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Minimizing the emission of material waste in the production process of batteries

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Abstract. Contemporary societies are strongly dependent existentially and economically on the supply of electricity, both in terms of supplying devices from the power grid, as well as the use of energy storage and constant voltage sources. Electrochemical batteries are commonly used as static energy storage. According to forecasts provided by the Environmental Protection Agency at the global and EU level, in 2025 lead-acid technologies will continue to dominate, with the simultaneous expansion of the lithium-ion battery market. The production, use and handling of used batteries are associated with a number of environmental and social challenges. The way batteries influence the environment is becoming more and more significant, not only in the phase of their use but also in the production phase. The article presents how to effectively reduce the environmental impact of the battery production process by stabilizing it. In the presented example, the proposed changes in the battery assembly process facilitated the minimization of material losses from 0.33% to 0.05%, contributing to the reduction of the negative impact on the environment.

Key words: sustainable development; lead-acid battery; material loss.

1. INTRODUCTION

Awareness of the climate and environmental changes taking place on our planet (Hickel, 2020) has been with people for several dozen years. The primary causes of these changes are energy and food production, and transportation. It is believed that these areas of human economic activity make the greatest contribution to the emission of greenhouse gases [1–3] which are the main culprits of global warming, and should therefore be of the greatest concern.

The impact of the production and consumption of material goods, such as cars, household appliances, electronic equipment, and furniture, is also not underestimated. However, it is difficult to determine its impact because the relationships occurring in the lifecycle of material goods are complex. Consumption of any material good generates a flow through the supply chains of the stream of materials and energy necessary to conduct the processes related to the extraction of raw materials, their transport, and conversion into energy or products (Fig. 1).

Activities aimed at limiting the flow of materials and energy, and thus the negative impact of the production of material goods on climate and environment, are conducted with greater or lesser success under so-called sustainable development, i.e. economic development that satisfies the needs of modern generations for future generations without harm [4–7]. The sustainable development strategy focuses primarily on replacing fossil fuels with renewable energy, and on implementing the principles of a "zero-emission", closed-loop (zero-waste) [8–10] economy, through:

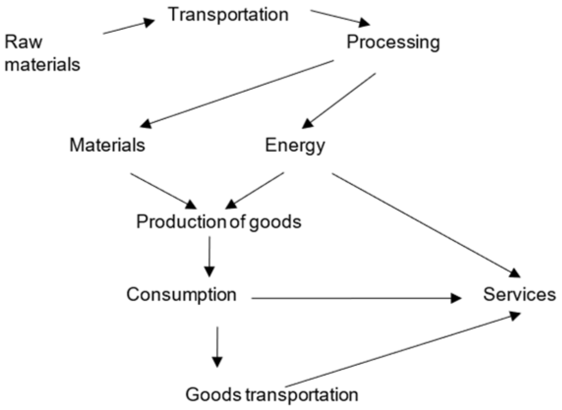

Fig. 1. Consumption of material goods as a source of material and energy flow (own study)

- Designing low-energy products made of easily recyclable materials, etc.
- Designing manufacturing processes with the lowest possible negative impact on the environment.

Activities in these directions are already widely used today. In the production phase, they consist of continuous improvement of production techniques and technological processes, ensuring that the design requirements are met "the first time", i.e. without the need for corrections (zero waste). It is of particular importance in processes where waste is harmful to the environment. An example of such a process is the production of automotive batteries.

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2. THE BATTERY AS A SOURCE OF WASTE EMISSIONS

Contemporary societies are very strongly dependent on electricity supplies, both in terms of supplying devices from the power grid, as well as the use of energy storage and constant voltage sources. Commonly used static energy stores are batteries and electrochemical accumulators [11–14].

Currently, there are many different types of batteries on the market (alkaline, lithium, or zinc-carbon) and accumulators (lithium-ion, lead-acid, or nickel-metal hydride). They contain many substances hazardous to the environment and humans.

