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Wear Performance of Agricultural Harrow Discs Coated by Plasma-Jet Thermal Deposition

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Abstract: A comparative analysis of wear performance of coated harrow discs by plasma-jet thermal deposition was evaluated under agricultural conditions to assess the performance of atmospheric plasma spraying systems. This paper presents a long-term comparative field evaluation under identical operating conditions on a quartz-rich argic luvisol soil. Disc wear was quantified by periodic measurements of mass loss and diameter of the studied discs.

The uncoated disc showed the most severe degradation, with a total mass loss of approximately 700 g and a rapid acceleration of wear after the first 5-10 ha of harrowing. The results obtained under field conditions demonstrate that the microstructural integrity of the coating is more critical than the nominal hardness and highlight the superior effectiveness of APS ceramic coatings for extending disc life in abrasive agricultural soils.

KEY WORDS: WEAR PERFORMANCE, HARROW, DISCS, PLASMA-JET THERMAL DEPOSITION, PLASMA SPRAYING SYSTEMS.

Introduction

Agricultural machinery components that interact with the soil, such as disc harrows, plowshares, tines, and other soil-cultivating elements, operate under conditions characterized by high abrasion and impact loads. During soil cultivation, the harrow disc blades are also subject to significant wear due to abrasive soil particles such as sand, small and big stones, and other hard materials that accidentally get into the soil.

Modern agricultural production relies on mechanized soil cultivation tools, such as plowshares, cultivators, disc harrows, cultivator blades, seed drill disc coulters, etc. These soil-engaging tools loosen, aerate, and mix the soil, and are essential for preparing the seedbed and ensuring crop emergence. Constant exposure to abrasive soil, rocks and agricultural residues inevitably leads to wear, which has a direct impact on operational efficiency and costs. Research shows that wear and tear is responsible for over 50% of agricultural machinery failures and can usually only function optimally after replacement.

Analysis of recent research and publications

All soil-working machines wear out faster with increasing sand content in the soil. This requires improving the mechanical properties of the working surfaces of the working parts of the machines mentioned above [1]. So, their constant exposure to soil, mineral particles, crop residue, and stones leads to progressive material degradation, affecting cutting efficiency and increasing fuel consumption to maintain consistent tillage quality [2].

Disc harrows require frequent replacement of heavily worn discs, which increases both downtime and maintenance costs, factors that are particularly important on large farms [3]. Increasing the wear resistance and service life of discs is essential for economically and environmentally sustainable agricultural production.

Insufficient wear resistance reduces the reliability and productivity of mechanized agriculture, potentially jeopardizing the efficiency of field work and even crop yields. Excessive wear of tillage machines changes the geometry, rounding the cutting edge or reducing their functional dimensions with an impact on the efficiency of soil work, increasing traction, and fuel consumption.

Extending the service life of agricultural machinery components is directly related to increasing energy saving, agricultural efficiency, and ultimately, economic sustainability. Therefore, the wear resistance of tillage tools is a priority for modern agriculture. It can be concluded that the best solutions should aim to increase surface hardness and structural strength to resist abrasion, while maintaining sufficient impact resistance [4].

Roșu et al. point out that the reduction in thickness and the loss of diameter of disc coulters of seed drills strongly depend on

the physical, mechanical and technological properties of the soil, including the presence of hard mineral inclusions (stones) [5].

Despite numerous studies on the wear of agricultural discs and soil tillage tools, most published work focuses on laboratory tests, short-term field studies or evaluations of a single coating system. However, comparative studies conducted under identical field conditions over the long term, including both coated and uncoated reference discs, remain limited.

The novelty of this study lies in the simultaneous long-term comparison of coating systems and an uncoated reference disc, operating under identical working conditions such as mechanical loads, soil profiles, working depths and speeds. Unlike previous studies, the discs were evaluated on an area of over 50 hectares per disc in quartz-rich argic luvisol soil, which allowed to identify nonlinear wear behavior and degradation mechanisms in advanced stages.

The most common solution for protecting tillage implements from wear used in practice remains hardening with Fe-Cr-C alloys, usually referred to as sormite or white high-chromium cast iron coatings. These coatings, usually applied by arc welding or plasma arc welding, extend the service life of workpieces several times compared to uncoated steel components. This is due to the presence of hard chromium carbides Cr_7C_3 or $(\text{Cr},\text{Fe})_7\text{C}_3$ embedded in a martensitic or austenitic matrix. Compared to sormite coatings, atmospheric plasma spraying (APS) allows for the application of thinner, more uniform, and more controlled coatings with minimal thermal impact on the substrate.

In this context, the present study investigates the wear performance of coated harrow discs by plasma-jet thermal deposition with three powders: Metco 71NS, Metco 136F and Metco 45C-NS, applied using a Sulzer Metco 9MCE atmospheric plasma spraying system [4].

The aim of the research is to conduct a comparative analysis of the wear performance of coated harrow discs by plasma-jet thermal deposition by plasma-jet thermal deposition method in field conditions, followed by an assessment of the effectiveness of atmospheric plasma spraying systems.

Materials and Methods

At the beginning of the study, the elemental composition of a new, uncoated harrow disc was determined using a spark optical emission spectrometer Spark-OES equipped with the SparkTiffe analytical software package [5].

Three 610 mm diameter disc specimens were prepared for coating. The method of preparing and coating the discs has already been described in several works [4, 6, 7].

Seven radial specimens were cut from the cutting edge towards the central area of the new harrow disc (Figure 1). The resulting chemical composition values were used as initial data for

correlating the substrate material with coating adhesion, microstructural behavior, and field wear performance.

Uniform melting of the powders produces dense, well-bonded deposits:

- Metco 71NS ($W_2C/WC-12Co$) supply a hard carbide surface suitable for use in highly abrasive soils;
 - Metco 136F ($Cr_2O_3-SiO_2-TiO_2$) provides a ceramic coating with high hardness, good impact absorption due to its silicon dioxide content, and excellent corrosion resistance;
 - Metco 45C-NS ($Co-Cr-Ni-W-C$) produces a metallic coating called Stellite with balanced strength and wear resistance, suitable for surfaces subject to combined abrasive and impact loads.
- These powders cover a broad functional spectrum of ceramic, carbide and cobalt metal systems, allowing for comparative evaluation of different harrow disc wear protection strategies in the field.

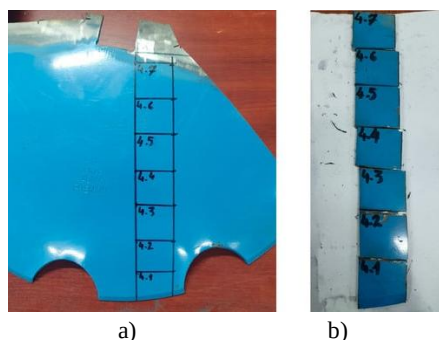


Figure 1. Studied radial samples:
a) radial marking and segmentation of the disk surface before cutting; b) extracted radial samples.

The coatings were applied to both sides of each harrow disc, forming a continuous ring-shaped coating around the entire working perimeter [6].

The coatings were applied to both sides of each harrow disc, forming a continuous ring-shaped coating around the entire working perimeter. Microstructural characterization of coated and uncoated disc samples was performed by scanning electron microscopy (SEM), which can provide detailed information about surface morphology, coating microstructure, wear patterns, and particle distribution [7].

An OTMA heavy disc harrow with a 4.0 m working width was used for field testing. These harrows are equipped with four groups of 10 concave discs (two groups in front and two in the rear). The test discs, both coated and uncoated, were mounted on the harrow's front axle at an attack angle of 15° relative to the direction of travel. This configuration improves soil penetration, crop residue removal, and lateral soil movement, as well as ensuring effective stubble incorporation and uniform soil cultivation across the entire working width. The disc harrow under study was coupled with a medium-sized John Deere 7230 tractor with a power of 230 hp.

The test disc harrow was coupled to a mid-size John Deere 7230 tractor with 230 hp and a powershift transmission with high hydraulic capacity, providing consistent traction and allowing precise control of working speed and tillage depth.



Figure 2. Installed testing discs on the harrow before field testing:
1) three coted discs; 2) uncoted discs.

During field trials, stubble disking was performed after grain harvesting (Figure 3). The disc harrow under study cultivated 1,000 hectares of land, meaning each disc on the two front axles cultivated 50 hectares.

According to agronomic recommendations, the main operating parameters were:

- working depth of 0.15 m;
- forward speed of 7-8 km/h.



Figure 3. Tractor and 4-metre OTMA disc harrow during stubble field work

Since all discs were exposed to the same soil profile and operating parameters during the disking operation, differences in wear can be attributed primarily to surface characteristics rather than positional influences.

According to the methodology, disk weight measurements were taken regularly, every 20 hectares of the total treated area, corresponding to 1 hectare per disk. Before weighing, the disks were thoroughly cleaned of soil residue and dried. The weight of each disk was measured using a calibrated digital scale with an accuracy of ± 1 g. For each weighing, three consecutive measurements were taken, and the average value was determined. The measurement error for the disk mass was less than ± 2 g, which is negligible compared to the observed mass loss.

Diameter measurements were taken using a digital caliper with an accuracy of ± 0.02 mm. The diameter of each disk was determined by measuring it in two sections and calculating the average value. This procedure allowed to identify uneven edge wear and reduce measurement variability.

To assess disk wear, four test disks (three coated and one uncoated) were weighed every 20 hectares of total cultivated area (i.e., 1 hectare per disk). This allowed us to accurately determine mass loss and increase in disk wear with increasing cultivated area.

Thus, all tested discs were subjected to identical the same operating parameters (field soil profile, operating travel speed, working depth, uniform residue load and disc attack angle), which ensured that any differences in wear could be attributed solely to the material and coating characteristics of the samples.

Results and discussions

Measurements of the disc masses taken before and after the coating process reveal differences in the amount of material deposited on each disc tested (Table 1).

Table 1. Mass of the disks before and after coating application

No	Disc	Coating Type	Initial Mass (kg)	Coating Mass (kg)	Final Mass (kg)
1	Sample 1	$Cr_2O_3-SiO_2-TiO_2$ Ceramic	10.483	0.105	10.588
2	Sample 2	WC/W_2C-Co Carbide	10.492	0.127	10.619
3	Sample 3	$Co-Cr-Ni-W-C$ alloy	10.481	0.116	10.597
4	Uncoated Sample	No coating	10.486	0	10.486

The dynamics of disc wear, expressed as mass loss in the range of 0–50 ha/disc, reveals significant differences between the three coated discs and the uncoated disc (control). All four curves shown

in the graph demonstrate nonlinear behavior, namely, low wear rates in the early stages of operation, followed by a gradual acceleration of mass loss as the total worked surface area increases (Figure 4). This trend reflects the typical behavior of tillage tools, which before the start of work (testing) had sharp edges and smoother working surfaces, but gradually with an increase in the processed field area, wear increases, since, being subjected to increasingly intense abrasion, the edges become rounded and the contact area of the soil with the metal of the disks increases. The uncoated (control) disc exhibits the steepest wear curve.

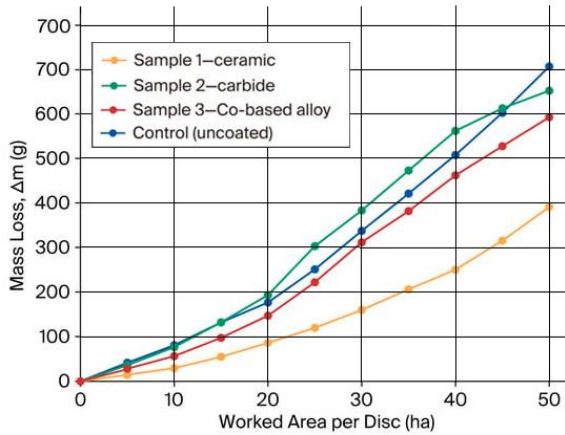


Figure 4. Mass loss of coated and control (uncoated) discs as a function of worked area of the treated surface per disc

Compared to all the samples tested, Sample 1 demonstrates the best results. The wear curve remains virtually flat over the first few hectares (10 hectares), and even over an area of 25 hectares, the weight loss is limited (0.15 kg). After this point, wear accelerates somewhat, but the total weight loss over an area of 50 hectares remains minimal at 0.39 kg. This behavior indicates the excellent long-term stability of the ceramic coating, especially in abrasive soils rich in quartz.

The wear curves, plotted against disc diameter and constructed for an effective operating range of 0–50 ha/disc, provide information on the degradation of the disc samples studied during field work. As expected for components in contact with the ground, all four discs show a non-linear reduction in diameter, with relatively low wear in the initial stage of operation, followed by gradually accelerating degradation towards the end of the the operating range.

This type of wear is typical of abrasive wear, where the disc edges initially retain a sharp geometry, but as the blade becomes dull (rounded), contact with the soil intensifies and material removal accelerates. The control (uncoated) disc exhibits the steepest wear trajectory, resulting in an overall diameter reduction of about 26 mm after 50 hectares of worked area per disc (Figure 5).

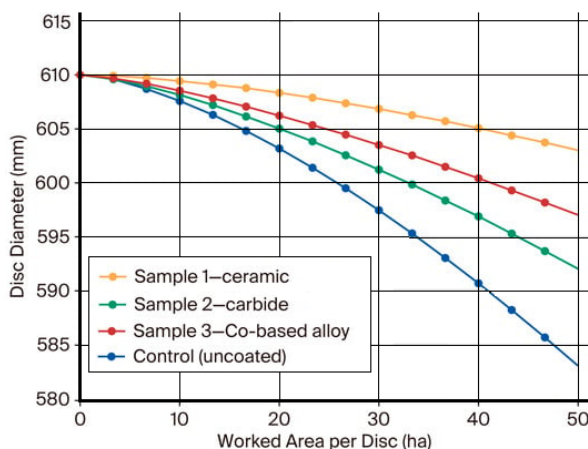


Figure 5. Variation of disc diameter as a function of the worked area per disc

The curve shows the most pronounced acceleration, confirming the susceptibility of untreated carbon steel to abrasive action in quartz-rich soils. This rapid wear in the later stages is consistent with previous studies reporting that unprotected agricultural harrow disc blades lose their geometry more quickly after the cutting edge becomes dull.

Sample 1 exhibits the smallest disc diameter loss after 50 hectares of work per disc and maintains the largest diameter throughout the entire test period. Sample 1 demonstrates the best results, with a final diameter loss of 7 mm. Its curve has the flattest slope, indicating that the ceramic coating effectively slows edge rounding and maintains the harrow disc's geometry significantly longer than discs with other processing methods.

Sample 3 demonstrates intermediate results, with a final diameter loss of 14 mm. The curve lies between the values for the ceramic and carbide coatings, reflecting the balance between strength and moderate hardness characteristic of cobalt alloys. The results of Sample 2 were better than those of the uncoated disc, but worse than those of the ceramic-coated (Sample 1) and alloy-coated (Sample 3) discs.

Compared to the uncoated (control) disc, the tested coated variants demonstrated significantly different wear reductions. The ceramic-coated disc (Sample 1) reduced overall weight loss from approximately 700 g to 390 g after 50 ha, representing a weight loss reduction of approximately 44%. The cobalt-based alloy coating (Sample 3) provided a more modest reduction of approximately 16%, while the carbide-coated disc (Sample 2) showed only a slight improvement of approximately 7%.

Similar trends were observed for disc diameter wear. The uncoated disc (Sample 1) lost about 26 mm in diameter, while the ceramic coating limited the diameter loss to approximately 10 mm (a 62% reduction). The Co-based alloy (Sample 3) and carbide coatings of Sample 2 reduced diameter loss by 46% and 31%, respectively.

Based on these trends, the ceramic coating provides approximately 1.8 times the wear life of an uncoated disc in field testing conditions ranging from 0 to 50 hectares per disc, while the cobalt-based alloy and carbide coatings increase wear life by approximately 1.2 and 1.1 times, respectively.

The minimum working diameter of a worn harrow disc depends on its initial size, but typically discs with a diameter of 620–660 mm should be replaced when they wear down to 500–520 mm. If the diameter is critically reduced more than 100–150 mm from the initial diameter, the disc no longer penetrates effectively and processes the soil efficiently.

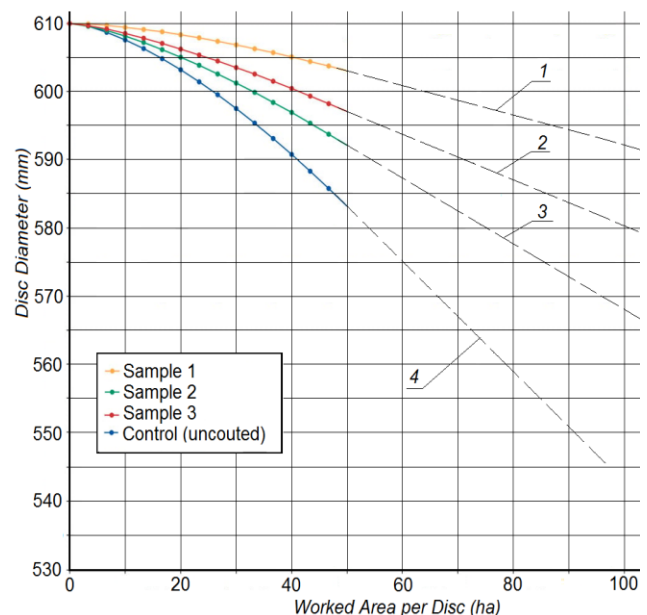


Figure 6. Experimental and theoretical method for expanding the variation of disc diameter as a function of the worked area per disc: 1 - Sample 1; 2 - Sample 3; 3 - Sample 2; 4 - uncoated disc.

A disc is considered worn out when its diameter decreases by 15-20% of the original, which critically affects the angle of attack and the depth of soil cultivation [8, 9].

The use of heavily worn discs leads to a decrease in the quality of stubble processing and increased fuel consumption.

If we continue the curves shown in Figure 5, we see that the minimum operating period of uncoated harrow disc is 0-150 hectares of processed area per disc or more precisely less than 110 ha/disc (Figure 6, curve 4). The uncoated disc will reach its maximum permissible wear at a minimum diameter of 530 mm. In Figure 6, we see that the minimum operating period of a ceramic-coated disc (Sample 1) is more than 0-150 ha/disc (Figure 6, curve 1) and it will also reach the maximum permissible wear at a minimum diameter of 530 mm.

However, it remains unclear how ceramic-coated discs Sample 1 and other Samples will perform in the future due to blade rounding as a result of wear, and changing of disc diameter (Figure 5, curve 1, 2, 3).

In this study, the APS ceramic coating provided an estimated increase in service life of approximately 1.8 times based on the mass loss factor and approximately 2.6 times based on the diameter retention factor, indicating that, depending on the functional failure criterion, thin APS ceramic coatings can approach the lower and mid-range performance reported for conventional hardfacings while providing improved thickness control and reduced geometric variations.

The wear assessment in this study was based primarily on quantitative measurements of mass and diameter loss, supplemented by previously performed microstructural analysis of the applied coatings using a scanning electron microscope.

Further research could be expanded to include field experiments until the discs coated by plasma-jet thermal deposition method are completely worn out.

Conclusions

1. This study examined the wear performance and behaviour of harrow discs coated by plasma-jet thermal deposition method with three different thermal spray systems:

- 1) Sample 1 - $\text{Cr}_2\text{O}_3\text{-SiO}_2\text{-TiO}_2$ ceramic;
- 2) Sample 2 - $\text{WC/W}_2\text{C-Co}$ carbide;
- 3) Sample 3 - Co-Cr-Ni-W-C alloy.

Their performance was compared with an uncoated (control) disc under field operating conditions.

2. Compared to the uncoated (control) disc, the tested coated variants demonstrated significantly different wear reductions. The ceramic-coated disc (Sample 1) reduced the overall weight loss by approximately 44%, the cobalt-based alloy-coated disc (Sample 3) had a reduction of approximately 16%, and the carbide-coated disc (Sample 2) only showed an improvement of approximately 7%. The results obtained in the field confirm that the microstructural stability of the coating determines the long-term wear resistance of harrow discs, and not only its density or nominal hardness.

3. Based on these trends, the ceramic harrow disc coating provides approximately 1.8 times longer disc life than the uncoated disc in field trials covering 0 to 50 hectares per disc, while cobalt-based alloy and carbide coatings increase disc life by approximately 1.2 and 1.1 times, respectively.

4. The research results clearly show that applying coatings to the surface of harrow discs can significantly reduce mass loss and extend their service life, and the degree of improvement largely depends on the coating materials.

5. The research results show that $\text{Cr}_2\text{O}_3\text{-SiO}_2\text{-TiO}_2$ ceramic coatings (Sample 1) represent a very perspective solution for increasing the durability of disc harrows operating in abrasive soil environments and significantly reducing wear of the discs coated by plasma-jet thermal deposition.

6. This study highlights the value of combining laboratory research with long-term field trials. The integration of scanning electron microscopy analysis, chemical profiling, and long-term performance data allows for more accurate predictions of coating performance than any laboratory test alone.

7. Further research could be expanded to include field experiments until the discs coated by plasma-jet thermal deposition method are completely worn out. Future research should expand field tests to study how ceramic-coated discs Sample 1 and other Samples will perform in the future due to blade rounding as a result of wear, and changing of disc diameter (Figure 5, curve 1, 2, 3).

Acknowledgments

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Experimental determination of the limit values of longitudinal accelerations of a motorcycle leading to loss of stability

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Abstract: Road experiments were conducted - when accelerating the motorcycle to the limit values of longitudinal geometric stability and the loss of contact of the front wheel with the road or reaching the "wheelie" phenomenon. From the theory of the motorcycle it follows that the critical accelerations depends on the height of the center of mass and its horizontal coordinate. In the presence of a passenger, the center of gravity is moved back and up, which leads to a decrease in the theoretical value of these accelerations. Therefore, the experiments were conducted on a motorcycle equipped with a suitcase and a passenger located on the back seat. The received information is recorded and visualized on a portable computer, and then processed in the Matlab and Excel environment. The results obtained from the experiments and the accumulation of databases can be used to create models for determining the influence of the driver's behavior, the passenger's influence, models for determining the behavior of the motorcycle and the comfort of the trip. During the measurements, the change in position of the driver and passenger is not taken into account.

Keywords: Motorcycle acceleration, wheelie, traffic safety, pitch angle, longitudinal accelerations

1. Introduction

The stability of two-wheeled vehicles during acceleration and braking is of critical importance for traffic safety. Transitions between these modes are particularly critical, as they lead to a great redistribution of weight between the front and rear wheels, changing the traction and dynamic characteristics of the system, leading to rear wheel slippage (during acceleration), locking or lifting of the rear wheel (during braking), or even complete loss of control. When a two-wheeled vehicle accelerates, the additional load on the rear wheel, which occurs due to the redistribution of the load, increases its traction, but at the same time the load on the front wheel decreases, which leads to instability in steering and limited ability to turn [1, 2]. When reaching the limit values of longitudinal acceleration, unstable conditions occur such as lifting the front wheel (wheelie), lifting the rear wheel (stoppie), slipping or complete loss of traction and reduced rolling resistance. In the scientific literature, theoretical and numerical models for the analysis of motorcycle instabilities are based on nonlinear tires (e.g. Pacejka model), multi-body simulations, and modal decomposition [3,4 and many others]. However, many of these approaches rely on simplifications that do not always reflect the real behavior of motorcycles under limit loads. Experimental determination of the critical accelerations is an important step towards validating these models and gaining a deeper understanding of the instability dynamics of two-wheeled vehicles. The use of inertial measurement units (IMU), sensors and GPS systems allows for highly accurate registration of motion parameters, including wheel slip, slip and change in the center of load [5,6,7 and other].

2. Importance of the mass center and theoretical limit values

The coordinates of the motorcycle's center of mass have a significant impact on its dynamic behavior, especially in acceleration and braking modes. In modern motorcycles, the tendency is for the load to be evenly distributed on both axles. This results in good motorcycle handling both during acceleration and braking. If the center of mass is positioned forward (the load on the front wheel is greater than on the rear wheel), better resistance to loss of contact between the front wheel and the road is achieved. Another advantage is the partial compensation of aerodynamic forces, which relieves the front wheel, which is particularly important for driving safety, especially at high speeds. If the center of mass is positioned rearward (the load on the rear wheel is greater than 50%), better braking properties of the motorcycle are achieved, and the risk of loss of contact between the rear wheel and the road and the occurrence of a longitudinal rollover is reduced.

The position of the total center of mass of the motorcycle, together with the rider, is shifted rearward and the rear wheel is loaded further.

The vertical coordinate of the center of mass h has a significant impact on the stable behavior of the motorcycle, especially in acceleration and braking mode. The high position of the center of mass during acceleration leads to a greater redistribution of load from the front to the rear wheel. With a higher load on the rear axle, more driving force can be applied, but stability during acceleration deteriorates and loss of contact between the front wheel and the road can occur if the vertical reaction in it becomes equal to zero.

In case of sudden acceleration in low gear, the amount of acceleration can be limited by the traction between the tire of the driving wheel and the road. Since the air resistance force is a function of the speed squared, maximum acceleration can be achieved at very low speeds in first gear on a smooth, improved road surface. In this case, it can be assumed that drag force $F_D=0$. The maximum acceleration is limited by traction, since the tangential reaction at the driving wheel cannot exceed the corresponding traction force, or the maximum driving force must be less than or equal to the maximum force obtained by the product of the adhesion coefficient μ and the vertical load [1]:

$$S \leq \mu N_r \quad (1)$$

where S indicates the driving force during acceleration, N_r normal reaction in the rear wheel.

Expressing the normal load, for the maximum acceleration in traction we get:

$$\ddot{x} \leq \frac{\mu g \frac{p-b}{p}}{\left(1 - \frac{h}{p}\right)} - \frac{F_D}{m} \quad (2)$$

The condition under which the loss of contact between the front wheel and the road will occur is met when the normal reaction in it becomes equal to zero ($N_f = 0$). In order to ensure stable movement of the motorcycle during acceleration without allowing loss of contact between the wheel and the road, it is necessary to fulfill the condition::

$$\ddot{x} \leq g \frac{b}{h} - \frac{F_D}{m}, \quad (3)$$

The present study aims to determine the limit values of longitudinal acceleration that lead to loss of stability of a motorcycle during acceleration. To achieve this goal, an experimental methodology has been developed, based on tests in a controlled environment (test track) with equipment for recording motion parameters, including linear and angular accelerations.

3. Selection and location of measuring equipment

In this study, a microelectromechanical system MEMS WT901 AHRS IMU sensor was used to measure horizontal and vertical acceleration in combination with a portable laptop on which the measurement data was recorded. It consists of a high-precision gyroscope, an accelerometer and a geomagnetic field sensor. The device can quickly determine the current real-time movement position of the module using a high-performance microprocessor, advanced dynamic solutions and the Kalman filter algorithm. The advanced digital filtering technology of this product can effectively reduce measurement noise and improve measurement accuracy. Maximum output data rate 200Hz. The output content can be arbitrarily selected, the output rate is adjustable from 0.2Hz to 200Hz. The parameters of the measuring device are presented in Table 1, and the measurement range and accuracy are in Table 2 [9].

Table 1: Equipment parameters.

Parameter	Specification
Working voltage	3.3V-5V
Current	< 25 mA
Dimensions	15.24mm x 15.24mm X 2.54mm
Data	Angles: X Y Z, 3-axis acceleration: X Y Z, 3-axis angular velocity: X Y Z, 3-axis magnetic field: X Y Z, 3-axis time, Quaternion
Output frequency	0.2Hz-200Hz
Baud rate	4800,9600(default),19200, 38400, 57600, 115200, 230400

Table 2: Measurement range and accuracy.

Measurement range and accuracy		
Sensor	Measurement range	Accuracy
Accelerometer	X, Y, Z, 3-axis $\pm 16g$	Accuracy: 0.01g, Resolution: 16bit
Gyroscope	X, Y, Z, 3- axis $\pm 2000^\circ/s$	Stability: 0.005g
Magnetometer	X, Y, Z, 3-axis ± 2 Gauss	Resolution: 16bit
Inclinometer	X, Y, Z, 3- axis X, Z-axis: $\pm 180^\circ$, Y $\pm 90^\circ$	Stability: 0.05°/s

Conducting road tests on a motorcycle is always a challenge and carries risks for both the rider and the measuring equipment. The placement of the measuring equipment is often a problem due to the limited space and mounting options. The accuracy and reliability of the measurement is largely influenced by the correct placement of the sensor. In the present study, the MEMS device used to measure accelerations and rotations is mounted on the motorcycle tank in a horizontal position, as close as possible to the motorcycle's center of mass (Fig. 1).



