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COMPOSITES THEORY AND PRACTICE

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THE STRUCTURE AND MECHANICAL PROPERTIES OF VIBRATION WELDED JOINTS MADE OF GLASS FIBRE REINFORCED NYLON 66

The results of vibration welding of glass fibre reinforced nylon 66 (TECAMID 66 GF30) are presented in this paper. The aim of the investigation was to determine the influence of the welding parameters on the quality of joints, which was conducted on the basis of light and scanning electron microscopic examinations as well as tensile tests. The results showed the influence of the vibration welding process on the way of creating the joint, on the material continuity, the orientation of the glass fibres in the welding area and on the joint strength. The joint is created as a result of joining the matrices of two welded materials. The glass fibres in the welding area are oriented in the direction of the vibrations and into the flash. A high tensile strength of joints is possible to achieve in a wide range of welding parameters.

Keywords: vibration welding, composite, nylon 66, glass fibres, microscopic examination, mechanical properties

STRUKTURA I WŁAŚCIWOŚCI MECHANICZNE ZŁĄCZY ZGRZEWANYCH WIBRACYJNIE Z POLIAMIDU 66 WZMOCNIONEGO WŁÓKNAMI SZKLANYMI

Poliamidy ze względu na swoje szczególne właściwości oraz możliwość przetwarzania różnymi metodami przeróbki staną ważną grupą konstrukcyjnych tworzyw sztucznych. Istnieje wiele metod, które można zastosować do łączenia poliamidów, również tych wzmacnianych włóknami szklanymi. Jedną z nowoczesnych technik łączenia jest zgrzewanie wibracyjne, stosowane powszechnie w produkcji seryjnej i masowej; około 15% wszystkich połączeń z tworzyw sztucznych jest wykonywanych właśnie tą metodą. Zastosowanie metody zgrzewania wibracyjnego do łączenia elementów z poliamidu wzmacnianego włóknami szklanymi pozwala na uzyskanie złączy o wysokiej i powtarzalnej jakości, co w znacznym decyduje o szerokim wykorzystaniu poliamidów w różnych zastosowaniach inżynierskich. W artykule przedstawiono wyniki badań zgrzewania wibracyjnego poliamidu wzmacnianego włóknami szklanymi o nazwie handlowej TECAMID 66 GF30. Celem badań było określenie wpływu warunków zgrzewania wibracyjnego na jakość złączy. Oceny jakości złączy dokonano na podstawie badań prowadzonych na mikroskopie świetlnym, elektronowym mikroskopie skaningowym (SEM) oraz badań wytrzymałości złączy w statycznej próbie rozciągania. Wyniki obserwacji mikroskopowych wykazały wpływ parametrów procesu zgrzewania wibracyjnego na sposób tworzenia się połączenia z poliamidu wzmacnianego włóknami szklanymi, ciągłość materiałową oraz na sposób układania się włókien w obszarze zgrzewania - zgodnie z kierunkiem drgań oraz w kierunku wypływki. Wysoką wytrzymałość mechaniczną złączy można uzyskać w szerokim zakresie parametrów zgrzewania.

Słowa kluczowe: zgrzewanie wibracyjne, kompozyt, poliamid 66, włókna szklane, badania mikroskopowe, właściwości mechaniczne

INTRODUCTION

Plastics and plastics composites are very popular engineering materials and are easy to fabricate, inexpensive, recyclable, exhibit good chemical resistance and low densities compared to metals [1]. Nylons are widely used thermoplastics for structural applications because of their overall properties. The large number of available nylons, with various combination of fillers and reinforcing materials, contribute to their usefulness [2]. Through their very special properties such as high mechanical strength, good sliding properties, high mechanical damping ability and fatigue resistance, these materials are gaining a greater presence in the mining, manufacturing, materials handling, marine, transport and packaging industries as well as in general engineering. The joining of polymers can be performed by using many different welding techniques such as friction welding, vibration welding, ultrasonic welding, thermal welding etc. [3]. In the group of welding methods, vibration welding is one of the most productive and precise welding methods used to join thermoplastic parts with advantages that include a short welding cycle, relatively simple construction of equipment, no surface preparation prior to joining and no additional substance introduced into the weld zone.

