Development of an experimental program for optimizing of process parameters used in high frequency welding of PVC coated PE fabrics

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1. Introduction

Coated fabrics have a very wide range of applications. They can be stretched in multi-directions and their tensile and tearing properties are very important features required by their end-use applications, such as roofing membranes, geo-membranes, airships, inflatable boats, rescue tents and, as the present case, truck covers and publicity banners [1-4].

A coated structural membrane usually consists of a woven base fabric stabilized and protected by a coating on both sides. The base fabric consists of warp threads running the length of the roll and weft threads, running across the width. A mesh fabric is a coated fabric with spacing between the thread bundles [5].

The joining of coated fabrics by welding is a hot-melt process. The welded joint has to exhibit higher tensile resistance than the base material, both in warp and weft directions. A common process is ultrasonic welding, where localized heat is produced by mechanical energy. The other methods are high-frequency (HF) and radio-frequency (RF) welding. The heat is produced in these methods by vibrating of molecules of the substrate in an applied alternating electrostatic field [6-8].

However, the scientific information regarding the mechanical properties of these materials is relatively scattered, partially due to the high variety of application-oriented materials. Recent studies show that there is an ongoing research effort with regard to simulating coated fabrics and their joints [1,9-11].

This paper presents the development of an experimental program with the goal to optimize the HF welding process parameters currently used in the production of truck covers and tents manufactured from the PVC coated PE fabric membrane material denominated Panama 900. A factorial experiment was designed and carried out in this purpose and an optimal configuration was obtained based on the estimated response surfaces of the created multi-factorial matrix.

2. Experimental plan, equipment and materials

The overall scope of the experimental plan was to create several HF welds from a PVC coated PE fabric currently used to manufacture covers in transportation, such as truck tarps, railway carriage covers, banners, etc. The experimental program was carried out according to the steps below:

- Programming the experimental HF welding conditions using the factorial experiment method [12] (Table 2.1 and Figure 2.1);
- Realization of the HF welds according to the proposed experimental conditions, along with thermographic monitoring of the temperature distribution in the welding zone;
- Sampling of test pieces (5 pieces from each welded strip, according to the relevant standard for tensile testing);
- Tensile testing of the specimens, according to SR EN ISO 1421:2002;
- Processing of the experimental results using the specialized software STATGRAPHICS Plus, in order to obtain the optimal welding conditions based on the analyzed parameters;
- Identification of the optimal welding parameters based on the factorial experiment parameters and comparison with the parameters currently used by the industry.

The experimental plan was established using the factorial design, implying 2^3 experimental conditions (3 parameters with 2 different levels). The goal was to obtain 8 different experimental conditions, plus one central condition, with regard

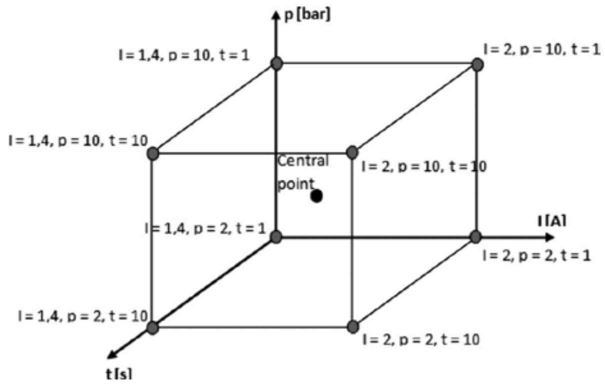

Figure 2.1. Representation of the planned factorial experiments.

to the HF welding of PVC coated PE fabrics. As mentioned above, the three HF process parameters that were varied across 2 levels (min-max) are the following: current intensity I (A), holding pressure p (bar) and welding time t (s). There was a fourth parameter that could be varied on the programmable welding equipment, i.e. the holding time [s], but this value was kept constant at 10 s in order to simplify the experiments.

