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A REVIEW OF STUDIES ON ULTRASONIC WELDING

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Abstract: This review work is to summarise the results of the experimental studies on ultrasonic welding of thermoplastics, blends of thermoplastic polymers and composites at Department of Engineering Technology, Technical University of Liberec, Czech Republic. The previous studies were focused on determining the effect of selected technological parameters in ultrasonic welding process, of different energy director shapes and of filler percentages in the thermoplastic matrix on the tensile strength of the welded joint under various welding conditions. In addition, this review also mentions the further research directions in this field.
Keywords: Ultrasonic welding, energy director shapes, joint strength, thermoplastic polymers, composites

1. INTRODUCTION

For bonding plastics and composites often use welding technologies. One of the most modern welding methods is ultrasonic welding technology, which has various applications in the engineering industry, especially in the automotive and textile industry, in the production of electrical appliances, in the packaging technology, etc. The main advantages of ultrasonic welding are fast, clean, efficient and repeatable process, producing a strong bond with the consumption of a very little amount of energy. To create the welded joint by ultrasonic technology requires no solvent, adhesive or external heat and the resulting joint is undetachable.

A whole range of welding parameters has an important effect on quality of the resulting welded joint. The control of parameters can be ensured by suitable design of the welding device and corresponding control software. The stability of the welding process is increased and the effect of the human factor is reduced with rising automation. Another condition for ensuring high-quality welded joint is the weldability of materials and to obtaining a high-strength joint must meet the following conditions:

- It is possible to weld only the same materials, although some technologies are possible to combine different plastic materials (e.g. by vibration welding).
- The melt index of the welded plastics must be equal or very close to each other.
- The chemical compatibility of materials.

Besides the above given effect, for proper evaluation it was also necessary to determine the effect of filler concentrations and the energy director shapes, which are presented in this paper.

2. ULTRASONIC WELDING

Ultrasonic plastic bonding is the joining or reforming of thermoplastics by using heat generated from high frequency mechanical motion. This can be achieved by converting electrical energy into high frequency mechanical motion (vibrations), which generates frictional heat at the joint area. The vibrations applied to a part under pressure/force, generate frictional heat at the interface and cause melting of the material and creating molecular bond between the welded plastic parts. Ultrasonic welding process is described in several phases shown in Figure 1 [1].

Description of individual phases :

1. The clamping of the parts to the fixture – two thermoplastic parts to be welded are placed together, one on top of the other and clamped to the fixture.
2. The contact with the horn – a titanium or plated aluminum horn is brought into contact with the upper part.

3. The application of pressure – a controlled pressure is applied to the horn, clamping two parts together against the fixture.
4. Welding time – the horn is vibrated vertically with a preset vibration frequency of 15 kHz or 30 kHz, at distances measured in microns for a predetermined time. The mechanical vibrations are transmitted through the parts to the joint interface to create frictional heat. When the temperature at the interface reaches the melting point, parts melt and flow, and the vibration is stopped, allowing the material to begin cooling.
5. Time of holding pressure – the clamping force is maintained for a predetermined time during solidification.
6. The return of the horn – once the solidification of the melted plastic has occured, the clamping force is deactivated and the horn is returned to its initial position. The two parts are now welded and are removed from the fixture as one part.

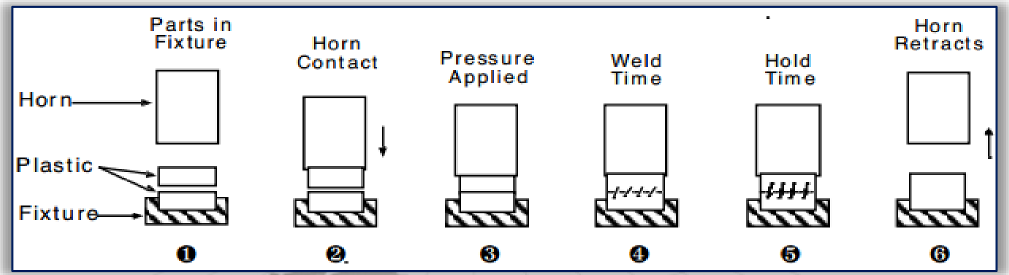


Figure 1. Phases of ultrasonic welding

The important ultrasonic welding parameters are weld time (time during which the vibrations are applied), welding pressure or force (providing the static force necessary to couple the horn and parts together for transferring the vibrations), hold time (time for solidification and cooling after vibration has stopped), hold force, trigger force (force applied to the part before initiating the vibrations), power level and amplitude of vibration. Before initiation of vibrations must take a proper contact between the horn and the top workpiece, welding can not be successfully performed if the horn comes in contact with the workpiece after initiating vibrations [2].