Fig. 1 Installation of the measuring equipment

4. Organization of the experiment

To determine the limit values of the motorcycle acceleration in acceleration mode, a series of experiments were conducted on a smooth horizontal section of the road surface in both directions. The test is carried out on a motorcycle with the participation of a driver and a passenger. It begins when the motorcycle is at rest. The recording is started by the passenger, and the driver engages first gear and accelerates the motorcycle along a straight trajectory by abruptly releasing the clutch until the front wheel loses contact with the road. Then the motorcycle stops accelerating and begins a smooth and safe braking to complete rest. A few seconds later, the recording equipment is stopped and the experiment is repeated. The average duration of the experiments is about 15 - 20 seconds. Before the experiment, the motorcycle tires were heated. The results obtained are compared with the minimum theoretical accelerations.

For the test motorcycle, through which the limit accelerations were experimentally determined, a BMW R1200 GS 2014 motorcycle was used. The motorcycle is factory-equipped with active safety systems ABS, TC and ESP, which can be switched off at the driver's request. The motorcycle parameters are listed in Table 3. Before the start of the experiments, the motorcycle was filled with fuel until the tank was full. The tire pressure was according to the manufacturer's instructions - 2.5 bar in the front and 2.9 bar in the rear.

Table 2: Measurement range and accuracy.

Parameter	Dimension	Value
Engine		
Volume, V_h	m^3	1170
Diameter/ Stroke, D/S	mm	101/73
Power, N_e	kW	92
By rpm n_N	min^{-1}	7700
Torque, M_e	Nm	125
By rpm n_M	min^{-1}	6500
Number of cylinders	i	2
Type		Air/water cooled, spark-ignition horizontal boxer engine
Number of valves per cylinder		4, Intake d=40 mm, Exhaust d=34 mm,
Exhaust system		3-component catalytic converter
Transmission		
Clutch		anti-hopping wet
Gearbox		Constant mesh 6-speed gearbox
Primary transmission ratio		1
Transmission input ratio		1,650
First gear i_1		2,438
Second gear i_2		1,714
Third gear i_3		1,296
Fourth gear i_4		1,059
Fifth gear i_5		0,943
Sixth gear i_6		0,848
Gear ratio of final drive i_f		2,91
Final drive		Cardan shaft
Frame		
Type		Tubular steel frame with supporting drive unit, steel pipe rear frames

Suspension		
Front suspension		Telelever
Suspension travel	mm	190
Rear Suspension		Cast-aluminium single swingingarm with BMW MotorradParalever
Suspension travel	mm	220
Trail, a	mm	100
Geometrical parameters		
Wheelbase	p	1507 mm
Castor angle ε	o	25,5
Distance from front axle to center of mass*	a	739 mm
Distance from rear axle to center of mass*	b	768 mm
Brake system		
Front	mm	Hydraulically actuated twin-discbrake with 4-piston radial monobloc calipers and floating brake discs, 305 mm
Rear		Hydraulically operateddiscbrake with 2-piston floating caliper and fixed disc, 276 mm
ABS		Integral, partially integral, switchable
Wheels and tyres		
Front tyre, r_f		120/70R19
Rear tyre r_r		170/60R17
Overall dimensions and weight		
Length, L	mm	2207
Width with mirrors, B	mm	953mm
Seat height, H_s	mm	850/870
Mass, m	kg	238
Weight distribution	%	51/49
Permissible total weight, m_t	kg	450
Tank capacity	L	20
Driver		
Own mass	kg	103
Passenger		
Own mass	kg	45

Due to the presence of vibrations from the engine and others, some error is inevitably introduced into the measurements .

5. Experimental results

According to equation 1, the condition at which the loss of contact between the front wheel and the road will occur is when:

$$\ddot{x} = g \frac{b}{h} - \frac{F_D}{m}$$

The calculation assumes that the entire mass of the passenger is assigned to the rear axle, and that of the driver is distributed in half between the front and rear axles.

Unlike automobile, the frontal area of a motorcycle is not constant. It is strongly influenced by the position and body of the rider and the presence of additional equipment. On some motorcycles, the fairings and windshield are available with different height and width settings. Therefore, it is difficult to determine the force from aerodynamic resistance theoretically with accuracy. In all cases, the speed of the motorcycle does not exceed more than 8,5m/s. The aerodynamic coefficient of the motorcycle is about $c_x=0.7$. The frontal area of the motorcycle without taking into

account the rider's participation is approximately $S=0,8$. Since the speed at which the front wheel loses contact with the road surface is relatively small in contrast to the acceleration achieved, in order to simplify the inequality, the assumption will be made that the aerodynamic force is approximately equal to zero. This assumption does not introduce an error of more than 0.05 g. According to table1. and the known methods from the literature for calculating the vertical coordinate of the center of mass, for the limiting acceleration is obtain:

$$\ddot{x} \approx 1 \text{ g}$$

The initial phase is characterized by an intense increase in the longitudinal acceleration of the motorcycle which also leads to a significant increase in vertical acceleration. As a result, a significant pitch angle is achieved.

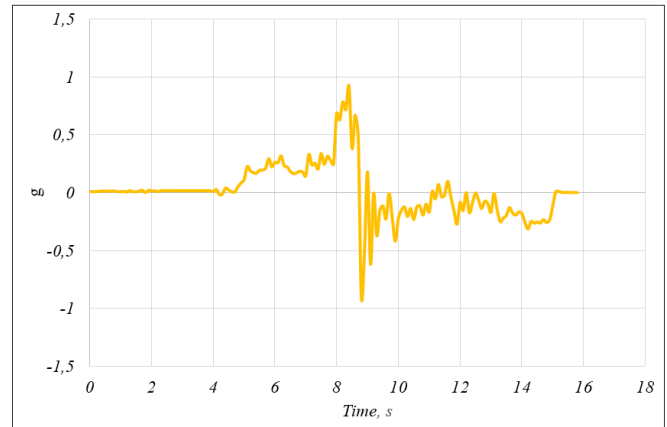


Fig.2 Longitudinal acceleration of the motorcycle

Fig. 2 presents the results of the longitudinal acceleration of the motorcycle. The acceleration begins shortly after the fourth second when the throttle is opened slightly above 50%. The motorcycle is accelerated with first gear engaged until the front wheel lifts off the road surface. The maximum value reached by the acceleration is 0.7 g, which is less than the theoretical value. This is due to the assumptions made in the theoretical calculation. The coefficient of traction is above the ratio b/h , the motorcycle cannot reach maximum acceleration, since the front wheel lifts off. With a smoother increase in speed (smoother opening of the throttle) and a smoother increase in longitudinal acceleration, the loss of contact between the front wheel and the road due to the increase in air resistance will not occur.

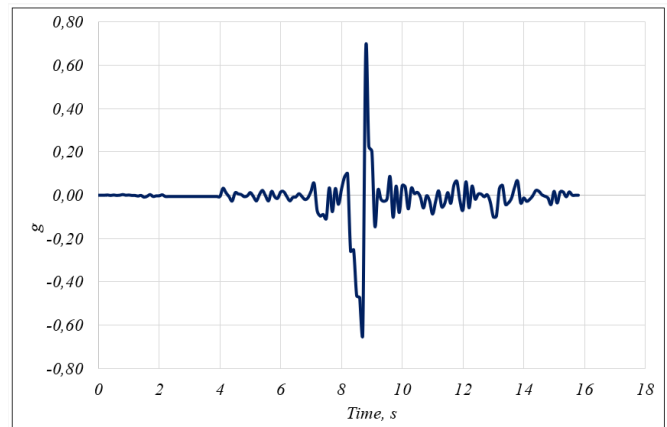


Fig.3 Vertical acceleration

As a result of the load transfer and the significant shift of the coordinate of the center of mass back and up, the normal reaction in the front wheel is exhausted and it loses contact with the road. Fig.3. shows the change in vertical acceleration. The maximum value of the vertical acceleration is 0.7g, which is reached with a delay of about 0.2 s compared to the maximum longitudinal acceleration. After landing of the

front wheel, as a result of the disturbances in the suspension, a slight fluctuation in the acceleration is observed until complete damping.

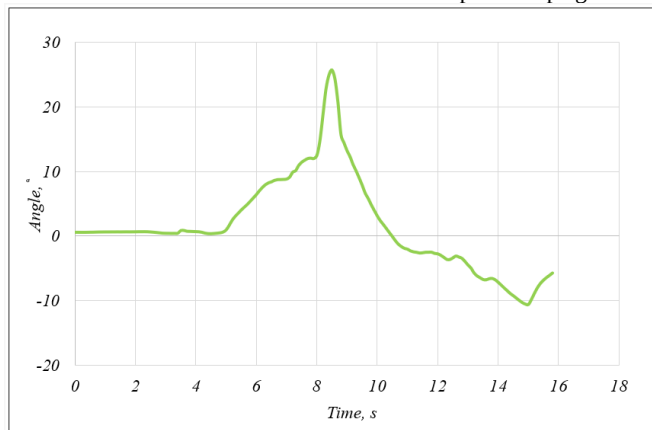


Fig.3 Variation in pitch angle

Fig.4. shows the measured pitch angle of the motorcycle. As a result of the load transfer and the compression in the rear suspension, a smooth rotation of the center of mass occurs. When reaching critical acceleration and lifting the front wheel (wheelie achieved), a jump in the pitch occurs. As a result of the reduction of the acceleration and the reduction of the load on the rear axle, the front wheel is again in contact with the road surface and the roll smoothly decreases. After the wheel lands, a roll in the opposite direction is recorded as a result of the deformation in the front suspension.

Conclusions

In this paper, the limit accelerations calculated theoretically and measured by a field experiment are presented. At the beginning, the influence of the center of mass and the redistribution of the load on the front and rear axles are clarified.

In an attempt to limit road accidents, the requirements for the active and passive systems of vehicles are increasing, which necessitates their constant improvement. This pressing topic is especially true for two-wheeled vehicles. The stability of the motorcycle's movement during acceleration and braking is of great importance for the safety of the driver and passenger. The transitions between these modes are particularly critical, as they lead to a sharp redistribution of weight between the front and rear wheels, changing the traction and dynamic characteristics of the system.

This emphasizes the need to accumulate knowledge and experience about the dynamic behavior of the motorcycle through road experiments in different modes. The focus of the study is on detecting the tendency for the front wheel to lift during acceleration and the rear wheel to lock up during braking, which leads to a significant decrease in stability and stability of movement, and in a more extreme case - to rollover and accidents. A methodology for measuring accelerations is presented. The analysis of the results shows that in modern motorcycles the grip boundary conditions are reached and exhausted very quickly, and active safety systems are not able to solve the problem of wheel lift fundamentally. The results obtained can be used in dynamic models studying motorcycle dynamics. Based on the results, optimizations can be made to the existing algorithms used in anti-lift and anti-lock systems.

Future research will be aimed at a thorough study of the influence of the passenger and the body position towards the driver on the stability and dynamics of the motorcycle and the capabilities of active safety systems to correct errors, especially from less experienced drivers. This is an insufficiently researched factor that has a significant impact on traffic safety.

Acknowledgements

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Two-stroke low-speed engines and maritime transition to net-zero

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Abstract: The world's maritime industry is currently undergoing an unprecedented transformation, driven by the climate crisis and the strict regulations imposed by the International Maritime Organization (IMO). The IMO's Greenhouse Gas (GHG) Strategy for 2023 has fundamentally redefined the industry's goals, from gradually reducing carbon intensity to comprehensively phasing out greenhouse gas emissions by 2050. At the heart of this transition is the low-speed, two-stroke engine, which serves as the main source of propulsion for most deep-sea merchant ships. Contrary to being considered a legacy of the limitations of the fossil fuel-dependent era, these engines are being transformed into highly efficient and adaptable platforms capable of using the next generation of carbon-neutral and zero-carbon energy carriers. This analysis examines the technical, operational and regulatory mechanisms that enable the maritime sector to meet its net-zero emission commitments, with a particular focus on dual-fuel engine architectures, advanced combustion control, and the holistic integration of ship energy systems.

Keywords: TWO-STROKE LOW-SPEED ENGINES, NET-ZERO 2050, ALTERNATIVE MARINE FUELS, EMISSION REDUCTION

1. Introduction

Two-stroke slow-speed diesel engines are used in majority on big containers ships. The two-stroke low-speed engine prevails in maritime applications because of its endurance and high thermal efficiency, generally exceeding 50%. Low-speed engines have an extended combustion stroke, enabling the complete burning of complex fuels. This feature makes the two-stroke engine a strong option for using alternative fuels.

The adoption of the 2023 IMO GHG Strategy represents a historic deal in the fight against climate change and signifies a breakthrough in reducing the environmental impact of international shipping. This revised strategy replaces the 2018 initial target of a 50% reduction in emissions by 2050 with a much more ambitious goal of reaching well-to-wake (WTW) net-zero emissions. The WTW perspective is critical, as it accounts for emissions throughout the entire fuel lifecycle, from production and transport to combustion at sea, thereby preventing the mere shifting of emissions to other industrial sectors [1].

To provide the industry with a clear trajectory, the IMO established a series of ambition levels and indicative checkpoints for 2030 and 2040. These milestones are designed to ensure that the global fleet stays on track with the Paris Agreement's 1.5°C temperature goal [2].

Table 1: IMO Decarbonization Targets (Base Year 2008).

Milestone Year	Minimum Ambition Level	Strive Target (1.5°C Aligned)	Primary Regulatory Mechanism
2030	20% Absolute GHG Reduction	30% Absolute GHG Reduction	CII Rating / EEXI Compliance
	40% Carbon Intensity Reduction	—	Fuel GHG Intensity Standard
	5% ZNZ Fuel Uptake	10% ZNZ Fuel Uptake	Early Market Incentives
2040	70% Absolute GHG Reduction	80% Absolute GHG Reduction	Global Fuel Standard / Pricing
2050	Net-Zero GHG Emissions	—	Net-Zero Framework (NZF)

The IMO's Net-Zero Framework (NZF) is the regulatory response to these goals [3]. The NZF sets a goal-based marine fuel standard that controls the gradual decrease of GHG intensity. It also includes an economic aspect: the first-ever global maritime GHG emissions pricing mechanism. Starting in 2028, this mechanism is expected to set an initial price of about USD 100 per ton, which would bring in between USD 11 billion and USD 13 billion a year. These funds will help pay for the development of zero- and near-zero (ZNZ) fuels, which will help close the big price gap between

regular heavy fuel oil (HFO) and alternative fuels, which are usually three to four times pricier. The NZF only applies to ships that are more than 5,000 gross tons and travel across oceans. These ships are responsible for 85% of all emissions.

The framework's adoption was pushed back by a year in late 2025, but the need to cut carbon emissions is still strong. The move is a clear sign to shipowners that the time of using fossil fuels is coming to an end.

Classic regulations often looked only at tank-to-wake (TTW) emissions, or what comes out of the exhaust, so, e.g., "green" gases or e-fuels seemed perfect. When you turn on WTT, you see that some fuels have very low TTW emissions (e.g., hydrogen, ammonia) but can have high WTT emissions if produced from fossil sources without capturing CO₂. Conversely, some fuel may have moderately high TTW emissions but a very favorable WTT if, for example, it is an advanced biofuel from waste.

To meet plans of net zero using two-stroke slow-speed engines alternative fuels like hydrogen, methanol and ammonia have to be used (Fig. 1). The MAN B&W ME series and WinGD X-engines exhibit a trend towards electronic regulation. Electronically controlled engines can accurately regulate fuel injection timing and pressure to accommodate the diverse physical and chemical properties of alternative fuels. Marine two-stroke engines have a high volume-to-surface ratio. This reduces heat loss through the walls and makes the temperature in the combustion chamber more even. This feature is especially useful when burning fuels like ammonia and methanol. Also, the dual-fuel design lets these engines run on regular fuels until the bunkering infrastructure for alternative fuels is ready.

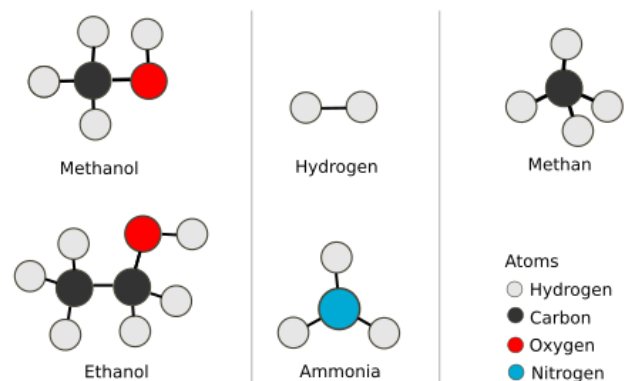


Fig. 1 Fuels that are in consideration for use in future to meet net-zero or near net-zero emissions in maritime.

2. Analysis of alternative fuels and other measures

Methanol and Ethanol

Methanol has become a leading and economically viable option for reducing carbon emissions in shipping. This is due to its liquid state at room temperature and the technological advancements that have been made.

Two-stroke methanol engines, such as the MAN B&W ME-LGIM, have been in operation since 2016, primarily on methanol carriers [5]. Recently, this technology has expanded into the Very Large Container Vessel (VLCV) segment, with hundreds of orders placed by major carriers.

When produced as green methanol using renewable hydrogen and captured CO₂, this fuel has almost no emissions throughout its life cycle. From a tank-to-wake perspective, burning methanol significantly reduces emissions and almost eliminates particulate matter. The diesel-cycle methanol engine utilizes a high-pressure direct injection system, where a small amount of pilot fuel is used to initiate combustion, maintaining the high efficiency associated with the conventional diesel process.

Ethanol is gaining traction as a secondary alcohol fuel, particularly in regions where bioethanol is produced competitively from agricultural biomass [6]. WinGD has pioneered the development of the first ethanol-fueled two-stroke engine, with deliveries scheduled to begin in 2026 [6]. This engine is an adaptation of the X-DF-M methanol platform, utilizing the same combustion concept and safety regulations [7].

Ethanol's technical challenges include its higher energy density compared to methanol. This requires changes to the fuel injector nozzle design and control systems to optimize the injection volume [6]. Research starting in 2014, like the EU-funded HERCULES 2 project, has confirmed the use of flexible injectors for different alcohol fuels, giving shipowners more options for fuel [6].

Ammonia

Ammonia is fuel that does not have carbon atoms so when burning it does not generate CO₂ emissions, but it does generate NO_x emissions and postprocessing is necessary to annulate them.

Ammonia (NH₃) is widely regarded as a critical enabler for the 2050 net-zero target because it contains no carbon and can be produced at scale as green ammonia using renewable energy [8]. However, its slow burning velocity, high auto-ignition temperature, and toxicity present formidable engineering hurdles.[4]

Major engine designers have achieved significant milestones in ammonia propulsion. MAN Energy Solutions completed full-scale testing of its two-stroke ammonia dual-fuel engine in Copenhagen in late 2024 [4]. Similarly, WinGD delivered its first X-DF-A ammonia-fueled engine for installation on an EXMAR LPG carrier in 2025 [7]. In Japan, the Green Innovation Fund project has supported the construction of the MAN B&W 7S60ME-Ammonia engine by Mitsui E&S, which will power a Newcastlemax bulk carrier built by Imabari Shipbuilding [9].

Ammonia combustion in two-stroke engines typically utilizes a diesel-cycle combustion process with a 5% mass (or energy) of diesel pilot fuel [8]. This approach addresses ammonia's poor ignition properties and allows for controlled combustion timing. A major concern with ammonia is the production of nitrous oxide, a greenhouse gas that is 298 times more effective at trapping heat than CO₂ [10]. Research indicates that advancing the pilot fuel injection timing (e.g., to 30° BTDC) can significantly reduce NO_x and unburned ammonia emissions. [11]

Advanced Combustion Control and Aftertreatment Systems

To comply with the IMO's Tier III limits while operating on alternative fuels, two-stroke engines rely on a combination of sophisticated in-cylinder measures and external exhaust aftertreatment.

Modern combustion control strategies involve the use of Variable Compression Ratio (VCR) and electronic injection timing to adapt to different fuel reactivities [12]. For ammonia engines, multi-pulse or split injection of pilot fuel has been shown to improve mixture preparation and reduce pressure oscillations [11]. Injector orientation and nozzle spray angles are also being optimized; vertical orientations with symmetric spray angles can reduce formation by up to 85% compared to conventional diesel combustion [13].

Selective Catalytic Reduction (SCR) remains the primary technology for abatement. In ammonia engines, SCR systems are particularly vital as they can also neutralize any ammonia slip that escapes the combustion chamber [14]. For LNG engines, the introduction of Intelligent Control by Exhaust Recirculation (iCER) has proven effective in reducing methane slip by 50% while improving thermodynamic efficiency [12].

Integrated, on-engine aftertreatment solutions are becoming the industry standard, allowing for more compact engine room designs and lower installation costs. These systems ensure that vessels remain compliant with air quality regulations while pursuing global GHG targets.

Integration and Hybridization

Decarbonization cannot be achieved by engine technology alone; it requires the optimization of the entire ship's energy system. As alternative fuels are more expensive and possess lower energy densities, the "efficiency first" is very important principle.

The integration of battery energy storage systems (BESS) with the main two-stroke engine allows for peak shaving and optimized spinning reserves [12]. By utilizing shaft generators—also known as Power Take-Off (PTO) systems—vessels can generate electrical power from the efficient main engine, reducing the need to operate less efficient auxiliary diesel generators.

Hybrid control systems, exemplified by WinGD's X-EL, regulate energy distribution among the main engine, shaft generator, and batteries, thereby maintaining the main engine's optimal operational efficiency. This strategy can diminish overall fuel consumption by 0.1–0.5 tons daily, translating to potential annual savings of up to USD 320,000 per vessel, contingent upon fuel type and operational parameters [15].

Furthermore, waste heat recovery systems, which harness thermal energy from exhaust gases to power steam turbines or supply process heat, are becoming increasingly vital on vessels utilizing cryogenic or ammonia-based fuels.

Hybrid arrangements incorporating fuel cells and batteries have shown promise in reducing emissions associated with shipboard power generation [16].

Operational Efficiency: EEXI, CII, and the Role of Slow Steaming

Operational measures provide the most immediate pathway to emission reductions, often requiring minimal capital expenditure compared to technical retrofits [17]. The regulatory drivers for these measures are the Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Indicator (CII).

A ship's speed and its fuel consumption are related in a way that isn't straightforward. Reducing speed, often called "slow steaming," can significantly lower fuel use and is often the main method ships use to improve their CII ratings [17]. Moreover, digital tools, such as data-driven voyage planning and weather routing, help improve operational efficiency.

Calculations suggest that if shipowners only focus on changing fuels without improving efficiency, the industry won't meet the 2030 indicative checkpoint [1]. This highlights the importance of these measures.

Table 2: Effectiveness of Short-Term Operational and Technical Efficiency Measures

Strategy	Estimated GHG Reduction Potential	Implementation Difficulty	Regulatory Context
Vessel Size Optimization	47%	High (Fleet Planning)	EEDI / EEXI
Speed Reduction / Slow Steaming	20–30%	Low (Operational)	CII Compliance
Hull Shape Optimization	15%	Moderate (Newbuild)	EEDI Phase 3
Air Lubrication Systems	8%	Moderate (Retrofit)	CII Improvement
Advanced Hull Coatings	5%	Low (Maintenance)	SEEMP Part III

Future Scenarios to 2050: Biofuels, Nuclear, and Arctic Routes

As the industry approaches 2050, several distinct pathways emerge depending on fuel availability and technological breakthroughs.

Sustainable biofuels, such as Hydrotreated Vegetable Oil (HVO) and Fatty Acid Methyl Esters (FAME), offer a "drop-in" solution that is fully compatible with existing two-stroke engines. While biofuels are crucial for achieving immediate objectives, their sustained utility may be constrained by the availability of feedstocks and competition from the aviation and terrestrial transportation industries.

For sectors where zero-carbon fuels are not feasible because of energy density constraints, like Ultra-Large Container Vessels (ULCVs) operating on high-speed routes, nuclear propulsion is being re-evaluated as a potentially disruptive technology [18]. Contemporary Small Modular Reactors (SMRs) present a high-power density and a 20-year operational lifespan, which could eliminate all bunker expenses and carbon-related costs. Lloyd's Register's analysis suggests that a 15,000 TEU nuclear-powered containership could attain a 38% greater annual cargo capacity by maintaining a speed of 25 knots, in contrast to slow-steaming vessels [19].

The opening of the Arctic Sea Route due to polar ice melt offers the potential to reduce voyage distances between Europe and Asia by 40%. While this could reduce emissions per voyage, modeling suggests that increased total traffic and the lack of strict fuel standards in the region could raise global shipping emissions by 8.2% by 2100 unless a net-zero strategy is strictly enforced in Arctic waters [20].

Economics of the Global Fuel Transition

A global carbon pricing system is crucial for encouraging the transition from fossil fuels. Without such a system, the higher cost of green methanol or ammonia is often a barrier for many operators. The International Maritime Organization's proposed price of USD 100 per ton of CO₂ is a starting point, but researchers suggest that higher prices may be needed to meet the 1.5°C limit [21]. Investing in energy efficiency on ships can significantly reduce the overall cost of this transition. Each percentage point of increased efficiency lowers the total need for expensive alternative fuels, which in turn reduces the investment needed for green fuel production infrastructure [1].

3. Conclusion

The maritime industry is no longer at a crossroads; it has chosen the path of decarbonization. The continued innovation in two-stroke propulsion and shipboard energy management ensures that this journey toward net-zero is not only technically feasible but also commercially sustainable for the global fleet.

To meet the needs of the world's clean energy fleet, currently unavailable amounts of renewable solar and wind energy are needed. Not only ships compete for this energy, but also land transport, heavy industry and households. The two-stroke engine's ability to burn methanol, ammonia, ethanol, and biofuels ensures that the global fleet can adapt to the most available and cost-competitive green fuels as they emerge. The shift from a single-engine focus to an integrated ship energy system—incorporating hybridization, shaft generators, and waste heat recovery—is essential for making the use of zero-carbon fuels economically viable. The IMO's 2023 Strategy and the subsequent Net-Zero Framework provide the long-term certainty required for shipowners to invest in expensive newbuilds and retrofits. Short-term goals will be met primarily through efficiency improvements and slow steaming. While biofuels and alcohols will lead the transition in the current decade, ammonia and potentially nuclear propulsion represent the long-term solutions for a truly zero-carbon maritime industry by mid-century. Nuclear propulsion would likely render two-stroke slow-speed "diesel" engines obsolete.

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Theoretical investigation into the influence of a teeth fault to gear train vibrations

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Abstract: The vibration behavior of a healthy gear train is modelled as a sum of sinusoidal accelerations of a pinion, a gear, and a gear-mesh. A while noise is added trough waveform of normally distributed random numbers. The corresponding time-diagram and spectrogram are obtained. After that, an impulse acceleration waveform is added to simulate a teeth fault. The time-diagram and spectrogram are obtained again and compared. Conclusions are made.

Keywords: GEAR TRAIN, FAULT, ACCELERATION WAVEFORMS, GEAR-MESH FREQUENCY, SIDE BANDS, VIBRODIAGNOSTIC, TIME-DIAGRAMS, SPECTROGRAMS, POWER SPECTRUM, CONDITION MONITORING

1. Introduction

The gear mesh frequency (GMF) is the rate at which a gear tooth make contact, and it appears in the frequency spectrum regardless of the condition of the gears. Gear sidebands (GS) are frequency peaks appearing symmetrically around the GMF peak in a vibration spectrum. By modulating the GMF at the rotational speed of a specific gear, the GS indicate issues like wear, eccentricity, or misalignment. Analysing GS spacing helps diagnose which gear is faulty. This is because the sidebands are spaced at the faulty running speed, so they can indicate problems and are crucial for predictive maintenance in gearboxes.

Predictive maintenance is essential for gearboxes because it allows for the early detection. Engineers can identify potential failures before they lead to costly breakdowns. This proactive approach significantly reduces downtime, ensuring that production remains steady and efficient. Furthermore, it extends the service life of the gearbox components by preventing catastrophic damage to the entire system.

2. Prerequisites and means for solving the problem

The complex and multi-element approach is to model a completely gear transmission (including bearings, shafts, box, etc.) and simulate with the help of FEM [1, 3, 4, 5]. This is problematic for the following reasons:

1. The initial modeling is slow, and the time required for the simulation is long even on clusters of powerful computers. Therefore, changing the values of the parameters again and again, requires a lot of calculation time;
2. Many elements influence each other, their influences are mixed, and the dependencies that are the subject of the current study cannot be separated and analyzed. That is, it turns out that the complex model used is not suitable for the specific investigation.
3. Each of the modeled elements has its own parameters to which values must be assigned. But these values are often: not completely clear; dependable by time, load, temperature, etc., and these dependencies cannot be guaranteed to be linear. All of these uncertainties and inaccuracies are very likely to distance the study from real behavior.