During vibration welding, one of the parts is fixed in the tooling and the other one is fixed in the tooling mounted on the vibration welding head which vibrates at a specific frequency and amplitude [4, 5]. The parts being joined are held together with a specific pressure. The heat generated through friction heats and melts the polymer at the welded interfaces [3, 6]. When a predetermined meltdown distance or predetermined weld time is reached, the vibration is stopped [7]. The following vibration welding parameters are: amplitude *a*, frequency *n*, weld pressure *p*, weld time *t* and penetration *s*. The vibration welding parameters influence the course of the welding process and also the heat generation which determines the weld structure and the mechanical properties of the joints [8, 9]. Light microscope micrographs of polished weld cross-sections have shown that only a few glass fibres in the weld zone are oriented perpendicular to the weld interfaces (cross the weld line). Investigation of the fracture surface (made with the use of scanning electron microscope) of the samples made from a glass fibre reinforced polymer showed a preferential glass fibre orientation in the direction of the vibrations and into the weld flash, which may reduce the strength of the welds [10].

MATERIAL, APPARATUS AND INVESTIGATION METHODOLOGY

Investigations were carried out at the Instytut Spawalnictwa (Institute of Welding) on a vibration welding stand equipped with a vibration welding machine, M 112H (Branson), and with a measurement system, VibRecord, designed at the Institute, used for the registration of welding parameters. The vibration welding machine is characterized by the following welding parameters: vibration frequency n - 240 Hz, vibration amplitude a is set in the range of 0.7÷1.8 mm, weld time t_z: up to 10.0 s and weld force F - up to 256.0 daN. The view of the welding stand is shown in Figure 1.

The material used in these studies was TECAMID 66 GF 30 (30% glass fiber reinforced nylon 66). The strength of the base material in a tensile test was about 87.0 MPa. The investigations were carried out by the butt welding of samples of the following dimensions: 10.0 x 16.5 x 56.0 mm. The butt-weld samples were oriented in the tool in such a way that a 10.0 x 16.5 surface became the welding area. In order to weld, two thermoplastic parts were clamped together under a specific weld pressure (p_w). The welding parameters used during welding are given in Table 1. The welding parameters used during these studies were selected on the basis of results obtained until now and the author's own experience. The welding process was conducted in a time module, which means that it was carried out for an established weld time.

a)

b)

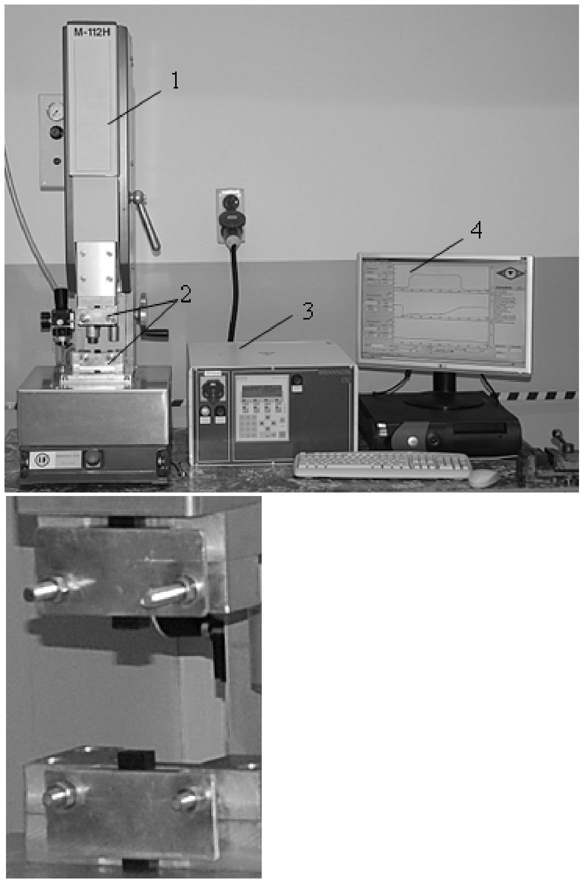


Fig. 1. View of vibration welding stand (a): 1 - vibration welding machine, 2 - tooling, 3 - control system, 4 - VibRecord device and view of tooling with mounted samples (b)

