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Influence of the Welding Process on the Quality of PVC Frames

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This paper focuses on the technical and practical aspects arising during the process of window production. One of the phases in the window manufacturing process is welding PVC corners. Therefore, the main subject is the flexural strength of PVC welds in the context of the required quality. In the first part of the paper, the authors highlighted the factors and conditions of the welding process and their influence on the final properties. In the next part of the study, attention is mainly paid to temperature control, which is often the cause of quality problems with welding corners. The welding process was conducted with the use of three types of welding machines, i.e. single-, double- and four-head units. In each case, the welding temperature was set in the controller of the machine; at the same time, the contact temperature measurement was taken. The next step was verification of the influence of temperature on the welded PVC corners by measuring the bending force according to PN-EN 514:2002. Additionally, the authors present the DIC (Digital Image Correlation) method used to assess displacements and strains for a selected case in the process of bending PVC corners. The study provides a basis for discussion and remarks about practical advice and identification problems associated with the durability of PVC welding in industrial processes.

Keywords: welding, temperature, PVC, bending, strength

1 Introduction

The joining of construction materials is an important operation within the product manufacturing process. This is determined by the increase in the use of plastics which has been observed in recent years. As a result, there is a demand for reliable and effective joining technologies for such materials in order to ensure a high quality of the joints. Depending on the method of heat supply, there are several welding methods [1,2,3], such as, heating the inside of the surfaces to be joined (heating element in the form of a wedge, rod or plate); heating the surfaces to be joined on the outside (contact welding, impulse welding) and also generating heat inside the elements to be joined (ultrasound, high-frequency current). For each of the above-mentioned methods, key factors influencing the final strength of the joint can be identified, which are related to the optimization of the process [4,5,6].

A particularly important issue for a company is the proper quality of the products manufactured and offered to customers at an acceptable price [7,8]. In the case of window production, what is important is the reliability of the components that are used in the final assembly. During the manufacturing of windows the most common process of joining PVC profiles is the hot-plate welding method. It does not require the use of any additional materials. This method can be successfully used for polyethylene, hard and soft PVC, ABS copolymers, polyamides (PA6), PMMA, and also polycarbonate [1,9,10,11]. Hot-plate welding involves plasticizing the surfaces of the parts to be welded by means of a hot plate inserted between the surfaces to be joined; the schematic diagram is shown in Fig. 1. Then, the hot plate is removed, and the parts being welded are pressed together. In this way, it is possible to join not only window profiles but also pipes, structural sections, bars or other shapes. The heating element can take various shapes depending on the geometry of the elements to be joined, e.g. it can be a ring-shaped plate for pipes [12,13]. In order to prevent the plasticized material from sticking, the heating surface is covered with an anti-adhesive material, e.g. PTFE-impregnated fabric. Welding machines are equipped with: thermostats which make it possible to maintain the set temperature at a specified level; devices for extending and removing the heating plate; and clamping devices that generate the right fusion pressure between the parts being welded, which produces a permanent joint. This affects the final effect at the joint and ensures high quality as well as the durability of the joint [1]. These are important technical issues determining the correctness of the joint not only in the case of PVC windows [14,15]. The basic control of durability of PVC corner welds is performed by checking the fracture strength of the corner. Other additional methods of checking welding quality that can be used are tools that enable inspection of the components [11,16,17,18], including the analysis of displacements and deformation maps of the item being tested [19,20,21].

Therefore, the main aim of the study was to verify the correctness of the welding process and the impact of temperature on the critical flexural strength for welding PVC frames. The secondary aim was to apply the DIC method to assess and verify the process of defect formation in PVC frames subjected to bending. On this basis, the strength of the welded frames will be determined depending on the actual welding temperature. This will allow conclusions and recommendations to be made regarding the effectiveness of the welding process and the quality of the welded window frames.

2 Factors determining the quality of the welding process

Corner joints in PVC window frames are made by the hot-plate welding method. In this method, a heating element heated to the right temperature is inserted between the elements being joined. This way the heat is evenly distributed over the surfaces to be joined [22]. As a result of this procedure, the material achieves a plastic state. Then, by quickly pressing the heated materials together, the process of joining the two parts takes place. At the end of the process, a finished permanent joint is obtained in the form of a weld. In this connection, several factors can be distinguished, which are the technological parameters of welding that determine the final quality of the welded PVC components. The first of them is the temperature (T_w), which should not exceed 250°C [23]. It is important to maintain the right temperature of the heating elements throughout the welding process [22]. The second factor is the pressure at which the components are pressed together during the heating (p_1) and at the moment of welding (p_2). The third factor is the pressing time. It is important at the moment of heating the profiles by the heating element (t_1) as well as at the final welding (t_2) of the components being joined.