As a consequence of the above, the aim of this investigation is to obtain results about the ability to identify a fault, analysing GS spacing of a phenomenological vibration model of a gear train with presence of white noise environment disturbance.

Therefore, in this investigation the vibration behavior of a healthy gear train is modelled as a sum of sinusoidal accelerations of a pinion, a gear, and a gear-mesh [2, 7, 6]. The influence of other transmission elements and of other mechanisms in the transmission environment, is taken into account adding while noise trough waveform of normally distributed random numbers. Finally, an impulse acceleration waveform is added to simulate a teeth fault. The time-diagram and spectrogram are obtained and compared. This is simple, but powerful method, which has flexibility and rapidity.

3. Solution of the examined problem

The parameter values used is shown in Table 1.

Table 1. Parameter values

Sample rate, KHz	f_s	10
Number of pinion teeth	N_p	20
Number of gear teeth	N_g	81
Rotation speed of pinion, rps	f_{pin}	50
Pinion acceleration amplitude, m/s ²	A_p	0.4
Gear acceleration amplitude, m/s ²	A_g	0.2
Gear-mesh acceleration amplitude, m/s ²	A_{GM}	1

The pinion acceleration waveform is generated according to

$$(1) \quad a_p = A_p \sin(2\pi f_{pin} t).$$

The gear acceleration waveform is generated according to

$$(1) \quad a_g = A_g \sin(2\pi f_{gear} t).$$

The gear-mesh acceleration waveform is generated according to

$$(3) \quad a_{GM} = A_{GM} \sin(2\pi f_{mesh} t).$$

Then, the healthy acceleration is obtained as a sum of (1), (2), and (3). After that, white noise is added trough waveform of normally distributed random numbers – Fig. 1. The time-diagram of the vibration acceleration of the healthy train model is shown on Fig. 2.

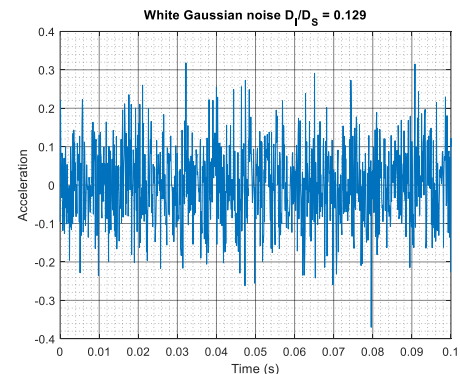


Fig. 1. The time-diagram of the white noise added

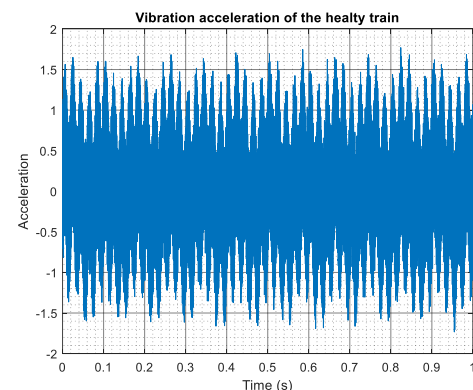


Fig. 2. The time-diagram of the healthy train

The Discrete Fourier Transform is performed according to

$$(4) \quad X(k) = \sum_{n=0}^{N-1} x(t) e^{-i\frac{2\pi}{N}kt},$$

where: x is the input signal in the time area, with length n ; X – output signal in the frequency area, with length k ; $x(t)$ – the value of the input signal at time t ; and $X(k)$ – complex number, carrying amplitude and phase information at frequency k .

Through (4), the spectrogram of the healthy vibration acceleration is obtained and presented on Fig. 3. With red vertical lines are marked gear sidebands frequencies. On Fig. 3, one can observe that there are **six peaks**, that matches with sideband frequencies – they are marked with green circles.

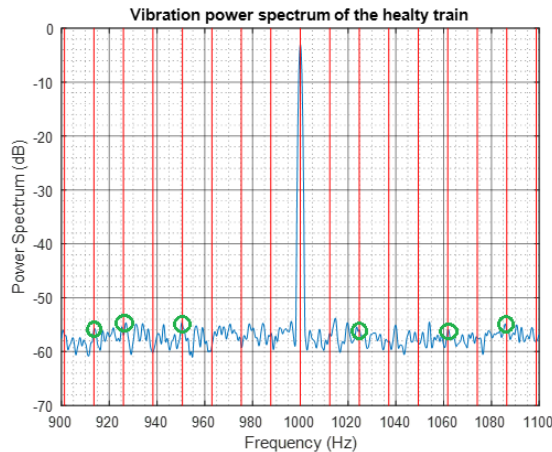


Fig. 3. The spectrogram of the healthy train

The next step is to add an impulse waveform to simulate a teeth fault – Fig. 4.

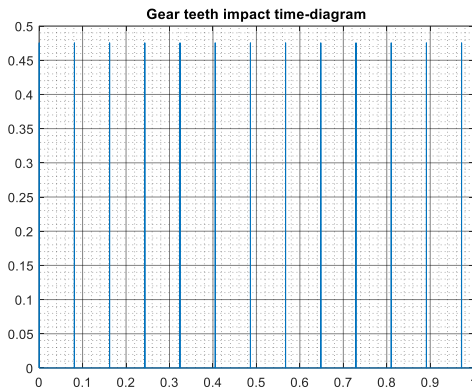


Fig. 4. The time-diagram of the impulse used

The resulting acceleration is shown on Fig. 5. One can observe and compare the time-domain signals from Fig. 2 and Fig. 5. There are not visible differences that indicates signal change and fault presence.

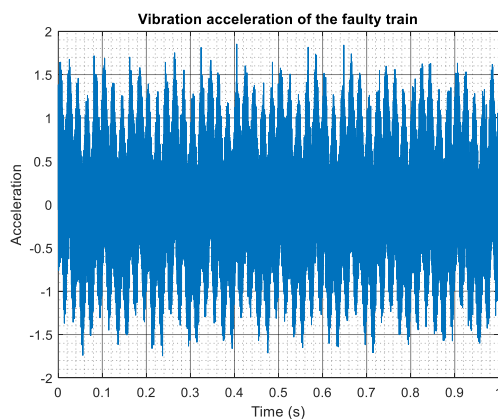


Fig. 5. The time-diagram of the faulty train

After that, the Fourier transform is performed again and the spectrogram of the faulty train is obtained – Fig. 6. One can observe that there are **thirteen peaks**, that matches with sideband frequencies – they are marked with green circles.

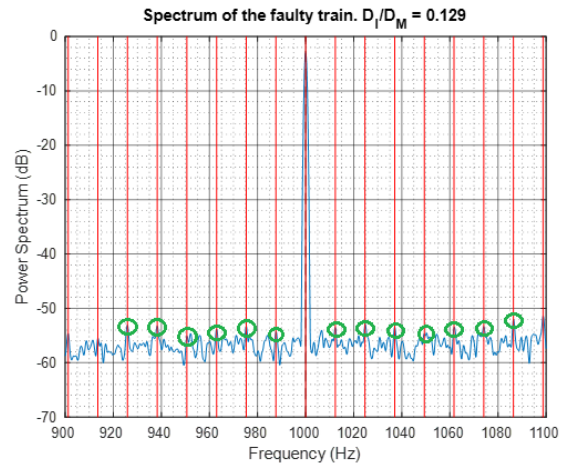


Fig. 6. The spectrogram of the faulty train

4. Conclusions

This investigation shows that by comparing the spectrogram of the healthy gear train model (Fig. 3) and the faulty train model (Fig. 6), one can identify the problem presence. But an interesting question is what is the influence of the white noise density and of the faulty impulse amplitude on this ability the problem presence to be identified. So, this can be marked as a topic for the future investigation.

A basis for this future investigation is the deviation indicator shown in the titles of Fig. 3 and Fig. 6. The standard deviation of the white noise used are calculated and marked with D_t . The standard deviation of the healthy acceleration (obtained as a sum of equations (1), (2), and (3)) are also calculated and marked with D_M . On Fig. 3 and Fig. 6 titles, one can see the indicator obtained by dividing of these deviations. By varying the values if this indicator, the influence of above-described factors will be investigated in the future researches.

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Implementation of slow stress rating test method (SSRT) in determination susceptibility to hydrogen embrittlement of P460NL1 steel

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Abstract: The hydrogen embrittlement susceptibility of P460NL1 pressure-vessel steel was assessed by slow strain rate testing (SSRT) with in situ electrochemical hydrogen charging. An electrochemical cell integrated with a tensile testing machine was used to generate hydrogen in a 3.5 wt.% NaCl solution containing 1 g/L thiourea. Cathodic charging was applied at a constant current of -20 mA (approximately -1.4 V). SSRT was performed at a strain rate of 10^{-5} s^{-1} in accordance with ASTM G129-21. Tensile specimens extracted from the base material and welded joints were tested in air and under hydrogen-charging conditions. The methodology enabled controlled hydrogen introduction during deformation of tensile probes and allowed comparison of hydrogen-assisted cracking susceptibility between base metal and welded material. Tested broken tensile probes were subjected to determination of dissolved hydrogen. Tensile probes were first tested in the air and after that in prepared solution.

To analyse hydrogen embrittlement of investigated steel hydrogen embrittlement index was determined through determination of fracture elongation and reduction of Area (RA) of the broken specimen. Light and SEM microscopy was used to analyse possible location of the present defects in material i.e. hot rolled steel. Types of non-metallic inclusions were determined too.

KEYWORD: HYDROGEN EMBRITTEMENT, P460NL1 STEEL, SLOW STRESS RATE TESTING (SSRT), TENSILE PROBE, FRACTURE ANALYSIS, SCANNING ELECTRON MICROSCOPE (SEM)

1. Introduction

Hydrogen embrittlement in installations for the transportation and storage of crude oil, natural gas, and oil derivatives has been known for more than one hundred years. However, due to current global energy challenges, this problem has become increasingly acute. For this reason, hydrogen embrittlement is a critical issue for steel producers (raw material suppliers), manufacturers of steel pipes, crude oil refineries, and similar industries.

In other words, steel producers must prove to pipe manufacturers that their materials—such as hot-rolled plates, steel sheets, and strips—are resistant to hydrogen embrittlement. More specifically, the produced equipment and installations must be safe during service with respect to hydrogen embrittlement. Refineries, their equipment, reservoirs, and tanks all depend on the long-term reliability of the steels used in their construction. Therefore, all users of steel products need assurance that the materials they build into their facilities are safe for long-term operation.

If hydrogen embrittlement occurs in such equipment, it can lead to material damage, environmental pollution, and, in many cases, loss of human lives.

The question arises: how can it be proven that the delivered steel fulfills the requirements for resistance to hydrogen embrittlement? Generally, two methods are mainly used: the slow strain rate testing (SSRT) and the fracture toughness (K_{IC}) method. Based on a literature review and our own knowledge and experience, we decided to use the SSRT method. The investigated steel has a yield strength of 460 MPa. For medium-strength steels, SSRT is recommended, whereas the K_{IC} method is typically used for high-strength materials (steels) with yield strengths above 800–900 MPa.

1 material and experimental

For determination tendency to hydrogen embrittlement of P460NL1 steel, slow stress rate testing was implemented (SSRT). Generally, it can be said that this method give real and reproductive results. For implementation of this method experimental, electrochemical cell was constructed Figure 1.

This cell was mounted to tensile testing machine. After putting the tensile probe in the testing machine, the cell was filled with prepared solution (Electrolyte: 3.5% NaCl, 1g/L Thiourea) Hydrogen was additionally added in the cell during testing - in-situ charging during SSRT with flow rate of 1 l/m . After breaking of the tensile probes concentration of dissolved hydrogen in the probes was determined. It value is approximately about 1 ml/g .

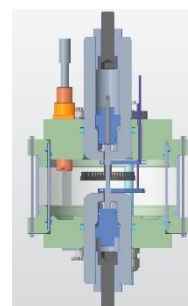


Figure 1 Experimental electrochemical cell

1.1 Investigated Material

P460NL1 steel was used for experimental work in this paper. The steel is produced in electric arc furnace (EAF) with capacity of 100 tons molten metal. As a raw material was used steel scrap. Chemical composition and mechanical properties of produced steel plates are given in the Tables 1 and 2. They are in accordance with standard requirements/

Table 1 Chemical composition of P460NL1 steel

El.	C	Si	Mn	P	S	Al	N	Cr
	0.16	0.25	1.22	0.016	0.005	0.055	0.08	0.07

Cu	Ni	Mo
0.3	0.25	0.1

$$C_{eqv}=0.427$$

Table 2 Mechanical properties – transversal of P460NL1 steel

	Rah (MPa)	Rm (MPa)	A %	ISO-V(-20) J
value	512	627	28.8	144

Molten metal was continuously casted in slabs. Produced slabs were hot rolled in wide plates with thickness of 12 mm. From the plates were taken pieces for machining tensile probes. Besides, from the plates, welded pieces were prepared in order to obtain tensile probes from the welded joints. These probes are with the same dimensions as probes from the plates. Location of the weld is in the middle of the probe.

Used welding process is SAW. As Welding wire was chosen BOHLER EMS 2 Mo // BB 24 - $\phi 4$. Used Welding flux is Bohler BB24. Tandem welding was performed figure 2.

Rounded tensile probes were prepared. Dimensions of probes are shown in the figure 3.

So, it was prepared tensile probes from the plates and from the welded pieces. The idea was to compare results of the both types of probes. The probes were tested in the air an in the experimental prepared solution.

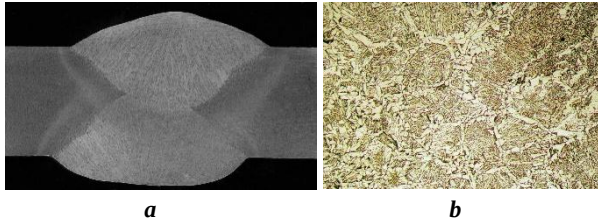


Figure 2 Macro picture of welded joint (a), Microstructure of coarse grained HAZ (b)

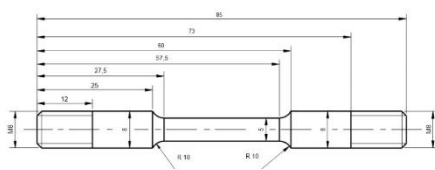


Figure 23: Schematic of the sample geometry used for ISLT and tensile testing, all dimensions in mm.

Figure 3 Rounded tensile probes for SSRT testing

What means designation P460NL1 steel?

P460NL1 is a European (EN) steel designation. Each part tells something specific about the steel. P460NL1 is a normalized (normalized rolling) fine-grain pressure-vessel steel with a minimum yield strength of 460 MPa and guaranteed impact toughness at -40°C .

Figure 4 show nonmetallic inclusions present in the investigated steel. Magnification is x100 according standard. Mainly oxide inclusions are detected at this magnification.



Figure 4 Non-metallic inclusions

Microstructure of steel is ferrite-perlite with more than 70% ferrite (figure 5) and grain size of steel is 9 (figure 6).

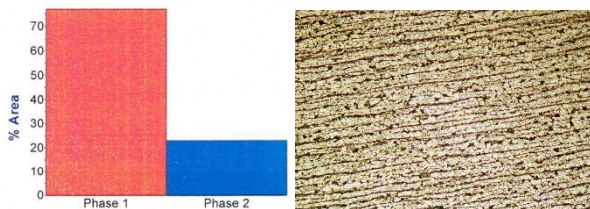


Figure 5 Microstructure of investigated steel P460NL1

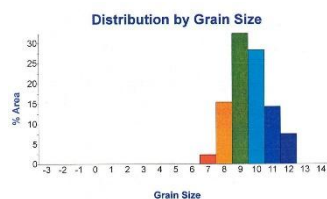


Figure 6 Grain size of steel

1.1 Performed investigations

Prepared tensile probes were first tested in the air. After that they were tested in the experimental electrochemical cell. It was concluded that base metal plate showed better resistance to hydrogen embrittlement compared to welded joints. Tested probes in electrochemical cells showed lower values which is in accordance with our expectations.

The tensile test was carried out with a Zwick / Roell ZMART.PRO testing machine. As a strain rate was accepted 10^{-5} s^{-1} (figure 8). Although some preliminary investigations was performed with strain rate of 10^{-4} s^{-1} (figure 7). The hydrogen charging (H-charging) was done with our Electrochemical Charging Cell (ECC) containing a solution of 3.5% NaCl and 1g/L Thiourea as an inhibitor to reduce the recombination of atomic H to H_2 on the surface of the working electrode. During H-charging the strain rate for the tensile test was reduced to 10^{-5} s^{-1} (Slow Strain Rate Test/SSRT). As a potentiostat a Metrohm Autolab PGSTAT128N was used with a constant applied voltage of -1.1 V (cathodic polarisation).

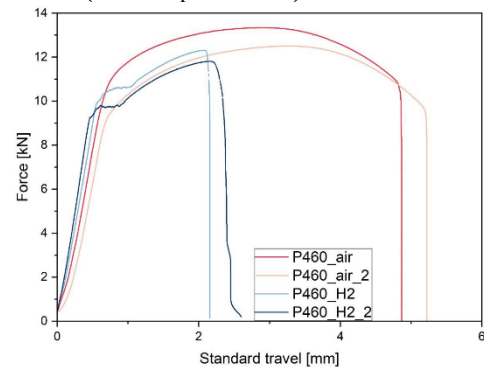


Figure 7 Diagram force/standard travel strain rate 10^{-4} s^{-1}

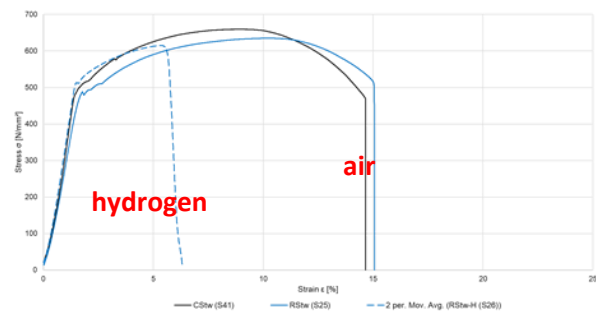


Figure 8 Diagram force/standard travel strain rate 10^{-5} s^{-1}

The question which has to be answered is what is tendency of investigated steel to hydrogen embrittlement?

More concretely, How susceptibility to environmentally assisted cracking (EAC) can be determined?

SSRT - Evaluate the susceptibility to EAC according to: ASTM G129 – 21. Suggested strain rate range $10^{-4}/\text{s}$ to $10^{-7}/\text{s}$ - Slow enough for H diffusion vs. fast enough to produce cracking in reasonable time period. We mainly used strain rate 10^{-5} s^{-1}

Parameters we used in investigations were taken from the tested tensile probes. Tensile specimen: $l_0 = 25 \text{ mm}$, $d_0 = 5 \text{ mm}$, Strain rate: $10^{-5}/\text{s}$ ($15 \mu\text{m}/\text{min}$).

Evaluation of hydrogen embrittlement (HE) was determined by Hydrogen Embrittlement Indices:

$$\text{Fracture Elongation A5: } HEI_E(\%) = \frac{A5_{air} - A5_H}{A5_H}$$

$$\text{Reduction of Area RA: } HEI_E(\%) = \frac{RA_{air} - RA_H}{RA_{air}}$$

Figure 9 shows broken tensile probes from which was detrmind A5, elongation after testing in the air and in the cell. Figure 10 show type of fracture.



Figure 9 Broken tensile probes

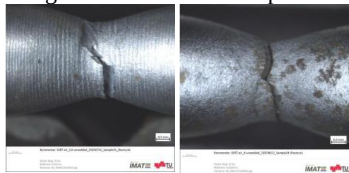


Figure 10 Type of fracture in tensile probes

Tested tensile probes from welded joints were subjected to hardness measurement (figure 11).

Submerged Arc Welding (SAW) process:

- weld hardness ca. 250HV1

- base material hardness ca. 230HV1

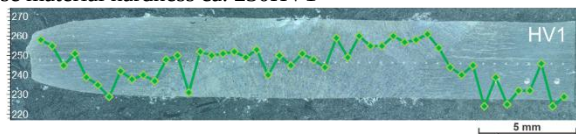


Figure 11 Hardness measurement of tensile probe from the welded joint

Figure 12 show how cross section of tested tensile probes was measured. Obtained values were used in order to determine reduction of area.

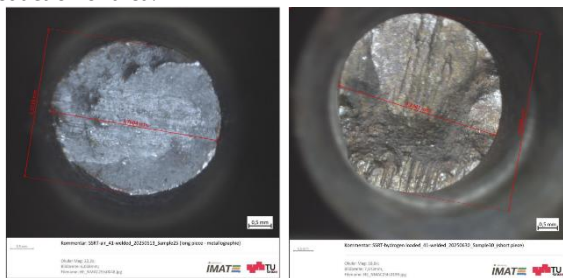


Figure 12 Measuring cross section of investigated tensile probes

Using determined values for elongation end reduction of area, hydrogen embrittlement index (HEI) was determined. Obtained results are in the table 3.

Table 3 Determination of hydrogen embrittlement index HEI which

steel	Yield strength R_{eL} (MPa) average	Tensile strength R_m (MPa) average	Fracture elong. A_5^* (%) average	HEI A_5 (%)	Reduction of Area RA (%) average	HEI RA (%)
RSt	451	637	20.3	62.1	66.9	85.9
RSt -H	475	615	7.7		9.4	
RStw	483	635	14.6	50.7	58.0	71.7
RStw -H	502	626	7.2		16.4	

1.2 Metallographic investigations

Scanning and optical microscopy was used for investigation of microstructure and present defects in investigated steel. Figure 13 clearly show detected defect on the polished and etched specimen.

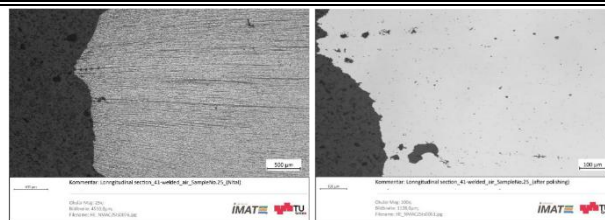


Figure 13 Detected defects in the specimen – tensile probes

From the figure14 was concluded that presence of defects was in the perlitic bands

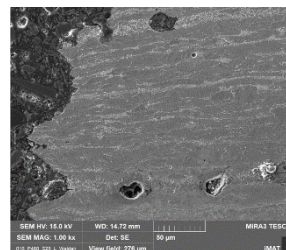


Figure 14 Defects in steel located in perlitic bands

From the figure 15 and 16 can be concluded that formed cracks on the probe surface propagate towards the probe interior. It can be seen too that some cracks are formed in pearlitic bands and are arrested in ferrite.

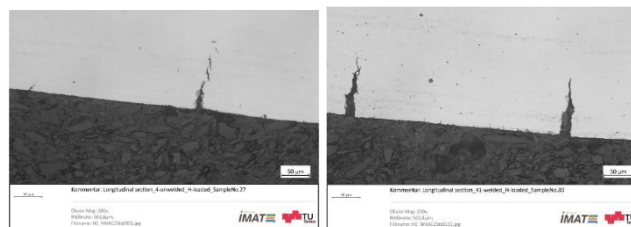


Figure 15 Polished specimen – cracks formed on the surface

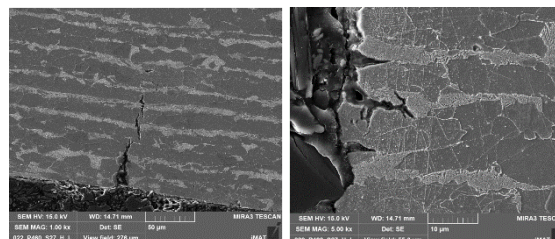
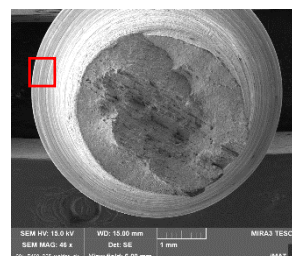


Figure 16 Cracks formed in pearlite and stopped in ferritic bands

Figure 17 presents macro fracture of broken tensile probes tested in the air and in the solution. Fragments of fractured surfaces inside the red squares are shown in the figure 18. It was concluded from the SEM figures that probe tested in the air shows typical dimple fracture while probe tested in the electrochemical solution has quasi cleavage fracture as results of influence of hydrogen to fracture.



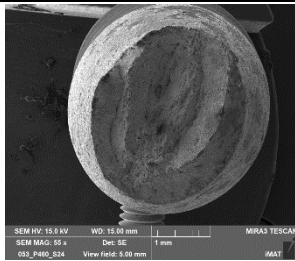


Figure 17 Macro fracture of tensile specimens

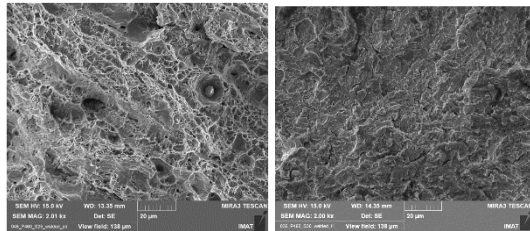


Figure 18 Types of micro fracture

1.3 SEM analysis

SEM with EDAX system was used for determination of different types of small inclusions. Nonmetallic NMI CaS-type and NMI AlMgO type were detected. Metallic inclusions MI NbTi-type: were detected too, figure 19.

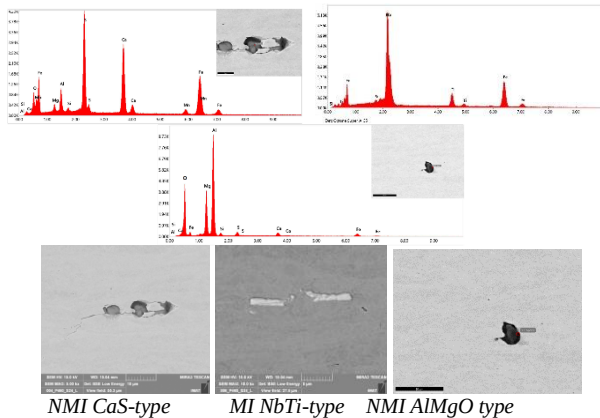


Figure 19 Inclusions detected by SEM

Discussion

The results obtained from slow strain rate testing clearly demonstrate that P460NL1 [1,2] steel is susceptible to hydrogen embrittlement, with a pronounced difference between the base metal and welded joints. The susceptibility to environmentally assisted cracking (EAC) increases significantly when hydrogen is introduced electrochemically, which is consistent with the observed degradation of plastic properties.

Effect of Hydrogen on Mechanical Properties

Hydrogen charging caused a substantial reduction in fracture elongation (A5) and reduction of area (RA) for both base metal and welded specimens. The calculated Hydrogen Embrittlement Index (HEI) values confirm that elongation is more sensitive to hydrogen than tensile strength, which remained relatively unchanged. This behaviour is typical for hydrogen embrittlement, where hydrogen primarily reduces ductility rather than strength [3,4].

The base metal exhibited higher resistance to hydrogen embrittlement compared to welded joints. This is attributed to the microstructural heterogeneity introduced by welding, particularly in the weld metal and heat-affected zone (HAZ), where local hardening and residual stresses are present. The higher hardness measured in the weld region (~250 HV1) compared to the base metal (~230 HV1) further supports the increased hydrogen susceptibility of welded joints [6].

The ferrite-pearlite microstructure with more than 70% ferrite generally provides good resistance to hydrogen embrittlement due

to the relatively high hydrogen solubility and low diffusivity in ferrite. However, the presence of banded pearlite significantly influences crack initiation and propagation [7].

Metallographic observations revealed that defects and crack initiation sites are predominantly located in pearlitic bands. During hydrogen charging, cracks initiated at the specimen surface and propagated along pearlitic regions, while ferritic areas often acted as crack arresters [8,9]. This indicates that pearlite, due to its higher strength and cementite lamellae, provides favourable paths for hydrogen-assisted cracking.

Fracture Behaviour and Hydrogen-Assisted Cracking Mechanism

Fractographic analysis showed a clear transition in fracture mode caused by hydrogen. Specimens tested in air exhibited a ductile dimple fracture, characteristic of microvoid coalescence. In contrast, hydrogen-charged specimens showed quasi-cleavage fracture, confirming the presence of hydrogen-assisted cracking mechanisms [10].

The observed fracture morphology suggests that hydrogen promotes localized plasticity and decohesion, leading to premature crack initiation and rapid crack propagation. The quasi-cleavage features are particularly pronounced in welded specimens, indicating a synergistic effect of hydrogen, microstructural inhomogeneity, and residual welding stresses.

Role of Non-Metallic Inclusions

SEM-EDAX analysis identified CaS, AlMgO, and NbTi-type inclusions, which can act as hydrogen trapping sites. These inclusions contribute to local hydrogen accumulation, increasing the likelihood of crack initiation under applied stress. In particular, elongated or clustered inclusions within pearlitic bands intensify hydrogen-assisted damage, explaining the preferential crack initiation observed in these regions [11].