Lead-acid batteries are the most widely used today. They consist of individual lead-acid cells (Fig. 2). The cells can be connected in a series and/or in parallel, in order to give the desired voltage and electrical capacity of the complete battery. A single lead-acid cell consists of positive and negative plates (electrodes) placed alternately, separated by a separator, and immersed in a solution of sulfuric acid. A set of plates of one character forming a single link is connected in parallel, the so-called pole bridge. Usually, a single cell contains one negative plate more; therefore, the battery capacity is limited by the capacity of the positive plates [15]. The battery cover, which is welded to the housing, is equipped with plugs for adding water or changing the electrolyte in the battery [15].

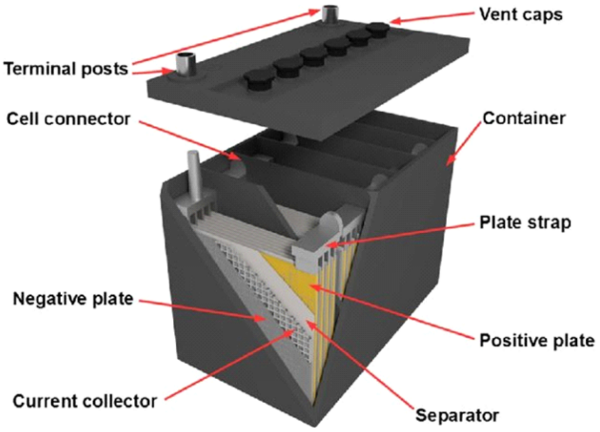


Fig. 2. Battery components [13]

A number of substances are used in the manufacturing of batteries that can be a nuisance to the environment. The most commonly used include manganese dioxide, iron, zinc, graphite, ammonium chloride, copper, potassium hydroxide, mercury, nickel, lithium, cadmium, silver, cobalt, as well as glass, silica, paper, foil and hydrogen. Heavy metals found in batteries (lead, cadmium and mercury) have negative health effects and acids or bases used to form an electrolyte have corrosive and corrosive properties. Lead, in particular, has pathogenic effects on living organisms, causing damage to the brain, nephrology and the digestive system, but also causing contamination of the soil and aquatic environment [15, 16].

One of the more difficult technological problems in the case of lead-acid batteries is the risk of sulfuric acid leakage from them and water evaporation increasing the electrolyte concentration, which requires periodic replenishment. Both problems are solved by using a special electrolyte entrapment design in a closed housing. Three technologies are distinguished in this respect [16]:

- MF (maintenance free) – maintenance-free classic batteries with liquid electrolyte with a closed structure and limited possibility of opening the housing.
- AGM (absorbent glass mat) – accumulators with liquid electrolyte absorbed in a separator made of glass.
- Gel batteries with gel electrolyte. Gel electrolytes are aqueous solutions of sulfuric acid; however, a gelling agent (e.g. silicone resins) is added to them, which at the same time prevents water evaporation and leakage.

Compared to other product waste, the lead-acid battery has a favorable recycling rate [17]. The Environmental Protection Agency – the US federal agency for the protection of the environment – published a report that ranked lead batteries first (with a recycling rate of 99%) among all consumer goods that are recycled, leaving behind cardboard boxes (88.5%), metal cans (71%) and aluminum (55%). It has also been proved that the materials used in car batteries are the most recycled consumer product in the world. What is more, lead can be recycled many times. In Europe, as much as 95 percent of materials from lead-acid batteries are recovered [17].

However, lead recycling is a source of many pollutants and is energy inefficient and expensive. It also does not offer the possibility to recycle unnecessary lead and convert it into an active lead oxide paste suitable for reuse as an essential component of lead-acid batteries [17].

In 2020, as part of the EU-supported NUOVOpb project, researchers separated waste materials from lead-acid batteries, recovering them through a water-based recycling process to produce ‘battery-ready’ lead oxide. The process has an initial cost of about one-seventh that of existing lead-acid battery recycling methods and comparable operating costs. The technology has no toxic emissions and can be considered ‘energy positive’ as it can generate up to 5 000 MWh of thermal energy. The NUOVOpb technology (marketed under the name FenixPB) also allows carbon dioxide emissions to be reduced by 80–89% [18].

The global lead-acid battery market is now worth $41.6 billion and is growing at a rate of 4.7% annually. This increase can be attributed to the development of renewable energy and the booming industry of digital data collection. It is expected that both directions will result in increased demand for lead-acid batteries to power, among other things [18].

