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# Quality Analysis of Welds Made with an Automatic Battery Pack Spot Welding Machine

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***Abstract*—This paper presents quality testing of battery pack welds for different welding time parameters of an automatic resistance spot welding machine. Several quality testing methods commonly used in studies of welded joints were described. Finally, the breakage test destructive method was chosen and used in this research. To investigate the influence of welder parameters on the quality of the welded joints, the programmable resistance spot welding machine was designed and constructed. As the studied samples, the 18650 cell type and the 8 mm × 0,15 mm cell packaging nickel plated steel tape were chosen as the most commonly used for the construction of battery packs for personal electric vehicles. The impact of each time constants set on the spot welding process was measured by the self-designed and constructed strength testing machine. After a series of tests with different parameters of spot welding process, the final conclusions were formulated.**

***Index Terms*—Battery cell; Battery pack; E-bike; Quality analysis; Spot welding; Spot welding machine.**

## I. INTRODUCTION

Today, one can observe a growing interest in electric vehicles and transport. It is becoming easier and easier to build a self-designed personal transport device like an electric skateboard, scooter, or bike [1]. There are many solutions available on the market that allow one to convert, e.g., a classic bicycle into the so-called "e-bike". Often, the most expensive part of the conversion kit is the battery. Many users try to make the battery pack themselves using available battery cells, e.g., 18650 type [2]. The connections between the cells are usually done with steel packaging tape. The spot resistance welding process for battery cell packaging is then widely used, especially for e-bikes battery packs production. It consists of flowing high-intensity currents at the contact points of the electrodes with the materials to be bonded [3]. The times of current pulses are short enough to minimise the risk of damaging the cell. The issue of the resistance welding is a complex process that requires consideration of many factors, e.g., maximal current, values of time pulses, contact area, pressing force, distance between the electrodes, material and geometry of the electrodes, etc. Nevertheless, packaging cells with this technique is widely used because of its high efficiency. However, this process is crucial for the safe operation of an electric vehicle, due to the potential internal and external short circuits [4]. Breaking the contact between the cell and the packaging strip can cause a short circuit and, consequently, an uncontrolled fire. Such a fire is very difficult to extinguish, as the power density of the battery pack is very high and can reach up to 270 Wh/kg for lithium-ion cells.

A less common method of connecting single cells is soldering [5]. It is considered a less safe method since it involves the use of a binder called "solder". In the soldering process, the melting point of the binder usually does not exceed 400 °C and the cell pole terminals have a high heat capacity. However, special care should be taken not to increase the temperature of the entire cell during the soldering process. Its sudden increase may lead, in extreme cases, to an explosion or self-ignition. This method is used in the modelling environment when the number of cells in the package does not exceed about three pieces.

Other welding techniques described in the literature are, e.g., laser beam welding (LBW) or ultrasonic metal welding (UMW) [6]. However, these methods have not found wider applications in battery cell welding.

In summary, in the following paper, weld quality of a personal transport device battery pack will be investigated using a programmable spot welding machine, as well as the self-designed strength testing machine. The welding process parameters are then the key issue for the battery pack mechanical durability and hence for the safe operation of an electric vehicle. If a soft internal short circuit occurs, the battery pack can also be protected by using early detection methods addressed in many publications, e.g., [7], [8]. Nevertheless, this paper focusses on preventing such events by increasing the overall mechanical strength of the battery pack.

## II. METHODS OF QUALITY ASSESSMENT AND TESTING OF RESISTANCE WELDS STATE-OF-THE-ART

Along with the development of various methods for joining metals or plastics, verification procedures are established to check their correctness and effectiveness. Among the various metal welding methods, electric welding has become very popular. The use of spot-welded joints forced the development of methods for controlling and verifying their quality. Before starting production and then during the production of welded elements, verification procedures are performed to eliminate possibly incorrectly designed or made welds [9].

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In general, the testing methods are divided into two groups: destructive tests (DT) and non-destructive ones (NDT). Destructive tests are characterised by the fact that the samples are destroyed or deformed during tests. Samples are properly prepared in advance. The tests are carried out under strictly defined simulated conditions. The disadvantage of such methods is the formation of scrap, i.e., unsuitable material for reuse. These methods are most often used in strength tests, where samples are subjected to various types of stress (e.g., bending, stretching, twisting, hardness tests, etc.). One of such tests is the breakage which occurs as a result of internal forces called "breaking stresses" (Fig. 1).