Assessment of EAC Susceptibility by SSRT

The applied SSRT strain rate of 10^{-5} s^{-1} , in accordance with ASTM G129, proved suitable for evaluating hydrogen embrittlement susceptibility. The significant reduction in A5 and RA under hydrogen charging confirms that SSRT is an effective method for assessing EAC susceptibility in P460NL1 steel.

Overall, the results indicate that welding significantly increases the susceptibility of P460NL1 steel to hydrogen embrittlement, and that the combined effects of hydrogen charging, microstructural banding, inclusions, and local hardening govern the EAC behaviour.

Conclusion

P460NL1 steel exhibits a measurable susceptibility to hydrogen embrittlement, which becomes pronounced under electrochemical hydrogen charging, as evidenced by a significant reduction in fracture elongation and reduction of area.

Welded joints show substantially higher hydrogen embrittlement susceptibility than the base metal. This is attributed to microstructural heterogeneity, increased hardness in the weld metal and heat-affected zone, and the presence of residual welding stresses.

Hydrogen charging has a limited effect on yield and tensile strength, while ductility-related parameters (A5 and RA) are strongly degraded, confirming that hydrogen primarily affects plastic deformation and fracture behaviour.

Crack initiation and propagation preferentially occur in pearlitic bands, whereas ferritic regions tend to impede crack growth, indicating the critical role of microstructural banding in hydrogen-assisted cracking.

Fractographic analysis revealed a transition from ductile dimple fracture in air to quasi-cleavage fracture under hydrogen charging, confirming the operation of hydrogen-assisted cracking mechanisms.

Non-metallic inclusions (CaS, AlMgO) and NbTi-based metallic inclusions act as hydrogen trapping sites and contribute to local stress concentration, promoting crack initiation.

The SSRT method at a strain rate of 10^{-5} s^{-1} , in accordance with ASTM G129, proved to be an effective approach for evaluating susceptibility to environmentally assisted cracking in P460NL1 steel.

Overall, microstructure, inclusion characteristics and welding-induced hardening, highlighting the importance of welding procedure control for applications involving hydrogen-containing environments, govern the resistance of P460NL1 steel to hydrogen embrittlement.

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A methodological framework for achieving sustainable hydrogen supply chain produced via biogas-based steam methane reforming

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Abstract: Growing energy and environmental challenges highlight the need for a transition to sustainable supply chains. This paper presents a methodology for assessing a hydrogen supply chain based on steam reforming of biogas (SMR), as a low-carbon alternative to conventional natural gas. The framework covers the entire life cycle, from feedstock to end use. The proposed framework supports strategic planning and provides a basis for future modeling, optimization, and assessment of environmental and socio-economic benefits.

Keywords: HYDROGEN, BIOGAS, STEAM METHANE REFORMING, SUSTAINABLE, SUPPLY CHAIN

1. Introduction

Hydrogen is often described as the "green energy carrier of the future" because it can be used in fuel cells, where it produces electricity through oxidation without emitting carbon dioxide. This electricity could be used to power cars and buses, to carry out chemical processes, to provide backup or peak power in energy systems, etc. Unlike conventional resources such as natural gas, hydrogen does not occur freely in nature and must first be produced, which is why it is considered an energy carrier rather than a primary fuel [1]. Various feedstocks such as water, natural gas, coal, oil, biomass, biogas, waste, and industrial by-product gases can be used for hydrogen production through chemical, electrochemical, or thermochemical processes. The choice of source and method determines the efficiency, cost, and environmental impact of production. At present, the most widely used technology for industrial hydrogen production is steam methane reforming (SMR) from natural gas due to its technological maturity and economic efficiency [2]. However, the SMR process generates significant CO₂ emissions (approximately 9–12 kg CO₂-eq/kg H₂), which motivates researchers to explore the development of alternative feedstocks and processes [3]. This poses serious challenges to the sustainability of hydrogen supply chains.

One of the most promising low-carbon alternatives that is attracting increasing attention is the use of renewable gas feedstocks, among which biogas stands out as a technologically compatible substitute for natural gas in reforming processes. Analyses indicate that integrating biogas into reforming processes can reduce emissions and improve energy efficiency, particularly when the feedstock is derived from waste streams [3]. In addition, biogas quality and the degree of purification are critical factors for reforming efficiency and catalyst stability [4].

Another key aspect is the availability of biogas as a resource. Its potential is highly dependent on regional factors such as biomass waste availability, collection infrastructure, regulatory framework, and economic incentives. Therefore, the sustainability of biogas-based hydrogen systems cannot be assessed solely at the technological level but requires an integrated system analysis that includes the resource base, logistics, and market conditions.

The hydrogen supply chain is a complex system of interconnected stages, including feedstock supply, biogas production, biogas upgrading, hydrogen production and purification, transport, storage, and end use [5]. Each of these stages has specific technological, economic, and environmental characteristics that influence the overall sustainability of the system.

Modern scientific research emphasizes that the optimization of hydrogen supply chains (HSC) requires a systematic approach that considers all stages simultaneously [6]. Analyses indicate that solutions optimal for an individual stage (e.g., production) are not always optimal for the system as a whole. For example, centralized production may be more technologically efficient but can result in high transport costs and emissions. Conversely, decentralized systems reduce logistical costs but often require greater production capacity.

The main parameters influencing the configuration of hydrogen supply chains include the geographic distribution of resources, spatial distribution of consumers, transport distances, infrastructure availability, and economies of scale. Modeling such systems is often performed using optimization methods, including linear programming, mixed-integer models, and scenario analyses. These approaches enable simultaneous minimization of costs and emissions under given constraints, such as facility capacity or infrastructure limitations. A particularly important aspect is the choice of hydrogen storage and transport technology. Different options—compressed gas, liquefied hydrogen, ammonia, or liquid organic carriers—exhibit different energy losses, capital costs, and risks. Therefore, the optimal configuration of the supply chain depends on the combination of technology, distance, and production scale.

An additional factor is uncertainty in future hydrogen demand [7]. Many models show that investment decisions are highly sensitive to demand forecasts, which necessitates the integration of scenario analyses and probabilistic methods. This is especially relevant for emerging markets where stable historical data are lacking.

In this context, multi-criteria assessment methods are considered a promising tool for strategic planning, as they allow simultaneous consideration of economic, environmental, and social indicators. They support decision-making under conditions of uncertainty and complexity characteristic of the hydrogen economy.

Existing literature identifies three main limitations: the lack of integrated methodologies combining life cycle assessment (LCA) and supply chain analysis, the limited number of studies on biogas-based hydrogen, and the absence of multicriteria frameworks for strategic planning. Therefore, the development of a systematic methodological framework for assessing the sustainability of biogas-based hydrogen supply chains represents a timely and scientifically justified research need.

This study focuses on developing a methodology for evaluating the sustainability of a supply chain based on hydrogen production via biogas-based steam methane reforming. The object of the study is a hydrogen supply chain encompassing feedstock supply, biogas production, biogas upgrading, hydrogen production and purification, transport, storage, and end use. The approach adopted in this work is based on a systems-level consideration of the chain and life cycle analysis, integrated within a multicriteria framework for sustainability assessment. The aim of the developed methodological approach is to support strategic planning and provide a foundation for future quantitative modeling and optimization.

2. Hydrogen production via biogas-based steam methane reforming

Before considering the technological process of producing hydrogen based on biogas (biohydrogen), it is important to analyze the raw material itself (biogas) - composition, potential and challenges.

2.1 Biogas as a feedstock for hydrogen

Biogas is a biogenic gas produced through the anaerobic decomposition of organic matter by microbial cultures [8]. It is typically obtained from municipal solid waste landfills, wastewater treatment plants, agricultural facilities fermenting animal residues, and industrial and food-processing waste.

Biogas primarily consists of methane (CH_4) and carbon dioxide (CO_2), along with trace impurities such as hydrogen sulfide (H_2S), water vapor, nitrogen, and other volatile components. Table 1 presents the compositional profile of biogas as a feedstock for hydrogen production via SMR [9]. The high methane content in biogas makes it a suitable feedstock for hydrogen production.

Table 1: Component composition of biogas, [9].

Components of biogas	Molar Fraction	Mass Fraction
CH_4	59.75%	35.05%
CO_2	40.00%	64.60%
N_2	0.20%	0.20%
O_2	0.02%	0.05%
H_2S	725 ppmv	900ppm

The composition of biogas can vary depending on the source and production conditions, but it usually contains about 50-70% methane, 30-50% carbon dioxide and up to a few percent of impurities. Impurities such as hydrogen sulfide and siloxanes can be corrosive and reduce the efficiency of subsequent technological processes, requiring preliminary upgrading [4].

The use of biogas as a feedstock for hydrogen production offers several key advantages [10]:

- **Low-carbon profile**

Biogas can significantly reduce life cycle greenhouse gas emissions compared to natural gas, particularly when derived from waste streams that would otherwise release methane into the atmosphere.

- **Utilization of waste resources**

The use of biogas in hydrogen production turns an environmental problem associated with waste from landfills, farms and sewage treatment plants into a valuable resource. The conversion of organic waste into energy and hydrogen contributes to the development of a circular economy, while reducing the need for landfilling and open fermentation.

- **Use of existing infrastructure**

Hydrogen production from biogas is achieved using established and widely applied steam methane reforming technology. Since biogas (after upgrading to biomethane) is nearly identical to natural gas, existing facilities can be used without major new investments in technology.

- **Continuous production**

Unlike “green hydrogen”, which is produced by electrolysis and is dependent on the availability of sun or wind, biogas-based hydrogen can be produced continuously. This makes hydrogen supplies predictable and stable for industry and transport.

- **Decentralization**

Biogas plants can be located close to waste sources, in agricultural areas or near urban centers. This allows hydrogen to be produced close to the point of consumption, reducing both transport costs and emissions.

- **Flexibility**

Biogas can be used either independently or blended with natural gas, allowing technological processes to be adapted according to feedstock availability.

According to the International Energy Agency (IEA) [10] and the International Renewable Energy Agency (IRENA) [11], biohydrogen provides reliable production with the potential for a negative carbon footprint, making it more environmentally friendly than gray hydrogen and more accessible than green hydrogen. Furthermore, biogas-based technology supports the circular economy by converting waste into a resource for clean energy. Table 2 presents a comparative profile of hydrogen production pathways.

Table 2: Hydrogen production pathways: a comparative profile

Characteristic	Grey Hydrogen (Natural Gas)	Bio-Hydrogen (Biogas/Bio methane)	Green Hydrogen (Electrolysis)
CO2 Emissions	High (Fossil-based)	Neutral to Negative	Zero (Renewable-only)
Availability	Constant (24/7)	Constant (Base load)	Intermittent (Weather-dependent)
Production Cost	Low	Medium	High
Raw Material	Fossil Methane	Organic Waste / Biomass	Water + Renewable Electricity
Energy Cycle	Linear (One-way)	Circular (Closed-loop)	Circular (Closed-loop)

Despite the potential benefits of using biogas as a feedstock for hydrogen production, several technological and economic challenges exist, including the need for biogas upgrading, compositional variability, infrastructure requirements, and others [3]. These limitations could be addressed through the development of a methodological framework for achieving a sustainable hydrogen supply chain.

2.2 Hydrogen production from biogas

The conversion of biogas into hydrogen is a multi-step thermochemical process that integrates biogas production, gas upgrading, and subsequent catalytic conversion [3]. Biogas is typically produced through the anaerobic degradation of organic waste under mesophilic conditions.

The first technological step is the preliminary upgrading of biogas, which involves the removal of sulfur compounds, moisture, and silicon-containing components, as these can deactivate catalysts and reduce process efficiency. If necessary, CO_2 is partially removed to produce biomethane with a higher CH_4 content.

The main conversion step is steam methane reforming in which a mixture of methane and steam reacts catalytically at high temperatures (typically 700–900 °C) in the presence of a nickel catalyst, forming syngas—a mixture of H_2 , CO , CO_2 , CH_4 , and water vapor. The reaction is highly endothermic and requires an external heat source. The composition of the resulting syngas depends on temperature, pressure, and the $\text{CH}_4/\text{CO}_2/\text{H}_2\text{O}$ ratio in the feed.

After reforming, the gas mixture undergoes a water–gas shift (WGS) reaction, in which carbon monoxide reacts with steam to produce hydrogen and carbon dioxide. In industrial practice, this stage is carried out in two consecutive reactors—a high-temperature reactor ($\approx 300\text{--}400$ °C) and a low-temperature reactor ($\approx 200\text{--}300$ °C)—to maximize CO conversion and increase H_2 yield.

The final technological step is hydrogen purification. Methods such as chemical absorption of CO_2 , methanation, membrane separation, or Pressure Swing Adsorption (PSA) are employed.

Modern systems often combine PSA and membranes, as this allows the production of high-purity hydrogen (over 99%) with relatively moderate energy consumption.

In addition to conventional SMR, biogas also allows the application of dry reforming, in which methane reacts directly with the CO₂ present in the feedstock. This approach is environmentally attractive, as it utilizes carbon dioxide as a reactant and potentially reduces overall emissions.

3. Hydrogen supply chain

The hydrogen supply chain for biogas-based hydrogen produced via steam methane reforming represents an integrated system of technological, logistical, and infrastructural stages. It covers the entire pathway—from feedstock to end user. The main stages are:

- *Feedstock supply*

This is the stage of waste biomass collection, transport to the anaerobic plant and preliminary preparation (grinding, homogenization, humidity control).

- *Biogas production and upgrading*

This stage includes the anaerobic digestion of biomass in the production of raw biogas and the subsequent biogas upgrading process.

- *Hydrogen production*

This is the stage of converting biogas into biohydrogen through a steam reforming process, in which the main process (SMR), Water-Gas Shift reaction and gas purification are carried out to obtain high-purity hydrogen.

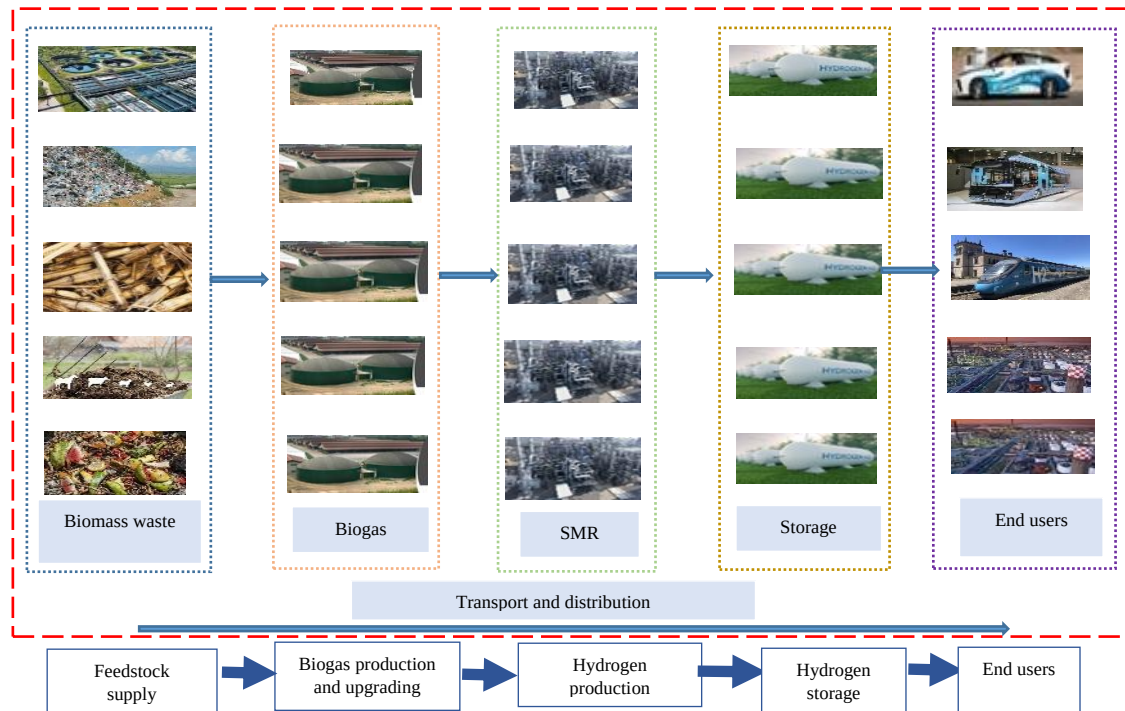


Fig. 1. Supply chain of hydrogen produced via biogas-based SMR

- *Hydrogen storage*

Hydrogen can be stored in liquid or gaseous form in buffer tanks at the production facility or at the end points of consumption.

- *Transport and distribution*

Transport and distribution of hydrogen can be carried out using specialized tube trailers or pipelines.

- *End use*

Biohydrogen can be utilized at hydrogen refueling stations for cars and buses, as well as in industry, energy systems, and other applications.

Fig. 1 presents the proposed superstructure of the hydrogen supply chain produced via biogas-based steam methane reforming, which considers the entire life cycle of the process—from feedstock to end user.

4. A methodological framework

The research methodological framework of the study is presented in Fig. 2 and is adapted from the framework proposed in [12]. The proposed in current work framework is structured into three main blocks: input data, optimization model, and output results, which together form a systematic architecture to support decision-making in the design and assessment of a sustainable hydrogen supply chain based on biogas resources. This framework allows for the integration of technological, economic, and environmental parameters, enabling a comprehensive evaluation of alternative configurations and their impact on overall system sustainability. By providing a structured approach, it facilitates strategic planning and supports the identification of trade-offs between cost, efficiency, and environmental performance.

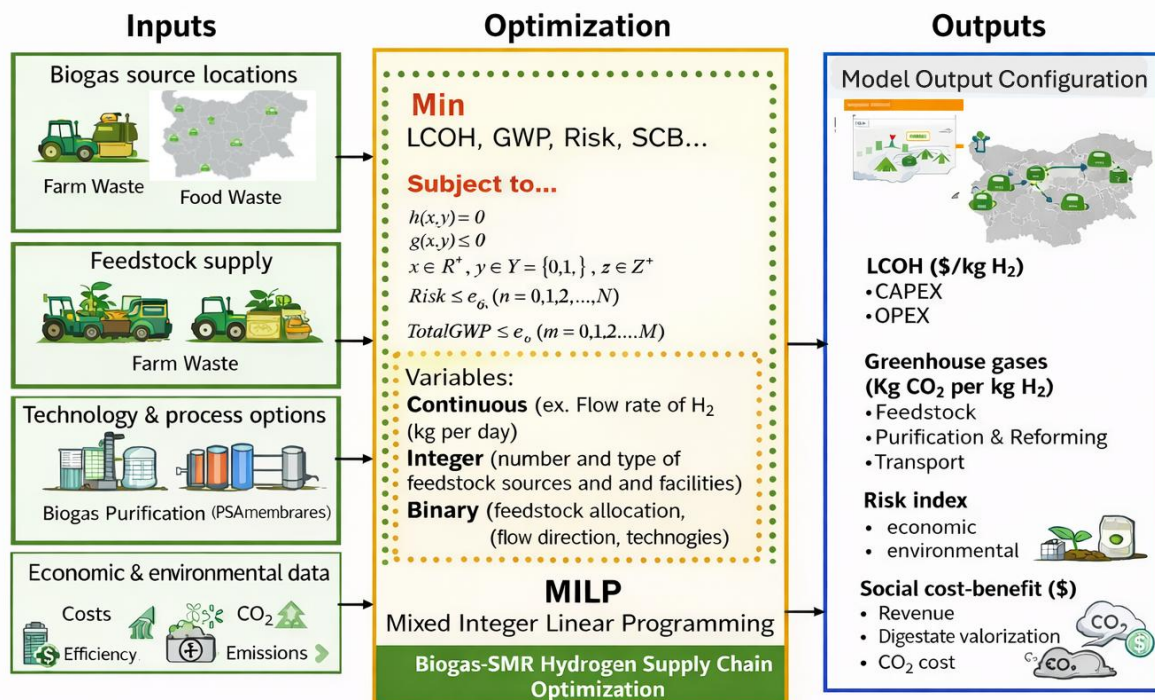


Fig. 2. Biogas-SMR hydrogen production methodological framework

The input block corresponds to all the databases, hypotheses, and scenarios. This stage collects the necessary information for system modeling, including the location of biomass waste sources, data on the quantity and type of available biomass, technological process parameters, as well as economic and environmental data. The purpose of this block is to initialize the model with consistent and realistic information, enabling both deterministic calculations and scenario-based analysis.

The optimization block integrates the mathematical model and the multi-objective optimization approach, constituting the core of the framework. The problem is formulated in terms of Mixed Integer Linear Programming (MILP). The proposed methodological framework aims to minimize key indicators such as economic efficiency, environmental impact, social benefits, and risks, while satisfying a set of constraints (e.g., technological, transport, material, environmental, logical, and others). This formulation allows for the analysis of trade-offs between conflicting objectives and helps identify optimal system configurations under different scenarios.

The outputs block corresponds to all results according economic, ecologic and risk and social benefits, so as to ensure a sustainable hydrogen supply chain. The set of results obtained allows a quantitative assessment of the sustainability of the system and supports decision-making processes.

5. Conclusion

This study presents an integrated framework for the analysis and design of the production and supply chain of hydrogen from biogas via steam methane reforming. The proposed approach combines resource assessment, process modeling, and systems analysis within a unified methodological structure, considering the entire system as an interconnected chain—from feedstock to end user. Sustainability is addressed comprehensively by simultaneously accounting for technological, economic, environmental, and social indicators. The developed framework can serve as a decision-support tool for planning, optimization, and scenario evaluation for the implementation of biogas-based hydrogen systems under varying regional and technological conditions.

Acknowledgments

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Modeling of Densification Kinetics during Electro-Pulse Consolidation of Titanium Powder

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Abstract This study presents a theoretical investigation of the densification kinetics of titanium powder during electro-pulse consolidation. A mathematical model was developed to analyze the influence of electrical current parameters in different sintering regimes – direct current (DC), alternating current (AC), pulsed current, and their superposition – on the thermophysical processes governing sintering.

The heating rates and the evolution of relative density were calculated for different applied pressing pressures. The results show that the superposition of currents is the most energy-efficient regime. This regime enables the material to reach a relative density above 99% within a minimal processing time. The effect is attributed to the combined action of intense Joule heating and the electroplastic effect.

KEYWORDS: TITANIUM POWDER, ELECTRO-PULSE CONSOLIDATION, DENSIFICATION KINETICS, JOULE HEATING, CURRENT SUPERPOSITION, SPARK PLASMA SINTERING.

1. Introduction

The production of high-density materials from refractory metals, particularly titanium, while preserving their microstructure remains an important challenge in materials science. Conventional sintering methods require prolonged thermal exposure, which promotes grain growth and leads to degradation of physical and mechanical properties.

The use of Electric Current Assisted Sintering (ECAS) technologies is a promising approach to address these issues. These methods provide rapid powder densification due to intensive Joule heating and electroplastic effects.

The modern market offers various types of equipment for electroconsolidation. Spark plasma sintering (SPS) is the most widely used ECAS technique. It employs pulsed current (typically ~1 kHz). This approach is implemented in systems such as the Dr. Sinter SPS series (SPS Syntex Inc.) [1] and HP D systems (FCT Systeme GmbH) [2]. For studies focused on the influence of alternating current (AC), direct current (DC), and their combinations, physical simulation systems such as the Gleeble 3800 [3] are often used, as they allow flexible control of the current waveform. Some experimental setups, for example the Gefest-10 [4], enable the application of current superposition to achieve a synergistic densification effect.

Despite the availability of different equipment, direct experimental comparison of the efficiency of various current regimes (DC, AC, pulsed current, and superposition) for the same material is challenging. Differences in chamber design, thermal units, and tooling geometry in industrial systems prevent the creation of identical processing conditions required for rigorous analysis.

To address this limitation, a theoretical modeling approach to densification kinetics was adopted. This method eliminates the influence of equipment-specific design factors. Titanium powder was selected as the model material because its relatively high electrical resistivity makes it well suited for the analysis of electrothermal processes.

The aim of this study is to theoretically investigate and compare the densification kinetics of titanium powder under different current regimes and applied pressures in order to determine energy-efficient consolidation conditions.

2. Methodology

This study is based on a supervised machine learning methodology. The general scheme of the model represents a powder compact placed inside a die between two punches. To ensure the adequacy and physical consistency of the model, several key assumptions were adopted [6]:

1. The temperature field inside the sample is assumed to be spatially uniform at any given time. This assumption is justified for small specimens and high heating rates typical of the process.

2. The electrical resistance is calculated for the entire specimen volume and treated as a single equivalent resistive element.

3. Heat losses to the environment through the die and punches are neglected.

4. The densification kinetics are described using phenomenological equations. The model parameters are calibrated to qualitatively reproduce experimentally observed trends rather than to simulate micromechanical processes at the level of individual particle contacts.

Mathematical Description of the Model

The model is based on a system of coupled differential and algebraic equations that describe heat generation, thermal balance, and the kinetics of structural evolution in the powder compact.

Electrophysical Submodel and Calculation of Joule Heating

The primary energy source during the process is Joule heat generation. The instantaneous power of heat release, Q , W , is calculated according to the Joule–Lenz law [5]:

$$Q = I_{eff}^2 \cdot R(t), \quad (1)$$

where I_{eff} is the effective (root mean square, RMS) current (A), and $R(t)$ is the instantaneous electrical resistance of the sample (Ω).

An important feature of the proposed model is the inclusion of the dynamic change in the specimen height, $h_{current}(t)$, during densification. This variation is calculated according to the law of mass conservation:

$$h_{current}(t) = h_{initial} \cdot \frac{\rho_{rel,initial}}{\rho_{rel}(t)}. \quad (2)$$

The instantaneous electrical resistance, in turn, is a function of the specimen geometry and its effective electrical conductivity, σ_{eff} :

$$R(t) = \frac{h_{current}(t)}{\sigma_{eff}(t) \cdot A_{sample}}, \quad (3)$$

where

$$A_{sample} = \pi \left(\frac{d_{sample}}{2} \right)^2, \quad (4)$$

The effective electrical conductivity, σ_{eff} , of the powder compact is approximated by a linear relationship between the electrical conductivity of the fully dense material σ_{Ti} and the current relative density $\rho_{rel}(t)$.

$$\sigma_{eff}(t) = \sigma_{Fe} \cdot \rho_{rel}(t). \quad (5)$$

Evaluation of the Effective Current

A key aspect of the electrophysical submodel is the accurate calculation of the effective current, I_{eff} , for different signal types

(see Figure 1), since the RMS value determines the average power released over an oscillation period.

The model considers four main types of current namely direct current (DC), sinusoidal alternating current at 50 Hz (AC), pulsed current (~1 kHz), and a superposition of direct and pulsed current at ~50 kHz, characteristic to the Gefest-10 system.

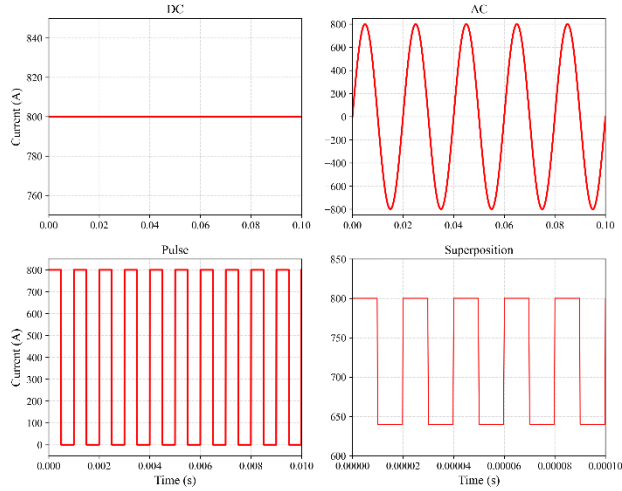


Figure 1: Considered current waveforms

The effective current, I_{eff} , for different waveform types was calculated as follows [7]:

Direct current :

$$I_{eff}^2 = I_{DC}^2. \quad (6)$$

Alternating sinusoidal current:

$$I_{eff}^2 = \left(\frac{I_{amp}}{\sqrt{2}}\right)^2 = \frac{I_{amp}^2}{2}. \quad (7)$$

Pulsed rectangular current with a duty cycle $D = 0.5$:

$$I_{eff}^2 = I_{amp}^2 \cdot D, \sigma_{eff}(t) = \sigma_{Fe} \cdot \rho_{rel}(t). \quad (8)$$

DC and AC superposition:

$$I_{eff}^2 = I_{DC,eff}^2 + I_{AC,eff}^2 = (0.8 \cdot I_{amp})^2 + \left(\frac{I_{amp}}{\sqrt{2}}\right)^2 = 0.66 \cdot I_{amp}^2. \quad (9)$$

The change in the average temperature of the sample, T , K, over time is described by the differential equation of thermal balance [8]:

$$m \cdot C_p \cdot \frac{dT}{dt} = Q_{eff}, \quad (10)$$

where m is the sample mass (kg), C_p is the specific heat capacity of the material (J/(kg·K)), T is the temperature (K), and Q_{eff} is the effective power of heat generation, W.