A suggestive 3D representation of the programmed factorial experimental conditions is presented in Figure 2.1. The planned test conditions were numbered, as it is shown in Table 2.1. Note that the 9th and 10th variants have identical parameter values in order to ensure a greater statistical stability of the results for the central point.

Table 2.1. Parameter values for the 9 different experiment conditions.

Test condition	Current intensity I [A]	Holding pressure p [bar]	Welding time t [s]	Comment
1	1.4	2	1	-
2	2	2	1	-
3	1.4	2	10	-
4	2	2	10	-
5	1.4	10	1	-
6	2	10	1	-
7	1.4	10	10	-
8	2	10	10	-
9	1.7	6	5.5	Central point
10	1.7	6	5.5	Central point

The welds were executed using a specialized HF welding equipment manufactured by FIAB Poland, of type CIF 3 FIAB HF, as shown in Figure 2.2, located at the headquarters of the company SC SATIMPEX SRL, Timisoara. The welding equipment was programmed prior to each welding operation to respect the process parameters from 1 to 9, as specified in Table 2.1.

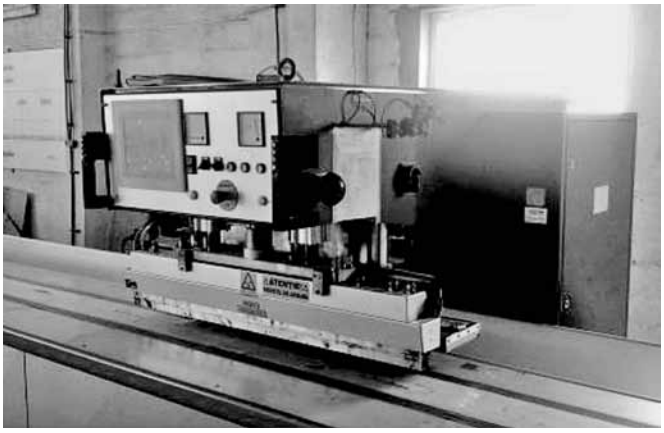

Figure 2.2. Equipment for high frequency welding of polymeric membranes, type CIF 3 FIAB HF.

All the executed HF welds were monitored using a thermographic camera type FLIR A40, in order to correlate the temperature distribution in the welding zone with the experimental conditions [13]. The camera's field of view was set to cover the HF welding electrode, the material strip and the upper part of the support plate, thus monitoring the boundary line between the welding electrode and the material. The camera and the data acquisition system are presented in Figure 2.3.

The tensile testing of the specimens was carried out in the laboratories of ISIM Timisoara, using a state-of-the-art tensile testing machine of type Zwick/Roell Z005 with a capacity of 5 kN and pneumatic flat grips (Figure 2.4).

The material used in the experimental program is a PVC coated PE fabric currently used to manufacture covers in transportation, such as truck tarps and also publicity banners. The material is denominated Panama 900 and it has a specific weight of 900 g/m^2.

Figure 2.3. Thermographic camera FLIR A40 and data acquisition system.