These factors have a direct impact on the quality of the welds. This translates into the strength of the joint, which is important in ensuring the required minimum flexural strength ($F_{B\ req.}$). Therefore, in order to fully and effectively control the welding process, these factors must be responsibly managed. Hence, the destructive bending force FB can be made dependent on five basic factors described by equation *(1)*:

$$F_B = f(T_w, p_1, p_2, t_1, t_2) \tag{1}$$

Other factors that may affect the quality of a hot-plate welded joint include thermal expansion of the material and conditioning of the material. Conditioning of the material means that the material was left at ambient temperature for 24 hours before commencing the welding process. Another factor indirectly related to the maximum value of the bending force is the humidity of the air, as well as the aging of the material under the influence of solar radiation (UV). This is directly related to the use of plastic welded parts over the years. Other possible causes of irregularities include human error, machine failure or inadequate material quality.

In summary, the factors mentioned above can to a greater or lesser extent influence the durability of a welded joint. Consequently, this translates into the quality of the windows. This paper addresses the subject of the strength of window frames depending on the welding temperature (T_w). Therefore, the remaining factors from equation *(1)* have constant and unchanging values, and their specific values are described in section 3.4.

3 PVC frames – the welding process

This chapter presents a detailed description of the welding process. The components of the sections are PVC window profiles, welding machines and independent temperature measurements.

3.1 The PVC welding material

The material used for the welding and bending tests was GEALAN 6077 PVC frame profiles with the same serial number. The technical data of GEALAN 6077 PVC test material are given in Tab. 1. The values in the table refer to overall dimensions (*e, d*), cross-sectional area (*A*), length of the outside (L_{out}) and inside (L_{in}) arms of samples required for the bending tests, the moment of inertia (J_y), recommended welding temperature (T_{wr}) and minimal required bending force ($F_{B\ req.}$) for this type of welded profiles. The cross-section of the GEALAN 6077 profile is presented in Fig. 2.

Tab. 1 *Technical data of GEALAN 6077 PVC profile [24,25]*

e	d	A	L_{out}	L_{in}	J_y	T_{wr}	$F_{B\ req.}$
[mm]	[mm]	[mm²]	[mm]	[mm]	[cm⁴]	[°C]	[N]
71	82.5	1014	337	197	34.37	245	2649

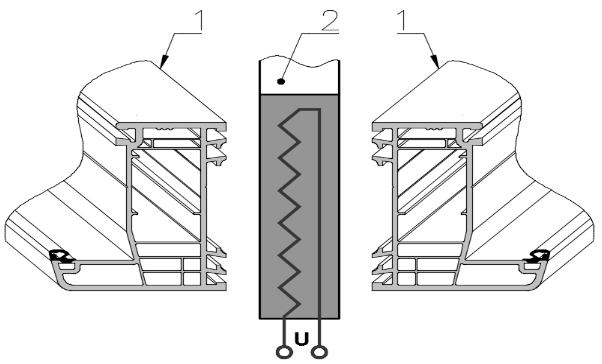


Fig. 1 *General scheme of the steel hot-plate welding position; 1 – parts being joined, 2 – heating element (hot plate)*

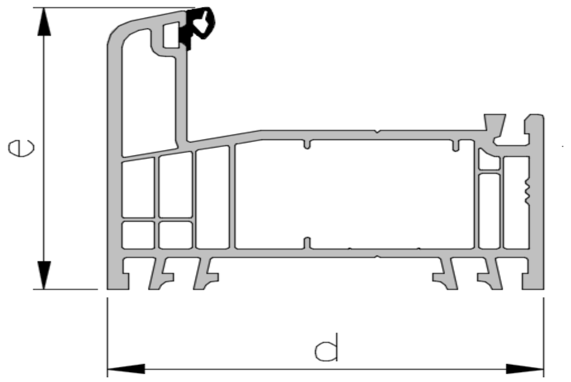


Fig. 2 *Cross-section of the GEALAN 6077 PVC frame profile (grey – PVC wall; black – rubber seal) [24,25]*

3.2 The welding machines

Three types of welding machines were used in the process of PVC welding. These included a single-head (SH) welding machine, a double-head (DH) welding machine and a four-head (QH) welding machine. Each of them is at a different level of automation, but the welding principle is the same. The higher level of automation and more heads make it possible to shorten the time of welding operations from four steps to one step.

The single-head (SH) station is the least advanced machine, and only one PVC corner can be welded during one machine operation cycle. To manufacture a complete frame, four such steps are needed. The double-head (DH) station is more automated with the adjustable distance between the heads. This means that it can be adjusted to the required dimension between two corners of the PVC frame. The process of fabrication of one complete window frame is possible in two steps. The four-head (QH) station is a modern and fully automatic welding machine with adjustable guides. With this feature it is possible to speed up the process of window frame welding by four times. The main advantage is that the entire frame is made in one operation.

The operation principle of this type of welding is described in the introduction. The illustrations of the welding machines are presented in Fig. 3.