According to forecasts of the Environmental Protection Agency, in 2025 at the global and EU level, lead-acid technologies (LAB; used mainly in the automotive industry) will continue to dominate; however, it has been pointed out that since 2018 the market of lithium-ion batteries has been systematically growing (LIB; batteries used in portable electronic devices) [19–21].

An analysis of the literature on the life cycle of lead-acid batteries indicates that research has largely focused on how to recycle them and how to recover and recycle the materials and compounds they contain. Unfortunately, there is a lack of comprehensive guidance on how to implement battery manufacturing processes while reducing its instability.

Indeed, the instability of battery manufacturing processes results in material losses and waste, which are not inert to the environment. This gap is filled by the research and proposals of the authors.

3. PRODUCTION PROCESS OF LEAD-ACID BATTERIES

The production of a lead-acid battery follows the scheme shown in Fig. 3.

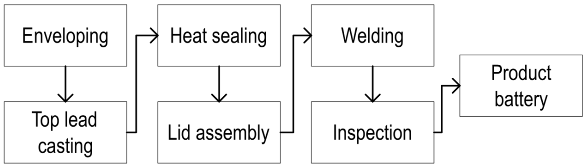


Fig. 3. Flowchart of the battery production process (own study)

In the first operation, sets of lead plates, insulated from each other, with opposite poles are built. The protrusions of the positive and negative plates are joined by cast strips which are then welded. In the assembly operation, the block of links is connected to the cover. This is done with a suitably shaped heating plate. The last operation is welding the battery terminals.

The last operations are quality inspections related to leakage testing, battery and pole height control.

4. PURPOSE AND RESEARCH METHOD

Four research tasks were set:

- Indication of critical technological operations in manufacturing process of lead-acid batteries, due to the amount of waste generated in them.
- Estimation of the degree of environmental hazards generated by the generated waste.
- Identification of the causes of waste generation.
- Proposing preventive actions, their implementation and demonstrating their effectiveness.

The following research tools were used:

- Adapted PFMEA analysis.
- Ishikawa diagram, Pareto diagram.
- Three-level and two-level factorial experiments.

5. RESEARCH

5.1. Identification of the operation with the highest material waste

The literature describes various methods of analyzing processes in terms of the possibility of detecting potential sources of threats leading to losses, including those having a negative impact on the environment [21]. In this research, the PFMEA method (Process Failure Mode and Effects Analysis) [22] was adopted for this purpose. The idea of PFEMA is to assess three indicators: severity (S), occurrence (O) and detection (D), which in the production process analyzed here, described in the diagram in Fig. 3, refer to the possibility of an error occurring and its significance in the context of material waste as well as the possibility of its detecting. Tables 1, 2 and 3 outline the scale

Table 1
Guidelines for Defect Impact Assessment (S – Severity) (own source)

S	The significance of the defect in the con- text of potential waste	Comment
1	Very slight	Zero waste
2–3	Slight	Little waste, e.g. individual plates, separator
4–6	Moderately slight	Significant waste, e.g. a set of plates
7–8	Moderately considerable	Large waste; waste of the lead part of the battery, e.g. a built-in block
9–10	Considerable	Very large waste; the whole battery

Table 2
Guidelines for Risk Assessment (O – occurrence) (own source)

O	Risk / How often the defect arises	Comment
1	Negligibly small	Level of defects; ppm* < 1,000
2	Very low	Level of defects; 1,000 < ppm < 5,000
3	Low	Level of defects; 5,000 < ppm < 10,000
4–5	Moderate	Level of defects; 10,000 < ppm < 20,000
6–7	Considerable	Level of defects; 20,000 < ppm < 50,000
8–9	High	Level of defects; 50,000 < ppm < 100,000
10	Very high	Level of defects; ppm > 100,000

*ppm – part per million. How many times per million units produced will a defective piece be revealed?

