53.5
	By the method of [9]	255.7	81.4	53.6
Mean square deviation	By the method of [2]	14.63	7.62	5.54
	By the method of [9]	14.36	7.32	5.89
Coefficient of variation	By the method of [2]	0.07	0.10	0.10
	By the method of [9]	0.06	0.09	0.11
Permeability coefficient of the sample, $\times 10^{-13}, m^2$		151.57	49.98	28.79

One-layer samples made of a mixture of electrolytic nickel powder with a pore-forming agent (carbamide)				
Defined parameters		The ratio of powder particles and pore forming agent		
		1:0.3	1: 0.6	1:0.9
Local permeability coefficient $\times 10^{-13}, m^2$	By the method of [2]	108	15.1	16.5
	By the method of [9]	2.4	3.2	4.7
Mean square deviation	By the method of [2]	1.62	1.82	2.14
	By the method of [9]	0.36	0.38	0.65
Coefficient of variation	By the method of [2]	0.15	0.12	0.13
	By the method of [9]	0.15	0.12	0.14
Permeability coefficient of the sample, $\times 10^{-13}, m^2$		1.29	1.95	2.81

Two-layer samples of a finely dispersed aluminum oxide powder (a thin filter layer 0.3–0.4 mm thick) and a mixture of electrolytic nickel powder with a pore-forming agent (substrate). The measuring head contacts the filter layer.				
Defined parameters		Ratio of powder particles and pore forming agent		
		1:0.3	1: 0.6	1:0.9
Local permeability coefficient $\times 10^{-13}, m^2$	By the method of [2]	10.6	14.9	16.8
	By the method of [9]	3.6	3.9	6.9
Mean square deviation	By the method of [2]	0.74	0.89	1.51
	By the method of [9]	0.25	0.27	0.62
Coefficient of variation	By the method of [2]	0.07	0.06	0.09
	By the method of [9]	0.07	0.07	0.09
Permeability coefficient of the sample, $\times 10^{-13}, m^2$		1.47	2.25	2.84

Two-layer samples of fine aluminum oxide powder (a thin filter layer 0.3–0.4 mm thick) and a mixture electrolytic nickel powder with a pore-forming agent (substrate). The measuring head contacts the substrate.				
Defined parameters		Ratio of powder particles and pore forming agent		
		1:0.3	1: 0.6	1:0.9
Local permeability	By the method of [2]	9.2	12.2	15.1

coefficient $\times 10^{-13}, \text{m}^2$	By the method of [9]	4.5	6.8	11.5
Mean square deviation	By the method of [2]	0.55	0.61	1.35
	By the method of [9]	0.22	0.34	0.92
Coefficient of variation	By the method of [2]	0.06	0.05	0.09
	By the method of [9]	0.05	0.05	0.08
Permeability coefficient of the sample, $\times 10^{-13}, \text{m}^2$		2.18	3.01	4.59

In the table, the average value was defined as the arithmetic mean of a set of values of the local permeability coefficient; the permeability coefficient was determined by measuring the permeability of the whole sample (by passing the air flow through the area of the whole sample).

As a result of the research, it was found that both methods can be used with a sufficient degree of reliability to assess the uniformity of permeability distribution over the filtration area: the variation coefficients values are almost the same. As it could be assumed, the lowest uniformity of the permeability distribution over the filtration area is found in samples made of the mixture of nickel powder with pore-forming agent (both single-layer and double-layer), which is explained by the difficulties in achieving uniform distribution of the pore-forming agent in the charge during traditional mixing. Nevertheless, all samples have good uniformity of permeability distribution over the filtration area, since the coefficients of variation determined by known methods [13], are in the range of 0.05–0.15, which allows, according to [13], to refer the set of their values to homogeneous aggregates.

Similar to the data of the research work [2], the research results indicate that in all cases the average value of the local permeability coefficient significantly differs from the measured permeability coefficients of samples, and, to assess the permeability of products, it is necessary to introduce correction factors. Obviously, the latter will be determined by such technological parameters as the size and shape of powder particles, the presence of a pore-forming agent, etc. However, this does not significantly affect the values of the variation coefficient, since measurement errors due to the reasons of the differences noted above (dispersion of a part of the local flow due to deviation from the direction perpendicular to the filter surface towards lower hydraulic resistances) have a systemic character and equally affect all measurements.

The study of permeability of two-layer samples confirmed the data given in the research [14] that when liquids flow in inhomogeneous porous media, the flow asymmetry is observed (the filtration rate in the direction of the porosity gradient is higher than in the opposite direction), and the difference in the values of the permeability coefficient for the studied samples is in the range from 1.34 to 1.62 times, if to compare the coefficient values of the samples themselves, and from 1.11 to 1.74 times, if to compare the average values of the local permeability coefficients.

The disadvantages of both methods include the negative impact on the measurement accuracy of the subjective factor at manual pressing of the measuring head, while the advantages include the simplicity of measurements and convenience in operation. In contrast to [9], the method of local flow direction through the head to the sample [2], as noted above, is simpler in hardware design and allows to study large-sized tubular flat products and samples, due to the absence of the need to seal their ends. Examples of studies of tubular and flat products are shown in Figure 4.



a)



b)

Fig. 4. The process of measuring the local permeability of tubular (a) and flat (b) porous powder products.

4. Conclusion

There are presented the results of investigations of local permeability of one-layer PFMs made of a mixture of elec tin-phosphorous bronze powder and titanium powders of different fractions trolytic nickel powder with different content of a pore-forming agent (carbamide) and of tin-phosphorous bronze and titanium powders of different fractions, and two-layer samples made by joint pressing of finely dispersed aluminium oxide powder (a thin filter layer 0.3–0.4 mm thick) and a mixture of electrolytic nickel powder with a pore-forming agent (substrate). The investigations were carried out by measuring local air flows using two methods: according to one method, the local flow was directed to the sample from the measuring head, in the other way the local flow entered the measuring head after passing through the sample. It is found that both methods reflect well the uniformity of local permeability distribution over the surface of the filter material (filtration surface). At the same time, the average value of the local permeability coefficient significantly differs from the real values of permeability coefficients of the samples, and to estimate the permeability of products, it is necessary to introduce correction factors. It is shown that the flow asymmetry is observed during the flow of liquids in two-layer materials.

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Prototype of a Wireless MEMS-Based Sensor Node within a Wireless Sensor Network Concept

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Abstract: The aim of this work is to implement a wireless communication system for MEMS-based sensors within the framework of Internet of Things (IoT) applications, specifically in the context of Predictive Maintenance (PdM). The focus is placed on developing a functional prototype of a wireless sensor node that enables efficient data acquisition and transmission from commercially available MEMS vibration sensors. The solution leverages an ESP32 microcontroller for data handling and Wi-Fi communication, forming the basis of a scalable wireless sensor network (WSN). The project emphasizes their integration into a wireless system architecture suitable for industrial monitoring scenarios. This approach aims to demonstrate how low-cost MEMS sensors, when combined with IoT technologies, can contribute to accessible and modular condition monitoring solutions aligned with Industry 4.0.

Keywords: MEMS, WIRELESS SENSOR NETWORK, PREDICTIVE MAINTENANCE, INDUSTRY 4.0, IOT

1. Introduction

The ongoing transformation of industrial systems towards the principles of Industry 4.0 has increased the demand for intelligent, interconnected, and self-monitoring infrastructure [1]. Although many existing predictive maintenance solutions are technically capable, they remain financially out of reach or overly complex for small and medium-sized enterprises (SMEs). This concept paper aims to bridge this gap by proposing a scalable, cost-effective, and easy-to-integrate wireless sensor network (WSN) architecture. At the heart of this system are low-cost microelectromechanical systems (MEMS) accelerometers paired with widely available microcontrollers [2]. MEMS sensors offer a compact and affordable alternative to traditional solutions, making the technology suitable for a wider range of industrial applications [3]. Effective PdM practices not only reduce unplanned maintenance costs, but also enhance equipment reliability, directly impacting production continuity and quality [4]. This is particularly relevant in industries where machinery failure can lead to costly production halts or even safety hazards.

By integrating MEMS accelerometers with the ESP32 [5] microcontroller, this wireless sensor node prototype achieves a balance between cost efficiency and technical performance. The proposed nodes are compact, energy efficient, and capable of collecting high-resolution vibration and temperature data. Designed with modularity in mind, the system can scale seamlessly by adding synchronized nodes to maintain a precise time correlation between measurements.

To enhance accessibility, the system uses Wi-Fi for data transmission, enabling rapid deployment without the need for extensive cabling. The data collected are transmitted to a centralized database for processing, anomaly detection, and visualization. The use of a time series database ensures efficient handling of high-frequency data streams. In addition, the modular design of the system allows it to adapt to a wide range of industrial scenarios [6].

By democratizing access to PdM technologies, this concept offers SMEs an affordable path to implement intelligent maintenance practices. The following sections discuss related research, system architecture, potential use cases, and the anticipated impact on industrial maintenance strategies.

2. System Architecture

The proposed architecture is designed to be both modular and scalable, enabling easy integration and future expansion. Ensures that it can evolve alongside technological advancements and accommodate growing industrial demands.

2.1. Sensor Node

The WSN is built around a custom-designed sensor node that integrates the IIS3DWB MEMS accelerometer with the ESP32 NodeMCU microcontroller. A prototype of the sensor node is presented in Fig. 1.

Each sensor node has [7]:

- three-axis acceleration measurement,
- temperature measurement,
- data at sampling rates of up to 6 kHz,
- wide selectable bandwidth of up to 2.67 kHz,
- low noise density,
- full-scale acceleration ranges from $\pm 2g$ to $\pm 16g$.

These characteristics make the IIS3DWB a highly suitable choice for PdM use cases where accurate temporal resolution and low-latency data handling are essential.

Each node operates autonomously and is powered by a 3.7V rechargeable lithium-ion battery. To support energy autonomy and operational safety, a dedicated power management circuit is integrated into the PCB, enabling efficient power regulation and secure battery charging.



Fig. 1 Prototype of MEMS-based sensor which could be use in WSN architecture.

2.2. Wireless Communication Architecture and Data Infrastructure

The proposed system architecture relies on Wi-Fi for data transmission, eliminating the need for physical cabling. This simplifies deployment, particularly in environments with limited accessibility or complex machine layouts. In this concept, the wireless connection is a fundamental design choice that supports scalability, modularity, and ease of integration.

Each sensor node is built around an ESP32-based platform, which includes an integrated Wi-Fi module. This component, sourced from the ESP32 development ecosystem, offers a cost-effective solution for wireless communication in IoT systems. As the network may consist of numerous sensor nodes deployed throughout a facility, one of the primary design considerations is the temporal synchronization of data acquisition. To achieve this, the Network Time Protocol (NTP) is implemented on all nodes. Synchronization through NTP ensures that all sensor measurements are time correlated, which is essential when assessing vibration patterns from multiple angles or comparing data across different machines on the same production line.

Data communication between the sensor nodes and the central server is carried out using the HTTP protocol. Basic

diagram is shown in Fig. 2. This choice is motivated by the need to handle relatively large volumes of high-frequency data continuously generated by multiple nodes. HTTP provides a scalable framework for transmitting these data efficiently and securely. Each node sends structured measurement packets to a back-end server, where the data is parsed and stored in an InfluxDB time-series database. This database is optimized for handling large-scale sensor data streams with high write throughput and time-based query performance.

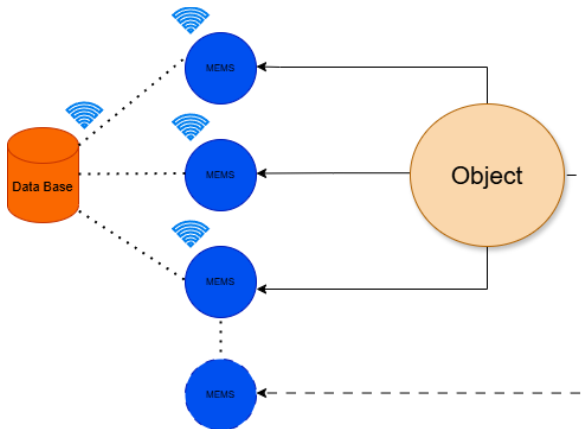


Fig. 2 Basic diagram for multi-node PdM architecture.