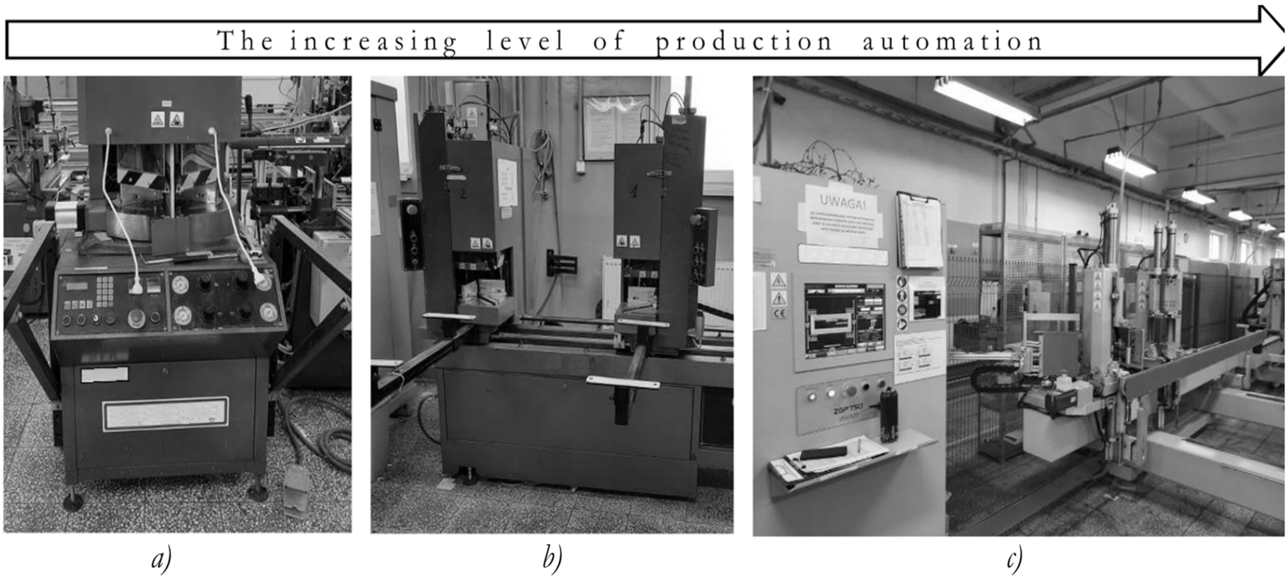


Fig. 3 *The welding machines with three different head configurations: a) single head (SH); b) double heads (DH); c) four heads (QH)*

3.3 Independent temperature measurement

A GTH 1200 digital thermometer from Greisinger Electronic was used to check the actual temperature on the steel surface of the hot plates. This device is a contact temperature measuring tool with a probe. The measurement was made using the second range of the measuring system, i.e. from -65°C to 1150°C. The resolution of the measurement was 1°C. The specification of parameters and data are given in the Tab. 2.

Tab. 2 *Specifications of the GHT 1200 Digital Thermometer [26]*

Range	range 1: -65.0 to +199.9°C	**Resolution**	range 1: 0.1°C from -65.0 to +199.9°C
	range 2: -65 to +1150°C		range 2: 1°C from -65 to +1150°C
Accuracy	better than 0.2 % ±0.5°C respectively ±1 digit	**Analog output (GTH 1200A)**	1mV/°C
Probe connection:	standard flat mono plug	**Probe**	NiCr-Ni, acc. to ½ DIN 43710 for plug-in operation
Working temperature:	0 to 45°C	**Nominal temperature:**	25°C
Power supply:	9V battery, type IEC 6 F 22	**Battery service life:**	approx. 100 operating hours
Low battery warning:	'BAT'		
Electromagnetic compatibility:	In accordance with EN50081-1 and EN50082-2 for unrestricted use in housing and industrial areas. Additional error: <0.5%		

3.4 The results of temperature measurements

The welding machines were prepared for the tests through the set a value temperature (programmer) to 245°C. During the PVC frame corners welding process the temperature of the hot plate was measured. The measure was conducted on the steel hot plates. In the welding process the time of heating PVC profiles to weld by steel heating-plates (t_1) was 35 seconds with pressure (p_1) equal to 6 bars. During the welding process the corner press time (t_2) was 37 seconds with the pressure (p_2) equal to 8 bar. The measurement results are presented in the Tab. 3.

Tab. 3 *The temperature measure of welding machines steel hot-plates*

No.	Type of welding machine	No. of heads	Set temperature (control unit)	Head no.	Temperature reading (GTH 1200 Greisinger Electronic)
[-]	[-]	[-]	[°C]	[-]	[°C]
1	single-head (SH)	1	245	1	264
2	double-head (DH)	2	245	1	250
				2	252
3	four-head (QH)	4	245	1	245
				2	244
				3	246
				4	245