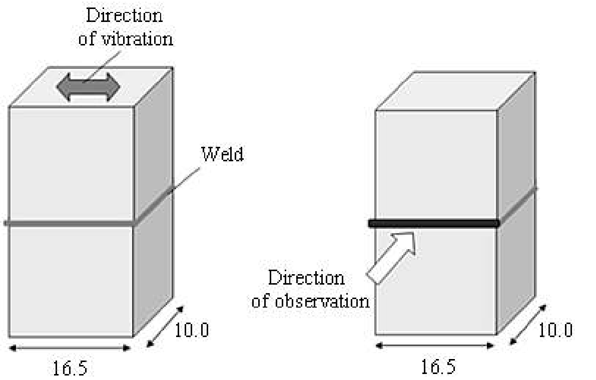
Rys. 1. Widok stanowiska do zgrzewania wibracyjnego (a): 1 - zgrzewarka wibracyjna, 2 - oprzyrządowanie, 3 - układ sterowania, 4 - przyrząd VibRecord oraz widok oprzyrządowania z zamocowanymi próbkami (b)

TABLE 1. **Set of welding parameters used during investigation**
TABELA 1. **Zestawienie parametrów zgrzewania zastosowanych w badaniach**

Welding parameters			
Weld pressure p_w = 2.7 MPa		Weld pressure p_w = 5.1 MPa	
Amplitude a [mm]	Weld time t_z [s]	Amplitude a [mm]	Weld time t_z [s]
1.0	4.5; 6.0; 6.5; 7.0; 7.5	1.0	4.0; 4.5; 5.0; 5.5; 6.0
1.4	2.5; 3.0; 3.5; 4.0; 4.5	1.4	2.0; 2.5; 3.0; 3.5; 4.0
1.8	1.5; 2.0; 2.5; 3.0; 3.5	1.8	1.0; 1.5; 2.0; 2.5; 3.0

The quality assessment was done on the basis of light microscope examination, scanning electron microscope examination (SEM) and tensile tests. The light microscope examination was done with the use of a MeF4M LEICA microscope. The examination was conducted in order to observe the welding region, the orientation of the glass fibres in the welding zone and the width of the weld. The procedure of the microscopic examination is shown in Figure 2.

a)



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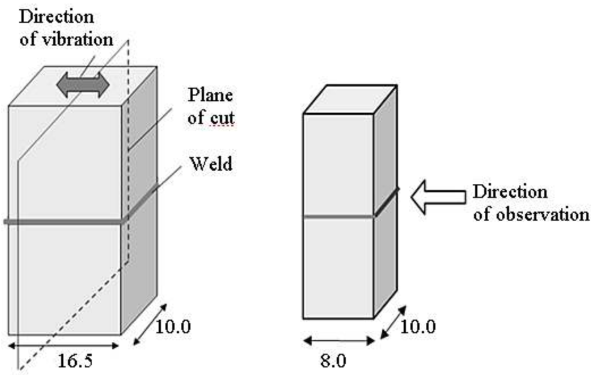


Fig. 2. Procedure of microscopic examination. Observation: a) interface parallel to direction of vibration, b) interface perpendicular to direction of vibration

Rys. 2. Sposób prowadzenia badań mikroskopowych. Kierunek obserwacji: a) powierzchnia równoległa do kierunku drgań, b) powierzchnia prostopadła do kierunku drgań

The welded samples were stretched on a tensile machine - INSTRON 4210. The fracture surfaces of selected samples, after the tensile test, were examined using the scanning electron microscope in order to assess the possibility of mixing of the matrix of two different nylons and to assess the glass fibre orientation in the weld zone. SEM was done with the use of a NEON 40EsB CrossBeam.

RESULTS OF INVESTIGATION AND DISCUSSION

Microscopic examination

The results of the light microscope examination of selected joints are shown in Figure 3 (along the parallel interface to the direction of vibrations as shown in Figure 2a) and 4 (along the perpendicular interface to the direction of vibrations, as shown in Fig. 2b). On the basis of the results of the light microscope examination, the orientation of the glass fibres in the welding zone, material continuity and the width of the weld were determined.

The results of the measurements of the weld width made during the microscopic examination of selected joints are given in Table 2.