Data synchronization across multiple nodes is achieved using the Network Time Protocol (NTP), ensuring accurate time correlation among the distributed sensor nodes. This synchronization is crucial for multi-point vibration analysis and comparative diagnostics, as it guarantees that data collected from various locations remains temporally aligned. Without proper synchronization, phase shifts between measurements could lead to inaccurate assessments, particularly in applications involving vibration pattern analysis or machine condition monitoring. By integrating NTP synchronization directly into the startup procedure, the system minimizes human error and ensures that each measurement cycle begins with accurately synchronized nodes.

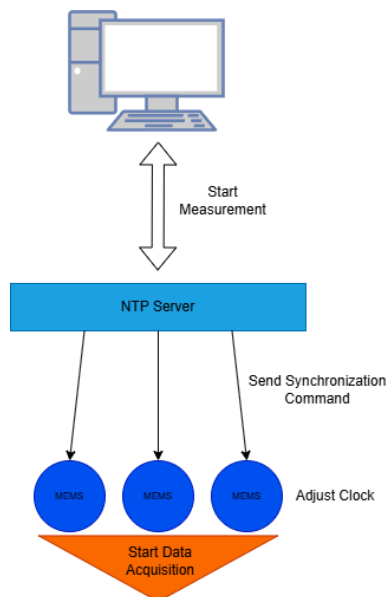


Fig. 3 Schematic for nodes synchronization.

To initiate the measurement process, an application is provided that allows operators to start, stop and manage data acquisition from a PC or mobile device. When the measurement is triggered, the application sends a synchronization signal to all sensor nodes, which in turn requests the current time from an NTP server. The nodes then adjust their internal clocks to match the received timestamp, achieving precise temporal alignment before data

collection begins (Fig. 3). Once synchronized, the sensor nodes begin data acquisition, packaging the collected data into structured packets. These packets include a timestamp, sensor ID, and measurement data, ensuring that each data point can be accurately linked to a specific moment in time and a particular sensor location.

The proposed architecture envisions broader applications for the collected data. Beyond standard monitoring, the infrastructure supports integration with advanced systems such as virtual reality environments, real-time diagnostics, and AI-based predictive maintenance platforms.

3. Use Case and Applications

The proposed wireless sensor network system is designed to be flexible and adaptable, catering to diverse industrial environments ranging from traditional machine workshops to modern smart factories. One of its key advantages is the ease of scalability and customization, which allows it to be tailored to various machine setups without significant adjustments. This makes it particularly valuable for small and medium enterprises that often face financial constraints when adopting proprietary condition monitoring systems.

Using MEMS technology, sensor nodes offer a compact and cost-effective alternative to piezoelectric-based solutions [8]. MEMS sensors are approximately ten times cheaper while providing sufficient accuracy and sensitivity for PdM applications. This cost advantage allows SMEs to deploy comprehensive monitoring systems without incurring prohibitive expenses.

The WSN architecture is modular. Sensor nodes can be easily mounted on industrial assets such as motors, compressors, CNC machines, or other rotating equipment. Each node collects high-resolution acceleration data across the XYZ axes and temperature readings, which are important to identify early-stage mechanical problems such as imbalance, misalignment, or bearing faults.

A fundamental feature of this system is its ability to scale without requiring complex configurations. New sensor nodes can be added seamlessly, with automatic synchronization. The plug-and-play nature of the ESP32 firmware further enhances usability, allowing rapid expansion or reconfiguration to accommodate different machine layouts.

Furthermore, the wireless nature of the WSN eliminates the need for extensive cabling, making it particularly advantageous in facilities where machinery configurations frequently change or where mobility is required. This allows for quick deployment in both permanent and temporary monitoring setups.

Real-time data can be integrated with digital twins of the factory floor, developed using platforms like Unity or Unreal Engine. These virtual environments enable operators and engineers to view the health status of machines through color-coded overlays or animated vibration patterns. Such interactive visualizations promote an intuitive understanding of the conditions of the equipment, facilitating routine inspections.

In addition, maintenance personnel can receive proactive notifications and detailed status reports through mobile apps or smart devices, such as augmented reality glasses. These alerts are based on anomaly detection algorithms running on historical data stored in a time series database. By identifying deviations from normal operational patterns, the system can prompt timely maintenance actions, reducing downtime and prolonging the useful life of the machine.

Integration of the system with real-time diagnostic platforms and AI-based PdM algorithms also supports predictive maintenance. Operators can remotely analyze machine performance, receive early warnings of possible failures, and even simulate fault conditions within a Virtual Reality training module [9]. This approach to machine health management not only improves operational

efficiency, but also enhances workforce training, allowing a deeper understanding of mechanical behaviors and maintenance strategies.

4. Discussion

The MEMS-based wireless sensor node presented within a WSN concept demonstrates significant potential for scalable, cost-effective predictive maintenance applications, especially in small and medium-sized enterprises. Using MEMS accelerometers, the system achieves a substantial reduction in cost compared to traditional piezoelectric sensors, making high-frequency vibration monitoring more accessible to a broader range of industrial settings.

One of the primary advantages of this architecture is its modularity and ease of integration. The use of the ESP32 microcontroller with built-in Wi-Fi enables seamless data transmission without the need for physical cabling, significantly reducing installation time and costs. Additionally, NTP-based time synchronization ensures that multinode data collection remains coherent, which is important when analysing vibration data from multiple measurement points.

However, some challenges remain to ensure data integrity and consistency as the system scales up. Network congestion and potential delays in NTP responses could affect the accuracy of synchronization, particularly in environments with fluctuating connectivity. To address this, it might be necessary to implement local time correction algorithms or to use alternative synchronization protocols in critical cases.

Moreover, reliance on Wi-Fi for data transmission could pose limitations in industrial environments with high electromagnetic interference or large physical obstructions. Future work could explore the incorporation of alternative wireless technologies to improve communication robustness and extend the operational range of the system.

Despite these challenges, the proposed system demonstrates a promising pathway for integrating PdM techniques into industrial processes cost-effectively. Its flexible architecture supports real-time monitoring, visualization, and scalable deployment, providing a foundation for the next generation of intelligent maintenance solutions.

5. Conclusion and Future Work

This paper posits a novel conceptual framework for a modular and scalable wireless sensor network based on accelerometer nodes based on MEMS, designed to facilitate predictive maintenance in a variety of industrial environments. By addressing key impediments to adoption, namely cost, architectural complexity, and proprietary systems, this concept aims to enable Small and Medium Enterprises to initiate their transition towards Industry 4.0 through a pragmatic and extensible instrumentation paradigm.

The proposed framework exhibits significant theoretical potential to transform conventional machinery condition monitoring practices via the provision of comprehensive data analytics and visualization modalities. The integrated aggregation of data streams from heterogeneous machinery within a unified monitoring architecture is theorized to enhance industrial process operational efficiency and underpin proactive maintenance strategies, thereby mitigating unscheduled downtime and associated maintenance expenditures.

Future work will involve empirical validation through physical instantiation and testing within operational environments to ascertain system performance characteristics and reliability metrics. Planned enhancements include the theoretical exploration and potential implementation of energy optimization strategies, such as adaptive sampling rates and duty cycling, alongside the investigation of alternative network connectivity protocols. The conceptual development of the Virtual Reality interface will be extended to incorporate real-time interactive capabilities and guided

maintenance protocols, further augmenting the theoretical utility of the framework.

Subsequent efforts will aim to conceptualize a user-centric interface for on-site configuration and data retrieval, potentially incorporating mobile application interfaces and augmented reality overlays for real-time maintenance assistance. By synergistically combining sensor-derived data with Artificial Intelligence-driven PdM models, the framework has the potential to evolve into a holistic platform for intelligent maintenance, supporting decision-making processes with actionable analytical insights.

In parallel, the conceptual development of a cloud-based management portal \cite{Wang2017} enabling remote monitoring and configuration of distributed deployments, thereby theoretically paving the way towards fully integrated digital twins and intelligent factory ecosystems.

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A new type of nail for wooden structures with increased resilience

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Abstract: In the following work, we present the results from a research of a type of nail with a new form of section, in comparison to the round section that currently used nails have. This new form is similar to an equilateral triangle, the sides of which are curves [Reuleaux Triangle]. The body section of this new type of nail has three curves and three edges; his surface SR is with 5.56% larger than the surface SC of a round nail with the same section area. From the experimental research that has been made so far, it was established: (i) because of the larger compaction of the wooden material in the ends of the edges, and of the larger surface, you get a bigger friction force, resulting in a pulling-out force $F_{to,R}$ that is on average twice as bigger as the pulling-out force $F_{to,C}$; (ii) because that the new form of nail has edges, this leads to bigger resistance during the rotating of the joined wooden elements one against another – the moment M_r is on average 60% bigger than the one with elements, joined with a normal nail. These advantages, as well as the use of the existing technology and machines for the production of nails without having to effect any major changes, create the conditions for the application of the new type of nail in construction, furniture production and in the everyday life, for an output of products with larger resistance to external forces. This effect will be especially useful for increasing the residential buildings' resilience during earthquakes, hurricanes and other natural disasters.

KEYWORDS: NAILS, REULEAUX TRIANGLE, WOODEN STRUCTURES

1. Introduction

The production of nails worldwide is one of greatest in fabricated metal products: reinforcing bars – 400 million tons, sheet metal – 240 million tons, pipes – 60 million tons nails, and screws – 32 million tons in 2014 [1]. Nails are used for connecting elements of wooden constructions; the largest quantities are used for wooden-frame houses. The average wooden-frame house uses require between 20,000 and 30,000 nails of various types and sizes [2]. Earthquakes or hurricanes are considered as extreme conditions for those structures. A variety of nails is available for wooden structures, which are to be under heavy loading conditions – Fig. 1 [3], [4], [5].

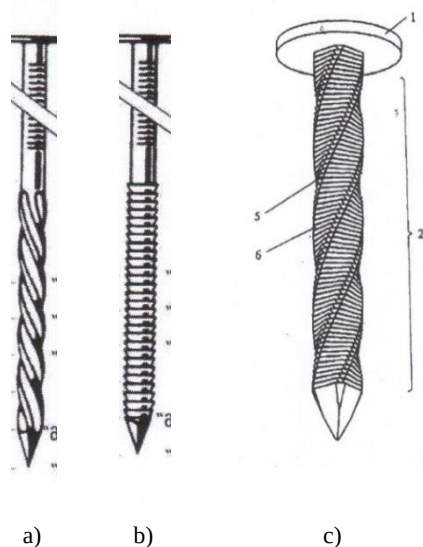


Fig.1. Design of nails for heavy loading wooden structures: a - with rolled rings; b - with rolled screw channels; c - with screw canals and rings: 1- nail head, 2 - nail body, 5 - screw cylindrical surface, 6 - linear rings

Most of these nails have a number of advantages, compared to conventional nails, but they are difficult to be manufactured in the existing automatic machines for nails and have a higher price.

The new type of nail [10] has a section, known as the Reuleaux Triangle. This geometrical figure has a shape, formed from the intersection of three circles, each having its center at the vertex of a triangle

– Fig. 2. The radius R is equal to the length of the triangle's side. In Fig. 2 we see that the Reuleaux Triangle includes three curves and three edges. The Reuleaux Triangle can be seen as a closed convex curve of constant width. This is a type of curves which, when rotated in a square, make contact with all four sides [6]. The

other definition is that of “curves of constant width that have the same “width” regardless of their orientation between the parallel lines” [7]. The surface – that is the curve with the largest area – also belongs to this type, while the Reuleaux Triangle is the closed curve with the smallest area, but with the same perimeter.

The more important qualities of the Triangle are:

- Its radius $R = 2,112r$, where r is the radius of a circle with the same area.
- With the same area, the perimeter of the Reuleaux Triangle PR is 5.56% larger than the perimeter PC of the given circle.