The breakage tests of the welded elements are performed in specialised machines for quasi-static tests. In most cases, they are used to test structural elements to determine the maximum force required to break the joint [10].

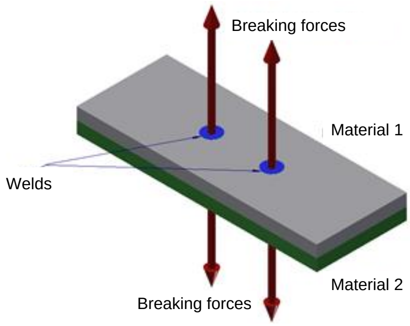


Fig. 1. Sample of a welded joint subjected to destructive forces.

The non-destructive tests provide information about the quality of welds according to certain quality criteria. They use phenomena that allow one to determine the quality of welds without destroying the samples. The basic method in the field of non-destructive testing is the visual testing (VT) (Fig. 2).

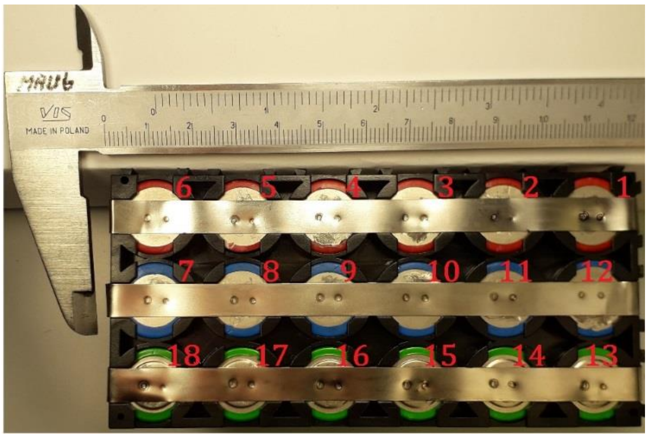


Fig. 2. Battery section prepared for visual test of the welds made with an automatic spot welding machine.

It has a priority in the evaluation of surface defects over other methods. VT is a process that involves visual inspection and measurements to check whether the tested object meets certain requirements [11]. It can be supported by additional optics, i.e., magnifying glasses or microscopes. Instruments such as rulers, callipers, or weld gauges can be used for measurements. In the case of testing welded joints, defects in the form of cracks, metal splinters, or holes formed during burnout due to an inadequate electrode pressure can be easily checked using the VT method. Nevertheless, the results of visual verification often depend strongly on the skills and meticulousness of the inspector and, above all, do not give the quantitative values of the weld strength. Therefore, in the studies presented, the VT method was only used to set the speed of the automatic spot welding machine by taking into account the correctness and repeatability of the welds made.

Whereas defects and imperfections hidden in the internal structure of the welds can be detected by ultrasonic, magnetic [12], or radiographic tests [13]. Due to the small size of the cell welds, some of the methods are difficult to use; nevertheless, ultrasonic testing is one of the most frequently used non-destructive methods for verifying welded joints. The principle of its operation is based on generating high-frequency waves and passing them through the area where the materials are welded. Interpretation of such a signal allows us to determine the degree of correctness of the performed welds. Some welding machines are coupled with ultrasonic measuring systems to control the welding process instantaneously [14]. Despite the availability of such technology, many production plants have resigned from its use in cell packaging for economic reasons. In addition, it is difficult to use this method when examining joints that do not exceed 0.5 mm in diameter.

Another group of methods used for the testing of welded joints are the simulation methods, which constitute a separate group of research. The development of simulation programmes that simulate specific physical phenomena made it very useful for the testing of welded joints [15]. The welding process can be simulated using many computer programmes that have electric current flow modules (e.g., Sorpas 3D, Comsol). Nevertheless, such simulations are usually time consuming, especially during geometry and physics model building, and always need some assumptions and simplifications.

In summary, in the following sections, the breakage destructive test will be used to find the best welding parameters in terms of mechanical strength of the welds, as this method gives the most reliable results for the battery pack design purpose. In addition, breakage tests were carried out on samples prepared on the same machine and under the same conditions as during the regular production of the battery pack. Moreover, the strength testing machine was specially designed and constructed for the above-mentioned samples testing with the most possible accuracy and precision, which makes the research unique.