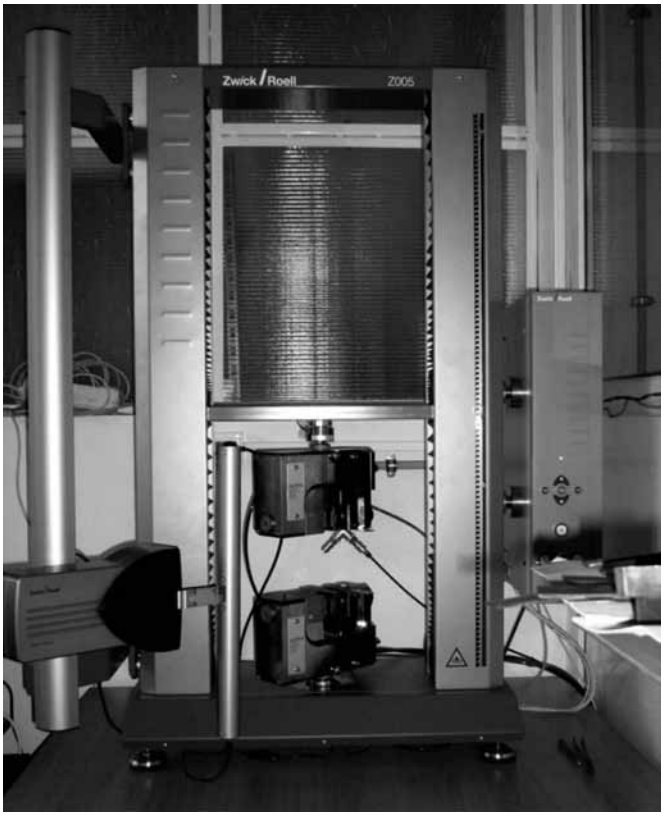

Figure 2.4. Tensile testing machine Zwick/Roell Z005, capacity 5 kN.

The strip-type specimens were prepared according to the tensile testing standard SR EN ISO 1421:2002, being 50 mm in width and 200 mm in length. The specimens were sampled along the transversal direction of the fabric and perpendicular to the welding direction. The width of the welding overlap was approximately 40 mm (Figure 2.5). All welds were carried out by specialized personnel of SC SATIMPEX SRL Timisoara.

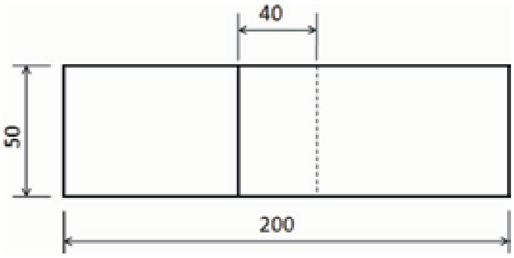

Figure 2.5. Dimensions of the welded tensile specimens.

3. Results and discussion

The resulting characteristic curves from the tensile tests are presented in Figure 3.1. For each set of 5 specimens per test condition, the average value of the maximum tensile force was calculated. The resulting values are presented in Table 3.1, in correlation with the experimental conditions.

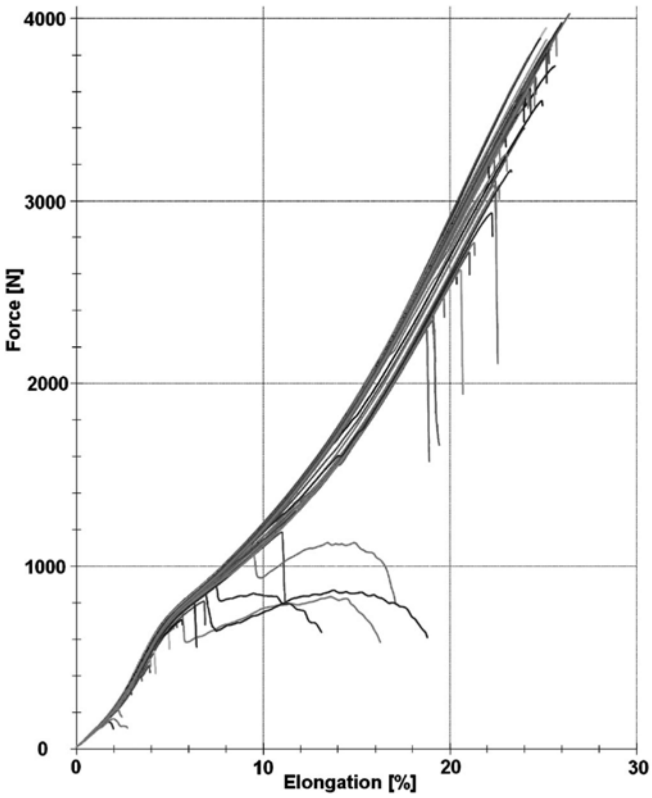

Figure 3.1. Characteristic curves resulting from the tensile testing of all 50 specimens.