The second moment of area I and the elastic section modulus S , when you have a circular section, are the same as regard to a coordinate system, passing through the center of gravity in the circle, therefore with a circle $I_{x,c} = I_{y,c}$, $S_{x,c} = S_{y,c}$. With the Reuleaux Triangle $I_{x,R} = I_{y,R}$, $S_{x,R} \neq S_{y,R}$ as regards to a coordinate system, passing through the section's center of gravity. In agreement with the definition for S [8], [9] from Fig. 2b we can see that with the Triangle there are two elastic section modulus $S_{R,y}$ ($S_{R,y1}$, $S_{R,y2}$) and one elastic section modulus $S_{R,x}$:

$$S_{R,y1} = I_{y1}/b; \quad S_{R,y2} = I_{y2}/a; \quad S_{R,x} = I_{x}/0.5R \quad (1)$$

By looking at the geometric proportions in an equilateral triangle it can be determined that $a = 0.577R$, $b = 0.423R$ and (1) becomes:

$$S_{R,y1} = I_{y1}/0.423R; \quad S_{R,y2} = I_{y2}/0.577R; \quad S_{R,x} = I_{x}/0.5R \quad (2)$$

where [6]

$$I_{x,y} = 1/48(10\pi - 17\sqrt{3})R^4 \quad (3)$$

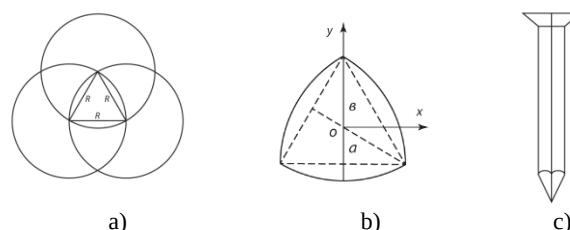


Fig. 2. a – a Reuleaux Triangle; b – a scheme for determining the elastic section modulus S ; c – a nail with a Reuleaux Triangle section

Here we present the results from our comparative experimental research for determining the maximal forces and moments, which impact wooden structures, the elements of which are to be joined with a nail with a round section, or a section of the Reuleaux Triangle type.

2. Methodics

A round section nail with the following characteristics: radius $RC = 3.5$ mm, length $LC = 190$ mm, area of the counter-section $A = 38.46$ mm², perimeter $PC = 21.98$ mm, was used in the experiments. The nail with the Reuleaux Triangle section, was with the same area A , radius $RR = 7.392$ mm, length of the section portion $LR = 85$ mm (the length of the entire round section nail is 145 mm), perimeter $PR = 23.2$ mm – Fig. 3; his edges were rounded with radius $R = 0.5$ mm. There have been made 10 such nails, with the Reuleaux Triangle section portion been made on a filament erosion machine.

In Table 1. are given the values of the second moment of area I and the elastic section modulus S for the two types of nails.

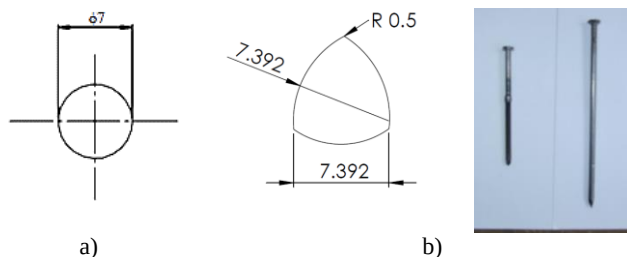


Fig. 3. Comparison of the ordinary and the new nails: a – comparison of the cross-section dimensions; b – view of the used nails with the new shape and $\phi 7$

Table 1. Value of I and S for ordinary and new nails

Section	I_x, mm^4	I_y, mm^4	$S_{y,1}, \text{mm}^3$	$S_{y,2}, \text{mm}^3$	S_x, mm^3
Circle	117.8	117.8	33.65	-	33.65
Relo	122.54	122.54	39.19	28.73	33.15

There were two types of experiments.

2.1 Experiments for determination of the take-out force P_{to}

In that case wooden elements (beams) made out of dry coniferous wood with sizes (length x height x width): 150 mm x 60 mm x 48 mm. We drive in them nails of the two types so that the top of the nail comes out of the other side of the wooden element. After that the nail is taken-out. A mechanical testing machine Instron1195 was used, allowing to mark-down the diagram moving – force when we drive and take-out the nails. From these diagrams we calculate the maximum force of the driving in and the removal. We drilled, in advance, holes with 3 mm diameter in the wooden elements, to assure the driving was to be done easily, and without unnecessary force that would possibly lead to the deformation of the nails. There were 10 experiments held with each of the two types of nails.

2.2 Experiments for determination of the torque M_r

In this case, wooden slats with dimensions (thickness x length x width) 30 mm x 200 mm x 65 mm from dry coniferous wood were used. Two slats are connected to each other with a nail at a 90° angle. The resulting wooden structure was tested in rotation under two types of load: when an external force acts simultaneously on the two slats - Fig. 4.; when an external force acts on only one slat - Fig. 5. The maximum moment at which the structure becomes inefficient (the slats are rotated relative to each other) is denoted with M_r and respectively. Using the calculation schemes for these moments shown in Fig. 3c and Fig. 4c is obtained:

$$M_r^{two} = 2 \times 0.2 \times 0.3543F, \text{ Nm} \quad (4)$$

$$M_r^{one} = 0.155F, \text{ Nm}$$

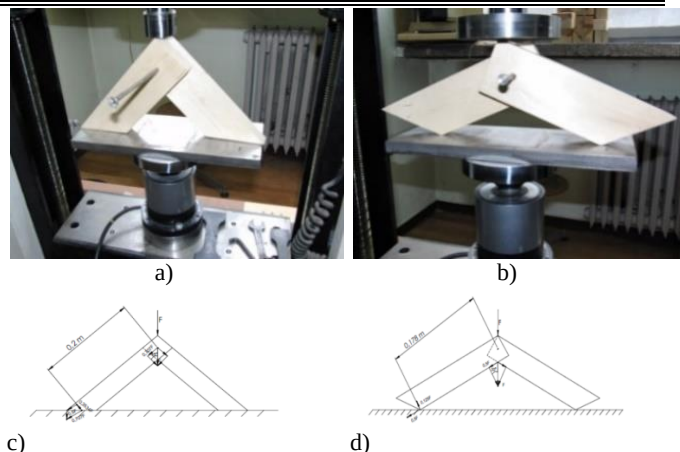


Fig.4. Pictures of tested wooden structure when force acts simultaneously on the two slats: a – in the beginning; b – during the experiment; c, d – scheme to determine the moment

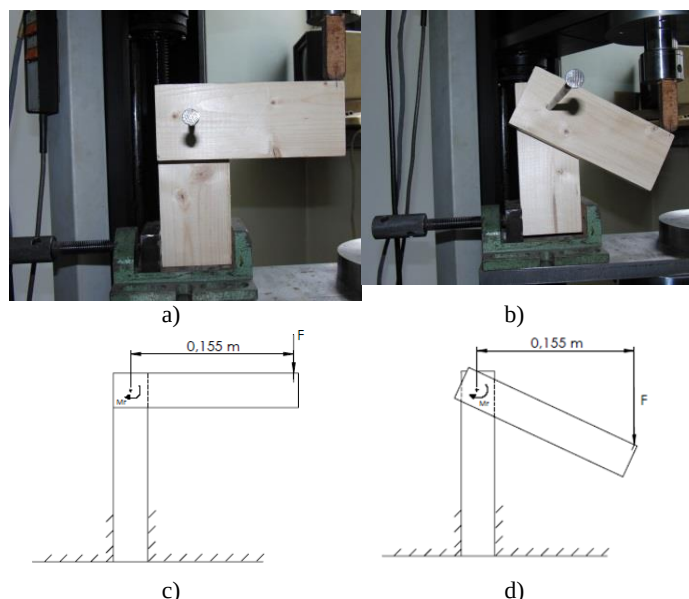


Fig.5. Pictures of tested wooden structure when force acts on one slat: a – in the beginning; b – during the experiment; c, d – scheme for determine of torque

3. Results

3.1 Determination of the driven and take-out forces

The driving of the nails is at a speed of 10 mm / min, and the removal of them is at a speed of 20 mm / min. The obtained values of the forces of driving F_d and take-out F_{to} are given in Table 2.

Table 2. Driven in and take-out forces

Type	Driven force F_d , N	Take out force F_{to} , N
Circle cross-section	3728	2453
	3267	2158
	3482	1864
	3709	2394
	2943	2551
	3434	2048
	3744	2366
	3160	2370
	3460	2483
	3420	2644
Average	3435	2333
Rele Triangle	4513	5494
	4218	4513
	4120	5297

cross-section	4120	5240
	4120	4905
	4218	5248
	4194	4463
	4124	4562
	4158	4470
	4262	5274
Average	4205	4947

3.2. Determination of the moment M_r

When connecting the wooden slats, the nails were driven in at a speed of 10 mm / min. The speed of movement of the contact element in the torque test M_r was 5 mm / min. The results are shown in Table 3. Due to the small differences in the values of the moments in the individual experiments, in Table 3 only their average values are given.

Table 3. Average values of M_r^{two} and M_r^{one}

Crosssection	M_r^{two} , Nm	M_r^{one} , Nm
Circle	20.83	7.6
Releaux Triangle	34.72	15.2

4. Conclusions

From Table 1 it can be seen that the resistance against elastic bending of a nail with a section of the Reuleaux Triangle depends on the application point of the external force. Fig. 6 shows the forces F_1 , F_2 and F_3 , which are used to determine the elastic section modulus S . The difference in the magnitude of these forces gives us grounds for the following conclusion:

- When it is necessary to achieve maximum resistance against elastic bending of a nail with a Reuleaux Triangle section, when driving the nail it must be oriented so that the external force acts in the direction of the force F_1 from Fig. 6. This means that, when using the new nail, an oriented driving can be performed according to the location of the edges on its stem. Oriented driving is a unique quality of the new nails, which will lead to drastic changes in the integration of wooden structures.

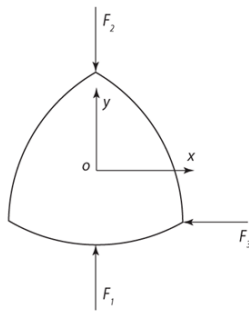


Fig. 6. A scheme of the forces, acting upon a section of a Reuleaux Triangle nail, when determining the elastic section modulus S : $F_1 > F_3 > F_2$

From Table 2. we can calculate the difference between the average forces of driving and removing a nail with a round section and with the Reuleaux Triangle one:

When driving a nail with a section of Rele's Triangle, the force $F_{d,R} = 1.24F_{d,C}$.

When removing a nail with a section of the Rele Triangle, the force $F_{to,R} = 2.12F_{to,C}$.

This means that wooden structures, whose elements are joined with nails with a Reuleaux Triangle section, will have twice as much resistance to destruction as those, joined with ordinary nails, when the wooden structures are subjected to superior destructive forces. This result can be explained by the following effects, which occur when driving and taking-out a nail with a Reuleaux Triangle section: (i) in the ends of the edges of the nail you get a compaction of the wooden material, which increases the coefficient of friction and the friction force in these areas along the length of the nail; (ii)

the larger perimeter determines a larger area of the surrounding surface of the nail body and hence a greater friction force on this surface than the friction force arising on the surrounding surface of a nail with circular section.

From Table 3. it can be determined:

When an external force acts simultaneously on two elements of a wooden structure, the maximum moment at which the elements will not rotate relative to each other is $M_{(r,R)}^{two} = 1.66 M_{(r,C)}^{two}$.

When an external force acts on an element of a wooden structure, the maximum moment at which the elements will not rotate relative to each other is $M_{(r,R)}^{one} = 2M_{(r,C)}^{one}$. This means that wooden structures, which elements are connected with a nail with a Reuleaux Triangle section will have between 1.66 and 2 times more resistance to destruction than those, connected with ordinary nails, when forces, which strive to rotate the wooden elements relative to each other, act on them. This result is due to the presence of three longitudinal edges on the body of the nail with a Reuleaux Triangle section.

The presented results were obtained by using one nail of each type to connect the wooden elements. When using N number of nails, the effects of applying a nail with a section of the Rele Triangle will increase in proportion to N , when building wooden structures. In this way, greater resistance of wooden structures can be achieved, both in conditions of static external forces (furniture) and in dynamic forces (hurricanes, earthquakes, floods).

An important feature that can help the wide application of the new type of nails is that for its production the same materials, machines and technologies are used, which are used for the production of nails with round section.

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Recent Innovations in Metal Processing with the Use of Lasers 2025

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Abstract: Laser technology has transformed metal processing, offering unmatched precision, efficiency, and adaptability across industries such as automotive, aerospace, and electronics. By focusing high-energy laser beams to cut, weld, or engrave metals, these systems deliver superior results compared to traditional methods. In 2025, advancements in laser sources, artificial intelligence (AI) integration, and applications in electric vehicle (EV) manufacturing are driving significant progress. This presentation explores these innovations, focusing on high-power fiber lasers, AI-enhanced process control, and the growing role of laser welding in EV battery production. It also examines market trends and challenges, drawing on the latest 2025 research to highlight the future potential of laser-based metal processing.