## III. SPOT WELDING PARAMETERS AFFECTING THE QUALITY OF WELDS

Welding is a process that creates an inseparable connection of at least two overlapping elements. It is done by heating two materials to the melting point and pressing them with the appropriate force. As a result of this process, a weld is formed, which is a consequence of the solidification of the melted material. The diagram showing the idea of spot welding is shown in Fig. 3.

The characteristic and basic parameters for resistance welding using a spot welding machine are the following:

– Current flow time;
– Value of the welding current;

– Electrode pressure force.

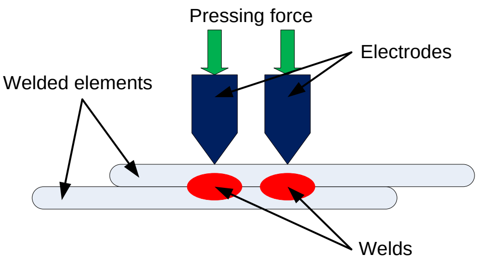


Fig. 3. Schematic diagram of resistance welding.

Heat generated when the current flows through the welded materials can be estimated using the Joule-Lenz law (1)

$$Q = \int_0^{t_z} J^2(t) \times R(t) \times dt, \quad (1)$$

where $Q$ is the amount of heat, $J(t)$ is the welding current, $R(t)$ is the total electrical resistance of the welding area, and $t_z$ is the welding time (welding current flow).

In the area where the welding takes place, there is a rapid release of heat. The total electrical resistance of the area consists of the contact resistance and the resistance of the material from which the elements to be welded are made. The parameters mentioned above have a direct impact on the quality of the connections made. They are selected depending on the thickness and type of the welded materials. The parameters that affect the quality of welds can be divided into three groups: soft, medium, and hard [16]. The hard parameters are those where there is a short time of high-intensity current flow and maximum pressure. Joints created with these parameters are characterised by a small heating zone and small deformations of the surface of the welded element. Soft parameters are those in which the arrangement of parameters is opposite to that of the hard group. There is then a larger heating zone and larger surface deformations in the form of depressions in the material. The intermediate parameters, between hard and soft, are the medium parameters. For optimal medium parameters, the joints are made correctly and the internal structure of the welds is the best compared to the other ones, which results in higher mechanical strength.

Different welding programmes are used in spot resistance welding. In machines with the possibility of adjusting the pressure force and heating time, various configurations are used, where these parameters are changed even during the welding process. The welding time is a key parameter directly related to the current intensity and the clamping force. It may contain several different time components, depending on the welder construction used. In advanced resistance spot welding machines, there are times of pressing and preheating, time of welding pulses, and pauses between them. Selection of welding times must be made taking into account the value of the current intensity to prevent material deformation or cell damage. This follows directly from the Joul-Lenz law (1). In the double current pulse mode, the first pulse, known as the “preheat pulse”, is used to heat the cell and the strip to a specific temperature before the actual welding takes place. This preheat pulse helps to ensure that the materials adhere well to each other and have the correct temperature for welding. It can also help to remove surface contaminants. The second pulse, known as the “weld pulse”, is used to create the actual weld and is usually shorter than the preheat pulse. The use of two separate pulses allows greater control over the welding process, helping to ensure that the cells are welded correctly and with a high level of precision, which transfers into improved weld quality, making them durable and more reliable. The welding times for the first and second welding pulses in lithium-ion cell welders should be selected according to the specific requirements of the cell. There are different methods for selecting these times, but the most commonly used are as follows:

– Experimental method which involves selecting welding times through trial and error. Experiments are conducted on different cells with different welding times, and the quality of the connections is evaluated to determine the optimal welding times [17];

– Theoretical method that involves mathematical modelling of the welding process and determining optimal welding times based on the model [18];

– Hybrid method that combines experimental and theoretical methods to select optimal welding times [19].

The main objective of the research is to investigate the optimal value of preheat pulse time in terms of the mechanical strength of the welds performed on the 18650 cell type using the experimental method.

The value of the welding current is a parameter that determines how much heat will be released during the formation of the joint. Too low of a welding current, even with an extended duration of the current pulse, makes it difficult to form a connection between the two materials. There is a phenomenon called “sticking the surface”. The strength of such a connection is so low that even a small force can cause a detachment of two elements.

The pressure force must be high enough to ensure precise contact of the electrode surface with the welded material [20]. It can be adjusted during the process itself. Because of this, the adjacency of the electrode and the welded material is improved.