Table 3
Guidelines for defects detection (D – detection) (own source)

D	Possibility of the defect detection	Comment
1	Very high	The applied control and supervision measures give almost certainty of early detection of the cause of the defect. The design of the component does not allow for a mistake, or tools are installed that do not allow for the error, such as poka-yoke.
2–4	High	The detection takes place where the defect occurs, and the product is automatically separated in the defect isolator.
5–6	Moderate	The detection takes place where the defect occurs, e.g. by the operator during a transition test, or in a subsequent process automatically.
7–8	Low	The detection takes place where the defect occurs, or in a subsequent process during the visual and tactile inspection.
9–10	Very low	The defect can be detected during audits (e.g. of the product), and the standard control and supervision measures applied do not make it possible to detect the cause of the defect.

used to assign a value to the indicators S, O, and D in the range of 1 to 10.

The S, O and D values are assigned to the analyzed defects. According to the guidelines set out in [22], each variant of the value (S, O, D) is assigned a sign of Action priority (AP): L – low, M – middle and H – high. High priority (H) defect requires corrective action first.

The FMEA sheet presented in Table 4 shows that the most serious defect of the battery (described by a high AP index) in the context of material waste is the lack of tightness and the resulting leakage of sulfuric acid.

The occurrence of leakage means that the battery cannot be transferred to the next stage of the technological process. It must be considered as waste. Based on the FMEA results, further research was focused on the lack of tightness of the battery.

5.2. Reasons for leaks

Determining the location of the leak

In order to identify the place of sulfuric acid leakage, a suitably prepared test was conducted for 47 batteries showing leakage. A high-voltage leak tester was used for the measurement.

The battery cover was divided into 56 squares. Tests identified three leak-prone squares: B5, E5, and F5 (Fig. 4). Detailed studies have shown that most leaks are so-called external leaks due to the leakage of the battery cover. They mainly arise after the molding operation. Therefore, further research has focused on this part of the process.

The required welding force

The leakage of the cover was found to be related to the contact surface between the cover and the battery body. It has been assumed that the larger the contact area, the greater the force

Table 4

PFMEA (legend: L – low; M – medium; H – high) (own source)

	Process stage	Defect	Effects	Reason	D	S	D	R
1	Enveloping	Punctured separator	Cell short circuit **Waste**: plate, separator	Bent battery plate	3	3	2	L
				Wire sticking out of the plate	3	4	2	L
		Plate pulled out of the separator	Cell short circuit **Waste**: separator	Ineffective sealing of the envelope (no embossing of the envelope edge)	2	2	3	L
2	Casting of the top lead	Partial or complete lack of remelting flag flags in the bridge	Low battery parameters **Waste:** a single plate set or a set (6) of plate sets	Inadequate casting parameters for top lead	3	8	5	M
				No flux	4	8	5	M
		Damage to the plate set during automatic loading	Short circuit **Waste:** a single plate set	Displacement of the cassette or grippers	2	6	2	L
		Bridges too thick, too thin, no bridge	Loose plates, rupture of the sternum, insufficiency of the sternum, traps on the sternum – short circuit **Waste**: a single plate set or a set (6) of plate sets	Too intense pouring of the mold, dirty mold, dross in the mold channels, inappropriate parameters	4	8	3	M
3	Inter-bulkhead welding	Lack of tightness No weld, cold weld, lead splashes	Possible corrosion of the weld and its breakage Loss of battery function Internal short circuit. **Waste**: a set of (6) plate sets	Wrong setting of pressure, welding current and welding time	5	8	2	M
4	Lid assembly	Poor connection or no connection between block and cover	The battery is leaking **Waste**: complete battery	Inadequate welding parameters	4	10	3	H
				Eccentric arrangement of the lid in relation to the block	4	10	3	H
				Block deformation	4	10	3	H
5	Welding	Poor welding of the battery terminal/poor connection of the pin with the sleeve	Breakage of it during use **Waste**: whole battery	Too strong/too weak flame	3	10	4	L

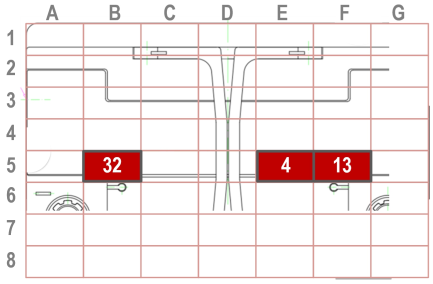


Fig. 4. Division of the lid area in leak tests (own source)

needed to detach the cover from the body.