1. Introduction to Laser-Based Metal Processing

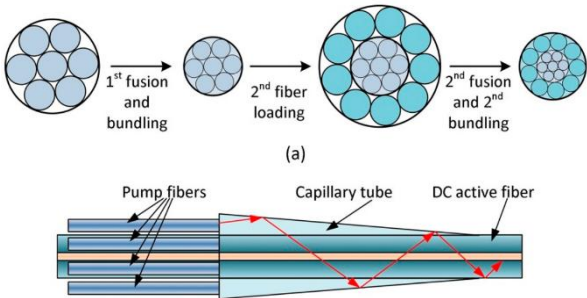
Laser technology is a cornerstone of modern metal processing, enabling precise joining, cutting, and surface modification with minimal material waste. Laser welding, in particular, uses a concentrated beam to fuse metals, producing strong welds with reduced thermal distortion. This method is highly valued in industries requiring intricate, high-quality work, such as automotive manufacturing and medical device production. Its non-contact nature and ability to automate processes make it ideal for high-volume production. In 2025, the field is evolving rapidly due to advancements in laser systems and smart technologies. The rise of electric vehicles, projected to reach 15 million units in global sales by 2025 [1], has spurred demand for laser welding in battery manufacturing. Additionally, the integration of AI and the Internet of Things (IoT) is enhancing process efficiency and quality control. This presentation delves into these developments, offering insights into how laser technology is shaping the future of metal processing.

2. Advancements in Laser Sources

Fiber Lasers: The Industry Standard

Fiber lasers have become the preferred choice for metal processing in 2025 due to their high efficiency, compact design, and ability to deliver precise, high-energy beams. These lasers use optical fibers doped with elements like ytterbium to produce a focused beam, enabling deep welds and fast processing speeds. Their low maintenance and long lifespan (up to 100,000 hours) make them cost-effective for industrial applications.

Recent innovations include high-power fiber laser systems capable of welding thick metals. For example, IPG Photonics’ 25-kW fiber laser, introduced in 2025, achieves weld depths of 25 mm in a single pass at 2.5 meters per minute, ideal for heavy industries like shipbuilding [2]. Additionally, portable handheld fiber laser welders, such as DenaliWeld’s 1500W model, weigh only 48.5 lbs and offer dual welding and seam-cleaning functions, making them accessible for small-scale operations [3].



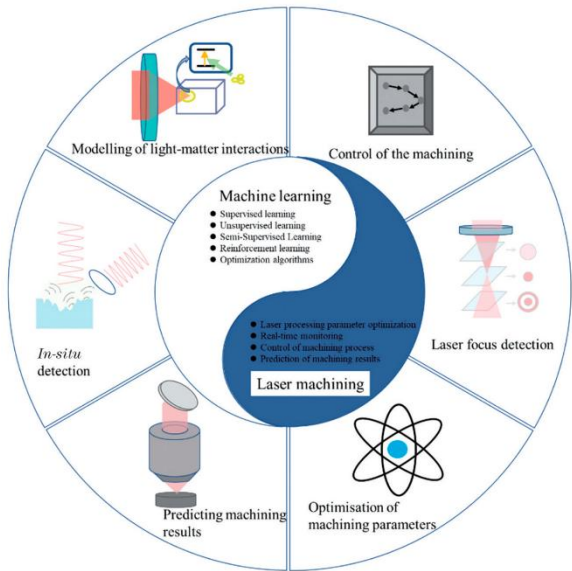
Pic 1. Fiber Laser assembly 2025

Emerging Laser Technologies

Beyond fiber lasers, other systems are gaining traction. Blue laser systems, operating at 450 nm, are increasingly used for welding highly reflective metals like copper, which absorb shorter wavelengths more effectively. In 2025, Coherent introduced a 1-kW blue laser system that achieves defect-free copper welds at speeds of 200 mm/s, critical for electronics and EV battery applications [4]. These advancements suggest a trend toward specialized laser sources tailored to specific materials and applications.

3. AI and Machine Learning in Laser Processing

The integration of AI and machine learning is revolutionizing laser welding by enabling real-time process optimization and quality control. AI-powered systems analyze data from sensors and high-speed cameras to adjust parameters like power and beam focus during welding, ensuring consistent results. For instance, Precitec’s Laser Welding Monitor with AI predicts weld strength by analyzing emissions, achieving 98% accuracy in detecting defects in automotive components [5].



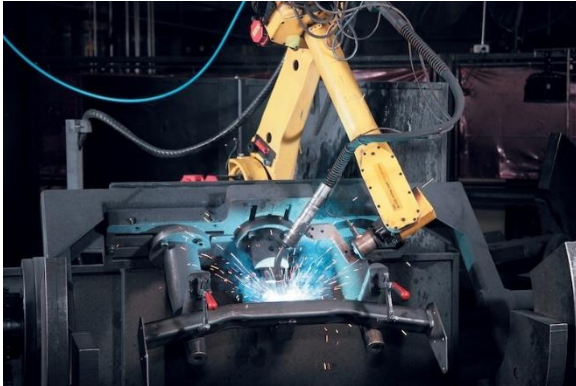
Pic 2. Machine Learning cycle

Machine learning also supports predictive maintenance, identifying potential equipment issues before they cause downtime. A 2025 study demonstrated that AI-driven systems could reduce maintenance costs by 20% in high-volume welding operations [9]. Additionally, research into self-learning laser systems, combining deep neural networks and

reinforcement learning, shows promise for autonomous welding processes that improve without human intervention [6].

4. Laser Welding in Electric Vehicle Manufacturing

The electric vehicle (EV) industry is a key driver of laser welding innovation, particularly in battery production. EV batteries require thousands of precise welds to connect tabs, busbars, and cells, often involving dissimilar metals like aluminum and copper. Laser welding's ability to minimize heat-affected zones and join these materials effectively makes it ideal for this application.



Pic 3. Frame Laser Welding

In 2025, companies like Laserax offer specialized welding machines with up to 6 kW of power, enabling high-speed production of battery packs for cylindrical, prismatic, and pouch cells [7]. These systems can weld dissimilar metals with minimal intermetallic compound formation, achieving electrical resistance as low as 0.1 mΩ. The growing EV market, expected to reach 23 million units by 2030, underscores the critical role of laser welding in meeting production demands [1].

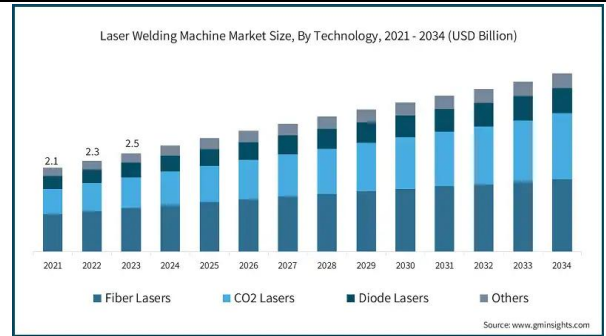
5. Other Metal Processing Applications

Beyond welding, lasers are advancing other metal processing techniques. Laser cutting, using high-power fiber lasers, achieves clean, precise cuts in metals up to 50 mm thick, with systems like those from IPG Photonics offering cutting speeds of 10 m/min for steel [2]. Laser cleaning, another emerging application, uses low-power lasers (50W–200W) to remove contaminants from metal surfaces, improving weld quality and reducing preparation time [7].

These applications are particularly valuable in aerospace, where precision and material integrity are paramount, and in electronics, where lasers enable micro-welding of delicate components. The versatility of laser systems, capable of welding, cutting, and cleaning, enhances their value in integrated manufacturing processes.

6. Market Growth and Future Outlook

The global laser welding market is experiencing robust growth, driven by demand from the EV sector and advancements in automation. Industry projections estimate a compound annual growth rate (CAGR) of 4.4% from 2025 to 2035, with the market expected to reach \$2.79 billion by 2029 [8]. The integration of AI and IoT technologies is likely to further accelerate this growth by enabling smarter, more efficient production lines.



Pic 4. Huge Market Growth expected by 2034

However, challenges remain, including high initial costs, which can exceed \$8,000 for industrial handheld welders [10]. Training programs and user-friendly systems are being developed to address these barriers, making laser technology more accessible to small and medium enterprises.

7. Challenges and Solutions

Despite its advantages, laser welding faces hurdles such as high equipment costs and the need for skilled operators. To mitigate these, manufacturers are introducing cost-effective portable welders and automated systems requiring minimal human intervention. For example, DenaliWeld's modular plug-and-play design simplifies integration with robotic arms, reducing setup time [3]. Additionally, AI-driven training tools are helping workers adapt to advanced systems, ensuring broader adoption across industries.

8. Conclusion

Laser technology is reshaping metal processing, offering precision, efficiency, and versatility that traditional methods cannot match. Innovations in fiber and blue laser systems, coupled with AI integration, are expanding the capabilities of laser welding, particularly in high-demand sectors like electric vehicle manufacturing. As the market grows and challenges are addressed, laser-based metal processing is poised to play a central role in the future of industrial production, driving advancements in quality, sustainability, and automation.

Table: Comparison of Laser Processing Techniques

Technique	Key Features	Applications	Advantages	Challenges
Fiber Laser Welding	High efficiency, 100,000-hour lifespan	Automotive, EV batteries, aerospace	Precise, low maintenance, versatile	High initial cost
Blue Laser Welding	450 nm wavelength, high absorption by copper	Electronics, battery manufacturing	Defect-free welds, fast speeds	Limited to specific materials
Laser Cutting	High-power beams, up to 50 mm thickness	Aerospace, automotive, manufacturing	Clean cuts, high speed	Requires precise calibration
Laser Cleaning	Low-power (50W–200W), removes contaminants	Surface preparation, weld enhancement	Non-abrasive, environmentally friendly	Limited to surface applications

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Optimization of long-chain alkene synthesis from lignocellulosic wastes using photocatalysis

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Abstract: Tall oil fatty acid (TOFA) is a valuable byproduct derived from the processing of lignocellulosic biomass, particularly in the pulp and paper industry. In the present study, TOFA, under optimized alkaline conditions, was firstly converted to soap, then TOFA-based soap was utilized to produce long-chain alkenes using photocatalysis (photoreactor equipped with a UVA-LED lamp). In addition, the performance of TiO_2 , as photocatalyst, was enhanced by introducing NH_4^+ onto its surface. Using response surface methodology (RSM), the effect of reaction time (135, 180, and 225 min), catalyst (80, 110, and 140 mg), and TOFA-based soap quantity (50, 100, and 150 mg) were evaluated. The highest yield (77.7 mg) of C_{n-1} long-chain alkenes was attained when $\sim 1:1$ ratio of TOFA-based soap: $\text{NH}_4\text{-TiO}_2$ was photocatalyzed at 365 nm for 180 min. The findings demonstrated that $\sim 55\%$ of TOFA-based soap can be converted to long chain alkenes by using photocatalysis under optimized conditions. Then, by using sulfuric acid, the alkenes were hydrated into corresponding long-chain alcohols that can serve as precursor for fabrication of bio-based extended surfactants. These findings highlighted the potential of the by-products of lignocellulosic wastes (i.e., TOFA) as a sustainable feedstock for producing high-value chemicals.

KEYWORDS: TALL OIL FATTY ACID (TOFA), ALKENE, LONG CHAIN ALCOHOL, PHOTOCATALYTIC REACTION, PHOTOREACTOR, $\text{NH}_4\text{-TiO}_2$

1. Introduction

Tall oil fatty acids (TOFAs), as by-product of lignocellulosic wastes, are separated during the kraft pulping process specifically from acidulation of crude tall oil. TOFAs primarily comprise fatty acids (oleic and linoleic), rosin acids as well as other unsaponifiables in varying amounts depending on the processing methods and wood source [1]. These fatty acids are characterized by their long-chain carboxylic acid structure and unsaturation, which contribute to their reactivity and utility in chemical synthesis. Due to their biobased origin and relative abundance, TOFAs have gained increasing attention as renewable feedstocks for various industrial applications, aligning with the broader movement toward sustainable and circular bioeconomics [2].

In recent years, research has focused on TOFAs potential for transformation into value-added chemicals, including polyols, esters, hydrocarbons and surfactants, through functionalization of the double bonds or carboxylic groups. Additionally, the use of TOFAs in hydrocarbon and biodiesel production has been explored due to their favorable fatty acid composition and low-cost relative to vegetable oils. However, challenges remain in optimizing catalytic processes for their chemical upgrading [3].