The designed automatic battery cell welder used in this research allows for the adjustment of two heating times. However, it is possible to disable one of the current pulses. There are many welding machines on the market that allow this type of regulation. Welding with the so-called “heat treatment” (tempering temperature) or “final heating” (annealing) are those in which two or more current pulses of different duration are used [21]. This is done to improve the conditions for the formation of the weld and to improve its properties. However, the selection of the appropriate welding parameters must be made individually for a given material that is subjected to the welding process.

Moreover, resistance spot welding requires systematic control of the electrode shapes. During welder use, they are subject to natural wear. Melted micro-fragments of the electrodes remain on the contact surface of the welded material. Therefore, it is necessary to make some adjustments to the electrode surface setting or replace them. This process must take place at regular, scheduled intervals.

## IV. METHODOLOGY AND TEST BENCH DESCRIPTION

To investigate influence of welding parameters on weld mechanical strength, the automatic spot resistance welding machine was designed and constructed. Then several samples of welded joints were prepared using different time pulses set on the machine. Finally, the breaking force for each sample was measured with the self-designed and constructed strength testing machine. The results obtained were analysed and presented on characteristics to find the optimal time pulse values in terms of mechanical strength of the welds, which translates into the final mechanical durability of the assembled battery pack.

### *A. Automatic Battery Pack Spot Welding Machine*

The constructed device is used to weld battery cells of type 18650 and has the function of setting two welding time pulses. It is presented in Fig. 4.

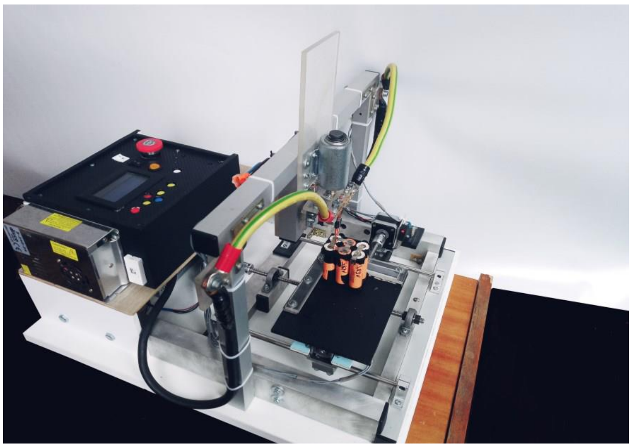

Fig. 4. Automatic spot welding machine for 18650 battery cell packaging.

Adjustments can be made directly from the control panel of the device. It is possible to set the duration of two current pulses, which is a common practise, or to turn off the second one completely. The pause time between two consecutive current pulses was programmed as a constant (equal to 100 ms) and cannot be changed from the control panel. The device has two working modes: automatic and semi-automatic. In the semi-automatic mode, it is possible to control the work table and set it in the right position in relation to the welding head. Once the electrodes are positioned, electrode pressure can be initiated, and then single or two current pulses can be triggered.

During the tests, it was noticed that the peak-to-peak current ($I_{pp}$) value can reach about 1820 A (Fig. 5) which gives about 643.5 A of the root mean square (RMS) value calculated using the standard formula for sinusoidal signals (2)

$$I_{RMS} = \frac{I_{max}}{\sqrt{2}}, \text{ where } I_{max} = \frac{I_{pp}}{2}. \quad (2)$$

Cell tests showed that when cells are welded, the specified heating time should not be exceeded. Excessive heating of the cell surface can cause damage (Fig. 6).

Moreover, when the time of a single pulse is greater than 120 ms, the cell temperature increases by approximately 5 °C, which also has a negative effect on the cell [22]. Therefore, for the double pulse welding mode, a safe cell welding time limit was adopted for the first heating pulse as $t_1$ = 80 ms.

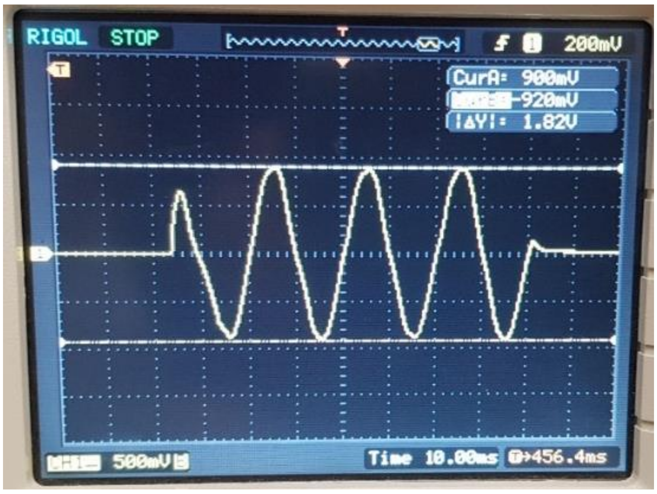


Fig. 5. Current pulse captured during the welding process (1 V~1000 A).