4 Bending tests

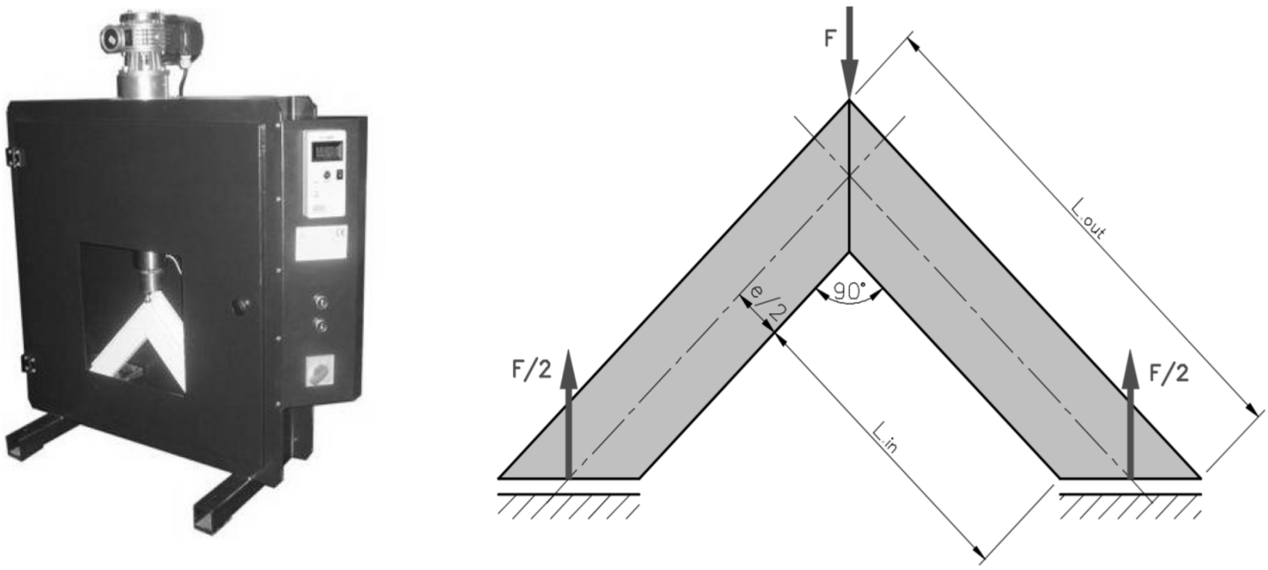
This chapter describes the testing machine used to conduct the strength tests, as well as the results of the experimental destructive tests. The detailed procedure and conditions for determining the strength of welded PVC window and door corners are contained in PN-EN 514:2018-02 [27]. The dimensions of the PVC profiles used for welding corners and the required minimal bending force are described individually by the supplier.

4.1 Delta LN-2000

The Delta LN-2000 machine is intended to inspect the strength of welded window and door corners made from PVC profiles in accordance with PN-EN 514:2018-02 [27]. Constant punch feed speed for corner breaking is possible through the use of a worm gear and a trapezoidal screw (as recommended by PN-EN 514:2018-02 [27]). This type of testing machine has an electronic force sensor (F_B measurement) with maximum value memory. It allows to check and control the strength of welds. Additionally, it is a very useful tool for immediate verification of the value of the strength of PVC corners after the regulated parameters of the welding machine. The stand does not have any traceability system for piston displacement. The machine has a calibration certificate issued by the Polish Central Office of Measures. The specification of the Delta LN-2000 stand is presented in Tab. 4. The illustration of the test stand is presented in Fig. 4a and the scheme with force reactions is presented in Fig. 4b.

Tab. 4 *Specifications of the Delta LN-2000 stand [28]*

Power supply	Three-Phase Voltage 400V	**Electric Motor Power**	150W
Breaking punch feed speed	50 mm/min (PN-EN 514:2018-02)	**Max. bending force**	20kN (~2000kG) (PN-EN 514:2018-02)
Accuracy of measurement	± 3 % (PN-EN 514:2018-02)	**Weight**	~80kg
Overall dimensions (height x width x depth)		1075 x 972 x 500	



a) b)

Fig. 4 *Illustrations of: a) Delta LN-2000 testing machine [28]; b) scheme of the test position for bending tests*

4.2 The results of PVC frame bending tests

The bending tests were carried out at a constant ambient temperature of 23°C. Before the tests, the samples were conditioned at a constant ambient temperature of 23°C. For the test to be performed, PVC corners must not be milled in the place of weld, and a minimum of three repeats should be performed. The required minimum value of bending force ($F_{B\ req.}$) according to GEALAN catalog is 2649 N (Tab. 1). This is the minimum force for which no cracks or defects occur. The results of bending GEALAN 6077 PVC frames at three different temperatures are presented in Tab. 5.

Selected defects and fractures are presented in Fig. 5.