Long-chain alkenes, typically defined as unsaturated hydrocarbons with carbon chain lengths greater than C_{10} , play a significant role in both natural systems and industrial applications due to their physical properties. These molecules are important intermediates in the synthesis of a wide range of value-added products, including lubricants, plasticizers, detergents, and surfactants [4, 5]. Their double bonds provide reactive sites for various chemical modifications, such as epoxidation, hydroformylation, and hydration, enabling the production of functionalized materials with tailored properties. Industrially, their hydrophobic nature and structural diversity make them suitable candidates for the formulation of valuable chemicals namely surfactants. As interest grows in utilizing renewable feedstocks, long-chain alkenes derived from biomass, such as via catalytic decarboxylation of fatty acids, are increasingly being explored as sustainable alternatives to petroleum-based chemicals [4, 6]. To produce long chain alkenes from TOFAs, the carboxyl groups need to be removed from the molecule. This can be done using a photocatalytic reaction in photoreactors. The photocatalytic process is a radiation-induced chemical process in which a semiconductor material provides a

surface that speeds up the degradation or synthesis of chemicals, or generation of clean energy. This process deals with events such as light absorption, generation of electron-hole pairs, charge separation, and redox reactions at the interface [7, 8].

A photoreactor is a specially designed equipment which helps to expose the chemical substances to the light in a controlled way, so that the light energy can activate chemical reaction. There are different types of photoreactors with various light source, operation mode, cell material, light irradiation mode, the type of photocatalysts which can be used, shapes and sizes [9]. The photocatalyst is usually a semiconductor material, such as titanium dioxide (TiO_2) or zinc oxide (ZnO), which can absorb the light energy and produce electron and hole pairs that cause the chemical reaction. With increasing attention on green chemistry and environmentally friendly processes, the development of desirable photoreactor systems and efficient photocatalysts is becoming more and more important for industrial applications [10, 11, 12].

The present study aimed to design and manufacture a lab-scale photoreactor and investigate its capability in decarboxylation of TOFA-based soap to produce C_{n-1} alkenes. Firstly, the effects of alkaline conditions on conversion of TOFAs to soap were optimized. Then, using RSM design, the effect of reaction time, photocatalyst and soap concentrations on the photocatalysis of TOFA-based soap to long-chain alkenes were investigated. The performance of plain TiO_2 and the TiO_2 doped with NH_4^+ was also compared. Finally, the long chain alkenes were hydrated into their corresponding alcohols which can be used as precursors for synthesis of bio-based extended surfactants.

2. Materials and Methods

2.1. Materials

Tall oil fatty acid (oleic acid 59%, linoleic acid 16%, conjugated linoleic acid (CLA) 4%, other acids 8% and unsaponifiable 9%) was purchased from commercial supplier (Linyi Company, China). Titanium dioxide nano powder (TiO_2 , anatase, 10-25 nm, purity 99+%, US Research Nanomaterials, Inc, USA), sodium hydroxide (NaOH), ammonium chloride (NH_4Cl) and nitric acid (HNO_3) were supplied from Merck Chemicals Company (Darmstadt, Germany). Ethanol ($\text{C}_2\text{H}_5\text{OH}$, 96%), sulfuric acid (H_2SO_4) and ethyl acetate ($\text{C}_4\text{H}_8\text{O}_2$) were purchased from Dr. Mojallali Industrial Chemical Complex Co. (Tehran, Iran).

2.2. Doping of photocatalyst (TiO₂) with NH₄

In order to improve the functionality of TiO₂, 3 gr of TiO₂ dissolved in 100 mL of NaOH (10 M), stirred for 24 hr, then heated (150 °C for 48 hr). Afterwards, 18 gr of NH₄ Cl was mixed with 100 mL of water: ethanol solution (1:1 ratio), and H-TNT was added to the mixture then heated (120 °C for 12 hr). After cooling at room temperature, the resulting white powder (i.e., NH₄-TiO₂) was collected [13].

2.3. Saponification of TOFAs

In order to prepare soap form TOFAs fatty acids (i.e., saponification), 5 mL of TOFAs was mixed with 10 mL of ethanol and 10 mL of NaOH (40% w/v), and the mixture then heated (120 °C for 30 min). During saponification process, the reaction vessel was purged with N₂ gas. Upon the completion of the reaction, by using a centrifuge, the TOFA-based soap was collected [13].

2.4. Designing a lab-scale photoreactor

A lab-scale photoreactor setup (Fig 1) was specially designed in our laboratory (Ghobadi and Abbasi, 2025). A UVA-LED (8 dotted LED, 12 V, 20 W, 365–370 nm, 20–40 LM, KN Lighting, China) equipped with heat sink, fan, and a matching driver was installed on the left side of the box and used as radiation or light source (Fig 1b). Heat-sink and fan prevent overheating of the LED lights. Round bottom quartz tube, as the reaction vessel, was designed and manufactured by a scientific glassware craftsman. The top of cuvette was sealed with conical rubber stopper with two holes through which N₂ gas was purged and the reaction gases were exhausted. In order to mix the contents of reaction vessel during photocatalysis, the setup was installed on top of a magnetic stirrer.

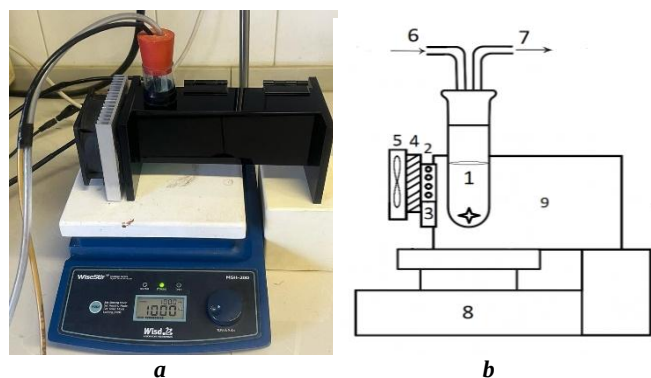


Fig. 1. a. A custom-made photoreactor, equipped with a 365 nm LED, designed to decarboxylate TOFAs. b. Schematic design of the photoreactor. 1: quartz tube containing reactant, photocatalyst and magnet, 2: UVA-LED lamp, 3: LED driver, 4: heatsink, 5: Fan, 6: N₂ input, 7: unwanted gases output, 8: heater-stirrer, 9: photoreactor box

2.5. Decarboxylation of TOFA-based soap using photocatalytic reaction

In order to convert the TOFA-based soap into alkenes, distinct amounts of TOFA-based soap and catalyst (plain TiO₂ or NH₄-TiO₂) were mixed with 15 mL of distilled water inside the quartz reaction vessel. Then, the vessel was placed in the photoreactor reaction chamber and stirred at 1000 rpm while N₂ was purged to evacuate the headspace gases. Irradiation was carried out using the LED lights at room temperature up to 4 hrs. Using response surface methodology (Box-Behnken design with 16 runs including 4 central

points), the effect of various decarboxylation conditions including reaction time (X_1 (180) $\pm \alpha$ (45), coded as -1, 0, +1 and their corresponding uncoded values: 135, 180, and 225 min), photocatalyst (X_2 (110) $\pm \alpha$ (30), coded as -1, 0, +1 and their corresponding uncoded values: 80, 110, and 140 mg), and TOFA-based soap quantity (X_3 (100) $\pm \alpha$ (50), coded as -1, 0, +1 and their corresponding uncoded values: 50, 100, and 150 mg) on alkene production were optimized (Table 1).

2.6. Conversion of alkenes to long chain alcohols

The alkene produced by the photoreactor (see subsection 2-5) was separated using ethanol, after which the ethanol was removed. Then, 10 mL of distilled or double distilled water and 10 mL of sulfuric acid (10% w/v or v/v) were added to the alkene, as a result of which a turbid solution was formed. This mixture was then centrifuged, the supernatant was discarded but sediment was dried (70 °C for 120 min) using an oven and collected as long chain alcohol [14,15].

2.7. Statistical Analysis

Design-Expert 13.0.0 (Stat-Ease Inc., USA), was used for the regression analysis of the experimental data as well as plotting the 2D graphs and counters.

3. Results and Discussion

As already briefly described (section 1), over the course of the photocatalytic decarboxylation reaction, the electrons on the surface of catalyst are usually excited and transferred to the conduction band and leaving behind holes (formation of an electron-hole pair) on the surface of catalyst [16, 17] Therefore, in the present study, when TOFA-based soap comes into the contact with the activated surface of catalyst (TiO₂ or NH₄-TiO₂), two different reactions are expected. On one side, they undergo oxidation in the hole site and lose hydrogen. Then, this hydrogen, combines with the excited electrons to form hydrogen radical. Finally, through the recombination of two hydrogen radicals, a hydrogen molecule (H₂) is generated [18, 19, 20]. Meanwhile, the TOFA-based soap radical interacts with the catalyst surface, undergoes oxidative decarboxylation and loses one CO₂ molecule. Due to the unsaturation of TOFA-based soap molecule, it is quite likely that the H₂ molecules (formerly produced) incorporate in the hydrogenation reaction as a result of which alkanes (C_{n-1}) can be formed. However, since the present study was aimed to produce alkenes, therefore the H₂ had to be evacuated from reaction vessel. Therefore, over the course of photocatalytic decarboxylation reaction, the headspace of reaction vessel was continuously purged with pure nitrogen.

Once the photocatalytic decarboxylation reaction conditions were established, the question was how one can maximize the alkene yield. To tackle this, by using one-factor-at-a-time approach, different experiments were conducted, based on which an RSM was employed comprising 3 variables at 3 levels each (16 runs including 4 central point) Table 1.

Table 2 shows the importance level of the independent variables in an individual and mutual interaction using F-test and analysis of variance. According Table 2, all independent variables showed significant effect on alkene yield ($p < 0.0005$). Among second order effects and interaction of two variables, time * time (A^2) and soap * soap (C^2) and time* soap (AC) showed to be significant ($p < 0.05$).

Table 1. Experimental RSM (Box-Behnken) design (coded and uncoded variables values) and alkene yield.

Run #	Coded			Uncoded			Response
	X ₁	X ₂	X ₃	A: Time (min)	B: Photocatalyst (mg)	C: TOFA-based soap (mg)	
1	0	0	0	180	110	100	52.1
2	+1	+1	0	225	140	100	57.2
3	0	-1	-1	180	80	50	20.3
4	0	+1	+1	180	140	150	77.7
5	0	+1	-1	180	140	50	26.1
6	+1	-1	0	225	80	100	43.5
7	-1	0	-1	135	110	50	19.5
8	0	-1	+1	180	80	150	63.4
9	+1	0	-1	225	110	50	25.2
10	0	0	0	180	110	100	50.9
11	0	0	0	180	110	100	51.3
12	-1	+1	0	135	140	100	46.4
13	+1	0	+1	225	110	150	73.4
14	-1	-1	0	135	80	100	32.6
15	-1	0	0	180	110	100	53.4
16	-1	0	+1	135	110	150	52.6

To determine the optimal levels of variables for maximum alkene production, three-dimensional plots (Fig. 3) were constructed by plotting the response (alkene yield) against each pair of independent variables, while keeping the third variable constant at its central (zero) level. With regard to time and photocatalyst (AB) interaction (Fig.3a), there was a slight increase in alkene production within the range of up to 120 mg of photocatalyst, 225 min of reaction time, and 100 mg of TOFA-based soap. These findings indicate that without increasing the soap amount, additional photocatalyst or longer reaction time does not improve the alkene production and are consistent with Table 2.

Table 2. Analysis of variance of the regression model derived from RSM design

Source	F-value	p-value	
Model	87.62	< 0.0001	significant
A-Time	48.65	0.0004	
B-Catalyst	47.44	0.0005	
C-Soap	648.62	< 0.0001	
AB	0.0004	0.9843	
AC	9.55	0.0214	
BC	3.03	0.1326	
A ²	21.01	0.0038	
B ²	1.31	0.2954	
C ²	8.93	0.0244	
Residual			
Lack of Fit	8.82	0.0535	not significant
Pure Error			
Cor Total			

Figure 3b also shows time and soap amount interaction (AC) on alkene yield. Increasing the reaction time by 225 min and the soap amount to 150 mg caused an increase in alkene production. These findings confirm that longer exposure time resulted in higher alkene production.

By looking at the photocatalyst and soap interaction (BC) on alkene yield (Fig.3c), a clear and likely linear increase in alkene

production was observed. This shows that both the catalyst and soap amounts have a significant effect on alkene yield. These findings are consistent with the data presented in Table 2.