The averaged model does not account for the effects of increased contact resistance between particles and current concentration during the initial stages of sintering, which lead to significantly more intense heating. To compensate for this simplification, a phenomenological heating intensification factor, K_{heat} , is introduced. This factor increases the calculated Joule heating power during the heating stage ($T < T_{target}$):

$$Q_{eff} = Q \cdot K_{heat}. \quad (11)$$

In this work, the value of this factor was taken as $K_{heat} = 2.5$.

To adequately describe the evolution of the relative density (ρ_{rel}) and the microstructure of the sample over time, a phenomenological kinetic model based on the principle of superposition was considered. According to this principle, the overall densification rate is the sum of contributions from several simultaneously occurring mass transport mechanisms [9–10]:

Plastic deformation and creep – this mechanism dominates at relatively low temperatures and during the initial stages of densification. It is accounted for through a rate dependence on the current porosity ($1 - \rho_{rel}$). The kinetic equation for this component is expressed as:

$$\left(\frac{d\rho_{rel}}{dt}\right)_{pl} = A_{pl} \cdot (1 - \rho_{rel}). \quad (12)$$

Here, the left-hand term represents the densification rate due to plastic mechanisms, and A_{pl} is an empirical coefficient characterizing the intensity of plastic flow and creep for the given material.

Thermally activated diffusion is the mechanism dominates at high temperatures and is responsible for the elimination of residual porosity during the intermediate and final stages of densification.

$$\left(\frac{d\rho_{rel}}{dt}\right)_{diff} = B_{diff} \cdot e^{\frac{-Q}{RT}} \cdot (1 - \rho_{rel}). \quad (13)$$

Here, the left-hand term represents the densification rate due to diffusion, B_{diff} is the pre-exponential factor, Q is the activation energy for diffusion of the material, R is the universal gas constant, and T is the absolute temperature.

The overall densification rate under standard conditions is the sum of the contributions from both mechanisms: plastic deformation/creep and thermally activated diffusion.

$$\begin{aligned} \left(\frac{d\rho_{rel}}{dt}\right)_{base} &= \left(\frac{d\rho_{rel}}{dt}\right)_{pl} + \left(\frac{d\rho_{rel}}{dt}\right)_{diff} = \\ &= A_{pl} \cdot (1 - \rho_{rel}) + B_{diff} \cdot e^{\frac{-Q}{RT}} \cdot (1 - \rho_{rel}). \end{aligned} \quad (14)$$

This base densification rate is further modified by the effects of pressure and athermal current phenomena. The influence of pressure (P) is considered as a linear driving force normalized to a reference pressure, P_{ref} . Athermal effects (such as electromigration and electroplasticity) are accounted for using a dimensionless athermal activation factor, $K_{athermal}$, which takes the following values: 1 for DC, 1.05 for AC, 1.2 for pulsed current, and 1.3 for current superposition [11].

The final equation for the densification rate used in the model is obtained by multiplying the base rate by these two factors.

$$\frac{d\rho_{rel}}{dt} = \left(\frac{d\rho_{rel}}{dt}\right)_{base} \cdot K_{athermal} \cdot \left(\frac{P}{P_{ref}}\right). \quad (15)$$

By substituting the expression for the base densification rate, the final equation is obtained, which incorporates all relevant physical effects: plastic deformation and creep, thermally activated diffusion, applied pressure, and athermal current effects.

$$\begin{aligned} \frac{d\rho_{rel}}{dt} &= \left(A_{pl} \cdot (1 - \rho_{rel}) + B_{diff} \cdot e^{\frac{-Q}{RT}} \cdot (1 - \rho_{rel})\right) \cdot K_{athermal} \cdot \left(\frac{P}{P_{ref}}\right). \end{aligned} \quad (16)$$

The developed system of coupled differential equations is solved numerically using the explicit Euler method with a constant integration step of $\Delta t = 0.1$ s.

The following constants [12] and initial conditions were used in the calculations:

Table 1. Initial conditions of the model

Parameter	Symbol	Value	Unit
Titanium density	ρ_{Ti}	4500	kg/m ³
Titanium specific heat	$C_{p,Ti}$	523	J/(kg·K)
Titanium electrical conductivity	σ_{Ti}	$2.38 \cdot 10^6$	S/m
Diffusion activation energy (Ti)	Q	$1.53 \cdot 10^5$	J/mol
Sample diameter	d_{sample}	0.01	m
Sample height	h_{sample}	0.01	m
Initial relative density	$\rho_{rel,0}$	0.6	—
Initial temperature	T_0	293.15	K
Target temperature (Ti)	T_{target}	1607.55	K
Integration step	Δt	0.1	s
Maximum simulation time	t_{max}	60	s
Plasticity coefficient	A_{pl}	$8.00 \cdot 10^{-5}$	s ⁻¹
Diffusion coefficient	B_{diff}	$8.00 \cdot 10^4$	s ⁻¹

For quantitative evaluation and comparison of the efficiency of different consolidation modes, a scatter plot was constructed showing “Total Energy Consumption versus Final Relative Density” [13–15].

The entire computational framework was implemented in the Python programming language using its standard scientific and engineering libraries.

3. Results and discussion

The simulations were performed by varying the current intensity at 400, 600, and 800 A, and the applied pressing pressure at 20, 35, and 50 MPa. The temperature regime was defined as reaching approximately $0.8 \cdot T_{melting} \approx 1300$ °C, followed by holding at this temperature until the maximum simulation time, t_{max} , was reached.

Based on the analysis of the obtained data, the heating rates for each consolidation regime were calculated (see Figure 2). At a current of 400 A, the heating rate was approximately 20 °C/s, regardless of the consolidation method. This is explained by insufficient power to reveal differences in thermal behavior at this energy level.

As the current increases, clear differentiation in heating efficiency is observed. At 600 A, the heating rate for samples processed with AC and pulsed current rises to about 30 °C/s, for the current superposition it reaches around 40 °C/s, while for DC it reaches approximately 60 °C/s. The most pronounced differences occur at 800 A: for AC and pulsed current, the heating rate increases to around 50 °C/s, for the current superposition to 70 °C/s, and for DC it reaches a maximum of approximately 120 °C/s.

This significant advantage of DC is attributed to the continuous generation of Joule heat, in contrast to AC or pulsed currents, where the effective power is reduced due to periodic zero crossings or pulse gaps. It is also noteworthy that the pressing pressure had little effect on the heating rate, indicating that volumetric heat generation dominates over contact resistance within the studied parameter range.

The presented densification curves for consolidation under direct current (see Figure 3) illustrate the nonlinear evolution of relative density, which can be divided into three characteristic stages:

1. An initial particle rearrangement stage with minimal density increase.

2. A stage of intensive plastic deformation and creep, where the densification rate reaches its maximum.

3. A final asymptotic stage corresponding to the closure of isolated pores.

At the maximum load (50 MPa) and a current of 800 A, the model predicts that the relative density reaches 0.99 by the 60th second of the process. In contrast, at 400 A and 20 MPa, the consolidation process is significantly prolonged.

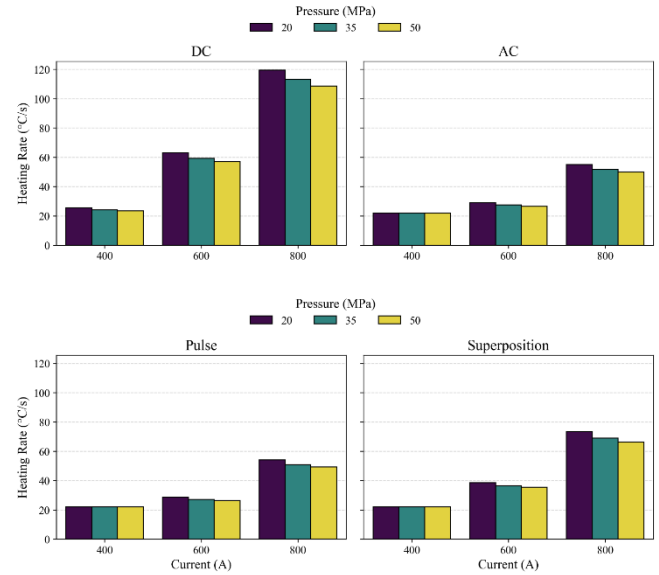


Figure 2: Comparative graphs of average heating rates

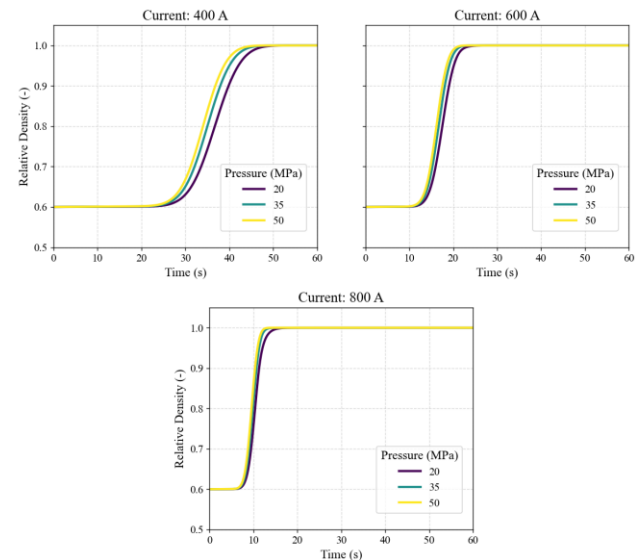


Figure 3: Evolution of the relative density of titanium powder during heating with direct current

The densification curves for alternating current (see Figure 4) show a delayed onset of intensive shrinkage compared to direct current of the same amplitude. However, due to the inclusion of the athermal activation factor, the densification rate during the active compaction stage is higher, allowing the relative density to reach 0.98–0.99 at 50 MPa. This indicates that the influence of the alternating field on the crystal lattice promotes more efficient stress relaxation.

Simulation results (see Figure 5) show that the pulsed current regime provides one of the fastest densification dynamics among the single-mode currents considered. The relative density curves exhibit a steep slope during the active sintering stage, which is

explained by the action of mechanisms such as surface oxide film removal and intensified mass transport under pulsed fields. This allows achieving a relative density of 0.99 in a shorter time than with direct current.

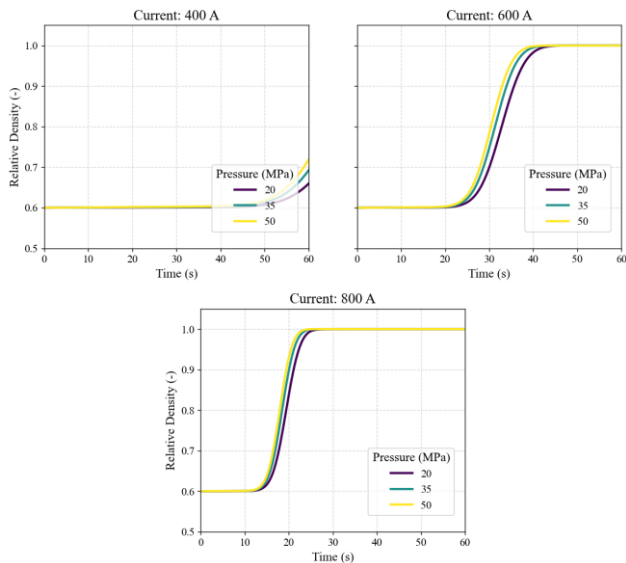


Figure 4: Evolution of the relative density of titanium powder during heating with alternating current

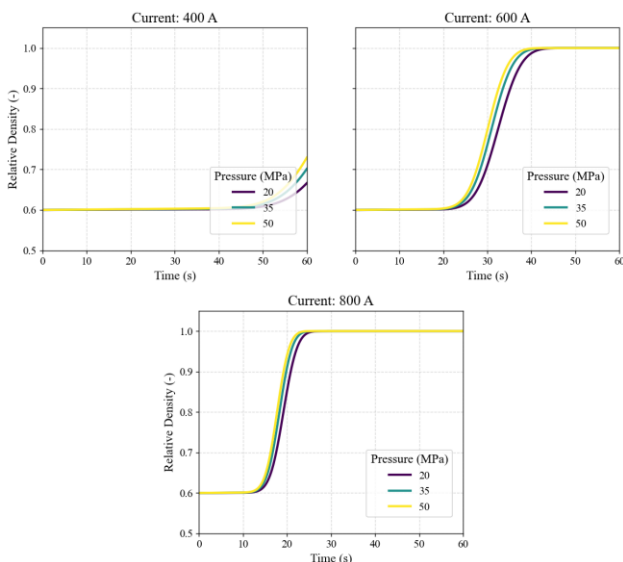


Figure 5: Evolution of the relative density of titanium powder during heating with pulsed current

The densification curves for current superposition (Figure 6) show a dynamics in which the consolidation process occurs almost immediately after reaching the threshold temperature. The high value of the athermal activation factor leads to a significant reduction of the material's yield limit (electroplastic effect), allowing the theoretical density (relative density > 0.995) to be achieved even under moderate external pressures. This makes this regime the most effective for producing high-density materials.

The derived "Total Energy Consumption – Final Relative Density" diagram (see Figure 7) clearly justifies the selection of the current superposition regime as the most promising. The points corresponding to this regime occupy the upper-left position on the graph, combining the highest achievable density (>0.995) with minimal total energy expenditure. These results indicate that high-quality densification can be achieved without increasing energy consumption.

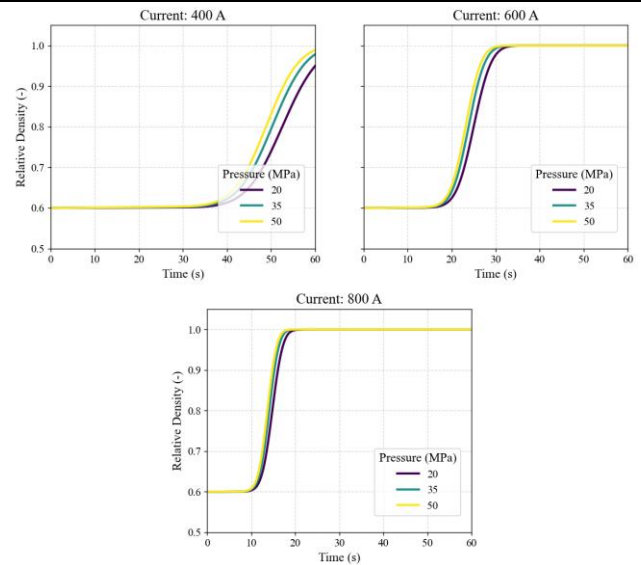


Figure 6: Evolution of the relative density of titanium powder during heating with current superposition

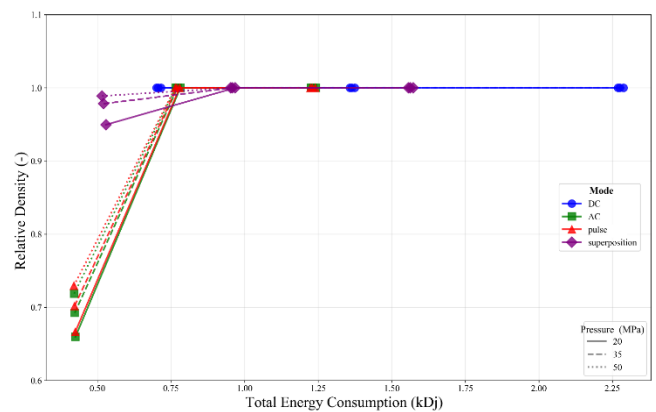


Figure 7: "Total Energy Consumption – Final Relative Density" diagram

For verification of the simulation results, titanium powder of PT-6 (TU U 14-10-026-98) (IT-6 TY Y 14-10-026-98) grade with an average particle diameter of approximately 60 μm was consolidated using a superposition of direct and pulsed current at 50 kHz on the Gefest-10 system under conditions corresponding to the simulations: currents of 400, 600, and 800 A and pressing pressures of 20, 35, and 50 MPa. The temperature regime was set to reach approximately $0.8 \cdot T_{\text{melting}} \approx 1300$ °C, followed by holding at this temperature until t_{max} .

The temperature was monitored using a thermocouple on the surface of the die. Figure 8 shows the heating curve of the titanium powder, recalculated according to the die temperature using the heat exchange equations.

Figure 9 shows the actual densification curve obtained during the physical experiment. A comparative analysis with the simulated curve (see Figure 6) reveals an overall agreement in trends; however, the experimental curve exhibits a smoother initial stage, often referred to as the "incubation period."

This discrepancy can be attributed to several physical factors not fully accounted for in the model: the presence of oxide films on powder particle surfaces, which require time and energy for electrical breakdown; imperfect contacts between particles at the start of the process; and the thermal inertia of the tooling and

temperature sensors, which causes a delay in recording the onset of active densification.

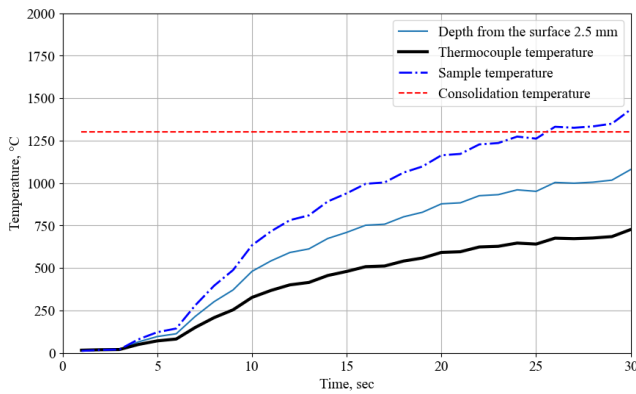


Figure 8: Heating curve of titanium powder under current superposition

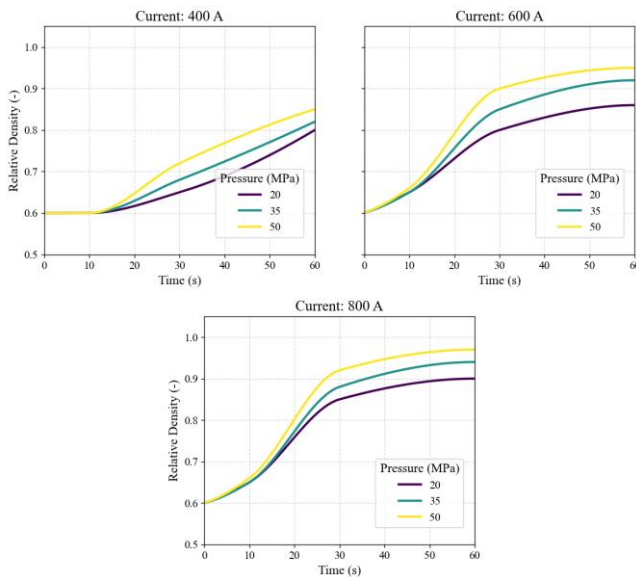


Figure 9: Experimental data of the specific density of titanium samples consolidated by current superposition versus consolidation time

4. Conclusions

1. It has been scientifically established that consolidation under direct current exhibits classical thermal kinetics, where the densification rate is linearly dependent on temperature. This regime is stable but requires a long time (over 150 s at 400 A) to achieve high density.

2. It was found that using 50 Hz alternating current introduces a cyclic loading effect, which enhances densification during the later stages of the process. However, the lower average heating rate compared to pulsed regimes limits its effectiveness at the initial stage of consolidation.

3. It has been theoretically shown that the pulsed regime (1 kHz) likely promotes effective particle surface cleaning and accelerated neck formation due to high peak current values and the presence of pauses, enabling faster achievement of high-density materials than with direct current.

4. A scientific hypothesis was proposed and justified based on simulation results regarding the synergistic effect of combining direct and alternating current components (50 kHz). This effect manifests as the highest heating rate and the activation of the electroplastic effect, allowing the theoretical density of the material to be reached in minimal time.

5. Analysis of the “energy–density” diagrams theoretically substantiates that the current superposition regime represents the technological optimum, as it uniquely combines the maximum physico-mechanical quality of the consolidated sample (relative

density > 99.5%) with the lowest specific energy consumption, outperforming traditional methods.

6. Comparison of calculated and experimental data confirmed the adequacy of the developed model for predicting the final material properties. Observed deviations in the kinetics during the initial stage highlighted the influence of surface oxide films and contact resistances, which should be considered in further model refinements.

7. Based on the “Total Energy Consumption – Final Relative Density” analysis, the optimal titanium powder consolidation regime was identified: superposition of direct and alternating currents (50 kHz) with a total current of 600 A under a pressing pressure of 50 MPa. This regime achieves a relative density of 99.8% in less than 60 s, combining a high heating rate with intensified mass transport (characteristic of the AC component). Specific energy consumption is 15–20% lower compared to regimes achieving similar density purely via thermal effects, making this regime the most promising for industrial implementation.

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Cathodic Protection Modeling of Steels in Corrosive Chemical Environments Using COMSOL Multiphysics

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Abstract: This study investigates the electrochemical performance of Sacrificial Anode Cathodic Protection (SACP) systems for offshore steel structures using Finite Element Analysis (FEA). Two structural substrates, S235JR carbon steel and S550QL high-strength steel, were modelled in a 3 wt.% NaCl electrolyte. A comparative analysis was performed between two sacrificial anode materials: a conventional Al-5Mg alloy and a quaternary Al-6Zn-0.2In-1Mg-0.03Ti alloy. The simulations evaluate the influence of anode placement errors by comparing an ideal symmetric distribution (90°) with a clustered configuration (10°). The results show that geometric clustering significantly alters the potential distribution along the structure. For S235JR steel, the clustered configuration produces localized underprotection with potentials reaching -0.78 V (vs. Ag/AgCl). In contrast, for S550QL steel, the same configuration results in localized over-polarization (≈ -0.96 V), thereby increasing the risk of hydrogen-induced stress cracking (HISC). The study demonstrates that improper anode placement may compromise cathodic protection efficiency even when high-performance anode alloys are used. These findings highlight the importance of accurate anode distribution and support the use of numerical simulations in digital twin approaches for offshore corrosion management.

Keywords: SACRIFICIAL ANODES, DIGITAL TWIN, CATHODIC PROTECTION, COMSOL MULTIPHYSICS

1. Introduction

Corrosion remains a persistent and costly challenge in offshore industrial environments, particularly in aggressive maritime conditions. If left unmonitored, electrochemical degradation can lead to catastrophic structural failures and significant economic losses [1]. To mitigate these risks, Cathodic Protection (CP) using sacrificial anodes is the most widely adopted method for preserving submerged offshore assets [1,2].

The effectiveness of CP systems depends on electrochemical thresholds that vary with substrate metallurgy. According to EN ISO 15589-2, standard carbon steels such as S235JR require a polarized potential maintained between -0.85 V and -1.05 V (vs. Ag/AgCl) for full corrosion immunity [1]. High-strength steels such as S550QL introduce a narrow operational window: while they require cathodic polarization to prevent mass loss, they are highly susceptible to Hydrogen-Induced Stress Cracking (HISC) if the potential drops below -1.10 V (vs. Ag/AgCl) [2, 3]. Achieving a uniform potential distribution is therefore a structural necessity.

Although theoretical designs assume perfect anode symmetry, industrial constraints and installation errors often result in asymmetric or clustered arrangements [4–6]. Such non-ideal configurations reduce the system's "throwing power," creating localized "shadowing effects" that leave areas vulnerable to accelerated corrosion or hydrogen-induced damage. Under Industry 4.0, Digital Twins allow engineers to simulate these non-ideal scenarios and predict structural behavior before failure occurs [1, 5, 7].

This study utilizes COMSOL Multiphysics® [8] to quantify the electrochemical impact of geometric clustering errors, specifically where anodes are placed at 10° intervals instead of the ideal 90° symmetry. Two sacrificial anode chemistries—the binary Al-5Mg alloy and the quaternary Al-6Zn-0.2In-1Mg-0.03Ti alloy—are compared across S235JR carbon steel and S550QL high-yield steel substrates. This analysis provides critical data for predictive maintenance strategies, supporting the transition toward Corrosion 4.0 [9].

2. Methodology

The numerical investigation was conducted using the Corrosion Module of COMSOL Multiphysics® [8], whether Secondary or Tertiary Current Distribution interface was used, and which kinetic boundary conditions were applied.

Model Geometry and Environmental Conditions

The computational domain consists of a cylindrical cathode (15 m height) representing a submerged structural pile. Two thermal scenarios were evaluated: 20°C for the S235JR substrate and 15°C

for the S550QL substrate, as temperature significantly influences electrolyte resistivity and oxygen solubility. While an isothermal comparison would isolate electrochemical kinetics, this study intentionally differentiates the thermal profiles (15°C for S550QL vs. 20°C for S235JR) to reflect the distinct operational depths and geographic deployments of these structural steels. This dual-variable approach (geometry + temperature) provides a more robust 'stress-test' for the Digital Twin's predictive

Anode Materials: Two distinct sacrificial alloys were defined. The traditional Al-5Mg alloy and the quaternary Al-6Zn-0.2In-1Mg-0.03Ti alloy. The latter is characterized by the addition of Indium (0.2%), which acts as an activator to ensure continuous activation and prevent the formation of a passive alumina film [3, 7]

Boundary Conditions: The anodes were modeled with an equilibrium potential E_{eq} relative to the Ag/AgCl reference electrode, following DNV-RP-B401 guidelines [7].

Simulation Scenarios: To quantify the impact of installation non-conformities, two geometric configurations were compared:

- Standard Configuration (Control): 4 anodes distributed with perfect 90° radial symmetry.

- Clustered Configuration (Error): A deliberate error where a group of anodes is positioned at a 10° interval (5 anodes), simulating spatial constraints or human error in the process industry [4].

The electrolyte was modeled as a substitute ocean water with a constant salinity of 3 wt.% NaCl (conductivity (σ) of 4.78 S/m). This concentration was chosen to simulate a standard aggressive marine environment, providing a baseline for analyzing the impact of temperature on ionic mobility. At this salinity, the transition from 20°C to 15°C induces a non-linear increase in kinematic viscosity and a corresponding decrease in the diffusion coefficient of dissolved oxygen, which are critical factors for the cathodic reaction kinetics [10, 11]. The study adopts a context-specific thermal mapping, simulating each alloy under its most frequent operational environment.

3. Results and Discussion

The surface potential analysis of the pile (Fig. 1) highlights the system's sensitivity to both geometric configuration and anode composition. According to DNV-RP-B401 [7], the optimal protection criteria for steel in seawater requires a potential between -0.80 V and -1.05 V (vs. Ag/AgCl). Results indicate that the Al-6Zn-0.2In-1Mg-0.03Ti alloy achieves a deeper polarization (approaching -1.08 V in adjacent zones) compared to the Al-5Mg alloy, which maintains a more conservative potential. This performance gap is attributed to the presence of Indium, which prevents anode surface passivation. However, in the 10° clustering error scenario, both materials fail to protect the distal ends of the pile (reaching -0.78 V), confirming that the superior chemical activation of the quaternary alloy cannot overcome the ionic

shielding induced by asymmetric distribution [12, 13]. For the S235JR carbon steel substrate, this error leads to localized underprotection, posing a direct risk of generalized corrosion. In contrast, for the S550QL high-strength steel, the same geometric error drives the potential near the cluster toward -1.10 V. While this represents over-polarization, for high-strength steels, such levels are hazardous as they promote hydrogen evolution and subsequent absorption into the metal lattice, triggering Hydrogen-Induced Stress Cracking (HISC) [14].