Tab. 5 *Bending force for GEALAN 6077 welded at various temperatures*

Input data and settings			**The experimental test results and visual assessment**		
Welding machine	**Head No.**	**Actual welding temperature (T_w)**	**Destructive bending force (F_B)**	**Visual inspection of the crack (1-5)* In/Out**	**Visual assessment of the profile colour at the weld****
[-]	**[-]**	**[°C]**	**[N]**	**[-]**	**[-]**
single-head (SH)	1	264	3070	5/5	1
	1	264	3050	5/5	1
	1	264	2980	5/5	1
	1	264	2870	5/5	1
double-head (DH)	1	250	3830	3/1	1
	2	252	3690	4/5	1
	1	250	3660	3/2	1
	2	252	3720	3/3	1
four-head (QH)	1	245	4000	4/5	1
	2	244	3820	3/3	1
	3	246	3770	4/4	2
	4	245	4150	5/4	1

**** Visual assessment of the crack (5 - crack along the weld, 4-2 – divided into (place of the crack), 1 – crack beside the weld)***

***** Visual assessment of the profile color at the weld (3 – yellow or brown discoloration, 2 - trace amounts of discoloration, 1 - no discoloration)***

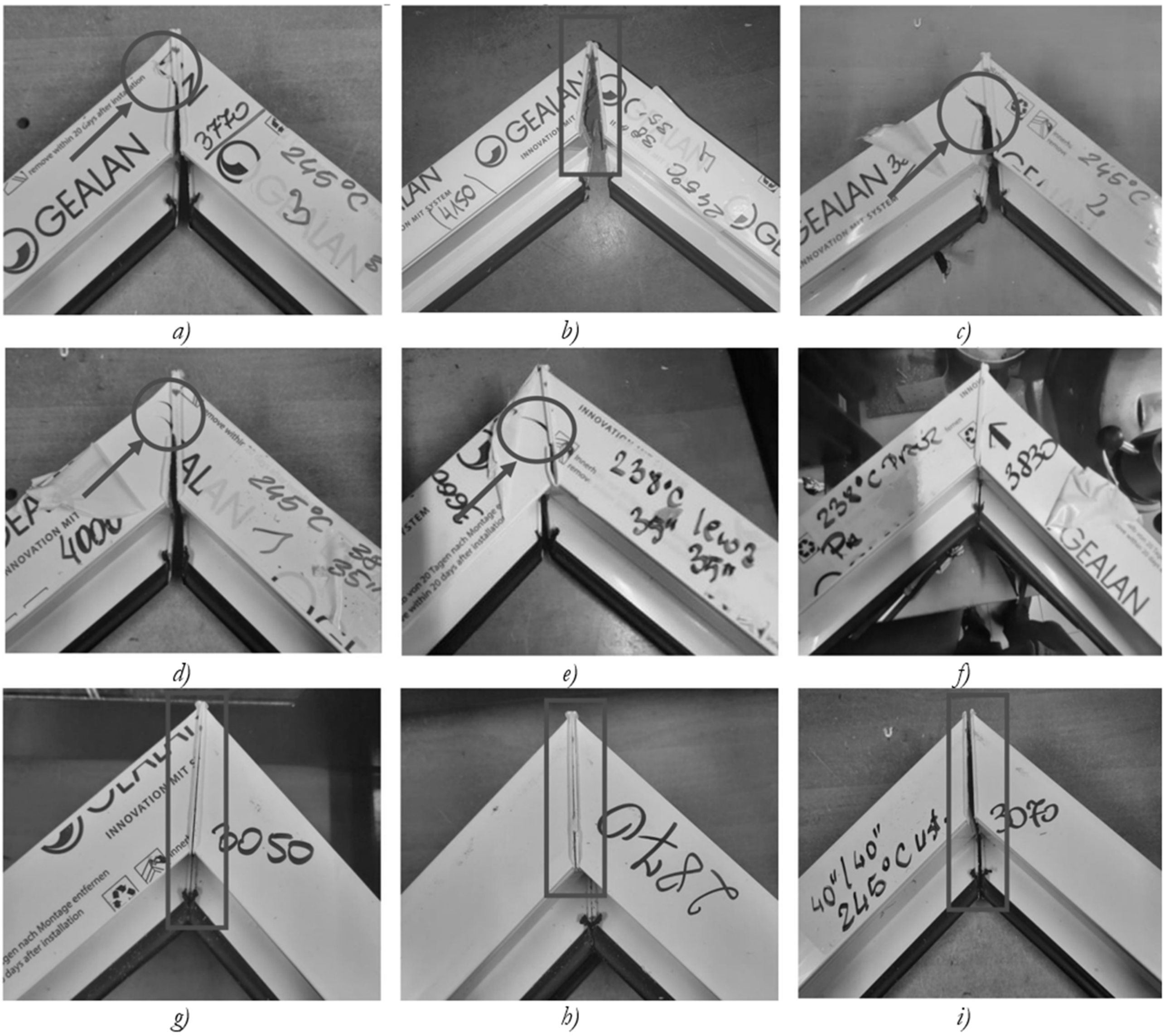


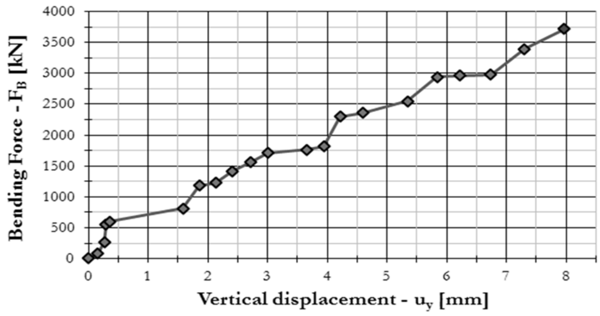
Fig. 5 *Shown in the photos are selected cases of defects: a) 3 370 [N] (4head); b) 4150 [N] (4head); c) 3820 [N] (4head); d) 4000 [N] (4head); e) 3660 [N] (2head); f) 3830 [N] (2head); g) 3050 [N] (1head); h) 2870 [N] (1head); i) 3070 [N] (1head)*