As shown at Table 3, the regression model had a significant F value but insignificant lack of fit. Its actual and adjusted R² values were 0.99 and its 0.98, respectively. R² value normally shows how far the regression model is deviated from data. Considering its high value here in this study, it is expected that the regression model could

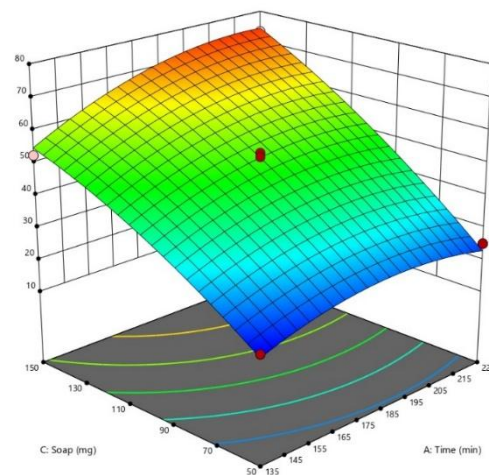
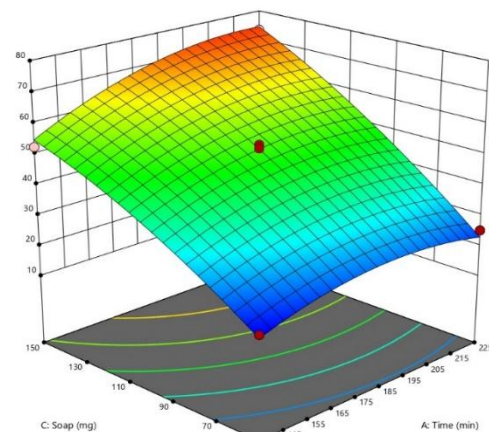
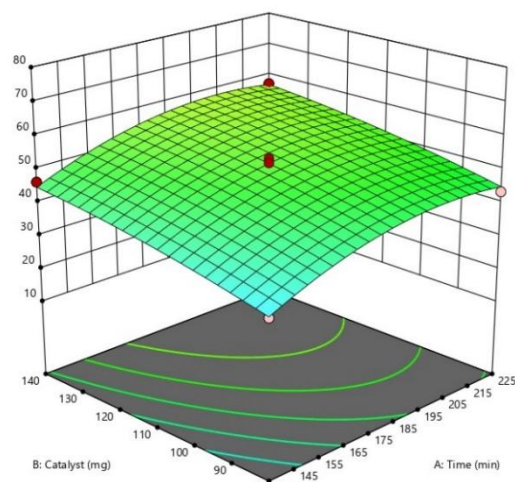


Fig. 3. a. Three-dimensional plot of the effect of time and catalyst amount on alkene yield, with the soap amount fixed at its central level. **b.** Three-dimensional plot of the effect of time and soap amount on alkene yield, while the catalyst amount is fixed at its central level. **c.** Three-dimensional effect of catalyst and soap amounts on alkene yield, while keeping time fixed at its central level

desirably and precisely predict the alkene yield under the combination of various ratios of the independent variables. Therefore, it can be used for optimization of the alkene production under photocatalytic reactions.

Table 3. Fit statistics of the regression model derived from RSM

Std. Dev.	2.44	R²	0.9924
Mean	46.60	Adjusted R²	0.9811
C.V. %	5.24	Predicted R²	0.8901
		Adeq Precision	30.2991

The model suggests that by choosing a time of 180 minutes, a catalyst amount of 140 mg, and a soap amount of 150 mg, the highest yield of C_{n-1} long-chain alkenes (77.7 mg) was achieved in the photoreactor. This indicates that a ~1:1 ratio of TOFA-based soap to catalyst over 180 minutes can provide the optimal conditions. This study showed that about 55% of TOFA-based soap can be converted into long-chain alkenes using photocatalysis under optimized conditions. This yield is comparable to the yield of older methods that require harsher experimental conditions, longer reaction times, and more expensive equipment. It shows that with recent developments in green technologies like photoreactors, similar results can be achieved under milder conditions using cheaper equipment.

Hydration of the produced C_{n-1} alkenes using sulfuric acid results in the related alcohols, which can then be used to produce high-value products such as surfactants.

4. Conclusion

The results of RSM showed that time, the amount of catalyst, and the amount of soap have significant effects on alkene production using a photoreactor. The custom-made photoreactor used in this study converted about 55% of TOFA-based soap into long-chain alkenes under optimized conditions. It proved to be a suitable device for alkene production and could be used as a replacement for older, more expensive methods.

efficiency at the base ambient state notably lower in comparison to other five valves, equal to 64.90% only.

- The exergy variables of any pressure reduction valve are more and more influenced by the ambient temperature change when the operating parameters of working fluid which flows through the valve (fluid pressure and temperature) are closer to the ambient state.

5. Acknowledgment

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Simulation of solar-coal hybrid power plant based on the Rankine cycle

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Abstract: The use of solar energy to generate electricity in Power Plant (PP) based on the Rankine cycle is currently a strongly developed CSP system (Concentrating Solar Power) technology. Combining CSP systems with an existing Rankine cycle in coal-fired Power Plant (PP) or Combined Heat and Power Plant (CHP) can increase the maximum output of a power plant and effectively provide a transition for fossil fuel-based technologies to the use of renewable energy sources such as hybrid or renewable energy-only systems. The paper presents simulation results of a steam Rankine cycle with solar power plant components. The hybrid power system makes it possible to reduce the use of coal fuel and provide high efficiency and output power. The calculations were carried out using Epsilon Professional software.

Keywords: RENEWABLE ENERGY SOURCES, HYBRID ENERGY SYSTEM, THERMODYNAMIC MODELING, ENERGY TECHNOLOGIES

1. Introduction

Coal continues to play a vital role in the energy mix of many countries, particularly in the developing countries, where power generation infrastructure is still largely dependent on this resource [1-3]. However, the environmental challenges posed by fossil fuel-based electricity production - most notably the emission of greenhouse gases - have become a pressing global issue, contributing significantly to climate change and global warming. These concerns underscore the urgent need to modernize existing coal-fired power plants and accelerate the integration of cleaner, renewable energy sources into national energy systems.

Concentrated Solar Power (CSP) systems and Thermal Energy Storage (TES) offer a promising solution for reliable power generation under varying solar radiation conditions. This advantage positions CSP above other renewable technologies, such as photovoltaics and wind power, which are often regarded as leading alternatives to fossil fuels. Concentrated Solar Power (CSP) technology has gained prominence for its potential to provide a sustainable, efficient, and diverse energy mix, making it an essential component of future energy systems [4]. CSP systems face significant challenges, including high initial investment costs, lower efficiency compared to fossil fuel-based systems, and the technical complexities associated with large-scale TES implementation. Integrating solar energy into coal-fired power plants forming a Solar-Coal Hybrid Power Plant (SCHPP), presents a viable approach to address these issues. This hybrid system has substantial potential to reduce coal consumption while mitigating the limitations associated with standalone CSP plants [5].

2. Analyzed energy systems

2.1. Steam power plant

The analyzed steam power plant is a power unit consisting mainly of a steam boiler, high-pressure steam turbine, low-pressure steam turbine, generator, condenser, three low-pressure feedwater preheaters, three high-pressure feedwater preheaters, a feedwater pump, and a deaerator (Figure 1). The plant operates to generate electricity, utilizing thermal energy produced by the combustion of solid fuel in a pulverized coal-fired boiler. The power output, efficiency, and thermal energy input depend on the current operating conditions and can vary across the power plant's load range. Under selected operating conditions, the main parameters of the analyzed steam power plant are presented in Table 1.

Table 1. Main factors of steam power plant.

Parameter	Unit	Value
Power output	MW	207.8
Thermal power input	MW	501.26
Thermal efficiency	%	41.45 %
Boiler inlet water temperature	°C	221
Steam mass flow rate	t/h	717.5
Steam temperature	°C	537.8
Steam pressure	bar	104.2
Vapour pressure in condenser	bar	0.067

2.2. Concentrated Solar Power (CSP) technology

Solar power collectors have proven to be an innovative and essential technology in the shift towards renewable energy. These devices harness sunlight and convert it into usable electricity, offering a sustainable alternative to traditional energy sources. Their growing popularity stems from several benefits, including the reduction of greenhouse gas emissions and the potential to lower electricity costs significantly. Utilizing solar energy, these systems contribute to global efforts to combat climate change, making them an attractive option for both residential and commercial use. One of the key advantages of solar power collectors is their versatility. They come in various forms, such as photovoltaic (PV) panels, solar power collectors (SPT), and concentrated solar power (CSP) systems. PV panels are the most widely recognized, directly converting sunlight into electricity using semiconductors. On the other hand, solar thermal collectors capture and store the sun's heat to produce hot water or heating for homes and businesses. CSP systems take a more advanced approach, concentrating sunlight to generate high-temperature heat, which drives turbines for electricity production on a larger scale. This diversity allows for various applications, from small household systems to large-scale solar farms. More than 6 GW of concentrated solar power (CSP) plants were installed in 2020 [6], and the largest TES from installed CSP can generate clean electricity for 24 hours by reducing CO₂ emission. The International Energy Agency (IEA) estimates that the CSP will contribute up to 11% of global electricity production in 2050 [6].

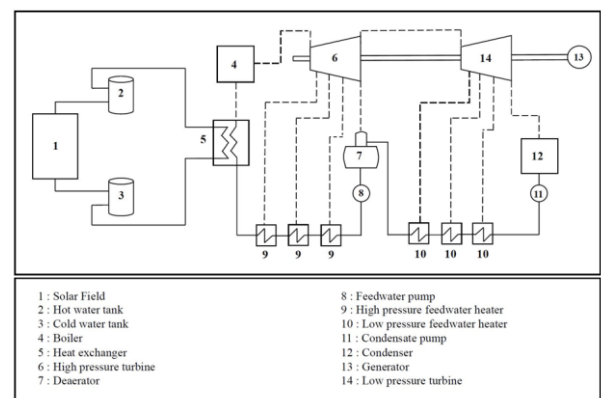


Fig. 1. Schematic layout of the Hybrid Solar Coal Power Plant general concept

3. Modeling of energy systems

3.1. Solar tower receiver and heliostat field

The sun angles and incident power calculations are essential for solar energy applications, particularly in Concentrated Solar Power (CSP) systems. Using the standard DIN 5034, the solar angles, such as the solar altitude and azimuth, is calculated [7]. For solar irradiance, the Direct Normal Irradiance (DNI) is considered and its estimation using the Clear Sky model by Hottel [8] or Clearness Index originally developed by Liu and Jordan [9]. The Clear Sky model estimates DNI for cloudless conditions based on atmospheric

parameters and solar geometry, while the Clearness Index considers cloud cover and atmospheric clarity. These parameters determine the usable solar irradiance and incident power on the receiver aperture.

The total usable solar irradiance $\dot{Q}_{usable}$ is calculated using the formula:

$$\dot{Q}_{usable} = DNI \cdot A_{helio\,stat} \quad (1)$$

where:

$A_{helio\,stat}$ - is the total aperture area of the heliostat field, m².

The incident power on the receiver aperture area is calculated as in Eq. (2):

$$\dot{Q}_{incident} = DNI \cdot \rho \cdot A_{helio\,stat} \cdot \eta_{field}(\gamma_s, \alpha_s) \cdot \eta_{wind} \quad (2)$$

where:

DNI - Direct Normal Irradiance, W/m²

ρ - the average field reflectivity, -

$\eta_{field}(\gamma_s, \alpha_s)$ - solar field optical efficiency depends on the sun azimuth γ_s , and the sun elevation α_s

η_{wind} - wind correction.

The amount of thermal energy transferred to the Heat Transfer Fluid (HTF) by the receiver to raise fluid temperature is calculated using the following formula:

$$\begin{aligned} \dot{Q}_{eff} &= \dot{Q}_{incident} - \dot{Q}_{loss} \\ \dot{Q}_{loss} &= \dot{Q}_{loss,opt} + \dot{Q}_{loss,conv} + \dot{Q}_{loss,rad} \end{aligned} \quad (4)$$

where:

$\dot{Q}_{eff}$ - power of effective heat, kW

$\dot{Q}_{loss}$ - losses composed of optical $\dot{Q}_{loss,opt}$, convective $\dot{Q}_{loss,conv}$ and radiation losses $\dot{Q}_{loss,rad}$, kW.