In order to determine the force connecting the cover with the battery body, a force was applied to the cover in a direction perpendicular to it, and its value was measured at the moment of the cover being torn off. The measurement was taken on a testing machine. Measurements were taken at four points, one on each of the four side walls of the battery (Fig. 5).

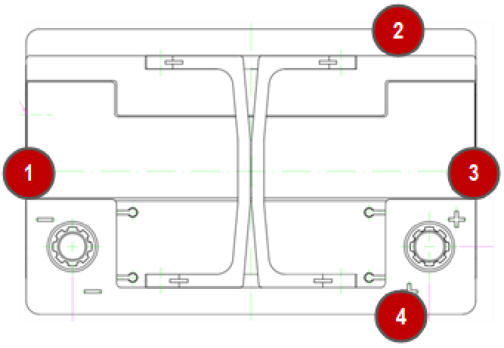


Fig. 5. Sampling points for testing (own study)

The analysis of the obtained results allowed us to state that all batteries in which the cover tearing force was lower than 630 N showed leakage. On this basis, the limit force value of 630 N was adopted, above which the connection is considered tight.

Reasons for insufficient welding force

In order to determine the reasons for not obtaining the appropriate force connecting the cover with the housing in the welding process, a brainstorming session was organized with the participation of process engineers and operators. As a result, 22 potential causes were identified.

Then, an ABC analysis was performed for the selected causes. [23]. Each of the five team members rated each of the potential causes on a scale of 1 to 10, where 1 is a very high impact of causes on the occurrence of the problem, and 10 is negligible. Based on individual assessments, a summary table was created and weighted ranks were calculated. Then the causes were ranked according to importance (the lower the value of the index, the more significant the cause). The highest ranks were obtained by (Table 5):

a) deflection of the body wall under the influence of the so-called centering clamps,
b) incorrect welding parameters,
c) dirty melting plates,
d) thickness of the plates.

Table 5
Ranking results for potential causes of battery leakage (own source)

Category	Name	Ranking										OP
		1	2	3	4	5	6	7	8	9	10	
Machine	Bended walls by centering paws							0	2		1	**1**
Method	Not appropriate parameters				0			1	2		0	**2**
Machine	Mirrors contaminated with dirt				0		1	1			1	**2**
Material	Thick plates						0	2		1	0	**2**
Man	No reaction to non-compliance					0	1		2			**5**
Man	Operator replacement						0	2	1			**5**
Machine	Damaged mirrors				1				1	1	0	**7**
Man	Work not in accordance with procedures					1		1	1			**8**
Man	Experience					0	2		1			**8**
Method	No test method for the quality of melt						1	2	0			**8**
Machine	Changeover quality					1		1	1			**8**
Machine	Flash taken away by the lid taker				1		1				1	**8**
Method	Lack of new tooling validation					0	3	0				**13**
Method	Faulty measuring system		0			1	1	1			0	**13**
Method	No changeover standard				0	1	1	1				**13**
Machine	Problem with machine adjustment				0	2		1	0			**16**
Material	Different thermal conductivity of mirrors		0			1	2	0				**16**
Man	Lack of changeover knowledge					2	1	0				**18**
Material	Different material MFI			0		2	1		0			**18**
Material	Too high poles (lid stops on them)		0		1	1	1			0		**20**
Material	Paper on the walls				2		1			0		**21**
Machine	Position reading faults		1		1			1		0		**22**
Method	No time for quality control		0	2				1	0			**23**
Machine	Unstable pneumatic pressure		0	1	1	1				0		**23**
Man	Operator's tiredness		1	1	1	0						**25**
Environment	Temperature	1	1		1							**26**