Fig. 6. 18650 cell type connector damage after welding with a single pulse of 130 ms and an RMS current of 643.5 A.

### *B. Breaking Force Measuring Device*

To determine the strength parameters of the welded joints, the measurements were carried out on samples prepared specially for this purpose. The breaking force measuring device used is presented in Fig. 7.

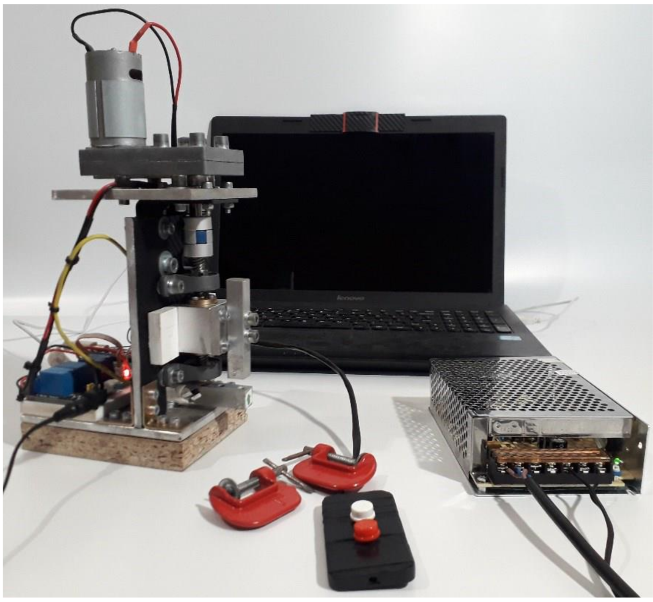

Fig. 7. Breaking force measuring device.

It consisted of a quasi-static breaking of welds made with an automatic battery cell welding machine. The measuring device recorded the force exerted on the joint during the breakage of the sample. Force measurement was carried out using a tensometric beam. It was connected to the HX711 measurement module and the Arduino Nano platform. Data registration was made using the Telemetry Viewer v0.7 software. It allows for a presentation of data from the COM port in the form of graphs and for exporting data to a CSV file. The force was created by a geared DC motor via a trapezoidal screw. The samples were attached to the device measuring beams with clamps.

### C. Samples Preparation

During the tests, the use of 18650 cells was abandoned due to the risk of damage to the cell housing during breakage. Instead, cells were replaced with plates made of the same material as the battery casings, i.e., steel plate of 0.2 mm of thick, covered with a nickel layer. They were cut to 45 mm in length and 8 mm in width. The second part of the sample was a 0.15 mm thick cell packaging tape cut to the same length. Before welding, both plates are profiled so that they can be adapted to the shape of the tensometric measuring beam and the element that exerts the breaking force. An example of the prepared samples is shown in Fig. 8. Before each welding attempt, the surface of both plates was checked for dirt and scratches.

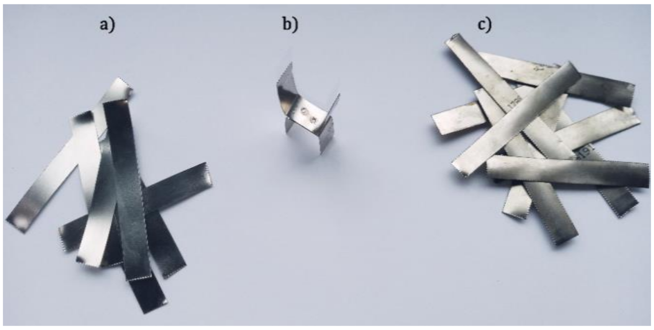


Fig. 8. Sample preparation: a) Plates 8 mm × 0.15 mm used for packaging cells; b) Prepared sample; c) Plates obtained from the 18650 cells used.