3.2. Rankine steam cycle

The Rankine cycle power unit is modeled assuming pseudo-steady-state energy balances. The solar and coal-fired components (i.e. boiler, superheater, etc.) are modeled dynamically to account for dynamics in DNI. The entire plant is modeled in Ebsilon Professional software [10, 11]. For all dynamic systems, the built-in integrator block of Ebsilon is used to solve differential equations arising from governing equations. Other major assumptions include neglecting conductive heat transfer, non-axial temperature distributions, and constant condenser operation. Constant values are assumed for saturation pressure during steam generation and isentropic efficiencies for turbomachinery.

3.3. Hybrid energy system

To investigate improvement of steam cycle performance by the use of additional heat source in the cycle, the power output and efficiency of the process were defined. The efficiency of the power plant can be calculated using the following equations:

$$\eta = \frac{N_{el}}{\dot{Q}_F} \quad (5)$$

where:

η - steam cycle fuel-driven efficiency, %

N_{el} - power output, MW

$\dot{Q}_F$ - heat rate to the cycle through boiler (energy from fuel), MW

4. Results and discussion

4.1. Solar field simulation

In the operation of a solar field within a CSP system, solar energy is captured, stored, and transported to enable electricity generation. The input data of Solar Field on 15th June 2021 is presented in Table 2. The process begins with the collection of solar radiation, which is concentrated and transferred to a working fluid. This fluid serves as the medium for storing and transferring thermal energy within the system. The thermal energy is stored in designated units to ensure continuous operation, even during periods when solar radiation is unavailable, such as nighttime or cloudy weather.

Table 2. Solar Field data on 15th June 2021.

Date and time	Power absorbed by the fluid	Effective receiver temperature	Effective field efficiency
12:00:00 AM	0.00 MW	274.71 °C	0 %
2:00:00 AM	0.00 MW	274.71 °C	0 %
4:00:00 AM	0.00 MW	274.71 °C	0 %
6:00:00 AM	46.44 MW	304.78 °C	35.72 %
8:00:00 AM	75.25 MW	323.41 °C	57.25 %
10:00:00 AM	83.91 MW	328.76 °C	63.72 %
12:00:00 PM	87.37 MW	330.86 °C	66.30 %
2:00:00 PM	83.89 MW	328.75 °C	63.70 %
4:00:00 PM	75.22 MW	323.39 °C	57.22 %
6:00:00 PM	46.44 MW	304.78 °C	35.72 %
8:00:00 PM	0.00 MW	274.71 °C	0 %
10:00:00 PM	0.00 MW	274.71 °C	0 %

Table 2 shows that the peak value is obtained during the middle of the day between 12:00 PM and 01:00 PM when the sun is visible at its peak temperature. During the nighttime, the value comes down after the sunset. During these hours, hot storage has to be used to supply heat to the power plant.

4.2. Steam cycle simulation

The steam Rankine cycle power plant operation simulation was designed using Ebsilon® Professional software. The components of the steam cycle in Ebsilon are the steam turbine, steam generator, condenser, pump, deaerator, and preheaters (Figure 2). The three model variants were developed for the simulations, where part of the feedwater before each HP preheater is diverted to the heat exchanger (HE). The hot medium in the HP preheaters is the bleed from stages of HP turbine, and the cold medium is the feedwater from the deaerator to the boiler. The diverted feedwater to the heat exchanger is again mixed with the feedwater line before the boiler inlet, keeping boiler feedwater temperature at the same level.

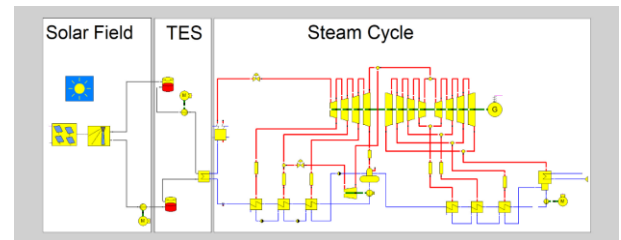


Fig. 2. Model of hybrid solar coal power plant in Ebsilon® Professional.

4.3. Hybrid Solar-Coal Power Plant simulation

The simulation then calculates heat balance to model energy flows through the solar field, thermal energy storage, and steam cycle. Turbine efficiency, fluid properties, and flow rates are meticulously modeled to align with design specifications and ensure efficient system operation.

Three different analyses based on the variants were classified according to the extraction of feed water. A part of the feedwater is extracted before the HP heater and flows through the heat exchanger to utilize solar energy. The flow rate of extracted feedwater is controlled from 10 kg/s to 100 kg/s. The simulated result data are presented and discussed below. The feedwater temperature at the boiler inlet is constant and equal to 221°C. The energy consumed by the steam boiler is also constant in all three variants regardless of the increase in the power generation of the electric generator. Extraction point of the variant 1 (a), variant 2 (b) and variant 3 (c) before HP preheater is shown in Figure 3.

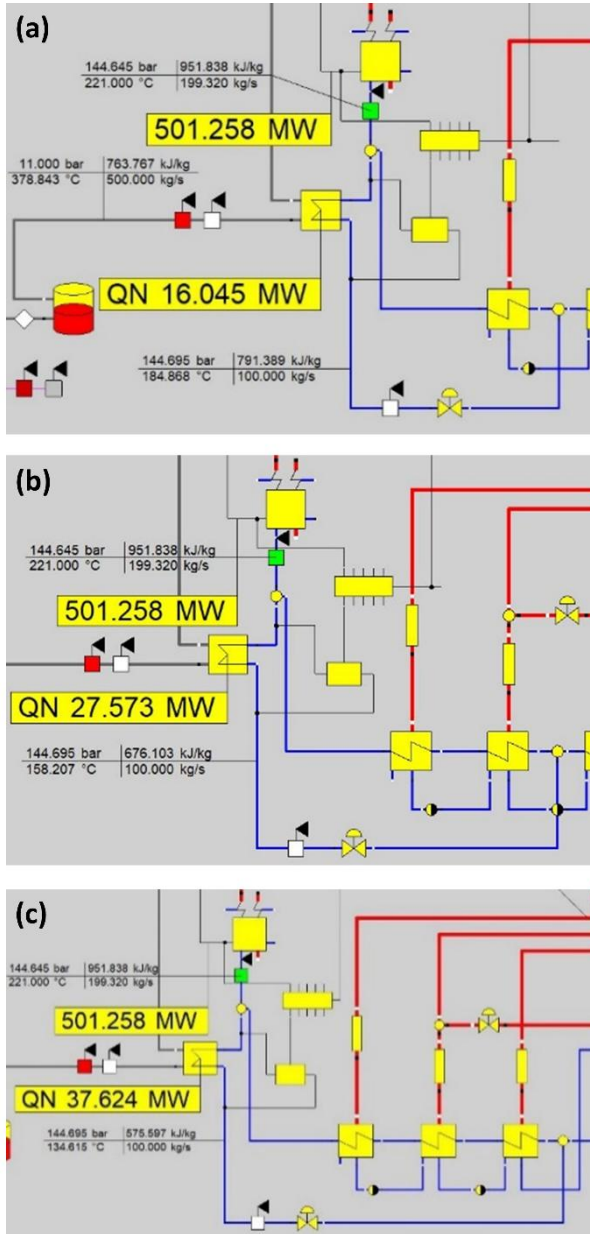


Fig. 3. Extraction point of the variant 1 (a), variant 2 (b) and variant 3 (c) before HP preheater in developed HSCPP model

The hybrid solar-assisted steam power plant simulation demonstrates the successful integration of solar energy with a conventional coal-fired power system. The increase in solar energy input leads to a consistent improvement in thermal efficiency across the analyzed configurations. Compared to results from variants 1 and 2, with efficiencies of 42.58% and 43.25%, this simulated result from variant 3 achieves the highest efficiency of 43.75%.

With a solar contribution of 37.62 MW, the coal consumption needed for generating electricity can be reduced. Although the coal input remains constant, the improved thermal efficiency indicates reduced fuel-specific energy requirements. The increased

integration of solar energy reduces the environmental footprint of the power plant by lowering coal consumption and greenhouse gas emissions. This highlights the potential for hybrid systems to contribute to cleaner and more sustainable power generation.

Table 4. Simulation results for variant 1.

Solar heat input	Power output	Efficiency
MW	MW	%
1.60	208.47	41.59
3.21	209.02	41.70
4.81	209.57	41.81
6.42	210.13	41.92
8.02	210.68	42.03
9.63	211.23	42.14
11.23	211.79	42.25
12.84	212.34	42.36
14.44	212.89	42.47

Table 4. Simulation results for variant 2.

Solar heat input	Power output	Efficiency
MW	MW	%
2.76	208.80	41.66
5.51	209.69	41.83
8.27	210.58	42.01
11.03	211.47	42.19
13.79	212.36	42.36
16.54	213.24	42.54
19.30	214.13	42.72
22.06	215.02	42.90
24.82	215.91	43.07

Table 5. Simulation results for variant 3.

Solar heat input	Power output	Efficiency
MW	MW	%
3.76	209.06	41.71
7.52	210.19	41.93
11.29	211.33	42.16
15.05	212.47	42.39
18.81	213.61	42.62
22.57	214.75	42.84
26.34	215.89	43.07
30.10	217.03	43.30
33.86	218.17	43.52

The relationship between mass flow rate and the efficiency of solar-assisted steam power plant, solar contribution for three variants are illustrated in Figure 4. Overall, the efficiency increases steadily as the mass flow rate rises. At lower mass flow rates (10–30 kg/s), all three variants show relatively low and similar efficiency levels, with Variant 1 performing the least efficiently.

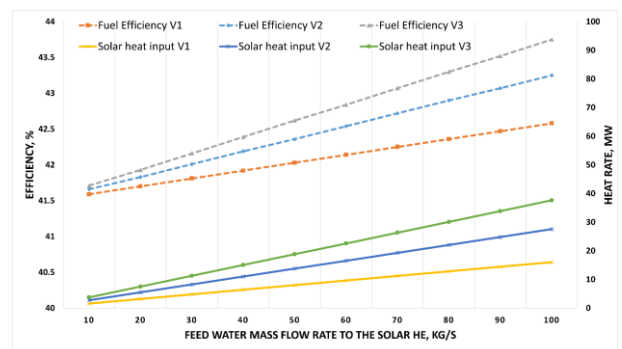


Fig. 4. Efficiency and solar contribution as a function of mass flow rate for all analyzed variants

Variant 1 achieves an efficiency starting at 40.5% at 10 kg/s and peaks just below 43.0% at 100 kg/s. Variant 2 performs moderately better, reaching around 43.25% efficiency at the highest mass flow rate. Variant 3 outperforms both, starting at approximately 41.0% at 10 kg/s and reaching nearly 44.0% at 100 kg/s.

5. Conclusions

The heat absorbed by the fluid from the solar tower receiver varies significantly, ranging from 0 to 86.41 MW, depending on the intensity of solar radiation during operating hours. This variability highlights the intermittent nature of solar energy and the critical role of solar thermal systems in effectively capturing and utilizing solar heat. Despite this variability, the feedwater temperature at the boiler inlet remains constant at 221 °C, ensuring stable operation of the steam cycle and preventing thermal stresses within the boiler system. This stability is achieved by integrating the solar thermal component into the conventional Rankine cycle without disrupting the boiler's operational parameters.

This integration strategy demonstrates the effective utilization of solar energy to supplement and enhance the performance of traditional coal-fired power plants without altering the boiler's energy input, ensuring operational consistency. Such designs improve thermal efficiency and allow for increased electricity generation during peak solar hours, making the hybrid power plant a promising solution for reducing fossil fuel dependence and CO₂ emissions while maintaining reliable power output.

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Immersive Technologies as an Educational Innovation for Training the Next Generation of Professionals

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Abstract: Immersive technologies, including virtual, augmented, and mixed reality, are transforming contemporary education by facilitating interactive learning environments. This paper examines the potential impact of these technologies on the training of professionals in different fields. The study identifies key tasks, including an analysis of the educational approach of the technology and an assessment of the applicability of these tools in different educational contexts and domains. The results of the study indicate an enhancement in educational outcomes, as evidenced by an increase in opportunities and benefits for learners. The paper also discusses the importance of VR, AR, and MR in preparing future professionals who will work in highly dynamic, technology-driven work environments. The research posits that immersive technologies are an indispensable component of contemporary educational approaches to teaching and learning, providing future professionals with the competencies required in evolving, technology-driven industries.