The values in Table 3.1 show that the lowest tensile force values were produced by the test conditions with the lowest welding time (test conditions 1, 2, 5 and 6). The highest tensile force was recorded in case of test condition 7.

During optical assessment of the tested specimens three different types of rupture were identified, as follows:

- Complete peeling of the joint (Figure 3.2);
- Partial peeling of the joint associated with rupture of the material in the welded region (Figure 3.3);
- Rupture in base material, outside of the welded region (Figure 3.4).

The welding process was monitored in case of all 10 welding conditions using the thermographic camera presented in the previous chapter. Figure 3.5 presents the thermographic image captured at the moment when the highest temperature was reached, as well as the variation of the temperature along the welding electrode's length, in case of welding condition 10. The registered maximum temperature was correlated with the welding conditions, as given in Table 3.2.

Table 3.1. Average values of the maximum tensile force, according to the HF weld conditions.

HF weld condition	Current intensity [A]	Holding pressure [bar]	Welding time [s]	Maximum tensile force [N]
1	1.4	2	1	973.06
2	2	2	1	2558.04
3	1.4	2	10	3732.52
4	2	2	10	3742.56
5	1.4	10	1	319.48
6	2	10	1	3132.24
7	1.4	10	10	3812.40
8	2	10	10	3478.06
9	1.7	6	5.5	3312.46
10	1.7	6	5.5	3459.50

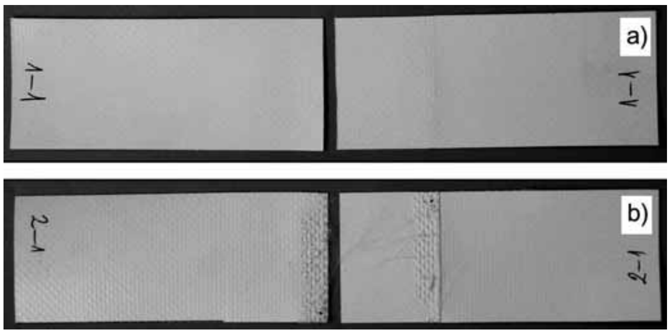

Figure. 3.2. Complete peeling of the joint as result of tensile testing (welding condition 1 (a), respectively 2 (b)).

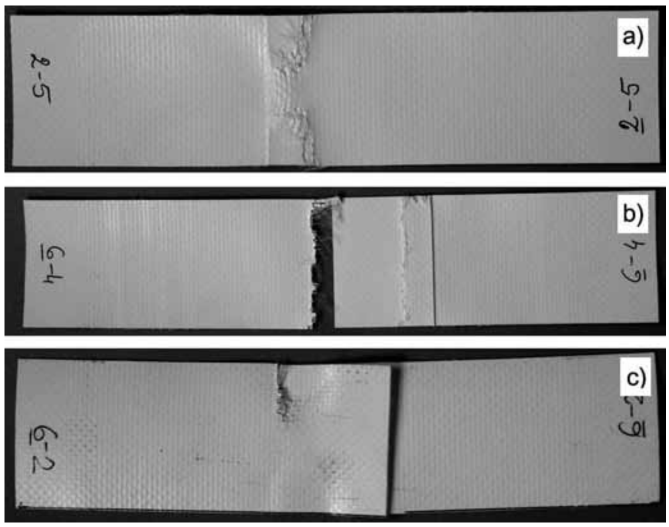

Figure. 3.3. Partial peeling of the joint associated with rupture of the material in the welded region, as result of tensile testing (welding condition 2 (a), respectively 6 (b) & (c)).

It can be seen from Table 3.2 that the welded joint was peeled partially or completely in case of the test conditions with the short welding time (test conditions 1, 2, 5 and 6). These welding conditions produced welded zones with unevenly distributed temperature and due to the short time (1 s), the joint was effectively welded only on certain portions.