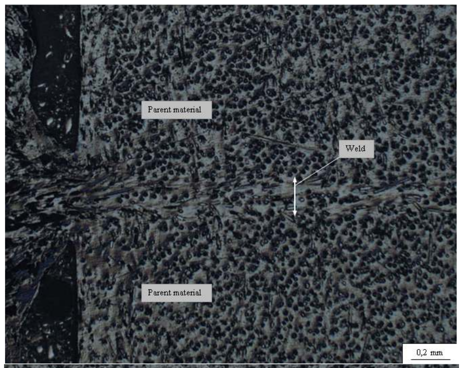
a)

b)

Fig. 3. View of weld microstructure: a) at edge of weld, b) in middle of weld. Welding parameters: $a = 1.4$ mm; $t_z = 4.5$ s; $p_w =$ $= 2.7$ MPa. Direction of observation: along parallel interface to direction of vibrations

Rys. 3. Widok mikrostruktury złącza: a) na brzegu złącza, b) w środkowej części złącza. Parametry zgrzewania: a = 1,4 mm; t_z = 4,5 s; p_w = 2,7 MPa. Kierunek obserwacji: wzdłuż powierzchni równoległej do kierunku drgań

a)



b)

Fig. 4. View of weld microstructure: a) at edge of weld, b) in middle of weld. Welding parameters: $a = 1.4$ mm; $t_z = 4.5$ s; $p_w =$ $= 2.7$ MPa. Direction of observation: along perpendicular interface to direction of vibrations

Rys. 4. Widok mikrostruktury złącza: a) na brzegu złącza, b) w środkowej części złącza. Parametry zgrzewania: a = 1,4 mm; t_z = 4,5 s; p_w = 2,7 MPa. Kierunek obserwacji: wzdłuż powierzchni prostopadłej do kierunku drgań

TABLE 2. **Set of results of measurements of weld width**
TABELA 2. **Zestawienie wyników pomiaru szerokości zgrzeiny**

Lp.	Welding parameters			Average weld width [mm]
	p_w [MPa]	a [mm]	t_z [s]	
1	2.7	1.0	4.5	0.18
2			6.0	0.19
3			7.0	0.20
4		1.4	2.5	0.19
5			3.0	0.20
6			4.0	0.22
7		1.8	2.0	0.18
8			2.5	0.19
9			3.5	0.24
10	5.1	1.0	4.5	0.16
11			5.0	0.18
12			6.0	0.19
13		1.4	2.5	0.16
14			3.0	0.18
15		1.8	1.0	0.04
16			1.5	0.15
17			2.5	0.17

On the basis of the results obtained from the microscopic examination, it was found that the glass fibres are concentrated in the welding area. It is connected with the penetration of the elements during the welding process and also with the flow direction of the plasticized material outside to the weld flash. In the case when the observations were conducted along the parallel interface to the direction of the vibrations (Fig. 2a), the glass fibres in the middle of the weld were placed perpendicular to the direction of welding and at the edge of the weld, the glass fibres were placed in both directions - parallel and perpendicular to the direction of welding (Fig. 3 a, b). Such orientation of the fibres in the welding area is connected exactly with the flow direction of the plasticized material under the influence of the welding parameters (amplitude, weld pressure and weld time). When the observations were conducted in accordance with the scheme shown in Figure 2b, the fibres in the middle of the sample were placed parallel to the welding direction and at the edge in both directions (Fig. 4 a, b). In this case, the orientation of the glass fibres in the welding area is connected with the welding direction and the influence of the welding parameters. From the two sides of the weld, the parent material (30% glass fibre reinforced nylon 66) with short, thin glass fibres is visible (Figs. 3, 4). The glass fibres are oriented in many different directions in the nylon matrix. In Figure 3, the fibres are visible along their length and in Figure 4, because of the cut of the fibres, only their cross sections are visible (in the case when microscopic observation was carried out along the surface which is perpendicular to the welding direction). The way of the glass fibre orientation in the matrix is connected with the manufacturing process of nylon plates. If the welding conditions are set properly, the material at the welding surfaces is regularly heated and plasticized. A layer of plasticized material is formed. The width of this layer is strictly connected with the welding parameters. At a lower weld pressure, a higher amplitude is needed and with a longer weld time, the width of the weld is greater. For example, with welding parameters: a = 1.4 mm, t_z = 3.0 s, the thickness of the layer was 0.20 mm with p_w = 2.7 MPa, and 0.18 mm for a = 1.4 mm and p_w = 5.1 mm.