Keywords: IMMERSIVE TECHNOLOGIES, VIRTUAL REALITY (VR), AUGMENTED REALITY (AR), MIXED REALITY (MR), ENGAGEMENT, MOTIVATION, IMMERSIVE LEARNING, IMMERSIVE TEACHING

1. Introduction

The rapid development of digital tools and technology's increasing role in all aspects of society have made changes to educational approaches necessary. Traditional teaching methods often fail to meet the needs of today's learners, particularly in subjects that require practical experience, problem-solving, and critical thinking skills. In response, immersive technologies - virtual reality (VR), augmented reality (AR) and mixed reality (MR) - have emerged as promising educational tools. They enable interactive, experiential learning by immersing students in simulated environments, thereby increasing engagement and bridging the gap between theoretical knowledge and practical application.

Immersive technologies are important to modern education because they meet the demands of dynamic, technology-driven industries. The job market increasingly values individuals who possess practical skills, adaptability, and critical thinking abilities. In this context, educational institutions must adopt approaches that effectively prepare learners for professional challenges. Immersive technologies provide a realistic, interactive environment that allows learners to safely practice their skills and develop competencies through experience. This makes them important for the future of vocational training [1].

The pedagogical benefits of immersive technologies remain understudied. On the one hand, it has been noted that immersive environments promote active learning, improve student engagement and retention, and facilitate a better understanding of complex concepts. Virtual reality, for example, enhances learning by providing a more hands-on approach to education. Augmented reality, on the other hand, enhances collaborative learning by enabling real-time interaction with digital content. However, the implementation of immersive tools faces challenges such as cost, technological barriers, and the need to train educators. Despite these challenges, research shows that using immersive technologies can significantly improve problem-solving, motivation, and critical thinking skills, particularly in STEM, medical, and technical education.

The impetus for conducting this research stems from the objective of examining and examining the potential of immersive technologies as an innovative educational approach for training future professionals. This objective is pursued through the description of existing immersive technologies and the theoretical justification of their use. The assessment results in the identification of strategies to address the evolving demands of preparing today's students to become the workforce. To that end, the following research tasks have been identified as necessary to achieve the main objective:

- To examine and describe existing educational immersive technologies,
- To explore and analyze the applicability of VR, AR and MR in different educational contexts and domains;
- To evaluate the impact of immersive learning on students' academic achievement, motivation and future readiness;
- To analyze the educational potential of immersive technologies to promote student engagement, critical thinking and practical skills to use immersive technologies in education.

2. The importance of immersive technologies in modern education and vocational training

The rapid development of digital technologies has precipitated a paradigm shift in the manner in which knowledge is acquired and applied. Consequently, educational institutions are compelled to adopt innovative approaches to meet the needs of today's learners. Immersive technologies, including VR, AR and MR, have emerged as novel pedagogical tools, offering interactive, experience-based learning environments that facilitate student engagement. The efficacy of these tools in facilitating the transition between theoretical concepts and practical applications has been demonstrated, particularly within professions that demand a high degree of manual dexterity and technical expertise, such as medicine, engineering, and related technical domains.

In the contemporary job market, experiential learning, problem-solving skills, and critical thinking are highly prized, thus rendering immersive technologies a pivotal component in the preparation of future professionals. Through the emulation of real-world scenarios, these technologies empower learners to apply their knowledge in a secure and controlled environment, enhancing learning outcomes and mitigating the risks associated with conventional training in high-stakes domains. Moreover, immersive learning has been demonstrated to enhance student motivation and learning engagement by addressing the challenges associated with student retention and participation in traditional classrooms [2].

The significance of these technologies extends to the realms of lifelong learning and professional development, where continuous upskilling is imperative in rapidly evolving industries. As the demand for professionals proficient in advanced cyphoric technologies increases, the integration of immersive technologies into education and training interventions is imperative to ensure that learners acquire the necessary competencies to thrive in dynamic and technological workplaces. Therefore, immersive technologies are not only relevant but also essential for modernizing education and ensuring learners' futures in changing professional environments [3].

In general, immersive technologies are proving to be effective tools in educational and training settings. These technologies

facilitate immersive, interactive experiences, enabling future professionals to hone their skills in authentic real-world settings. The evident advantages of immersive learning in the professional training context can be categorized across various domains of human activity, including [4]:

- *Increased engagement and knowledge retention* - immersive tools stimulate multiple senses, which promotes deeper engagement; studies show that knowledge retention increases when learners actively participate rather than passively absorb content);
- *Experiential learning* - immersive environments offer hands-on experience through virtual simulations; medical students, for example, can perform surgeries in VR, gaining confidence without real-life risks);
- *Safe environment for making mistakes* - learners can practice and make mistakes without real-world consequences; for example, pilots use flight simulators to train in difficult conditions without endangering their lives;
- *Develop and practice complex skills* - fields such as engineering and healthcare require mastery of complex tasks; immersive technologies allow learners to practice repeatedly, honing motor skills and critical thinking);
- *Global and remote access to learning* - using immersive platforms, learners from anywhere can collaborate in the same virtual environment, facilitating distance learning programs.

Immersive technologies have the potential to transform education and vocational training, allowing learners to engage in learning in safe, realistic, and risk-free environments using immersive simulations of real work environments. The utilization of a virtual reality module in an educational setting facilitates the acquisition of practical skills in a risk-free, engaging, and demanding environment, thereby enhancing students' readiness for the professional realm.

It is imperative to acknowledge the accelerated advancements in technology, which are progressively broadening the scope of virtual reality's integration into contemporary learning methodologies. This proliferation of possibilities renders the technology potentially obsolete even before its formal incorporation into the educational and training curricula of future professionals [5].

3. A brief overview of virtual, augmented and mixed reality tools

Immersive technologies, including VR, AR and MR, have emerged as innovative tools to enhance educational experiences by integrating digital content with learning environments. The utilization of these instruments fosters distinctive functionalities, thereby facilitating interactive and experiential learning methodologies [6, 7]. These instruments empower learners to engage with academic materials in a more profound manner:

- *Virtual reality* has emerged as a significant technological advancement in recent years, with applications ranging from entertainment to education and beyond. VR engenders a sense of total immersion in a digital environment, effectively isolating users from the physical world. Through the use of virtual reality headsets and motion-tracking devices, learners are able to explore simulated spaces, perform virtual experiments, or participate in interactive scenarios. The utilization of VR technology has gained significant traction across diverse disciplines, including medicine, engineering, and architecture. This technological advancement facilitates the execution of procedures and operations in a controlled and risk-free environment, thereby promoting skill development and training for practitioners in these fields.
- *Augmented Reality* is a technology that overlays digital content onto the physical world using smartphones, tablets or augmented reality glasses. In contrast to the immersive experience offered by VR, AR enables learners to maintain a connection with

their physical environment while engaging with virtual content or information in real-time. The technology has applications in science education, language learning, and fieldwork, as it provides contextual information or enhances physical models with digital elements.

- *Mixed Reality* combines the virtual and physical worlds so that digital elements not only appear in the real environment, but can also interact with it. The utilization of MR headsets enables learners to interact with virtual objects in a manner that is indistinguishable from real-world interactions, rendering it an optimal medium for technical training and collaborative endeavors. The utility of MR is particularly evident in fields such as engineering and product design, where learners require the ability to visualize complex processes in an interactive environment.

Nowadays, the most popular VR Headsets are shown in the figure below:



Fig. 1 1) Meta Quest 3; 2) Lenovo ThinkReality VRX; 3) HTC VIVE Focus 3; 4) PICO 4 Enterprise.

4. A discussion of potential applications and benefits of educational immersive technologies

A growing body of research has identified a correlation between certain applications and the subsequent benefits associated with immersive learning [8, 9, 10]:

- *Efficacy*: The efficacy of hands-on, immersive training is well-documented. This training method has been shown to increase confidence in on-the-job performance, leading to improved skills, knowledge retention, and behavior transfer. These devices have been shown to enhance the retention of material.
- *Efficiency*: The efficiency of the system is such that a training period that previously required a full day can now be completed in as little as 15 minutes, without compromising the desired results. Immersive training has been demonstrated to enhance focus, accelerate skill acquisition, and enable multiple individuals to learn simultaneously in an interactive environment.
- *Cost-effectiveness*: The issue of cost-effectiveness is paramount in the context of traditional training. This training method entails various expenses, including travel costs, organizer salaries, expert fees, and room and equipment rental. Immersive training eliminates the need for these by offering reusable modules and increasing productivity.
- *Standardization*: The standardization is often compromised due to variations in training programs, which can be attributed to differences in instructor location and expertise. These inconsistencies can lead to variations in the quality and effectiveness of training programs. Immersive training provides a standardized, repeatable experience that can be easily scaled across the organization. The translation of modules into different languages serves to ensure uniformity across regions and cultures.
- *Measurement*: The measurability of outcomes is a critical component of immersive technology training. This training utilizes xAPI data tracking to assess learner readiness, ensuring the accuracy and reliability of the measurement process. The process of

personalization and performance assessment entails the utilization of metrics such as decision-making, task completion time, and performance deviations. Indeed, this combination serves to maintain the engagement of the learning process.

- *Security and safety:* In environments characterized by elevated risk levels, errors can have deleterious consequences that may result in severe injury or death. Immersive training provides a risk-free environment in which learners can safely participate in complex scenarios and learn from their mistakes.

Immersive technologies have been shown to complement each other, with each offering unique benefits for different educational needs. The utilization of these tools fosters engagement, facilitates hands-on skill development, and encourages problem-solving, all of which are paramount for a new generation of professionals [11]. As these instruments become increasingly available, their incorporation into educational settings, such as classrooms, laboratories, and professional development programs, will undergo significant expansion. This integration will precipitate a fundamental shift in the manner by which knowledge is transmitted, acquired, and transferred.

Table 1: Examples of applications in various fields.

Field	Description
Medicine	Virtual reality has been incorporated into surgical training regimens, enabling learners to execute intricate medical procedures on virtual patients. Augmented reality (AR) applications offer the capability to overlay anatomical structures onto a three-dimensional model of the human body.
Military and Defence	Virtual simulations are utilized to equip military personnel with the skills necessary to respond effectively to combat scenarios and disaster situations by enhancing their decision-making abilities under high-pressure circumstances.
Aviation	Pilots and crew members are subjected to an intensive training regimen that utilizes a variety of simulators to instruct them in both routine procedures and emergency responses.
Architecture and design	Augmented and virtual reality tools facilitate the visualization of three-dimensional structures, enabling learners to assess their designs in real time.
Engineering	The utilization of virtual, augmented and mixed reality facilitates the design and evaluation of prototypes through the employment of holographic instruments.
Business skills and leadership	Immersive simulations have been shown to facilitate the development of leadership skills by subjecting participants to high-pressure business scenarios, thereby enhancing their problem-solving abilities.
Foreign Language	The integration of VR and AR technologies with artificial intelligence (AI)-powered language learning tools has the potential to offer an even more immersive and interactive learning experience.

Source: created by the author

5. Conclusion

The past decade has seen a particular move towards the integration of various new technologies in education and training, including immersive technologies. The integration of these technologies into the educational environment has been shown to enhance teaching and experiential learning, promote engagement, and link theoretical knowledge with practical skills. The present study is an ongoing investigation and examination of immersive technologies as an innovative educational approach. This investigation has yielded several key conclusions related to the tasks outlined in this article. These conclusions suggest that immersive technologies have the potential to create numerous opportunities and benefits for education and training systems.

In the context of technological development, these tools offer new educational opportunities and benefits for learners by promoting interactive and experiential learning for better theoretical knowledge and its practical application. Therefore, immersive technologies have their significant potential and role in the

development of educational approaches, respectively in quality improvement.

The analysis of previous state-of-the-art experimental studies contributed to drawing relevant conclusions about the appropriateness and high effectiveness of using educational immersive technologies for teaching university students. This finding indicates that immersive environments can effectively enhance students' motivation, problem-solving abilities, and critical thinking skills. Nevertheless, in order to obtain more objective conclusions, additional field studies and observations are necessary to directly address these issues.

In conclusion, it can be posited that immersive technologies represent an essential component of modern educational approaches, providing future professionals with the competencies needed in evolving, technology-driven industries. The examples presented in this study lay the foundation for further research and projects at both the theoretical and practical level. Subsequent researchers may wish to direct their attention to the exploration of factors that enhance learner motivation through interactive learning.

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