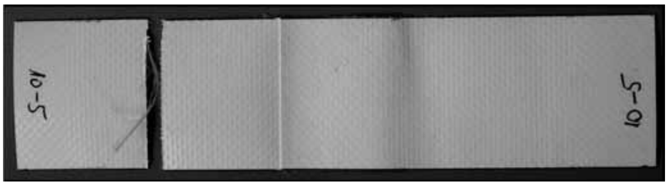

Figure. 3.4. Rupture in base material, outside of the welded region, as result of tensile testing (welding condition 10).

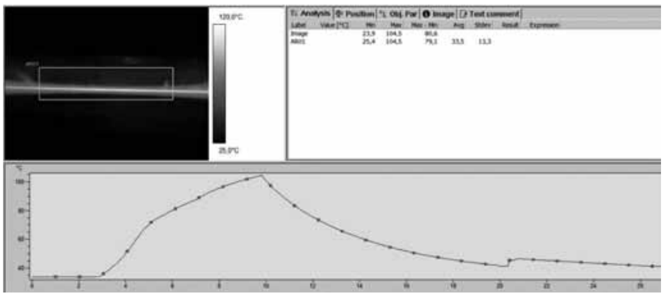

Figure 3.5. Thermographic capture of the temperature distribution during HF welding, using the parameters of test condition 10.

The obtained experimental data was processed using a dedicated software, with the goal to optimize the three analyzed parameters in order to obtain the highest tensile force. Thus, the factorial experiment had three influence factors (i.e. current intensity, holding pressure and welding time) and one objective function (i.e. tensile force).

The influence factors and their interactions are presented in Figure 3.6.

It can be seen from Figure 3.6 that the welding time is the most important influence factor from a statistical point of view in the analyzed multi-factorial space. This factor influences positively (ascending) the objective function. The interactions between the influence factors are relatively small, while the other two influence factors have a relatively reduced importance.

The chart of the main effects of the influence factors is given in Figure 3.7 and it shows how each of the factors influences the objective function between the limit values. Furthermore, the estimated response surfaces for the considered objective function are presented in Figures 3.8÷3.10.

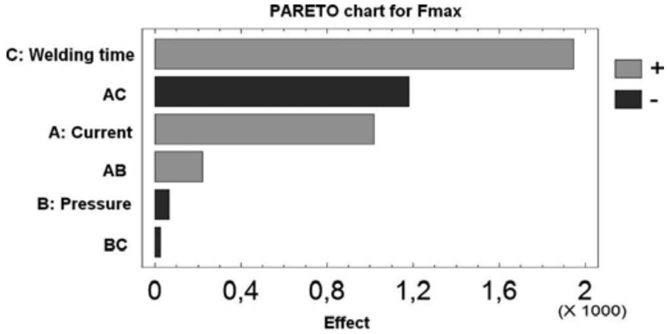

Figure 3.6. Effects of the influence factors and their interactions.

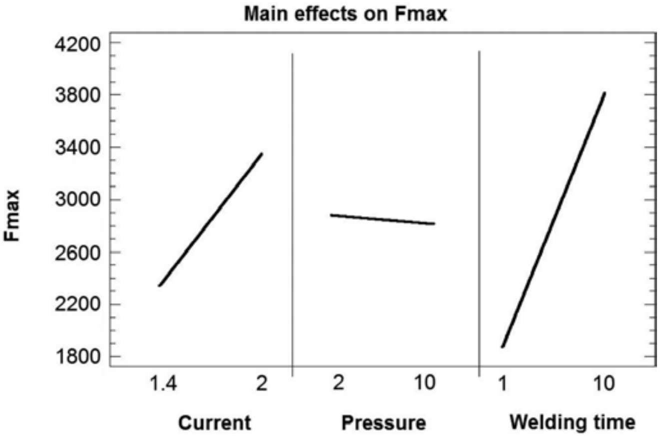

Figure 3.7. Chart of main effects of the influence factors on the objective function.