Table I presents the list of the time pulses set for each sample preparation. Each sample was made in three copies to verify the repeatability of the measurements and the elimination of faulty samples. For the time pulses below $t_1$ = 40 ms and $t_2$ = 20 ms, no proper welding process was performed. The surfaces were just stacked together because there was no proper melting of the materials.

TABLE I. WELDING TIMES OF TESTED SAMPLES.

| Sample number | Time pulse 1 [ms] | Time pulse 2 [ms] | Number of samples |
|---|---|---|---|
| 1 | 40 | 20 | 3 |
| 2 | 50 | 20 | 3 |
| 3 | 60 | 20 | 3 |
| 4 | 70 | 20 | 3 |
| 5 | 80 | 20 | 3 |
| 6 | 40 | 60 | 3 |
| 7 | 50 | 60 | 3 |
| 8 | 60 | 60 | 3 |
| 9 | 70 | 60 | 3 |
| 10 | 80 | 60 | 3 |

## V. TESTS RESULTS

Each sample was subjected to a breakage test. Three trials were performed for each set of time pulses. The highest recorded force value during breakage was taken into account. Based on these three values, the arithmetic mean and standard deviation were calculated according to (3)

$$\sigma = \sqrt{\frac{(x_1 - \bar{X})^2 + (x_2 - \bar{X})^2 + \ldots + (x_n - \bar{X})^2}{n-1}}, \tag{3}$$

where $\sigma$ is the standard deviation, $x_1$, $x_2$, $x_n$ are the values analysed, $n$ is the number of samples, and $\bar{X}$ is the arithmetic mean of the values.

Figures 9 and 10 present the increasing breaking force waveforms over time for three trials of exemplary samples no. 4 and no. 9, respectively.

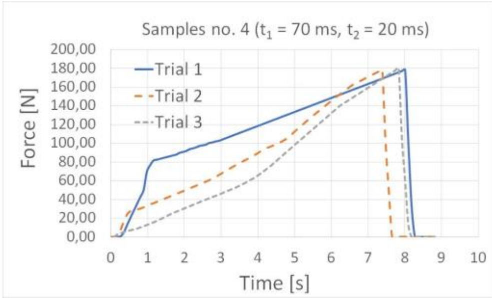


Fig. 9. Waveforms of breaking force for time pulses equal to $t_1$ = 70 ms and $t_2$ = 20 ms.

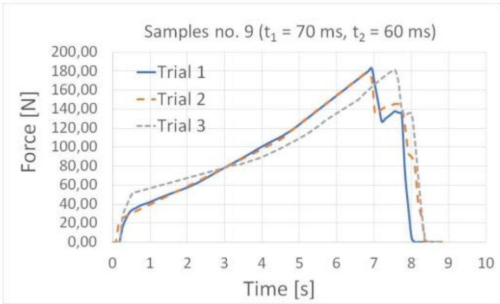


Fig. 10. Waveforms of breaking force for time pulses equal to $t_1$ = 70 ms, and $t_2$ = 60 ms.

During the measurements, one could notice that for the vast majority of trials, both welds were broken practically at the same time (Fig. 9). Sometimes, it was noticed that one of the welds breaks as first (Fig. 10 at a time of about 7 s). This was due to an uneven pressing force of both electrodes, which resulted in the weakening of one of the welds. It can also indicate the wear of one of the electrodes. After the electrodes have been adjusted, this issue disappears.

At a load of about 60 N, the engine speed drops slightly, which is reflected in the change in the inclination of the curves representing the increase in the breaking force. These different inclination values are not relevant to the research and are due to the lack of the DC motor speed controller.

The results of each individual trial for the two sets of samples tested corresponding to Fig. 9 and Fig. 10 are gathered in Tables II and III.

TABLE II. RESULTS OF BREAKAGE TEST FOR SAMPLES NO. 4.

| Breaking force [N] | | Mean value [N] | Standard deviation [N] |
|---|---|---|---|
| Trial 1 | 178.34 | 179.02 | 1.02 |
| Trial 2 | 178.53 | | |
| Trial 3 | 180.20 | | |

TABLE III. RESULTS OF BREAKAGE TEST FOR SAMPLES NO. 9.

| Breaking force [N] | | Mean value [N] | Standard deviation [N] |
|---|---|---|---|
| Trial 1 | 182.80 | 180.39 | 2.72 |
| Trial 2 | 177.44 | | |
| Trial 3 | 180.93 | | |

All the results of measurements performed are presented in Table IV where all the mean values of the breaking force are presented.