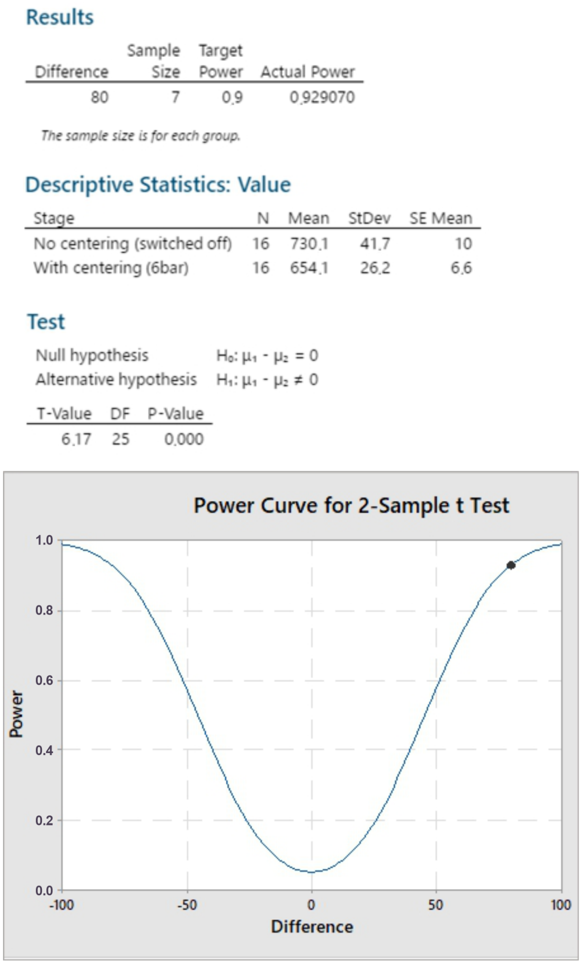
Ad a)

In order to verify the hypothesis that the deflection of the battery body wall is caused by too much pressure of the clamps centering the block in the machine, two experiments were conducted, each with eight repetitions. In the first experiment, a higher and in the second, a lower downforce was used.

In order to verify the hypothesis that the deflection of the battery block wall occurs by too much pressure of the block centering clamps in the machine, a series of experiments were conducted to investigate whether reducing the pressure of the clamps would have a beneficial effect on the strength of the lid weld. A total of 16 samples were prepared: 8 were used with the current process parameters and 8 with the new parameters (reduced pressure). This arrangement of experiments was used to verify

- The null hypothesis H_0: *All tensile strength means are equal.*
- The alternate hypothesis: H_1: *Not all tensile strength means are equal* (Fig. 6).

The test results showed that the clamping force of the centering clamps has a significant effect on the strength of the connection between the cover and the wall – P-Value less than 0.05 (Fig. 6).



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Results

                Sample  Target
Difference        Size   Power  Actual Power
--------------------------------------------
        80           7     0.9      0.929070

The sample size is for each group.

Descriptive Statistics: Value

Stage                         N   Mean  StDev  SE Mean
------------------------------------------------------
No centering (switched off)  16  730.1   41.7       10
With centering (6bar)        16  654.1   26.2      6.6

Test

Null hypothesis          H₀: μ₁ - μ₂ = 0
Alternative hypothesis   H₁: μ₁ - μ₂ ≠ 0