The complete equation of the objective function, also accounting for the effects of the interactions between the influence factors, is given below:

$$F_{\max} = -4346.61 + 3549.98 \cdot I - 160.651 \cdot p + 963.869 \cdot t + \\ + 92.0146 \cdot I \cdot p - 437.231 \cdot I \cdot t - 0.73125 \cdot p \cdot t \quad (1)$$

where F_{max} is the maximum tensile force (the objective function), I is the current intensity, p is the holding pressure and t is the welding time.

Table 3.2. Correlation of the registered maximum temperature with the welding conditions and the type of rupture.

HF welding condition	Process parameters			Maximum temperature	Rupture type
	Current intensity [A]	Holding pressure [bar]	Welding time [s]	[°C]	
1	1.4	2	1	50.3	Complete peeling of joint
2	2	2	1	58.3	Partial peeling of the joint associated with rupture of the material in the welded region
3	1.4	2	10	75.9	Rupture in base material
4	2	2	10	70.0	Rupture in base material
5	1.4	10	1	55.0	Complete peeling of joint
6	2	10	1	67.5	Partial peeling of the joint associated with rupture of the material in the welded region
7	1.4	10	10	75.1	Rupture in base material
8	2	10	10	82.2	Rupture in base material
9	1.7	6	5.5	75.6	Rupture in base material
10	1.7	6	5.5	104.5	Rupture in base material

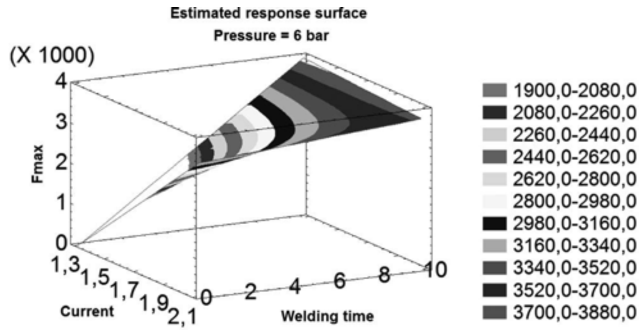

Figure 3.8. Estimated response surface of the objective function, at a holding pressure value of 6 bar.

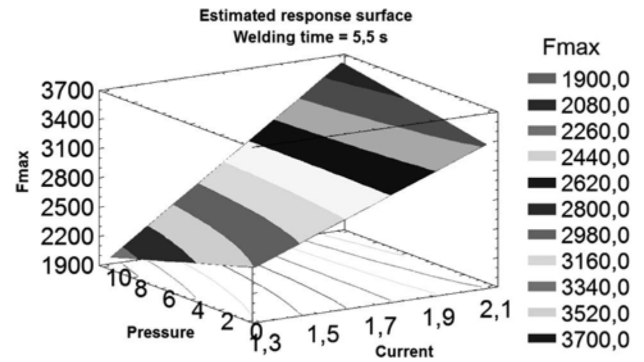

Figure 3.9. Estimated response surface of the objective function, at a welding time of 5.5 s.

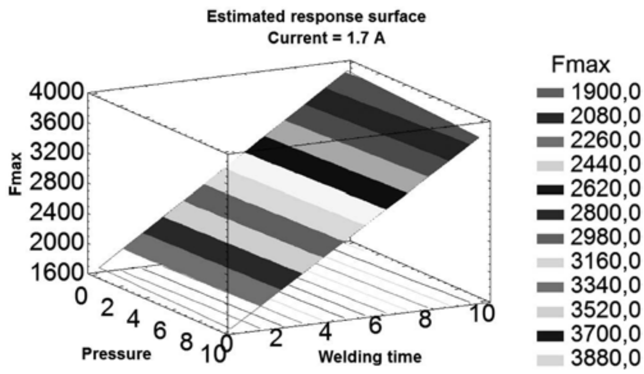

Figure 3.10. Estimated response surface of the objective function, at a current intensity of 1.7 A.