TABLE IV. BREAKING FORCE VALUES FOR DIFFERENT CURRENT PULSES.

| Sample number | Time pulse 1 [ms] | Time pulse 2 [ms] | Breaking force [N] |
|---|---|---|---|
| 1 | 40 | 20 | 66.62 |
| 2 | 50 | 20 | 106.72 |
| 3 | 60 | 20 | 151.02 |
| 4 | 70 | 20 | 179.02 |
| 5 | 80 | 20 | 186.59 |
| 6 | 40 | 60 | 67.29 |
| 7 | 50 | 60 | 118.57 |
| 8 | 60 | 60 | 165.56 |
| 9 | 70 | 60 | 180.39 |
| 10 | 80 | 60 | 194.56 |

Analysing the results from Table IV one can notice that the preheating time $t_1$ has an important influence on the strength of the welds. With the increase in the pulse value of the first heating time $t_1$, a significant increase in the breaking force value was observed. Then, this trend is stabilising, which is shown in Fig. 11 and Fig. 12.

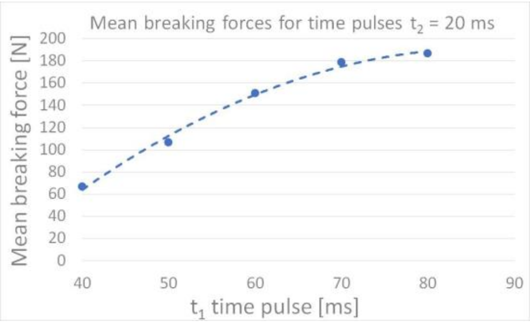


Fig. 11. Mean breaking force values for the second time pulse $t_2$ = 20 ms.

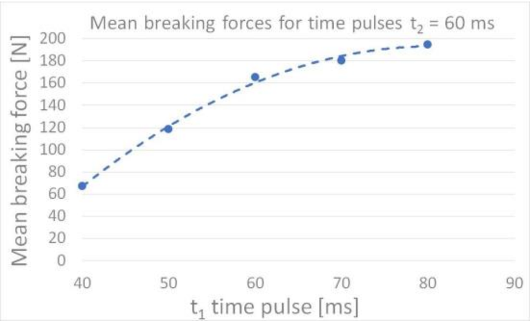


Fig. 12. Mean breaking force values for the second time pulse $t_2$ = 60 ms.

The second weld pulse responsible for the creation of the actual weld does not improve the overall mechanical strength significantly. Increasing the pulse time value $t_2$ from 20 ms to 60 ms increases the mean value of the breaking force by only 0.67 N to 14.54 N depending on the first time pulse value. Higher time values of the current pulses resulted in burnouts and cell connector damages; therefore, they were not included in the analysis.

## VI. CONCLUSIONS

In the article, the influence of the time parameters of an automatic spot welding machine on the mechanical strength of the welds was investigated. The samples in the form of two stripes made of two materials used for respectively 18650 cell type connectors and cells packaging type were welded using two current pulse modes. The results showed that the preheat pulse time value has a crucial influence on the weld strength.

The second important condition is the electrode pressure. During sample production, some visible surface defects were observed in the form of burns and uneven weld shapes. This was mainly due to the lack of proper pressure between the strips during welding. It is important to carefully place the packaging tape on the surface of the cells, as it is easily subjected to deformation. Therefore, one of the disadvantages of the proposed method is the need for sample preparation for the breaking force measuring device. In fact, these samples can be of better quality than the welds made during the regular battery pack production process.

The maximum breaking force obtained during the tests without cell damage was equal to 194.56 N for the current pulses $t_1$ = 80 ms and $t_2$ = 60 ms. This weld has sufficient mechanical strength for battery pack construction purposes. In some rare cases, one needs to replace only one cell from the battery pack. If such a situation occurs, it is possible to disassemble the battery pack as the packaging tape is less resistant than the cell connector. Moreover, after the cell connectors are cleaned, such a cell can be welded again. However, depending on the weld strength, it may be necessary to replace the used packaging tape used.

From the economical point of view, such a machine can bring some relevant savings, taking into account that the cost of self-constructed spot welding machine parts oscillates around 300 €, while the 48 V, 20 Ah battery pack for an e-bike on the market can cost about 400 €, where about 50 %–60 % is the cost of the cells.

## ACKNOWLEDGMENT

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## CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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