5 Measurements of displacements and bending strains for PVC corners

The investigation of displacements and strains was carried out using the Digital Image Correlation method. This method is based on comparing images taken during a bending test. Importantly, the sample to be tested must be covered by a special speckle pattern that contains small black dots on a white background (matte lacquer) in high contrast. The testing requires a tripod, uniform lighting (direct current) of the sample and remote control to make sure the digital camera remains perfectly stationary. By meeting these conditions it is possible to assess any changes on the surface of the PVC corner subjected to bending. The first step is to capture a photo of an unloaded sample – this image will serve as a template and allow the assessment of displacements and strains on the surface of the sample in subsequent photos. This part of the investigation was conducted using a Nikon D3500 digital camera, Yongnuo YN204 Pro Led Video Lighting and a JJC RM-E2 Remote Control unit. The distance between the sample and the lens was 500mm.

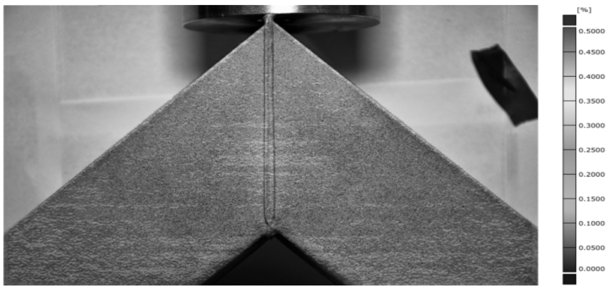
A random PVC corner sample was selected for an analysis of displacements of the piston and in order to generate a map of strains. The sample was prepared using a double-head weld station at 252°C. A total of 21 photos were taken during the test with the use of remote control. The images were analyzed using the GOM-Correlate 2D software [29]. The size of the facets and facet step were set to 61 and 15, respectively. These settings allow to achieve a correct and sufficient quality of the speckle pattern. This parameter is verified by means of a specialist software tool. The result of the verification is displayed in the form of a curve with a smooth profile (Fig. 6a).

a)

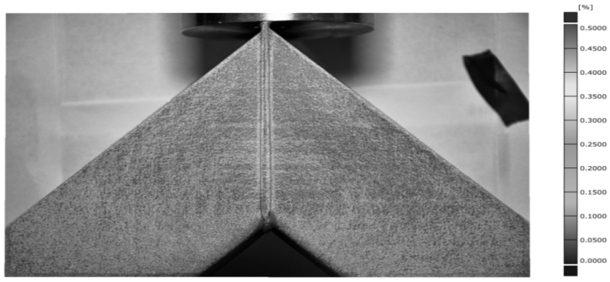


b)

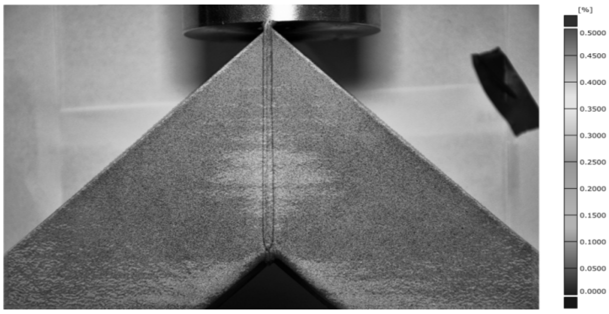
Fig. 6 *Verification of the quality pattern profile for 61×61 facets sizes and facet step equal 15 is visible on the right side (a); The chart: bending force versus vertical displacement (b)*



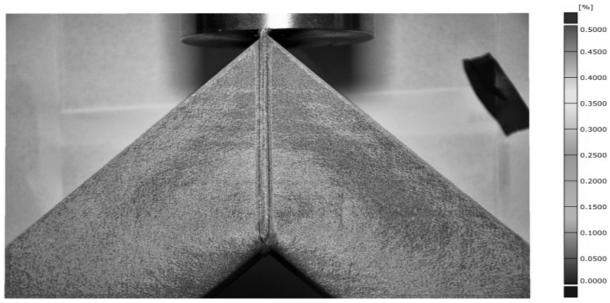
a_1)



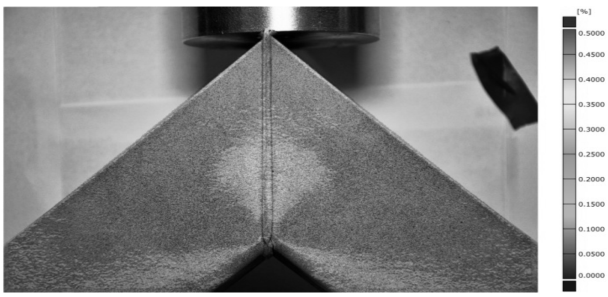
a_2)