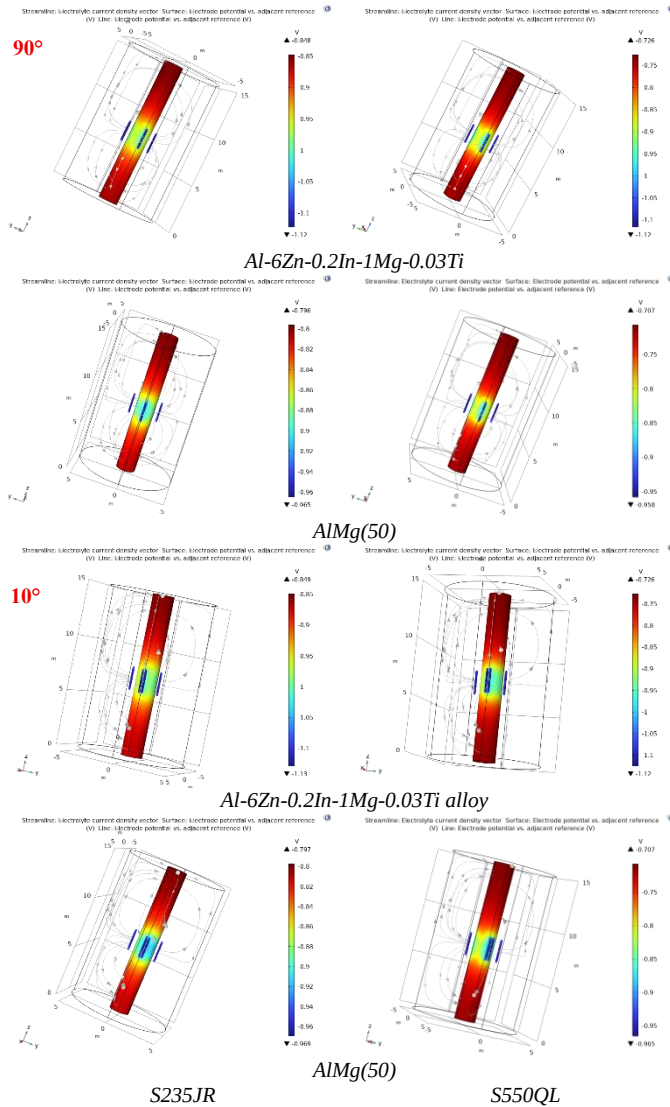


Fig. 1. Surface electrode potential distribution on S235JR and S550QL piles protected by Al-Zn-In-Mg-Ti and Al-Mg sacrificial anodes under symmetric (90°) and clustered (10°) configurations.

The multislice electrolyte potential plots (Fig. 2) reveal the physical mechanisms behind underprotection: the 'potential shadow' effect and the ohmic IR drop. The quaternary alloy generates a more extensive potential field in the electrolyte due to its higher electrochemical activity. However, on the S550QL substrate, this drives the potential toward the critical -1.10 V threshold. Conversely, the Al-5Mg alloy offers a higher safety margin against hydrogen embrittlement but demonstrates significantly lower 'throwing power'. The IR drop is most pronounced in the 10° clustering case, where the density of equipotential lines indicates a massive ohmic resistance that isolates the leeward side of the pile, a well-documented phenomenon by Peabody [15]. The S550QL high-strength steel shows a higher vulnerability to the IR drop generated by clustering. The 'potential shadow' effect is more critical for this substrate because its electrochemical safety window is significantly narrower: it must be polarized below -0.80 V to ensure corrosion protection but maintained above -1.10 V to avoid hydrogen damage.

This delicate balance is easily disrupted by the 10° anode positioning error.

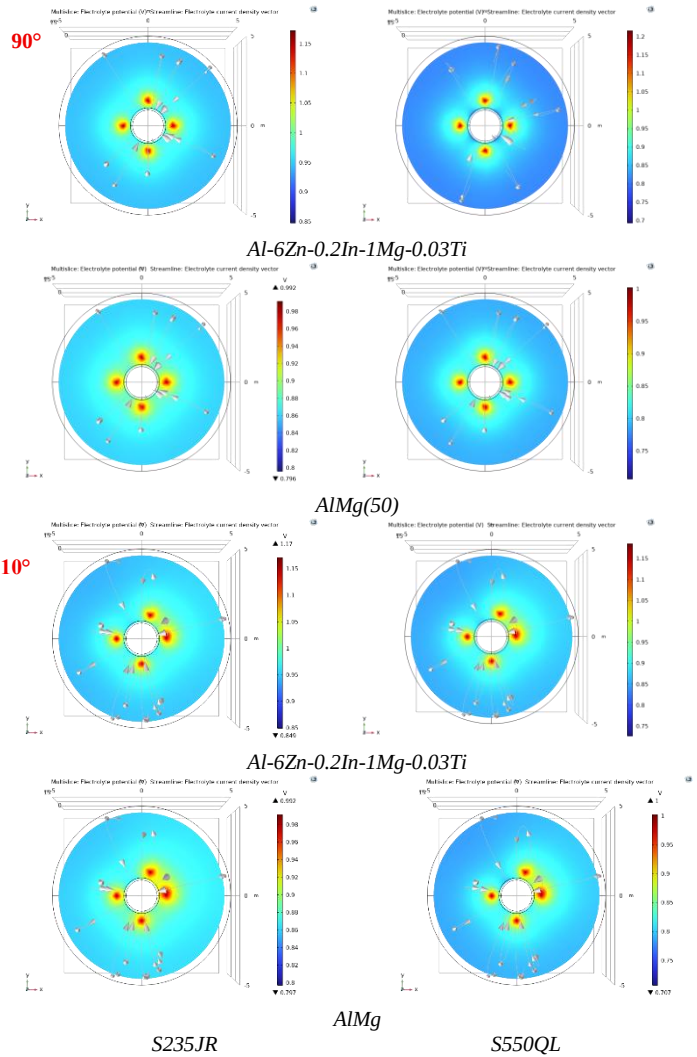


Fig. 2. Multislice electrolyte potential (ϕ_l) and current streamline distribution for S235JR and S550QL substrates: (a) clustered anode configuration (10°); (b) symmetric configuration (90°).

The visualization of current streamlines (Fig. 3) emphasizes the 'current crowding' effect and the overall current conversion efficiency of the system. The Al-6Zn-0.2In-1Mg-0.03Ti alloy delivers a significantly higher local current density, which is particularly advantageous in colder waters (15 °C) where electrolyte resistivity increases according to Sharqawy's correlations [11]. In contrast, the Al-5Mg alloy tends to passivate more rapidly under these thermal conditions, restricting the flux lines and failing to reach critical zones of the structure. In the 10° clustering scenario, negative interference is observed as adjacent anodes 'compete' for the same ionic pathways, leading to an inefficient distribution of protective current. This demonstrated inefficiency underscores the value of a Digital Twin framework [16, 17] in detecting 'hidden' current hotspots that could lead to premature anode consumption without ensuring total structural protection. The simulation quantifies a 'divergent failure mode': the 10° error leads to material loss (corrosion) in S235JR steel and structural embrittlement (HISC) in S550QL steel. While the quaternary alloy's high current output is beneficial for polarizing the S235JR pile in resistive environments, it becomes a liability for the S550QL substrate by creating localized zones of high current density that exceed the safe hydrogen evolution limits defined by DNV-RP-B401 [3].

In conclusion, the results highlight that cathodic protection design must consider the operational potential window of the protected steel. While conventional structural steels such as S235JR

require sufficient polarization to avoid corrosion, high-strength steels such as S550QL exhibit a narrower safe potential range due to the risk of hydrogen-induced damage.

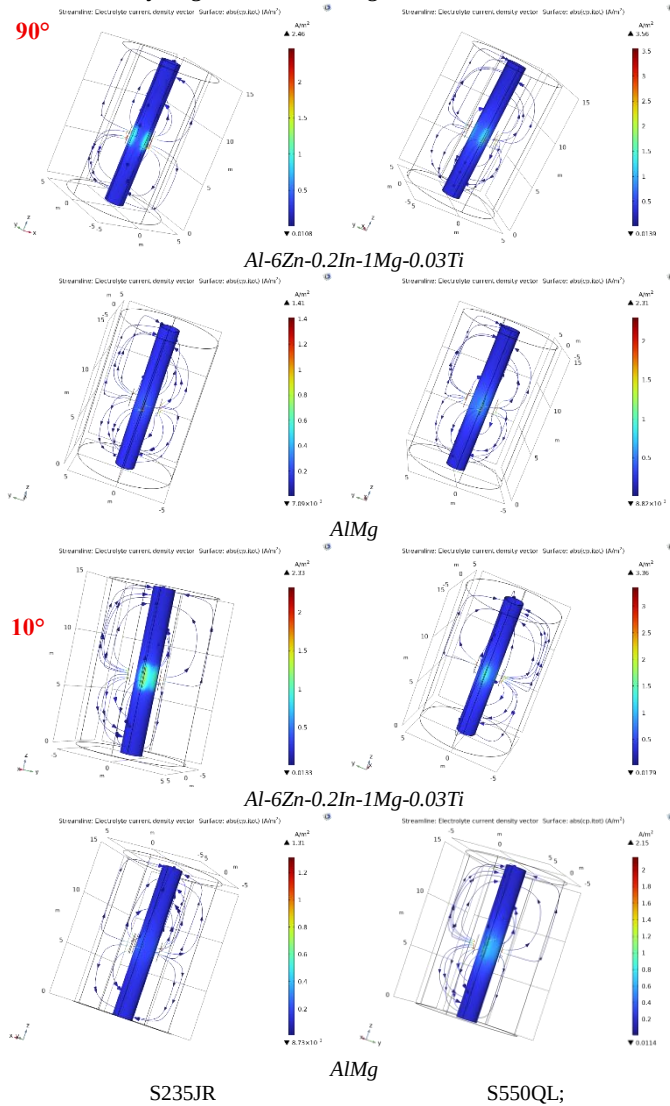


Fig. 3 Electrolyte current density and streamline distribution illustrating current flow for S235JR and S550QL substrates with Al-Zn-In-Mg-Ti and Al-Mg sacrificial anodes under symmetric (90°) and clustered (10°) configurations.

3. Conclusions

The numerical investigation into the cathodic protection of offshore structural piles under geometric and environmental stress yields the following key findings:

Impact of Geometric Non-Conformity: The simulations indicate that anode placement is the primary determinant of system integrity. A 10° clustering error creates a "potential shadow" effect, leaving structural extremities at potentials more positive than -0.80 V (vs. Ag/AgCl). Consequently, localized corrosion may occur despite the use of high-performance sacrificial alloys, as the configuration fails to meet ISO 15589-2 protection standards.

Divergent Failure Modes: Identical geometric faults produce distinct risks depending on the steel grade. For S235JR carbon steel, localized underprotection leads to material loss through oxidation. For S550QL high-strength steel, the clustering of quaternary anodes drives local potentials to be more negative than -1.10 V, introducing a critical risk of Hydrogen-Induced Stress Cracking (HISC) due to excessive cathodic polarization.

Anode Chemistry and Environmental Sensitivity: The quaternary Al-6Zn-0.2In-1Mg-0.03Ti alloy exhibits superior "throwing power" in colder, more resistive electrolytes (15 °C) compared to the binary

Al-5Mg alloy. However, its higher electrochemical activity requires precise spatial distribution to prevent the formation of localized over-polarization "hotspots" on the substrate.

Predictive Modeling and Industry 4.0: The correlation between electrolyte potential (ϕ_i) and current streamline dynamics confirms that multi-physics modeling can identify shielded regions not detectable by traditional surface-only measurements. This underlines the necessity of integrating Digital Twin frameworks into predictive maintenance strategies within the Corrosion 4.0 paradigm.

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Machine Learning Prediction of Mechanical Properties for Al-Cu Alloys Using Monte Carlo Data Augmentation

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Abstract: This study presents a machine learning framework for predicting the mechanical properties of 2xxx series Al-Cu alloys (2024, 2219, 2524) across 11 temper conditions. Monte Carlo augmentation generated 8,800 synthetic samples from compositional specification ranges of a literature-mined dataset. Three regression models, Random Forest, Gradient Boosting, and SVR-RBF were evaluated via 5-fold cross-validation (CV) to predict ultimate tensile strength (UTS), yield strength (YS), and elongation. All models achieved coefficient of determination $R^2 > 0.991$, with Mean Absolute Error MAE ≤ 7.4 MPa for UTS, ≤ 5.4 MPa for YS, and $\leq 0.51\%$ for elongation. Feature importance analysis revealed that temper condition encoding dominated predictions ($>75\%$ importance), while individual compositional features contributed $<5\%$ each. The high predictive accuracy reflects the effectiveness of the augmentation scheme in capturing within-group property-composition-temper relationships, though generalization to unseen alloy-temper conditions remains to be validated. The results illustrate the potential of combining corpus-mined data with Monte Carlo augmentation for rapid alloy property screening.

Keywords: Al-Cu ALLOYS; MACHINE LEARNING; MECHANICAL PROPERTIES; MONTE CARLO AUGMENTATION; RANDOM FOREST; GRADIENT BOOSTING

1. Introduction

The 2xxx series Al-Cu alloys (2024, 2219, 2524) are critical structural materials in aerospace applications, valued for their high strength, fatigue resistance, and damage tolerance [1,2]. Their mechanical properties depend strongly on both composition and temper condition, making property prediction across alloy-temper combinations a non-trivial task. Machine learning (ML) methods have shown promise for materials property prediction [3–5], but limited dataset sizes per alloy-temper condition remain a challenge [6,7]. Monte Carlo augmentation, which generates synthetic samples by sampling from compositional specification ranges, offers a physically motivated strategy to expand training datasets [8]. In this work, we apply three ML regression models to predict UTS, YS, and elongation of three 2xxx alloys across 11 temper conditions, using Monte Carlo-augmented data derived from a publicly available dataset.

2. Materials and Methods

Composition and property data were obtained from the dataset compiled by Pfeiffer et al. [9] and uploaded in Materials Cloud Archive, which contains aluminum alloy data extracted from scientific literature and US patents. Three alloys were selected: 2024 (T3, T351, T4, T6, T8), 2219 (O, T6, T62, T851), and 2524 (T3, T351). The feature space comprised 10 elemental compositions (Al, Cu, Mn, Si, Mg, Zn, Cr, Fe, Ti, Zr), 3 alloy-type and 8 temper-type one-hot encodings, and 1 ordinal temper code (22 features total). Figure 1 presents the mean experimental properties for each alloy-temper combination.

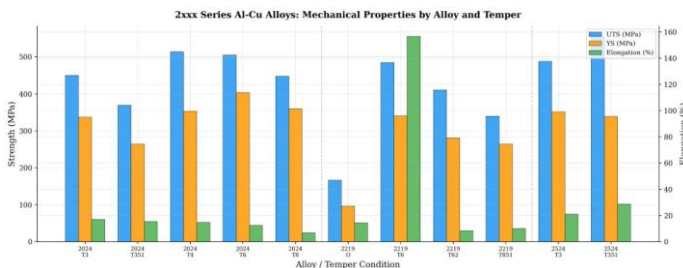


Fig. 1 Mechanical properties (UTS, YS, elongation) by alloy and temper for 2xxx series Al-Cu alloys.

For each of the 11 conditions, 800 synthetic samples were generated (8,800 total) by uniformly sampling element concentrations from specification ranges, computing Al as the balance, and adding 2% Gaussian noise to mean experimental property values. Three models were trained: Random Forest (RF, 200 trees, max depth 12, min samples split 5), Gradient Boosting (GBR, 200 trees, max depth 6, lr = 0.1, min samples split 5), and SVR-RBF (C = 100, ϵ = 0.1, γ = scale, features standardized). Performance was assessed by 5-fold cross-validation using coefficient of determination R^2 , Mean Absolute Error (MAE), and Root Mean Square Error (RMSE).

3. Results and Discussion

Table 1 summarizes model performance. All models achieved $R^2 > 0.991$ for all targets. RF provided the best overall accuracy (UTS MAE = 7.04 MPa, YS MAE = 5.08 MPa, elongation MAE = 0.46%). The marginal differences among models indicate that the augmented dataset effectively captured property-composition-temper relationships. Figure 2 shows predicted vs. actual plots confirming tight clustering along the 1:1 diagonal across all alloy clusters.

Table 1: Cross-validation metrics for ML models.

Model	Target	R^2	MAE	RMSE
Random Forest	UTS (MPa)	0.9924	7.04	9.06
	YS (MPa)	0.9931	5.08	6.56
	Elongation (%)	0.9994	0.46	1.03
Gradient Boosting	UTS (MPa)	0.9921	7.20	9.24
	YS (MPa)	0.9928	5.19	6.69
	Elongation (%)	0.9993	0.49	1.11
SVR (RBF)	UTS (MPa)	0.9916	7.39	9.52
	YS (MPa)	0.9923	5.32	6.90
	Elongation (%)	0.9993	0.50	1.06

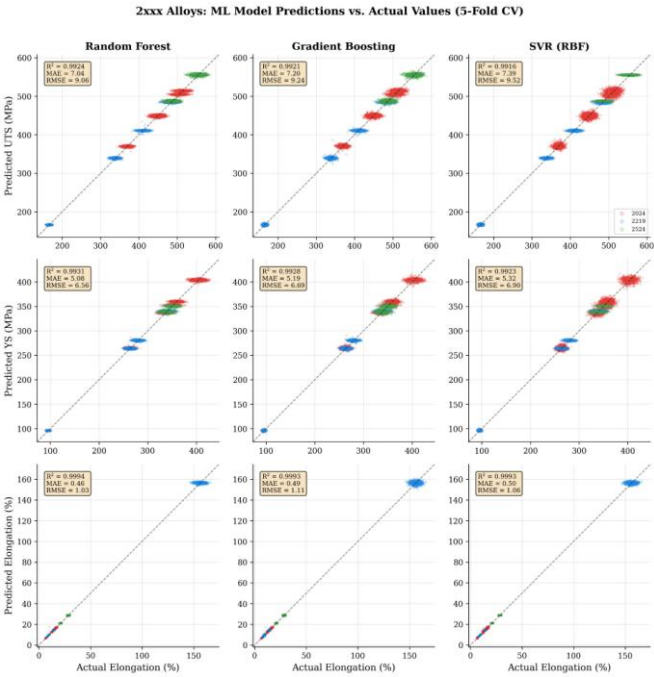


Fig. 2 Predicted vs. actual values for RF, GBR, and SVR-RBF models (5-fold CV), colored by alloy: 2024 - red, 2219 - blue, and 2524 - green.

Feature importance rankings (Fig. 3) show that temper-related features dominated all property predictions. For UTS, the temper code and O temper indicator together accounted for ~80% of importance. For elongation, the T6 indicator was most important (RF: 0.42), reflecting the anomalous 2219-T6 elongation (156.5%). This value should be interpreted with caution: the source dataset contains only two elongation records for 2219-T6 (11.0% and 302.0%), and the 302% value is physically unrealistic for a conventional precipitation-hardened Al-Cu alloy, where typical elongation ranges from 10 to 17%. The resulting mean (156.5%) is therefore likely dominated by a data extraction error in the original corpus and may inflate the elongation R^2 through a lever-arm effect. Individual compositional features contributed <5% each, consistent with the fact that within the 2xxx system, property differences arise primarily from thermomechanical processing history rather than minor compositional variations [10,11].

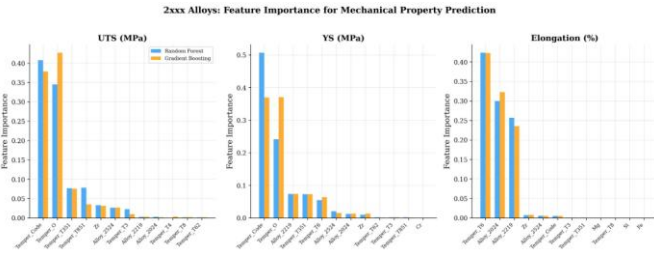


Fig. 3 Feature importance from RF and GBR models for UTS, YS, and elongation prediction.

The correlation heatmap (Fig. 4) confirms strong UTS-YS correlation ($r = 0.93$), a strong negative correlation between O temper and strength ($r = -0.81$ to -0.85), and weak negative Cu-strength associations ($r \approx -0.16$). The augmented property distributions (Fig. 5) show that Monte Carlo sampling preserved realistic property ranges for all conditions, with the noted exception of the 2219-T6 elongation discussed above.

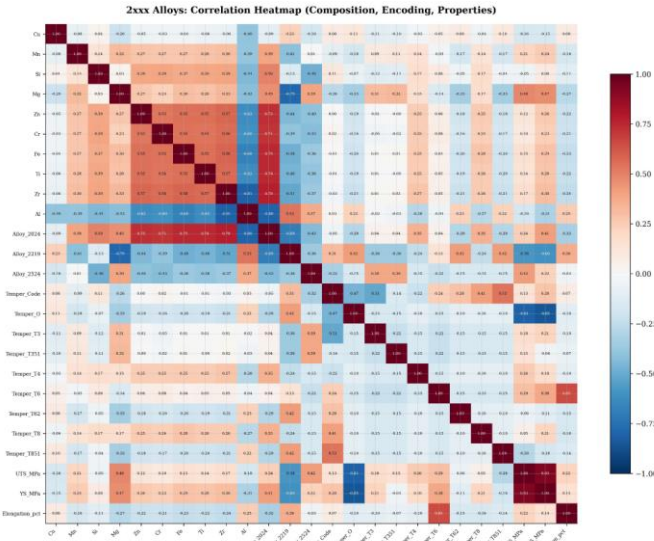


Fig. 4 Pearson correlation heatmap of compositional features, encoding variables, and mechanical properties

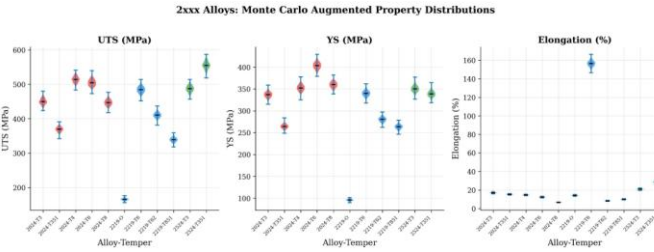


Fig. 5 Monte Carlo augmented property distributions (violin plots) for each alloy-temper combination.

4. Conclusions

A Monte Carlo augmented ML framework was developed for predicting UTS, YS, and elongation of 2024, 2219, and 2524 Al-Cu alloys across 11 temper conditions. All three models (RF, GBR, SVR-RBF) achieved $R^2 > 0.991$ for all targets. RF provided the best performance with MAE of 7.04 MPa (UTS), 5.08 MPa (YS), and 0.46% (elongation). Temper condition dominated feature importance (>75%), while compositional features contributed <5% each. It should be noted that the high R^2 values partly reflect the augmentation design: since all synthetic samples within a given alloy–temper condition share the same mean property values with only 2% noise, the cross-validation task effectively reduces to recovering group means from categorical encodings. The present results therefore demonstrate strong interpolative accuracy within the training domain but do not establish extrapolative generalization to unseen alloy–temper conditions. Additionally, the 2219-T6 elongation data should be treated with caution due to a likely outlier in the source dataset. Future work should evaluate leave-one-condition-out cross-validation to assess true predictive capability, and incorporate broader alloy systems to improve compositional sensitivity. Despite these limitations, the framework illustrates how combining literature-mined datasets with Monte Carlo augmentation can serve as a practical tool for rapid property screening of aluminum alloys within known compositional and processing domains.

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Analysis of workover operations over a ten-year period in an oil and gas field with sucker rod pump production

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Abstract: At the start of exploitation of any hydrocarbon or geothermal water reservoir, production of reservoir fluids is driven by natural energy in the form of reservoir pressure. Therefore, the primary task for production engineers is to maintain this reservoir pressure for as long as possible, ensuring long-term economic production. Unfortunately, sooner or later it becomes necessary to introduce mechanical methods of fluid lifting. Today, there are numerous solutions on the market for mechanical lifting of reservoir fluids (progressing cavity pumps-PCP, electric submersible pumps-ESP), and one of the oldest mechanical methods for producing reservoir fluids is the sucker rod pump. In the Republic of Croatia, sucker rod pumps are among the most commonly used mechanical methods for lifting reservoir fluids. Although Croatian production engineers have significant experience working with sucker rod pumps, operational problems are common and are accompanied by additional expenses related to workover operations. This paper presents an analysis of workover operations over a ten-year period (from 2011 to 2022) in an oil and gas field in the Republic of Croatia. Based on the collected data, an analysis was conducted to determine the volume of fluid not produced during equipment maintenance and repair, the waiting time for repairs, the duration of equipment maintenance as well as the cost-effectiveness of the repairs. Special attention is given to the analysis of the causes of problems in using sucker rod pumps and the identification of problematic wells.

Keywords: SUCKER ROD PUMP, PROBLEMATIC WELLS, WORKOVER OPERATIONS, FAILURES OF DOWNHOLE EQUIPMENT, CAUSES OF EQUIPMENT FAILURES

1. Introduction

At the start of the exploiting of any hydrocarbon or geothermal water reservoir, production of reservoir fluids is driven by natural energy in the form of reservoir pressure. This reservoir pressure, depending on the location of the reservoirs (depth, density of overburden layers, regional tectonics), may be normal, overpressure or underpressure. Under normal circumstances, it is about normal reservoir pressure which corresponds to the pressure of the column of formation water from sea level to the depth of the reservoir. Unfortunately, starting production of the reservoir fluid (oil, gas, or geothermal water) inevitably causes a decline in reservoir pressure. These trends in reservoir pressure decline can be mitigated through reservoir management strategies, and one of the most commonly strategies is reinjection of the produced water in water-driven reservoirs or gas in gas-cap driven reservoirs.

Therefore, the primary task for production engineers is to maintain reservoir pressure for as long as possible, ensuring long-term economic production. However, sooner or later it becomes necessary to introduce some form of artificial fluid lifting. According to Perrin (1999), at the end of the 1990s artificial lift was used in 75% of the world's production wells (excluding the USA) or even more (90%) if data relating to the USA is included. Artificial method for reservoir fluid lifting can be divided into two groups [1]:

- mechanical lifting by pumping, and
- reduction of reservoir fluid density by mixing the reservoir fluid with gas (natural gas, carbon dioxide) injected into lower part of the production string.

Today, there are numerous solutions on the market for mechanical lifting of reservoir fluids (progressing cavity pumps-PCP, electric submersible pumps-ESP), but one of the oldest and most widely used mechanical methods for producing reservoir fluids is the sucker rod pump. The most important part of the sucker rod pumping system is the positive-displacement pump driven from the surface by rod strings. Despite availability of different and modern solutions for reservoir fluid pumping, the sucker rod pumping system still occupies a large share of the market today. For example, according to data published in 2012, in China there were 118000 wells equipped with sucker rod pumping system, representing 96% of all producing wells [2]. Also, according to data from Matanović i Moslavac (2011), at the beginning of 2000 in the Republic of Croatia were 1,133 active wells, of which 484 were equipped with sucker rod pumping systems while 310 were equipped with gas lift systems [3]. The reason for this probably lies

in the fact that it is the oldest artificial system, with extensive technical and engineering experience in its operation.

2. Sucker rod pumping system

As mentioned earlier, the sucker rod pumping system is probably the oldest and most widely used mechanical system for pumping reservoir fluid. The sucker rod pumping system, shown in Fig. 1, consists of surface pumping units (usually mechanical or hydraulic propulsion systems) powered by an electric motor or engine (gas or diesel) as well as a pumping head, and a subsurface part which includes the rod string, tubing, and a positive-displacement pump at the bottom.

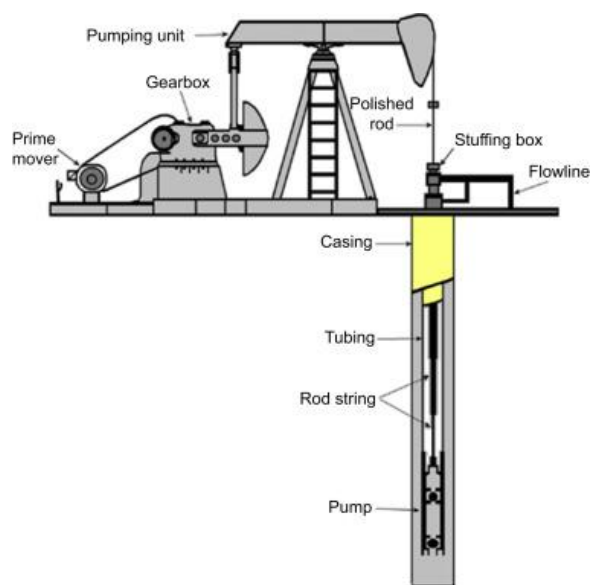


Fig. 1 Sucker rod pumping system [4]

Despite technological improvements over the years, the basic working principles of positive-displacement pumping remain unchanged. The core of the system is a positive-displacement pump composed of a cylinder (pump barrel) with a standing valve at the bottom and a hollow plunger with a travelling valve. The hollow plunger is connected to the surface system by a steel rod string, and fluid pumping is achieved by the reciprocating motion of the hollow

plunger and the alternating operation of the valves mentioned above. Depending on their installation method, sucker rod pumps can be classified as rod pumps (R pumps) and tubing pumps (T pumps), each with specific advantages and disadvantages (Fig. 2).