Due to the relatively low effect of the interactions between the influence factors, the equation of the objective function can be written in a reduced form, which describes 95% of the analyzed values, as follows:

$$F_{\max} = -1172.92 + 1697.29 \cdot I - 8.24812 \cdot p + 216.188 \cdot t \qquad (2)$$

Based on the calculations, the maximum attainable tensile force will be F_{max} = 4062.52 N, and it can be reached using the following HF process parameters: I = 1.4 A, p = 2.0 bar, t = 10.0 s. These are the experimentally determined optimal HF welding parameters.

Table 3.3 gives an overview of the experimentally determined optimal welding parameters, in correlation with the maximum obtainable tensile force and the parameters currently used in the welding process.

Analyzing the values from Table 3.3, it can be seen that the maximum force determined by the factorial experiment is well above the value guaranteed by the material's manufacturer, i.e. 3800 N [14]. As for the conditions used by the industry, the obtained maximum tensile force is lower than the value given by the manufacturer.

When considering the process parameter values, the current intensity in case of the experimentally determined optimal condition is somewhat lower than the current value used in production, while the holding pressure's value is significantly lower. The welding time however is almost double in case of the determined optimal condition relative to the welding time used in production. Taking into account the almost negligible effect of the holding pressure on the tensile force and the relatively reduced effect of the current, it can be stated that these two parameters can remain the same, since the estimated obtainable force is higher than the necessary value. On the other hand, the difference in welding time of the experimentally determined optimum and the value used in production cannot be neglected. This observation would lead to the conclusion of this study that the welding time should be modified to 10 s in the industrial practice. However, it is very important to notice that even though the obtained tensile force in case of test conditions 9 and 10 (which are identical with the welding conditions currently used in the industry) is lower than both the experimentally obtained optimum and the value given by the manufacturer, the rupture in all these cases occurred in the base material while the welded joint remained intact. This suggests that the obtained tensile force was the result of the material's quality and not the experimental process parameters.

4. Conclusions

This paper presents an experimental program created to optimize the HF welding parameters of PVC coated fabrics used in the manufacturing of transportation covers. The experimental program was planned using the factorial experiment method, resulting in a 2^3 matrix, where the influence factors were the current intensity, holding pressure and welding time, while the objective function was the maximum tensile force.

It has been found that the multi-factorial space created through the factorial experiment described sufficiently the parameters' effects on the result of the analyzed process. It has been highlighted that out of the three analyzed parameters the welding time had the most significant effect on the objective function, while the holding pressure's effect was negligible.

Table 3.3. Overview of the optimal HF welding parameters and the currently used one by the industry.

No.	Description of HF welding condition	Maximum tensile force [N]	Process parameters		
			Current intensity [A]	Holding pressure [bar]	Welding time [s]
1	Optimal conditions (experimentally determined)	4062.52	1.4	2	10
2	Conditions currently used by the industry (identical with the factorial experiment's central point)	3312.46*	1.7	6	5.5
		3459.50*			

*the tensile resistance of the material for transversal samples is 3800 N, given by the manufacturer [14]

It has been found that the welding conditions with the lowest welding time (1 s) produced non-uniform joints and these got peeled totally of partially as results of the tensile tests. These findings are consistent with the thermographically registered temperature variation in the welding zone. The temperature was considerably lower in case of the 1 s welding time experiments when compared to the other parameter sets.

The process parameters were optimized in order to obtain the highest tensile force and the results showed that the determined optimal welding parameters would produce forces at break higher than the prescribed value. Also, the welds created using identical parameters with the currently used industrial practice remained intact during tensile testing, rupture being always observed in the base material. Finally, it has been found that the currently used HF welding parameters are appropriate for the given application and do not need to be modified.

Acknowledgements

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