T-Value  DF  P-Value
--------------------
   6.17  25    0.000
```

Fig. 6. Results of the data analysis from the experiment of the influence of the pressure force of the centering clamps (own study)

Ad b)

Three welding parameters were selected which – as has been shown in practice – have the greatest impact on the results of welding the plate to the body and which can be controlled during the process. These are:

- Melting point (controlled by a set of heaters built into the heating plate)
- Melting time (block and cover heating time)
- Penetration height (i.e. the depth of melting)

A full factorial, three-level experiment with two replications was planned and performed (Table 6).

Table 6

Level values for three selected factors (own study)

Factor	Level	Value
Melting point [°C]	3	330; 355; 380
Melting time [s]	3	4.5; 5; 5.5
Penetration height [mm]	3	1; 1.5; 2

Table 6 presents the values of each factor. The melting temperature was set at three levels: 330, 350, and 380 degrees Celsius. Melting time was set at levels: 4.5; 5; 5.5 seconds with penetration height at the values: 1, 1.5, and 2 mm.

Table 7 presents the results of the statistical analysis of the experiment and the statistical significance of the individual factors. The experiment showed that the penetration height has a statistically significant influence on the strength of the connection between the cover and the body – P-Value is less than assumed level of significance (0.05) (Table 7).

Table 7

Experiment results (own study)

Factor	Effect	Coeff	SE Coeff	T-Value	P-Value
Melting point [°C]	–94.7	–47.4	29.3	–1.61	0.124
Melting time [s]	13.7	6.9	29.3	0.23	0.817
Penetration height [mm]	–159.5	–79.8	29.3	–2.72	0.014

Ad c)

In order to check whether the strength of the connection between the cover and the battery body depends on the cleanliness of the surfaces to be joined, the process was conducted under standard conditions and under conditions where the surfaces were prepared with particular care.

Table 8 presents the results of a statistical test to verify the hypothesis that the level of waste in both methods is the same. The results of the test did not provide grounds to reject the null hypothesis (P-Value is greater than the test significance level – 0.05). The results showed that in both cases comparable results were obtained (Table 8).

Table 8

Results of the comparison of the level of scrap before cleaning the plates and after introducing cleaning activities (own study)

Null hypothesis H0: $p1-p2=0$ Alternative hypothesis H1: $p1-p2\neq 0$						
Sample	N	Event	P	Method	Z	p
Sample 1	91487	36	0.000393	Normal app	–0.89	0.376
Sample 2	241758	112	0.000463	Fisher's exact		0.461

Ad d)

The strength of the connection between the cover and the body was compared for 24 batteries with a separator thickness of 0.9 mm (12) and 0.8 mm (12) (Table 9).

Table 9

Results of the comparison of the breaking force of the lid for batteries with 0.9 mm and 0.8 mm thick plates (own study)

Null hypothesis H0: $\mu1-\mu2=0$ Alternative hypothesis H1: $\mu1-\mu2\neq 0$							
Sample	N	Mean [N]	StDev [N]	SE Mean	T Value	DF	p-Value
0.9 mm separator	12	689.8	43.1	12	–0.11	21	0.910
0.8 mm separator	12	691.9	48.1	14			

Table 9 presents the results of a statistical test verifying the hypothesis that there is no difference between the average weld break strength for different separator thicknesses. The results indicate that there are no grounds to reject the null hypothesis.

There was no significant difference between the strength in both groups of separators (Table 9). Therefore, it can be concluded that this is not a source of the battery leakage problems.