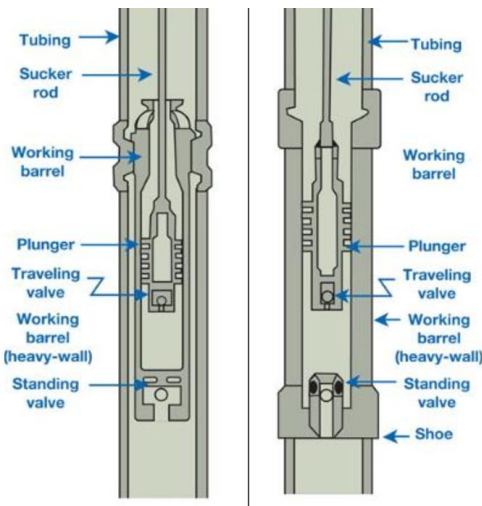


Fig. 2 Rod pump (left) and Tubing pump (right) [5]

The pumping unit is installed on the surface and, using electric motors or various types of engines, ensures continuous reciprocating movement of the rod string in opposite direction, enabling the pumping of reservoir fluids accumulated within the wellbore. In addition to the power source for driving the pumping unit, the methods of converting rotational motion from the power unit into linear motion of the rod string is also important. The oldest system, still relevant today, is the mechanical walking beam (Fig. 3), balanced with a mechanical counterweight or compressed air. Beside this, there are also hydraulic types of pumping units, as well as various derivatives of these two basic types, such as the linear rod pumping unit (LRP) and other commercial solutions.



Fig. 3 Mechanical walking beam balanced with counterweight

The design of the sucker rod pumping system and the selection of the appropriate pump and pumping unit are specific to each location and depend on various parameters, such as the depth of the reservoir, production index, static level of the reservoir fluid column within the wellbore, inside diameter of the installed

production casing, pressure required to lift the reservoir fluid and transport it to surface facilities, and the amount of gas within the reservoir fluid, etc.

3. Sucker rod pumping system

As mentioned earlier, the sucker rod pumping system is the oldest method of artificial lifting of reservoir fluid. Given the extensive engineering experience accumulated over 150 years of practical application, the sucker rod pumping system represents a long-term production solution with low operating costs and significant potential for process automation [6]. Despite these advantages, the sucker rod system is accompanied by numerous problems, which can lead to operational halts and associated production losses. Outages in the sucker rod system result in two distinct costs: the first is related to the workover operation required to resolve the cause of the outage, and the second, equally important, is the cost of fluid production interruption (unrealized production of reservoir fluid). Accordingly, from the production engineer's perspective, it is very important to schedule workover operations at specific locations, as reducing the time between problem detection and taking corrective action lowers the costs associated with lost production. This is especially important for large fields with several hundred sucker rod pumping systems installed and possibly only a small number of workover units available in the area.

The sucker rod system outage is most often caused by mechanical wear and material fatigue but can also result from corrosion or their combined effects. The first issue mentioned relates to well construction and system operating principles. Unfortunately, some wells, even those designed as vertical, contain wellbore sections with unwanted changes in inclination and azimuth. Ideally, any contact between the moving rod string and the fixed tubing string within the wellbore should be avoided, but this is practically impossible. According to Hart (2003), between 10% and 20% of the inside surface of the tubing comes into contact with rod couplings [7]. This contact causes excessive wear of the rod couplings and creates a groove on the inner side of the tubing along the length corresponding to the pump stroke. This wear leads to tubing leakage and system downtime, necessitating the removal of the damaged tubing joint from the production string, even though more than 80% of the tubing surface area remains untouched (Fig. 4).

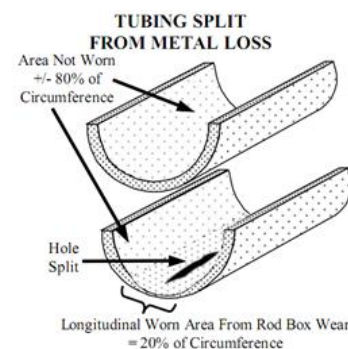


Fig. 4 Mechanical wear of the tubing [8]

Apart from mechanical wear, problems also arise from corrosion, especially when the produced fluid contains various admixtures such as carbon dioxide, hydrogen sulfide, or a high proportion of reservoir water. The subsurface components of the sucker rod pump production system, damaged by mechanical action, are particularly susceptible to these processes. Specifically, movement of the rod string inside the tubing removes both the corrosion product and corrosion inhibitors from the inner surface of the tubing, allowing these processes to continue [9]. The chemical

effect of the reservoir fluid on the inner surface of the tubing is shown in **Fig. 5**.



Fig. 5 Pitting corrosion of the tubing [10]

Considering all the above, it is very important to detect the primary mechanism of tubing and rod wear as soon as possible. The initial assessment can be made based on chemical analysis of the produced reservoir fluid. In the case of mechanical wear, the produced fluid will contain only metal shavings, whereas in the case of corrosion, the produced fluid will contain products of steel corrosion such as FeS, FeCO₃, or iron oxide [7].

4. Analysis of workover operations in an oil and gas field over a ten-year period – Case study from Republic of Croatia

The Republic of Croatia has a long tradition of exploiting hydrocarbon reservoirs both onshore and offshore, as well as geothermal water reservoirs. The oil-gas field under consideration is located in the continental part of the country. Of the 195 wells drilled in this field, only 30 are currently active (less than 15%), of which 29 are production wells and one is an injection well. There are also 43 observation wells (**Tab. 1**) [11].

Table 1. Status of the wells in the oil-gas field under consideration.

Well status			Well number
Active	Oil wells	Sucker Rod Pumps	26
		Electrical Submersible Pumps (ESP)	1
		Natural flowing wells	2
	Injection wells		1
Inactive	Oil wells		39
	Gas wells		2
	Injection wells		6
Observation wells			43
Abandoned wells			75

During the period under consideration, 292 workover operations were conducted on 60 wells. According to the available information, of the 60 wells where workover operations were carried out, one was horizontal, 44 were vertical, and for 15 wells (or 25% of workover operations) there was no information about the type of well (**Fig. 6**) [11].

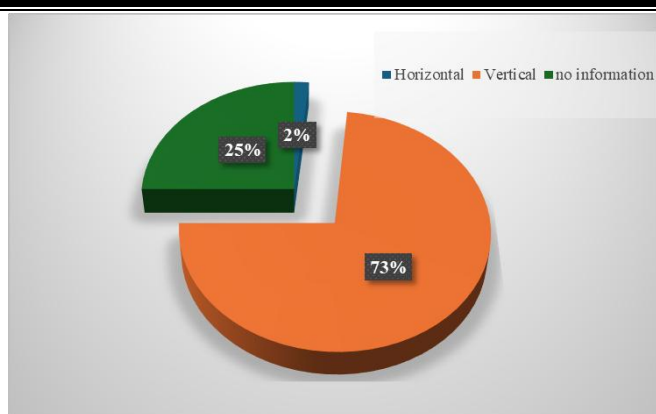


Fig. 6 Type of wells under workover operation in the period from 2011 to 2022

Of the 292 workover operations mentioned above, 263 (90%) were conducted in vertical wells, 3 (1%) in horizontal wells, while for 26 operations (9%) there was no information about the type of well construction. Furthermore, 94% of all workover operations during the period from 2011 to 2022 were carried out in wells with a sucker rod pump production system (**Fig. 7**). In addition, 273 workover operations were conducted on rod-type pumps, while information about the type of installed pump was missing for only two operations.

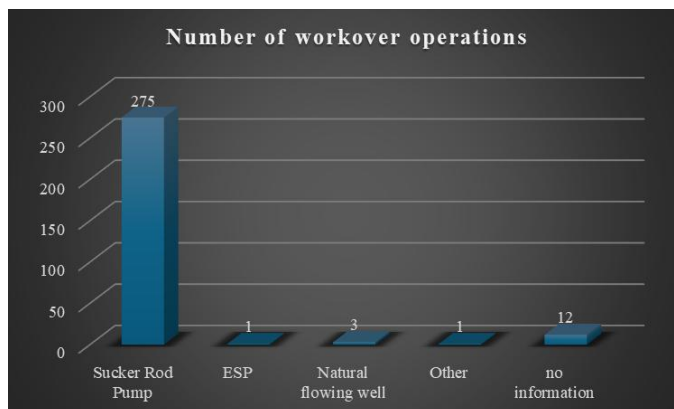


Fig. 7 Number of workover operation during the period from 2011 to 2022 by production system

It is particularly interesting to examine the reasons for stopping production and conducting workover operations. Most workover operations (43%) are caused by tubing failure, followed by sucker rod pump failure at 20% and rod string failure at 11% (**Fig. 8**). In 95% of tubing string failures, leakage was the cause, while 87% of rod string failures were due to breakage. Unfortunately, a large number of workover operations lack accurate information about the cause of production stoppage and the need for workover operations. This lack of accurate information makes analysis of the problem more difficult, and in some cases, impossible.



Fig. 8 Workover operations during the period from 2011 to 2022 in relation to the part of the production system in failure

In addition to identifying the problematic part of the installed production system, determining the failure type is equally important for a thorough analysis. According to the available information, of the 123 workover operations conducted between 2011 and 2022, 42% were related to leakage, 11% (32 operations) to breakage, and 66 operations to other types of failure. For a large number of workover operations (71), accurate information about the failure type is missing. The cause of problems related to the sucker rod pump is particularly unclear. Based on the available data, in 47 (80%) of the workover operations attributed to the sucker rod pump, the specific cause of the problem remains unknown. The exact cause of the pump-related problem is stated for only 20% of these workover operations (for example, paraffin or formation sand) (Fig. 9).

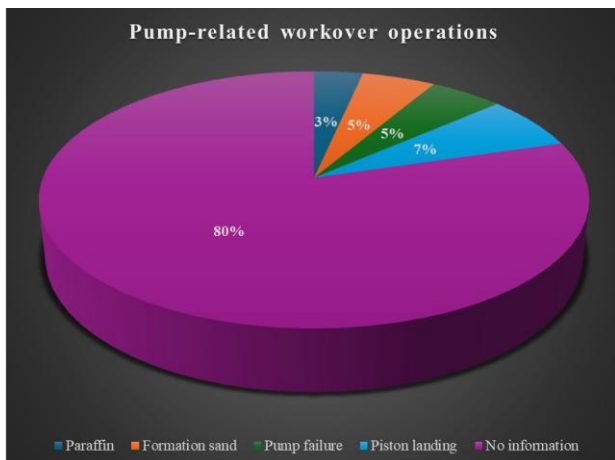


Fig. 9 Workover operations during the period from 2011 to 2022 related to problems with sucker rod pumps

Also, the cost of the workover operation varies considerably between operations, ranging from €3,500 per operation to more than €450,000 per workover operation and well. Half of the workover operations cost between €11,000 and €20,000 (Fig. 10). The data in Fig. 10 show that 15 workover operations cost between €40,000 and €450,000, while for 57 workover operations, information about the cost is missing [11].

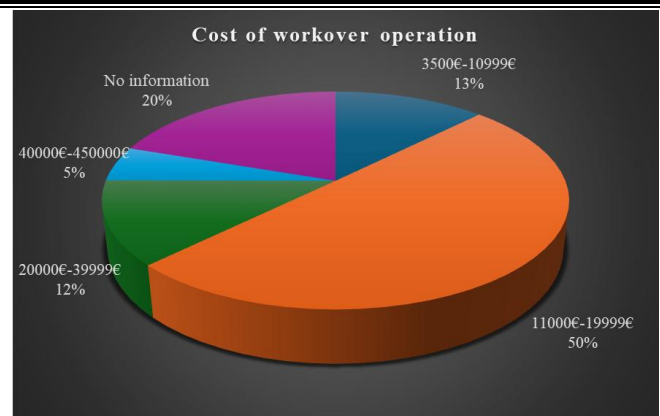


Fig. 10 Cost of workover operations during the period from 2011 to 2022

5. Conclusions

Despite being a well-established technology with over 150 years of global use, the sucker rod pumping system experiences problems related to its mode of operation. As expected, most issues with installed sucker rod pumping systems in the oil-gas field studied were associated with the subsurface equipment, primarily the tubing, but also the rod string and the pump itself. The analysis presented in the paper highlighted issues with the consistent collection of all relevant data and the absence of important information. Unfortunately, without all relevant information, identifying problematic wells and implementing preventive actions is significantly more difficult.

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A MES Application for OEE Improvement in Plastic Injection Facilities

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Abstract: In plastic injection and plastic welding processes, the inability to accurately classify machine downtimes, the lack of visibility regarding performance discrepancies between shifts, and the reliance on largely manual methods for operator tracking hinder the sustainable improvement of Overall Equipment Effectiveness (OEE). Furthermore, the retention of production and energy consumption data in isolated systems complicates integrated performance evaluation.

In this study, the HBS MES system, developed by the in-house engineering team of Pleksan

A.S. and fully integrated with HBS ERP, is examined within the scope of a field application aimed at real-time production tracking, performance analysis, and energy consumption reporting in plastic injection lines. As of 2025, HBS MES is actively used in its V1 version across three different plastic manufacturing enterprises; this paper exemplifies a facility predominantly focused on plastic injection.

The paper presents the system architecture, data collection logic, modeling of production and downtime events, the approach to calculating OEE and its sub-metrics, and user interface components in detail. As a result of the implementation in the studied facility, an improvement of approximately 25% in production quantities was reported, particularly during night shifts, and the mechanisms underlying this improvement are discussed. The findings demonstrate that MES solutions integrated with machine-embedded data collection modules can provide measurable productivity gains even in small and medium-sized enterprises.

KEYWORDS: MES, OEE, PLASTIC INJECTION, DIGITAL TRANSFORMATION, REAL-TIME MONITORING

1 Introduction

Plastic injection and plastic welding processes play a critical role in many sectors, such as automotive, white goods, packaging, and machinery manufacturing. In such production lines, efficiency is often managed through operator experience and instantaneous decisions within the shift, while reasons and durations of downtimes are tracked via paper forms or scattered electronic spreadsheets in most enterprises. Energy consumption data is frequently kept in separate monitoring systems, preventing integrated analysis with production data. This situation weakens the reliability of OEE calculations and impedes data-driven improvement efforts.

Manufacturing Execution Systems (MES) aim to provide enterprises with real-time visibility, traceability, and performance analysis by processing data collected from the field. In plastic injection processes, MES applications manage production resources online, shortening processing times and reducing operating costs [1, 3]. Furthermore, literature emphasizes that real-time monitoring systems significantly increase OEE values and provide managers with instantaneous decision-making capabilities [4]. Specifically, the automatic detection of machine states (running, planned downtime, unplanned downtime, setup, quality rejection, etc.) and the accurate calculation of OEE components are fundamental elements of continuous improvement and lean manufacturing practices.

The enterprise adopted a strategy of developing its own unique solution to overcome the flexibility constraints of existing package programs and to fully meet facility-specific needs, rather than acquiring a ready-made off-the-shelf solution.

In this study, the HBS MES system, developed for plastic injection and plastic welding machines, is technically examined through a real-world facility application. HBS MES employs a three-layer structure consisting of HiLog data collection modules connected to machines, an application server, and a Blazor/SignalR-based web interface, operating in integration with HBS ERP. The focus of the study is not only to introduce the system's functions but also to model and examine the performance gains obtained in the field from an engineering perspective.

The remainder of the paper first defines the industrial environment and system requirements, followed by an explanation of the HBS MES architecture and data model. Subsequently, the approach to calculating OEE and sub-metrics is presented, and results obtained from the field application in a selected plastic injection facility are provided. The final section discusses the system's limitations, strengths, and areas for future development.

2 Industrial Environment and System Requirements

2.1 Facility and Production Process

HBS MES is primarily designed for use in multi-shift production facilities operating with plastic injection and plastic welding machines. Typically, in these facilities:

- Production is carried out on a 24-hour basis, in day and night shifts,
- Multiple injection and welding machines operate in parallel on the same line,
- Work orders are opened via HBS ERP, and machine/mold pairings are planned through this system,
- Production quantities, scrap amounts, and downtime durations are still reported via semi-manual methods in many locations.

During night shifts, the limited availability of management and engineering staff leads to insufficient monitoring of operator behaviors and machine usage habits. This situation can result in significant efficiency differences between day and night shifts on the same machinery fleet.

2.2 Functions Expected from MES

The fundamental functions expected from the MES system for the enterprises in question can be summarized as follows:

- Monitoring real-time running/stopped status on a machine basis,
- Automatic or semi-automatic classification of downtimes under categories such as *planned maintenance*, *unplanned breakdown*, and *setup/mold change*,
- Calculation of OEE and sub-performance metrics on the basis of shift, machine, station, and operator,
- Identification of operators via RFID cards and generation of operator-based performance reports,
- Automatic transfer of work orders to the MES environment through integration with HBS ERP and feedback of realized production data to the ERP side,
- Provision of user interfaces to support downtime planning, maintenance organization, and production planning processes,
- Reporting of production and energy consumption data on a common data model [6].

Based on these requirements, monitoring, reporting, planning, production management, and quality management modules have been designed within HBS MES.

3 HBS MES System Architecture

3.1 General Architectural Structure

HBS MES consists of three fundamental layers:

1. **Machine Layer:** HiLog data collection modules connected to plastic injection and plastic welding machines monitor digital signals on the machine (running/stopped, mold open/close, fault signals, energy measurements, etc.) and transmit them to the upper layer on an event-driven basis.
2. **Application Server:** Data received from HiLog modules is acquired, processed, and recorded in a relational

database via services running on the server side. This layer manages the relationships between work orders, machines, stations, operators, and downtime records.

3. **User Interface Layer:** HBS MES offers a Blazor-based web interface and real-time data updates via SignalR. Users access dashboard screens, Gantt charts, downtime planning, and performance reports via a browser.

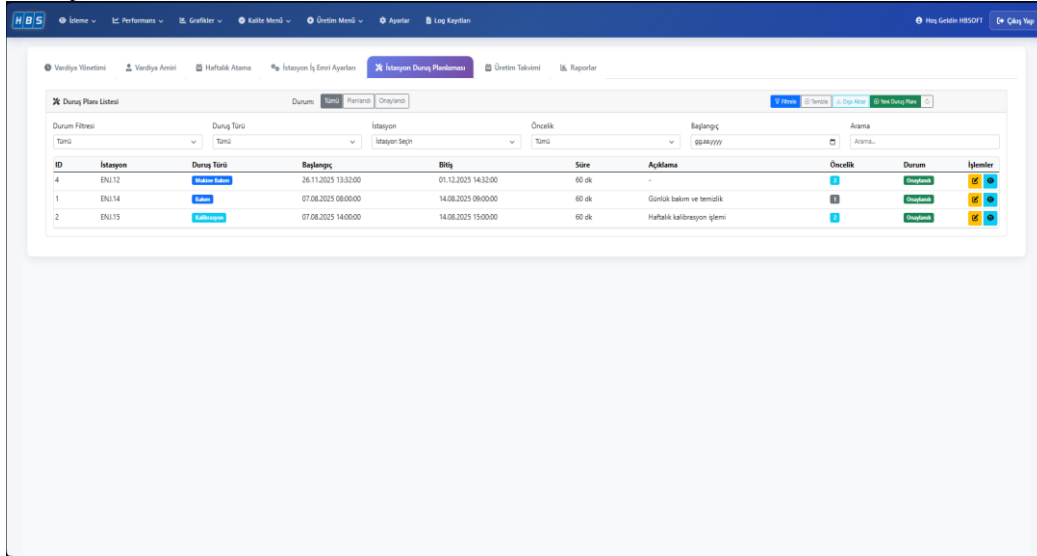


Figure 1: Station downtime planning screen; planning, prioritizing, and approving maintenance and calibration downtimes.

This structure meets the real-time requirement at the machine level while providing an integrated production management flow with the ERP [2, 7].

Hardware and Communication Infrastructure

HiLog modules are connected to machine control panels to monitor relevant digital and analog signals. Data such as machine status, cycle completion signals, fault information, and energy consumption are packaged and sent to the server the moment the event occurs. Ethernet-based TCP/IP communication is preferred for data transmission in accordance with the enterprise infrastructure.

The service layer running on the server side records incoming events with timestamps and matches them with machine and work order information. Thanks to the event-driven data collection approach, time-based calculations can be performed accurately even for machines with variable cycle times or frequent stop-and-go operations [5].

3.2 Software Modules and User Interfaces

The prominent modules within HBS MES are as follows:

- **Instant Monitoring:** Monitoring of instantaneous states (running, stopped, setup, breakdown, etc.) on a machine and station basis, station lists, and summary indicators.
- **Downtime Planning:** Planning of maintenance, calibration, and other planned downtimes on a station basis, approval processes, and prioritization.
- **Gantt Charts:** Visualization of machine activities on a time axis per shift; display of running, downtime, and setup blocks on a single screen. Combining multiple work orders on the same activity facilitates planning and analysis.
- **Machine Performance Dashboard:** Presentation of OEE components and related time/quality metrics on a machine basis via donut charts and completion indicators.
- **Operator and Work Order Cards:** Display of operator name, work order quantity, produced quantity, elapsed time, and estimated completion time on a single card.

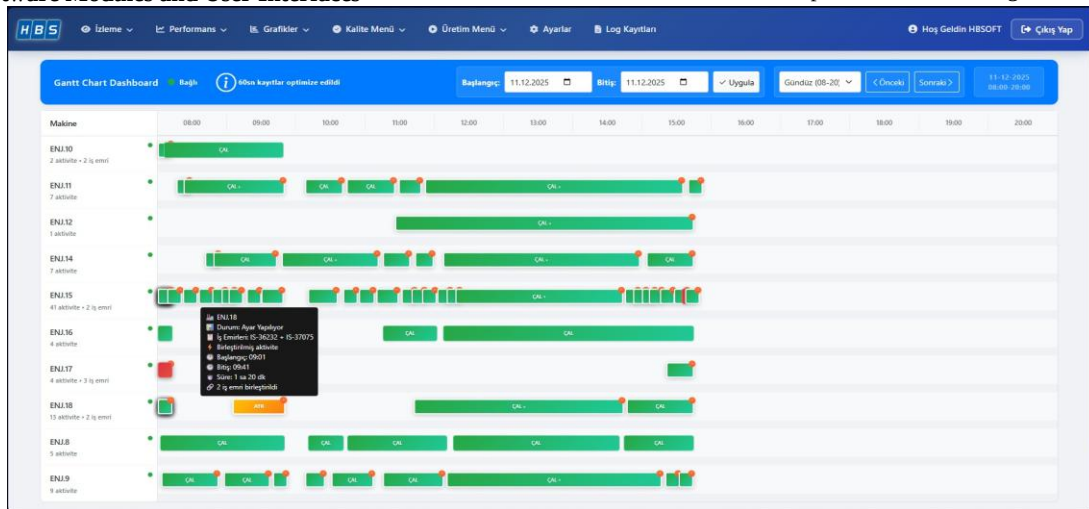


Figure 2: Gantt Chart dashboard; visualization of running, downtime, and setup activities on a time axis throughout the shift on a machine basis.

These screens serve as decision support tools not only for executive-level users but also for shift supervisors and

maintenance teams.

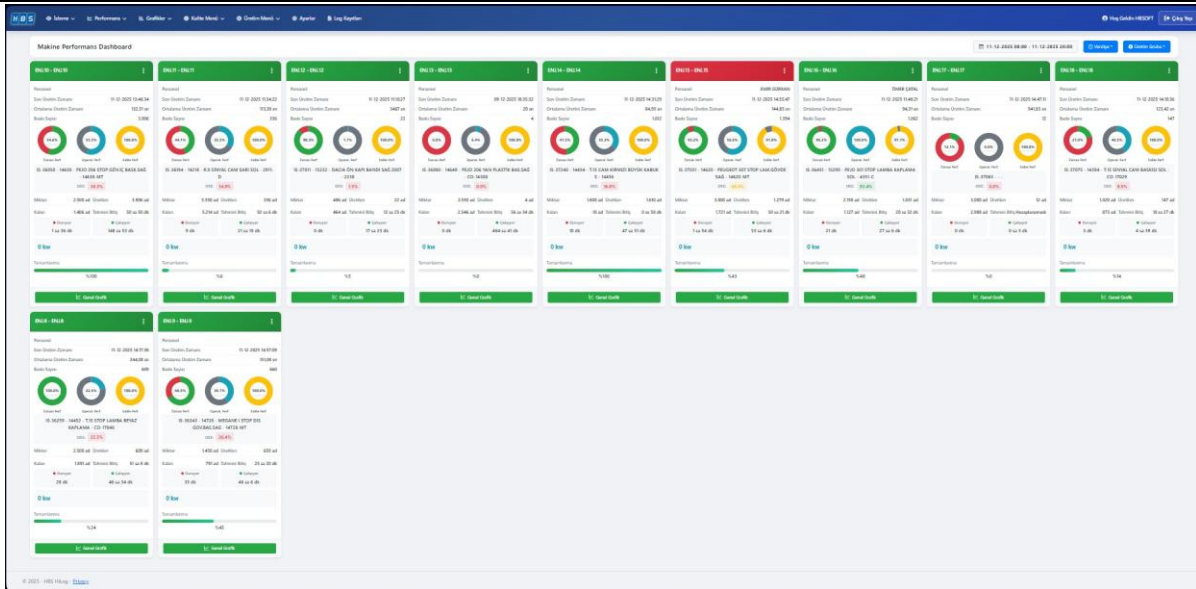


Figure 3: Machine performance dashboard; summary of machine status with OEE components and completion indicators.

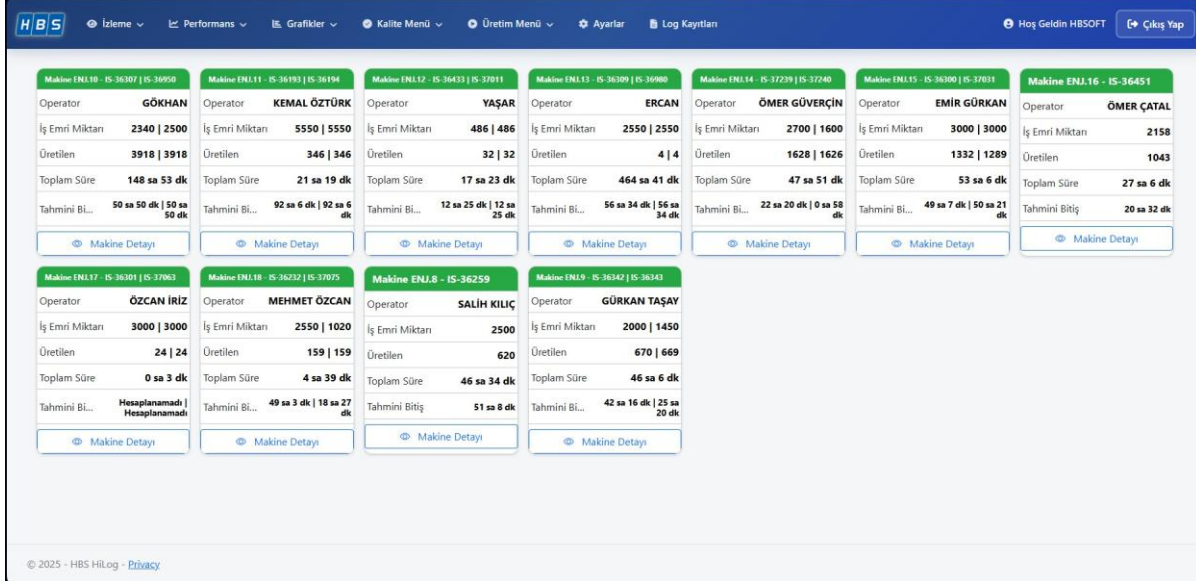


Figure 4: Operator and work order cards; monitoring production performance and estimated completion times on an operator basis. Real-Time Data Processing

Thanks to the SignalR-based web interface, changes in machine and station statuses are reflected on user screens with latencies in the order of seconds. The event-driven data model ensures that for each machine:

- Activity start and end times,
- Activity type (production, planned downtime, unplanned downtime, setup, etc.),
- Associated work order (multiple work orders if necessary),
- Relevant operator are stored as single records. Thus, both Gantt charts and OEE calculations can be generated based on the same data model [5].

4 Data Model and Performance Metrics

4.1 Data Collection and Event Types

In the HBS MES data model, the fundamental monitoring unit is the concept of *activity* [7]. Each activity possesses the following fields for a specific station or machine:

- Start timestamp,
- End timestamp,
- Activity type (production, planned downtime, unplanned downtime, setup, calibration, etc.),
- Relevant work order or work orders,
- Relevant operator (based on RFID card),

- Associated energy consumption or count information, if applicable.

The data collection logic is based on opening a record when an event occurs, rather than fixed-period sampling. When production or a stop occurs, the event is monitored via the HiLog module, and the occurrence information is transmitted to the server via the service. This allows accurate time-based calculations even for machines with variable cycle times or those that stop frequently or malfunction often.