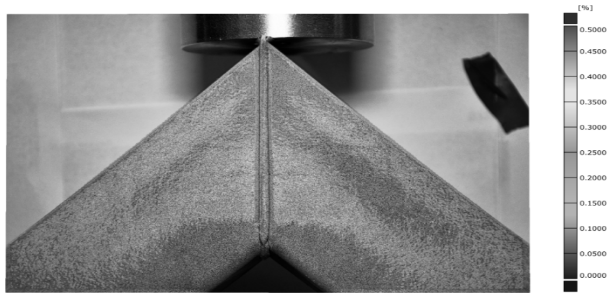
b_1)



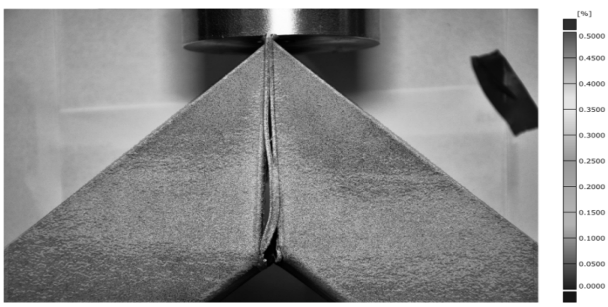
b_2)



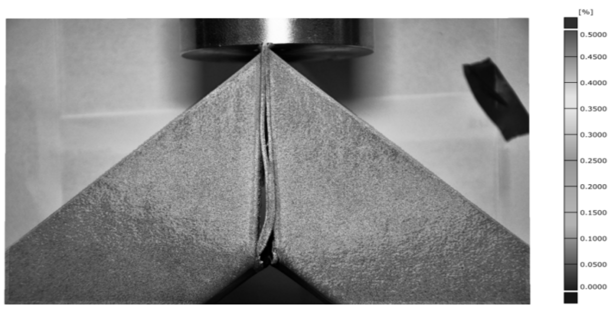
c_1)



c_2)



d_1)



d_2)

Fig. 7 *Strains ε_y (a_1,b_1,c_1,d_1) and major strains ε_1 (a_2,b_2,c_2,d_2) of the bending PVC frame corner for:*
a) F_B=600[N] ; b) F_B=1760[N]; c) F_B=3390[N]; d) F_B=3720[N]

As a result of the data processing, the displacements and strains for the PVC corner component could be collected. Shown in Fig. 6b is a graph of the bending force (F_B) versus displacement on the Y-axis (u_y). The last point (red) is recorded for the highest recorded force after the crack. In Fig. 7 the strains ε_y and major strains ε_1 for selected images are presented. The upper range of the strains was limited to 0.5% and the higher values are presented as extremes (dark red).

6 Conclusions and remarks

In the discussion of the results, it has to be marked taken subjects about the order influence factors on the welding PVC profiles, independent measurement of the real temperature of steel hot-plate, temperature influence on the critical bending force and results of the assessment displacements and strains on the PVC corner surface.

During the welding process, it is important to consider every change in the values of the factors that can influence the final strength of the welded connections. The essence of the problem is appropriate management through which it is possible to ensure the appropriate quality of the product. Equation (*1*) allows analysis of the factors and provides the possibility of avoiding mistakes related to the production of PVC corners as part of the production of windows.

The actual temperature measurements allowed to identify problems with set temperature in the control unit of the welding machine. The identified range between set temperatures reaches from 245°C to 264°C. The differences between extreme values equal ΔT_w=19°C, which is 8% more than the recommended welding temperature. This is probably due to worn-out machines and caused by their long (effective) run time. Unfortunately, neglecting the need to check the correctness of the temperature may result in the low quality of the final product, which may involve the occurrence of pores, cracks or material degradation at welding temperatures above 250°C [23]. Therefore, regular temperature checks are necessary for the welding process. Regular maintenance is also advisable.

The temperature differences affect the final strength of PVC frames. It must be noted that it is not only the temperature specified by the manufacturer of the PVC profiles that can ensure the minimum required bending force ($F_{B\ req.}$). On the contrary, a higher welding temperature results in lower bending force results, which is a satisfactory result, too. The analysis of the results in the form of charts can be seen in Fig. 8a. Additionally, for the average results, the trend line is generated in the polynomial form. For this type of trend line the best match achieved is R^2=0.9377. It follows to predict results only for higher temperatures because the function shows a downward trend. In the view of the parabola curve, the result for 245°C cannot be recognized as the extreme point of the function so it makes it impossible to predict results for lower temperatures, whereas the temperature of 245°C is the optimum temperature specified by the profile manufacturer. The effect predictions of results for higher temperatures are presented in Fig. 8b.