On the basis of the scanning electron microscope examination (SEM), the orientation of the glass fibres on the fracture surfaces was determined. The typical way of distribution of the glass fibres in the welding area for a selected sample is shown in Figure 5.

a) b)

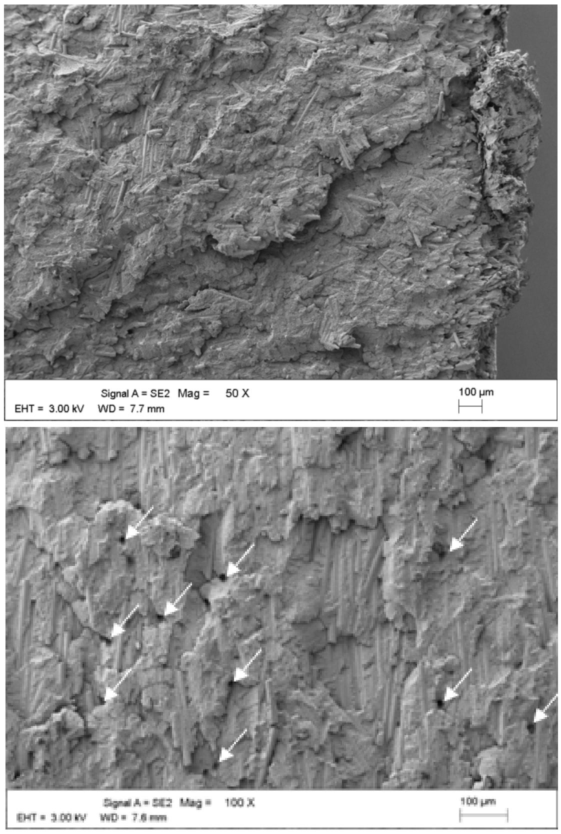


Fig. 5. View of fracture: a) view of edge of sample, b) view of middle of sample. Welding parameters: a = 1.4, t_z = 4.5, p_w = 2.7 MPa

Rys. 5. Widok przełomu złącza: a) widok brzegu próbki, b) widok próbki w części środkowej. Parametry zgrzewania: a = 1,4 mm, t_z = 4,5, p_w = 2,7 MPa

From the SEM, it appears that the strength of vibration welded joints depends mainly on the quality of the join of the matrix of the welded elements. Glass fibres do not significantly influence the strength of the joints, which is closely connected with the direction of their distribution in the welding area. On the basis of the observation and analysis of the fracture surfaces, the concentration of the glass fibres is visible. It was also found that the orientation of the fibres changes in particular areas of these surfaces. At the edge of the fracture, the glass fibres are oriented in all directions, but mainly in accordance with the flow of the plasticized material - outside the weld, to the flash (Fig. 5a). In the middle of the fracture, the fibres are oriented in accordance with the welding direction (Fig. 5b). On this surface a few holes are also visible due to fibres that were pulled out of the matrix (marked with arrows). These glass fibres were placed perpendicularly to the welding surface and the welding direction. At the edge of the fracture, only some of the fibres are oriented perpendicularly to the welding surface or at an angle (Fig. 5a). The perpendicular orientation of some fibres does not significantly influence the strength of the joints.

Tensile strength

The results from the tensile test of the joints made from the 30% glass fibre reinforced nylon 66, welded in different welding conditions are shown in Figure 6.

From the tensile test, it can be observed that the change of the weld strength as a function of time is similar for every used amplitude and weld pressure (Fig. 6). When the weld time is short, the weld strength is low (20÷35% of the base material). As the weld time lengthens, the strength of the joints increases until the maximum strength is reached. The results indicate that the highest strength of joints is at the level of 52% of the base material, and it was reached using the following welding parameters: a = 1.0 mm, p_w = 2.7 and p_w = 5.1 MPa and for the weld time t_z = 6.5 and 6.0 s respectively. Further lengthening of the welding process does not increase the weld strength, but it rather increases the penetration. It was also noticed that the higher the amplitude, and the higher the weld pressure, the shorter the weld time is, by which it is possible to achieve a high strength of welds.