The main variables collected include:

- Machine cycle counts and cycle times,
- Machine downtime durations and downtime types,
- Machine setup and calibration times,
- Energy consumption data,
- Downtime records on a line and station basis,

4.2 Operator and machine/work order pairings.

Definition of OEE and Sub-Metrics

Overall Equipment Effectiveness (OEE) is widely defined in the literature as the product of three basic components: availability, performance, and quality [8, 9]. In this study, HBS MES data has been evaluated based on the classical literature definition [10].

Availability (A), where T_{plan} is the planned production time and T_{downtime} is the unplanned downtime duration, is defined as:

$$A = \frac{T_{\text{plan}} - T_{\text{downtime}}}{T_{\text{plan}}}$$

(1) The performance component (P) for the net operating time T_{net} , theoretical cycle time t_{cycle} , and total produced quantity N_{total} is expressed as:

$$P = \frac{N_{\text{total}}}{t_{\text{cycle}} T_{\text{net}}}$$

(2) The quality component (Q) for the total produced quantity N_{total} and the quantity of good products N_{good} is:

In this case, OEE is calculated as:

$$Q = \frac{N_{\text{good}}}{N_{\text{total}}}$$

$$(3) \text{OEE} = A \times P \times Q \quad (4)$$

Within HBS MES, these components are calculated on the basis of shift, machine, station, and work order, and presented to the user on dashboard screens.

The system also produces derived indicators such as Time Performance, Quality Performance, and Operator Performance according to enterprise needs. While time and quality performance are directly related to the OEE components summarized above, operator performance is normalized by taking into account the production, downtime, and quality profile that occurred during the shifts the operator was on duty. In this paper, the operator performance index is treated as a decision support indicator rather than being detailed with its formula. As emphasized in the literature [4], the systematic classification of downtime reasons and the monitoring of operator performance play a critical role in detecting hidden efficiency losses.

4.3 Statistical Analysis and Decision Support

In the discussed V1 version of HBS MES, decision support functions are presented through reporting screens that allow the enterprise to evaluate collected cycle and downtime data using classical statistical methods. Users can observe trends in production quantities and OEE components over time, rank downtime reasons according to their share in total time, and make basic comparisons between shifts.

In the machine performance dashboard, status indicators are presented for each machine via three donut charts related to time, performance, and quality, based on threshold values (e.g., red for below 60%, yellow for 60%–80%, green for above 80%). Thus, shift supervisors and maintenance teams can see on a single screen which machines require rapid intervention.

Table 1: Normalized comparison of night shift production performance (sample machine group).

Indicators production quantity (normalized)	Pre-MES 1.00	Post-MES 1.25	Change +25	[%]	Average
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Table 1 shows that there was an increase of approximately 25% in average production performance on a normalized basis during the night shift after the system was commissioned. Furthermore, according to field observations and enterprise evaluations, improvements were observed in downtime management and process stability. Obtained Results

According to enterprise feedback and HBS MES reports, after the system was commissioned, the following were observed during night shifts:

- An increase of approximately 25% in average production quantities per machine,
- Improvement in maintenance and setup organization thanks to the transparency of down- times based on reason and duration,
- Visibility of performance differences between operators and, consequently, more systematic execution of feedback and shift management processes.

Thanks to Gantt charts and station downtime planning

5 Field Application: HBS MES in a Plastic Injection Facility

5.1 Facility Description and Installation Process

The field application detailed in this study was carried out in a facility producing with plastic injection machines. The facility houses multiple injection machines of different tonnages and plastic welding stations. Production is carried out in a three-shift order; performance drops and lack of downtime records, especially during night shifts, were identified as a significant problem by the enterprise.

Within the scope of the HBS MES installation:

- HiLog modules were connected to the control panels of selected machines,
- Machine signals (running, stopped, breakdown, cycle) were determined and assigned to HiLog inputs,
- Work order, product, and customer definitions and machine lists on the HBS ERP side were synchronized,
- Operators were defined in the system with RFID cards, and the use of these cards at shift entries/exits was ensured.

In the first stage, the system was used mostly for monitoring purposes; a short adaptation process was undergone for operators and shift supervisors to get used to the screens, select downtime reasons correctly, and improve data quality.

5.2 Experimental Design and Evaluation Approach

In the evaluation of the field application, the pre-MES and post-MES periods were compared. The enterprise specifically aimed to reduce fluctuations in production quantities during the night shift and to close performance gaps between shifts.

The evaluation analyzed:

- Night shift production quantities and downtime profiles in the pre-MES reference period,
- Night shift production quantities and downtime profiles for the same machines in a period of similar length after MES was commissioned,
- OEE components and scrap rates on a shift basis.

Enterprise data has been shared using normalized indicators observing commercial sensitivities within the scope of company permission, in order to substantiate the effects of the field application. A normalized comparison for a sample night shift is shown in Table 1. Here, the pre-MES period is scaled as 1.00, and the post-MES period is scaled according to the improvement reported by the enterprise.

screens, maintenance and setup downtimes were planned in a more controlled manner, reducing unnecessary waiting times within the shift. Since work order quantity, produced quantity, total time, and estimated completion time for each operator could be seen on a single screen via operator and work order cards, shift supervisors were able to make load balancing and intra-shift intervention decisions more quickly. The 25% production increase reported in night shifts is not solely due to HBS MES; however, the transparency provided by the system, the correct classification of downtimes, and the activation of operator-based tracking can be evaluated as the main contributing components of the observed improvement.

6 Discussion

6.1 Evaluation of Gains

The field application is particularly noteworthy in the following respects:

- Thanks to HiLog modules directly connected to the machine, production and downtime data are collected with minimum dependence on operator input, which ensures high accuracy in the calculation of OEE and sub-metrics [4].
- Gantt charts and the machine performance dashboard provide a strong visual ground for shift-based performance analysis. Managers and engineers can quickly see which machines have bottlenecks and in which time intervals downtimes are concentrated.
- Thanks to RFID-based operator cards, performance differences between operators become tangible; this is used both in identifying training needs and in feedback processes.
- Since the installation is designed as a solution embedded in the existing machine and ERP infrastructure, the commissioning process remains relatively short for enterprises.

These gains are consistent with OEE improvements reported in the literature with MES applications. In particular, the transparency provided by the bidirectional integration with HBS ERP in the field application [2, 7] coincides with findings in other studies [1, 2, 3]. This synchronization provided via modern APIs minimizes deviations in planning processes. A noteworthy point here is the reporting of a production increase in the order of 25% in night shifts with the first MES application in an enterprise that initially had limited systematic data collection infrastructure. System Limits and Constraints
HBS MES has currently been applied and verified mainly in discrete manufacturing processes such as plastic injection and plastic welding. For continuous processes (chemistry, cement, refinery, etc.), the data model and user interfaces may require additional adaptations.

Although the system architecture is designed to support a large number of machines in terms of scalability, current field applications are limited to medium-sized facilities. In very large machinery fleets, additional optimization steps may be needed in matters such as database size, network traffic, and dashboard performance.

From an analytical perspective, the discussed version of HBS MES primarily offers decision support mechanisms based on classical statistical analyses and threshold values. Functions such as predictive maintenance, advanced machine learning models, and automatic root cause analysis are potential areas for development that can be added to the core structure of the system.

6.2 Application Perspective

Different studies in the field of MES and OEE improvement report efficiency increases at various rates [1, 3]. The night shift production increase in the order of 25% reported in this study indicates that the impact of the initial MES application can be high, especially in enterprises with limited systematic data collection infrastructure at the outset.

However, this evaluation, based on a single facility and a specific period, is not sufficient for generalization. More comprehensive field studies comparing different sectors, different MES solutions, and different organizational structures will strengthen the body of knowledge in this field.

7 Conclusion and Future Work

In this study, the application of HBS MES in a production facility operating with plastic injection and plastic welding machines was technically examined; the system architecture, data model, user interfaces, and field results were presented within a holistic framework. Thanks to machine-embedded HiLog data collection modules, an event-driven data model, and

Blazor/SignalR-based web interfaces, the enterprise achieved performance visibility on a machine, shift, and operator basis in a short time.

In the field application, an improvement of approximately 25% in production quantities was reported, especially during night shifts; this improvement was associated with the visibility of downtimes, the strengthening of planned maintenance organization, and the activation of operator-based performance tracking. The results obtained demonstrate that MES solutions that are appropriately designed and integrated at the correct point can provide tangible productivity increases even in small and medium-sized facilities.

Within the scope of future work, it is suggested to:

- Examine HBS MES applications in different sectors (e.g., metal machining, assembly lines) and perform cross-comparisons,
 - Develop data analytics and machine learning models focused on predictive maintenance and process optimization on the collected data,
 - Integrate energy efficiency-oriented metrics more strongly into the system and define energy-based OEE-like indicators,
 - Address indicators used in operator performance measurement together with human factors, ergonomics, and training dimensions.
- In conclusion, the HBS MES example demonstrates that meaningful contributions can be made to the field of production efficiency from both academic and industrial perspectives with domestic software and hardware solutions.

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Photoluminescence properties of Sm^{3+} -doped $\text{ZrO}_2\text{--TiO}_2\text{--Al}_2\text{O}_3$ coatings

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Abstract: The emission spectrum of the $\text{ZrO}_2\text{--TiO}_2\text{--Al}_2\text{O}_3\text{--Sm}_2\text{O}_3$ coating was recorded at different excitation wavelengths. Under UV excitation ($\lambda_{\text{ex}} = 354 \text{ nm}$), broad band with a maximum around 420–440 nm was observed and can be associated with oxygen vacancies in ZrO_2 together with Ti^{3+} centers. Weakly intense and narrower emission bands at 600 nm and 647 nm are assigned to the $^5G_{5/2} \rightarrow ^7H_{7/2}$ and $^5G_{5/2} \rightarrow ^7H_{9/2}$ transitions of Sm^{3+} ions. Under excitation with 404 nm the emission is dominated by defect levels in the oxide coating. The values of the chromaticity coordinates of the coating excited under 354 nm correspond to the pale pink color of emission (0.252, 0.272) and under 404 nm has orange color of emission (0.353, 0.370).

Keywords: EMISSION SPECTRUM, SOL-GEL METHOD, DIP COATING, $\text{ZrO}_2\text{--TiO}_2\text{--Al}_2\text{O}_3\text{--Sm}_2\text{O}_3$

1. Introduction

The use of oxide coatings is a classic technological approach for effective protection or modification of the characteristics of the working surface of various technical parts and finished products [1-4]. Coatings with increased chemical, corrosion and thermal resistance, high hardness and wear resistance, suitable optical properties, adequate biocompatibility and other performance indicators are widely used [5-11]. Various technological approaches have been developed for the deposition of functional coatings. In this aspect, a number of methods are applicable: [12-22]: physical vapor deposition (PVD), chemical vapor deposition (CVD), combustion synthesis, micro-arc oxidation, laser cladding, plasma spraying, sol-gel technique and a number of others.

Ceramic materials with increased Al_2O_3 content exhibit good wear resistance and friction, as well as stable chemical properties [23-28]. On the other hand, in some product categories, relative brittleness, inadequate thermal shock resistance, tendency to stress concentration and crack formation, as well as other operational problems are observed [29]. The development of optimized compositions based on Al_2O_3 in combination with other oxide components allows the production of coatings with appropriate phase composition, adequate microstructure and functional characteristics [25-28].

The mechanical properties and oxidation resistance of multilayer thermal barrier coatings $\text{Al}_2\text{O}_3/\text{ZrO}_2$ prepared by plasma-sprayed method were investigated [30]. Nanocomposite coatings $\text{Al}_2\text{O}_3\text{--ZrO}_2$ were prepared, which showed lower porosity and higher values for toughness and microhardness than those found for monophase coatings of Al_2O_3 or ZrO_2 [31,32]. At the same time, lower thermal conductivity was registered for $\text{Al}_2\text{O}_3\text{--ZrO}_2$ coatings than for Al_2O_3 samples [31].

Compared to Al_2O_3 , the titanium dioxide TiO_2 is characterized by smaller brittleness and a number of favorable technological properties, therefore it is considered as a suitable oxide component applicable in the development of binary and more complex compositions. The effect of the introduction of TiO_2 to Al_2O_3 -based oxide coatings on the microstructure and operational properties of the experimental samples has been analyzed [33].

The role of the composition and tribological behavior in the prepared coatings with a change in the TiO_2 content has been studied [34]. With $\text{Al}_2\text{O}_3/\text{TiO}_2$ coating, higher wear resistance was registered than that found with Al_2O_3 coating [35]. It has been established that the reinforcement with TiO_2 of the composite coating $\text{Al}_2\text{O}_3\text{--}3\%\text{TiO}_2$ provides more favorable tribological properties than the reinforcement with zirconium dioxide ZrO_2 [36].

It has been proven that the $\text{Al}_2\text{O}_3\text{--}40\%\text{TiO}_2$ coatings have a higher wear resistance than the $\text{Al}_2\text{O}_3\text{--}13\%\text{TiO}_2$ oxide coatings. With an increase in the content of the introduced TiO_2 in the $\text{Al}_2\text{O}_3\text{--TiO}_2$ coatings, a decrease in porosity and the presence of cracks was found, and at the same time, an increase in tightness and the corrosion resistance [37]. At the $\text{Al}_2\text{O}_3\text{--}40\%\text{TiO}_2$ coating, a higher microhardness was registered compared to that found at the substrate used [38].

In the ternary oxide system $\text{Al}_2\text{O}_3\text{--ZrO}_2\text{--TiO}_2$, a series of composite coatings and a comparative two-component sample were obtained. The effect of introducing 2 wt%, 6 wt% and 10 wt% TiO_2 to the composition of eutectic $\text{Al}_2\text{O}_3\text{--ZrO}_2$ (at 6:4 molar ratio) on the properties of the samples, microstructure and change in the phase composition was analyzed [29]. Composite powders (by spray granulation) were obtained from the prepared compositions, which were deposited on substrates by plasma spraying.

The presence of the crystalline phases t- ZrO_2 , $\alpha\text{-Al}_2\text{O}_3$, m- ZrO_2 and TiO_2 (in rutile form) was proven in the obtained composite powders. At the prepared composite coatings ($\text{Al}_2\text{O}_3\text{--ZrO}_2\text{--TiO}_2$) only the crystalline phases t- ZrO_2 , $\alpha\text{-Al}_2\text{O}_3$, $\gamma\text{-Al}_2\text{O}_3$ and amorphous phase were registered [29]. At the studied coatings, the diffraction peaks of TiO_2 were not observed, even in compositions with a content of 10 wt% TiO_2 . Due to the specificity of the used technological approach and extremely high undercooling, an amorphous phase is formed in the obtained $\text{Al}_2\text{O}_3\text{--ZrO}_2\text{--TiO}_2$ coatings. It is assumed that a probable dissolution of TiO_2 in the amorphous phase or the formation of a solid solution together with $\gamma\text{-Al}_2\text{O}_3$ occurs during the cooling period [29].

With increasing TiO_2 content, a decrease in the porosity of the prepared $\text{Al}_2\text{O}_3\text{--ZrO}_2\text{--TiO}_2$ coatings was observed. At a concentration of 10 wt% TiO_2 (with $\text{Al}_2\text{O}_3\text{--ZrO}_2\text{--TiO}_2$ coating), a dense and uniform microstructure and higher values of adhesive strength, toughness and microhardness were found than those found for the comparative $\text{Al}_2\text{O}_3\text{--ZrO}_2$ coating. For an experimental sample with the composition $\text{Al}_2\text{O}_3\text{--ZrO}_2\text{--}10\text{wt}\%\text{TiO}_2$, the adhesive strength of 25.38 MPa was registered, while for $\text{Al}_2\text{O}_3\text{--ZrO}_2$ coating, a value of 21.50 MPa was found [29]. It has been proven that the obtained three-component oxide coating $\text{Al}_2\text{O}_3\text{--ZrO}_2\text{--TiO}_2$ (with a content of 10 wt% TiO_2) has a lower friction coefficient and a lower wear rate compared to the studied two-component coating ($\text{Al}_2\text{O}_3\text{--ZrO}_2$). The established characteristics reduce the risk of various mechanical damage to the integrity of the coatings with a higher content of TiO_2 .

At the same time, the development of innovative coatings based on modified compositions of the $\text{ZrO}_2\text{--TiO}_2\text{--Al}_2\text{O}_3$ system is of fundamental and applied interest.

The aim of the present work is to study the photoluminescence properties of Sm^{3+} -doped $\text{ZrO}_2\text{--TiO}_2\text{--Al}_2\text{O}_3$ coatings prepared in laboratory conditions. During the analysis and interpretation of the registered emission spectrum (recorded at different excitation wavelengths), experimental data on the structure and characteristics of the prepared experimental coatings were obtained.

2. Experimental Procedure

2.1. Reagents and Materials

Zirconium oxychloride octahydrate ($\text{ZrOCl}_2 \cdot 8\text{H}_2\text{O}$), samarium oxide (Sm_2O_3), alumina (Al_2O_3), titanium(IV) butoxide ($\text{Ti}(\text{OBu})_4$), nitric acid (HNO_3), acetylacetone (AcAc), diethanolamine (DEA), ethanol ($\text{C}_2\text{H}_5\text{OH}$) and deionized water were used as received without further purification. Microscopic glass slides made of soda-lime glass were used as substrates.

2.2. Sol preparation and hydrolysis control

Multicomponent sols were prepared by the sol-gel method. Initially, 8.048 g $\text{ZrOCl}_2 \cdot 8\text{H}_2\text{O}$, 0.527 g Sm_2O_3 and 0.255 g Al_2O_3 were dissolved in ethanol with continuous stirring. Subsequently, 1.1 mL of titanium(IV) butoxide ($\text{Ti}(\text{OBu})_4$) was added dropwise under vigorous stirring. Acetylacetone (AcAc) was used as a chelating agent to control the hydrolysis of the Ti(IV) particles.

After homogenization, hydrolysis of the mixed sol was initiated by adding 85 mL of ethanol, 65 mL of deionized water, 10 mL of nitric acid, and 2.5 mL of AcAc. The resulting sol was stirred for 30 min and then allowed to stand for 24 h at room temperature to ensure stabilization and completion of the sol-gel reactions.

The molar ratios of the precursors in the final solution were as follows:

- Zr : Ti = 27.3 : 1
- Zr : Sm = 43 : 1
- Zr : Al = 87 : 1
- $\text{Ti}(\text{OBu})_4$: AcAc $\approx$ 1 : 1.7
- H_2O : (Zr + Ti) $\approx$ 16 : 1
- EtOH : (Zr + Ti) $\approx$ 72 : 1

2.3. Substrate cleaning

The glass substrates were ultrasonically cleaned sequentially in acetone, ethanol and deionized water, followed by air drying.

2.4. Dip coating

Before coating, the sol was filtered through a 0.45 μm PTFE membrane. Thin films were deposited on glass substrates using the dip technique at 25 $^\circ\text{C}$ and 40–50% relative humidity, with drawing speeds of 72.9 mm/min.

After each deposited layer, the coatings were dried at 100 $^\circ\text{C}$ for 10 min to remove residual solvent and promote partial gelation. Typically, 3–5 coating layers were applied to obtain films of the desired thickness.

2.5. Thermal treatment

The deposited films were thermally treated in air to obtain transparent multioxide coatings. The heating program consisted of a first stage to 300 $^\circ\text{C}$ at a heating rate of 1 $^\circ\text{C}/\text{min}$ with a holding time of 1 h, followed by additional heating to 450 $^\circ\text{C}$ at 2 $^\circ\text{C}/\text{min}$

3. Results and Discussion

The emission spectrum of the $\text{ZrO}_2\text{-TiO}_2\text{-Al}_2\text{O}_3\text{-Sm}_2\text{O}_3$ coating was recorded at different excitation wavelengths. Under UV excitation ($\lambda_{\text{ex}} = 354 \text{ nm}$), a broad emission band was observed in the region 370–550 nm with a maximum around 420–440 nm (fig.1).

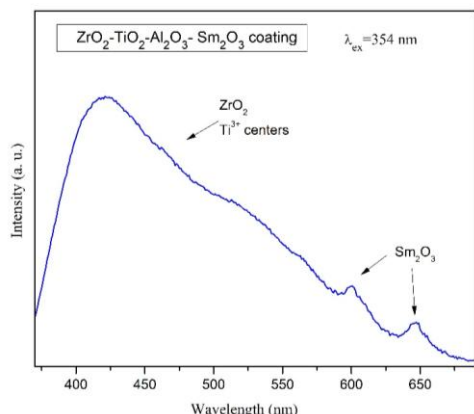


Figure 1. Emission spectrum of deposited $\text{ZrO}_2\text{-TiO}_2\text{-Al}_2\text{O}_3\text{-Sm}_2\text{O}_3$ coating under 354 nm excitation.

Three kinds of different mechanisms have been proposed to explain ZrO_2 blue-green luminescence - an impurity luminescence center model, intrinsic self-trapped excitons and a structure-defect model. [P. Iacconi, D. Lapraz, R. Caruba: *Phys. Status Solidi A* 50, 275 (1978); M. García-Hipólito, R. Martínez, O. Alvarez-Fregoso: *J. Luminesc.* 93, 9 (2001); V.A. Emeline, N. Serpone: *Chem. Phys. Lett.* 345, 105 (2001) 20 W.C. Hsieh, C.S. Su: *J. Phys. D: Appl. Phys.* 27, 1763 (1994); Liang J, Deng Z, Jiang X, Li F and Li Y 2002 *Inorg. Chem.* 41 3602]. At present, the generally

accepted model is the structure-defect one, suggesting that the luminescence of ZrO_2 arises from oxygen-vacancy defects (F^+ centers). Thus the observed broad band with a maximum around 420–440 nm can be associated with oxygen vacancies in ZrO_2 together with Ti^{3+} centers.

Sm^{3+} ions are characterized by narrow, sharp emission lines in the wavelength range 500 nm -750 nm, which are attributed to the characteristic intra-configuration f-transition of $\text{Sm}^{3+} {}^5\text{G}_{5/2} \rightarrow {}^7\text{H}_J$ where $J = 5/2, 7/2, 9/2, 11/2$. [W.T. Carnall, P.R. Fields, K. Rajnak *J. Chem. Phys.*, 49 (1968), p. 4424; W.T. Carnall, G.L. Goodman, K. Rajnak, R.S. Rana *J. Chem. Phys.*, 90 (1989), p. 3443]. Based on this, the observed weakly intense and narrower emission bands at 600 nm and 647 nm (fig1.) can be assigned to the ${}^5\text{G}_{5/2} \rightarrow {}^7\text{H}_{7/2}$ and ${}^5\text{G}_{5/2} \rightarrow {}^7\text{H}_{9/2}$ transitions of Sm^{3+} ions.

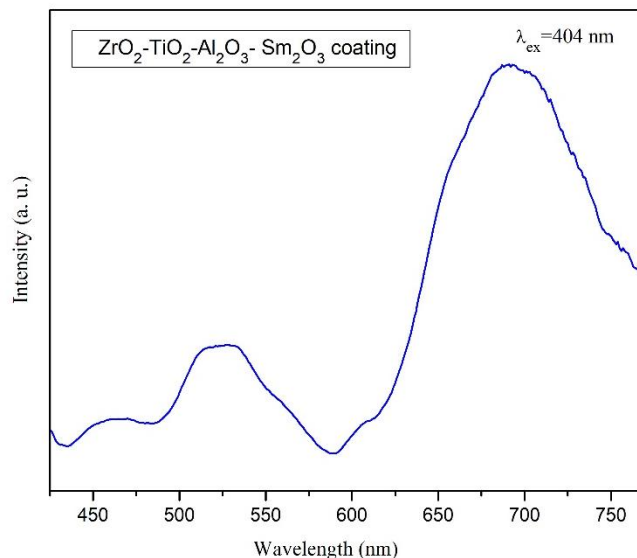


Figure 2. Emission spectrum of deposited $\text{ZrO}_2\text{-TiO}_2\text{-Al}_2\text{O}_3\text{-Sm}_2\text{O}_3$ coating under 404 nm excitation.

When excited with 404 nm the spectral profile changes significantly. A broad emission in the region 500–750 nm is observed with a maximum around 680–710 nm, without clearly pronounced narrow lines characteristic of the 4f–4f transitions of Sm^{3+} . This indicates that under these conditions the emission is dominated by defect levels in the oxide coating.

It is clear that the direct luminescence of Sm^{3+} ions, which falls in the same region (680-710 nm), is strongly suppressed and does not dominate the observed emission.

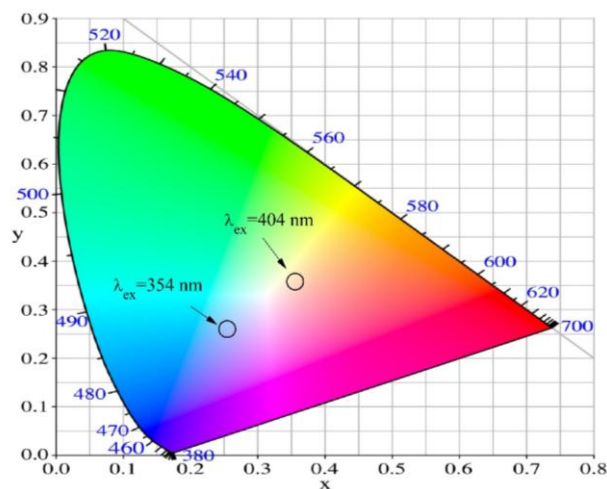


Figure 3. CIE chromaticity diagram of coatings under 354 nm and 404 nm wavelength of excitation.

In order to estimate the actual emitted color, the Commission International de l'Eclairage (CIE) 1931 chromaticity diagram was used [Smith, T.; Guild, J. The CIE colorimetric standards and their use. *Trans. Opt. Soc.* 1931, 33, 73.]. The chromaticity coordinates

were calculated from the emission spectra by using color calculator software SpectraChroma (CIE coordinate calculator) [Paolini, T.B. SpectraChroma (Version 1.0.1) [Computer Software]. 2021. Available online: <https://zenodo.org/records/4906590> (accessed on 7 June 2021).]. The values of the chromaticity coordinates of the coating excited under 354 nm correspond to the pale pink color of emission (0.252, 0.272) and under 404 nm has orange color of emission (0.353, 0.370).

The color purity of the synthesized samples can also be calculated via chromaticity coordinates of CIE 1931 diagram. The following expression was used:

$$\text{Color purity} = \frac{\sqrt{(x-x_{ee})^2 + (y-y_{ee})^2}}{\sqrt{(x_d-x_{ee})^2 + (y_d-y_{ee})^2}} \cdot 100\% \quad , \quad [\text{book:}$$

Schubert, E. F. (2006). *Light-emitting diodes*, Cambridge university press, p. 300]

where (x,y) represents the color coordinates of the synthesized glasses; (x_{ee}, y_{ee}) is the illuminant point of the 1931 CIE Standard Source C with color coordinates (0.3101, 0.3162); (x_d, y_d) are the chromaticity coordinates of the dominant wavelength point, which were obtained by extending the straight line between the point of (x, y) and the illuminant point (x_{ee}, y_{ee}) to the other side of the chromaticity diagram. Generally, it is accepted that 100 % is for pure color and 0% is for white light. The established values for the color purity of coatings excited by 354 nm wavelength is 26% and for 404 nm is 25%.

Discussion:

The lack of clearly defined linear emission peaks of the active Sm³⁺ ions, even under direct excitation around 404 nm, can be explained by competing non-radiative processes in the oxide coating, as well as by possible concentration quenching and strong interaction between Sm³⁺ ions and defect states of TiO₂/ZrO₂. The broad character of the observed emission is typical of defect-driven luminescence in amorphous or nanocrystalline oxide systems.

The obtained results show that the luminescent properties of the studied coating are determined mainly by the defective structure of the coating, creating prerequisites for further optimization of the composition and thermal treatment in order to activate the emission of rare earth ions.

4.Conclusion

Transparent Sm³⁺-doped ZrO₂-TiO₂-Al₂O₃ coatings were successfully synthesized on glass substrates using a sol-gel dip-coating technique followed by thermal treatment. The applied synthesis approach enabled the formation of homogeneous multicomponent oxide films suitable for optical investigations.

Photoluminescence analysis revealed that the emission properties strongly depend on the excitation wavelength. Under UV excitation at 354 nm, a broad emission band centered at 420–440 nm was observed, which is mainly associated with oxygen-vacancy defects in ZrO₂ and Ti³⁺ centers. Weak emission lines at 600 nm and 647 nm correspond to the characteristic transitions of Sm³⁺ ions. When excited at 404 nm, the emission is dominated by defect-related luminescence in the oxide matrix.

Chromaticity analysis indicated pale pink emission under 354 nm excitation and orange emission under 404 nm excitation. The obtained results demonstrate that the luminescent behavior of the coatings is largely governed by defect states in the oxide structure. Such transparent luminescent coatings may be considered as promising materials for photonic applications and potentially for light management in photovoltaic devices.

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