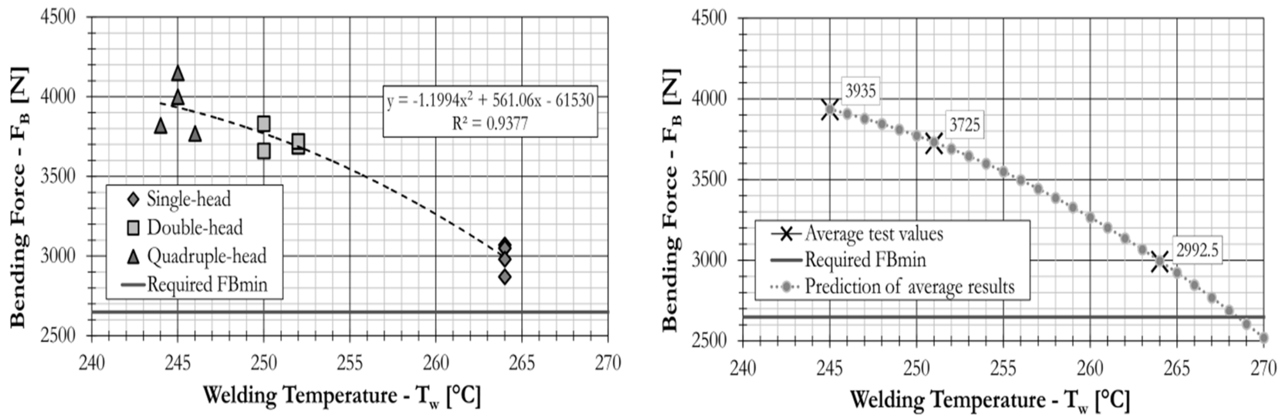


Fig. 8 *Curves of statistical data of bending results as a function of temperature (a); The predicted results of average bending force versus welding temperature (b)*

The cross point of the prediction line and required force bending is T_0=268.5°C. The margin of error is 4.5°C. The difference between the higher welding temperature T_w=264°C and between the determined limit of temperature provides the required bending force. It can be concluded that the lower welding temperatures can be risky for obtaining the required bending force as correct results due to the scattering of the results. The statistical study is presented in Tab. 6.

Tab. 6 *Numerical results for bending force versus temperature*

		Welding temperature (T_w)			Bending force (F_B)		
Welding station	**Head No.**	**Actual**	**Average**	**Deviation**	**Destructive**	**Average**	**Deviation**
[-]	**[-]**	**[°C]**	**[°C]**	**[°C]**	**[N]**	**[N]**	**[N]**
single-head (SH)	1	264	264	0	3070	2992.5	90.32
	1	264			3050		
	1	264			2980		
	1	264			2870		
double-head (DH)	1	250	251	1.15	3830	3725.0	74.16
	2	252			3690		
	1	250			3660		
	2	252			3720		
four-head (QH)	1	245	245	0.82	4000	3935.0	174.07
	2	244			3820		
	3	246			3770		
	4	245			4150		

The defects observed and presented in Fig. 5 stand out in two similar fracture forms. The first form of defect is crack along the weld – noticeable mainly at the temperature of 264°C. The second form presents a fracture along the weld with a profile crack outside the weld. It can be supposed that the characteristics of the material and the repeatability of the welding process are imperfect. The form of fracture can also depend on slight changes in the conditions of the welding process as irregularity of the cut surface PVC profile.

The Delta LN-2000 testing machine is not supported by the displacement system of the piston. Therefore, the Digital Image Correlation (DIC) method can be used as a replacement (to a certain extent) for the aforementioned system for this type of machines (Fig 6b). Additionally, it has to be stressed that the tests and analyses of strain maps are presented in Fig. 7. These analyses are presented for selected photos to show the steps in the development of defects for ε_y and ε_1. From the DIC analysis for a chosen example it is known (base in Fig. 7) that the most loaded zone is the corner place of PVC profiles that is in contact in the bottom and the zone in the middle of the weld (Fig. 7a_1,a_2). In both cases propagation of the failure process and plastic zones spread have been presented (Fig. 7b-c). The effect of development zones is visible in the form of fracture (Fig. 7d). It shows the possibility and effectiveness of using the DIC system to analyze other loaded structural components and indicate the points of weakness. This solution makes it possible to detect propagations of failure, their development and damage to the structure.

In terms of welding efficiency management, there are some noteworthy differences between the welding machines. The process using a 4-head welding machine has a higher level of automation and is approximately four times shorter than that using a 1-head welding machine and twice as short as that using a 2-head welding machine. It is therefore justified to use 4-head welding machines in high-volume production. This allows to ensure quality, stability and process efficiency. It is particularly important when it comes to manufacturing repeatable products of sufficiently high quality. At the same time, the cost of purchasing more expensive equipment is spread over a large number of manufactured products resulting in a relatively low unit cost.

In conclusion, the tests and analyses carried out provide a basis for quality control and optimization of the PVC frame welding process. As a result of improving the quality of the welding process, the number of defects that may cause later complaints is reduced. The methodology presented here can also be used for quality control of welded PVC window sashes and casements. Moreover, this method of testing may be used for other welded PVC components. The results of this study can also be used to manage maintenance in an enterprise in terms of monitoring the state of wear of welding stations and purchasing new welding machines.

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