5.3. Parameter optimization

The results of the tests described in Section 5.2 show that the strength of the connection between the cover and the body is influenced by two factors: the clamping force of the centering clamps and the penetration depth.

Two variants of clamps have been prepared, both with the possibility of adjusting the pressure. The first was standard clamp (old one) – with one paw and the second (new one) with two paws (Fig. 7).

In order to determine the optimal set: type of clamp and force; a two-factor – two-level experiment was conducted. The contact pressure was set at the levels of 2 and 6 bar.

The penetration height was set at level 1.5, which is considered to be better (see Section 5.2b).

Figure 8 presents diagrams of the main effect of two factors on the strength of the joint: type of clamps and pressure. Their influence is not statistically significant; moreover, there is no interaction between the factors.

The evaluation of for batteries where the lid was welded using new clamps and with a pressure of 2Bar also confirms the

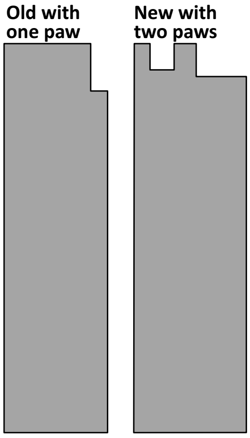
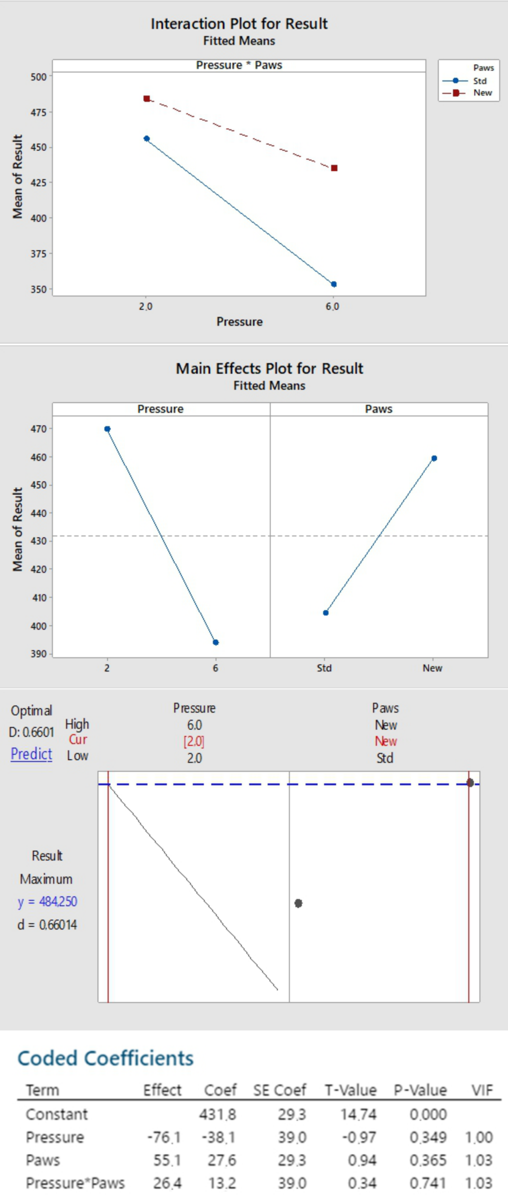


Fig. 7. Comparison of the old and new centering clamps (own study)



Coded Coefficients

Term	Effect	Coef	SE Coef	T-Value	P-Value	VIF
Constant		431.8	29.3	14.74	0.000	
Pressure	-76.1	-38.1	39.0	-0.97	0.349	1.00
Paws	55.1	27.6	29.3	0.94	0.365	1.03
Pressure*Paws	26.4	13.2	39.0	0.34	0.741	1.03

Fig. 8. Visualization of the strength of the influence of the experimental results for two factors: type of clamps, pressure (own study)

experimental result. The strength of the connection for this arrangement is on average higher than the weld strength with the current joining method – Fig. 9.

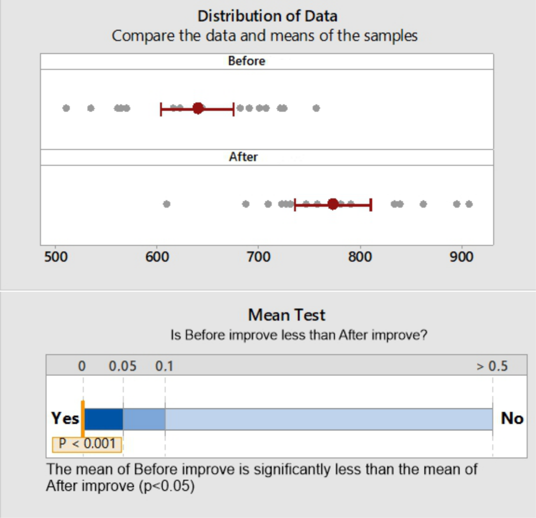


Fig. 9. Comparison of data distributions and the average strength of the weld for the current and new joining method (own study)

The results of the experiment show that the strongest connection between the cover and the cover is achieved with the use of new clamps and with a low-pressure force (Figs. 8 and 9).

5.4. Verification

In order to verify the effects of the implementation of the modified operation of connecting the cover to the body, the production process of the batteries was monitored within 13 weeks from the moment of introducing the changes. All non-compliant units, i.e. those showing leakage in the connection, were identified.

During the research period, the share (fraction) of non-compliant units decreased from 0.33% to 0.05%. From an environmental perspective, the weight of lead waste due to leakage has been reduced, in one year, from 23 595 kg to 3575 kg.

6. CONCLUSIONS

The production of batteries is an energy-consuming process. The batteries themselves contain many materials that are hazardous to the environment and to humans. Therefore, all causes leading to non-conformities in the production process, resulting in the generation of waste, should be absolutely eliminated. They are a source of energy waste and emissions of pollutants.

The causes of waste are often difficult to see. They cannot be identified on the basis of simple observations.

The example described in the article shows that a methodical approach to process improvement based on quality management instruments, statistical analysis and experiments can effectively support activities leading to waste minimization. The changes introduced in the battery assembly process minimized material losses from 0.33% to 0.05%. The introduced changes also increased work safety and standardized control processes.

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