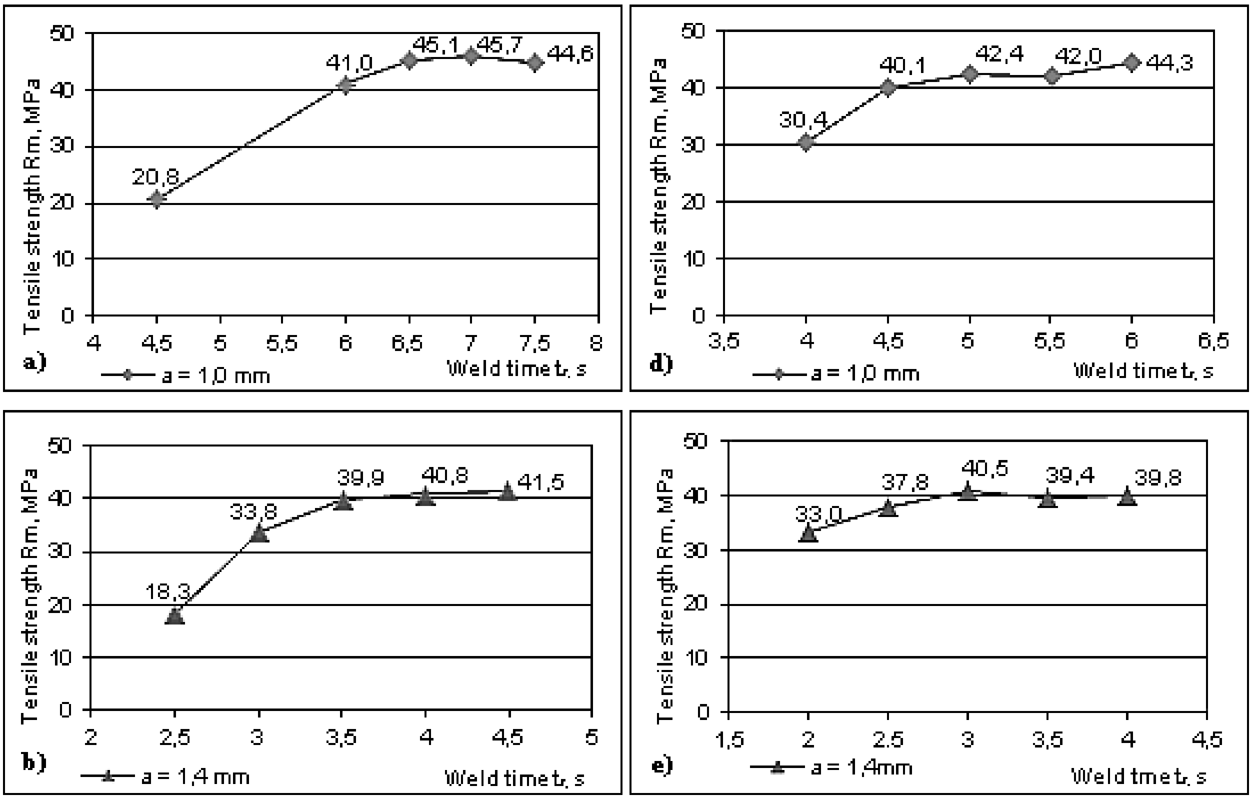


Fig. 6. Tensile strength R_m as function of weld time t_z for different amplitude and weld pressure: a, b, c) p_w = 2.7 MPa; d, e, f) p_w = 5.1 MPa

Rys. 6. Wpływ czasu zgrzewania t_z na wytrzymałość złączy zgrzewanych R_m przy różnej amplitudzie drgań i docisku zgrzewania: a, b, c) p_w = = 2,7 MPa; d, e, f) p_w = 5,1 MPa

CONCLUSIONS

On the basis of the results, the following conclusions were formulated:

1. Orientation of glass fibres in the weld is connected with the direction of vibrations and with the flow of plasticized material outside the weld - into the flash.
2. If welding conditions are set properly, the polymer at the welding surfaces is regularly heated and plasticized - a layer of plasticized material is formed.
3. Width of the weld depends on welding parameters: weld pressure, amplitude and weld time.
4. Glass fibres in the weld are oriented in different directions, which does not increase joint strength.
5. Tensile strength of joints made from 30% glass fibre reinforced nylon 66 depends on the quality of join of nylon matrices of the welded samples.
6. From the tensile test it follows that the maximum strength of welded joints is at the level of about 45.0 MPa (52% of base materials). Maximum strength of joints was achieved by the following parameters: a = 1.0 mm, p_w = 2.7, t_z = 6.5 and a = 1.0 mm, p_w = 5.1 MPa and t_z = 6.0 s.

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