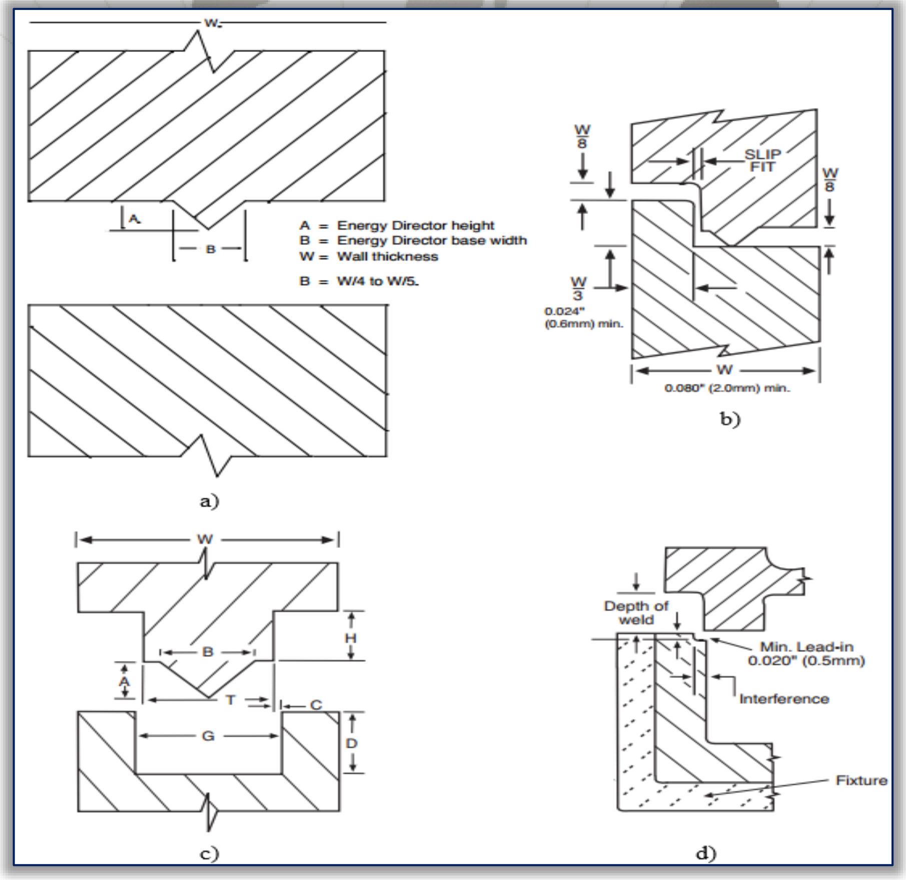


Figure 2. Types of joints, a) butt joint, b) step joint, c) tongue and groove joint, d) shear joint

Figure 2 shows the four different types of joints in ultrasonic welding. The butt joint with an energy director is suitable for amorphous plastics, because they are capable of molten flow and gradual solidification. However, this type of joint is not the best for semi-crystalline, because the material displaced from the energy director usually solidifies before a seal is formed across the joint. This causes a reduction in overall strength and creation of hermetic seals is difficult to obtain. In order to overcome these problems, the energy director should be larger and have a steeper angle to give it a sharper apex. The step joint can be used when cosmetic appearance of joint is important. This type can eliminate flash on the outer side and create a strong joint, because material from the energy director will typically flow into the gap between the tongue and the step. The tongue and groove joint is another variant of the energy direction. This type of joint prevents internal and external flash, because the redundant material is caught by flash traps on both sides of the interface. The tongue and groove joint is primarily used for self-location and flash prevention. This joint is excellent for applications, which require low pressure hermetic seals.

The main disadvantage of this joint is low weld strength because less area is affected by the joint. The shear joint is used when a strong hermetic seal is required, especially for semi-crystalline plastics. This joint requires a certain amount of interference into the part. In addition, rigid sidewall support is very important with shear joint welding to eliminate part distortion during welding [1].

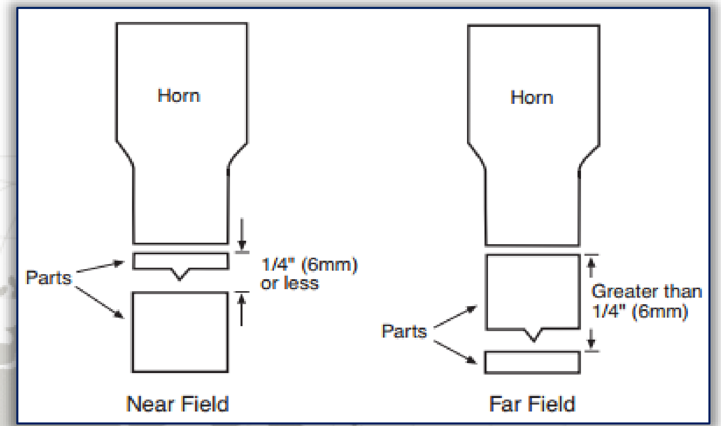


Figure 3. Nearand Far field welding

The two types of welding ultrasonic are near field and far field, as shown in Figure 3. Near and far field welding refer to the distance from the ultrasonic horn to the weld interface. When this distance is 6 [mm] or less, the weld is considered near field and when this distance is greater than 6 [mm], it is considered far field. Whenever possible, it is always best to use near field welding, since it tends to require lower amplitudes, shorter weld times and lower air pressures. Generally, far field welding is recommended only for amorphous plastics, which transfer energy better than semi-crystalline plastics [1].

3. EXPERIMENTAL RESULTS

Juraj Gürtler [3] had investigated the effect of technological parameters in ultrasonic welding process of Bayblend T65 (PC/ABS) on the joint strength. In this work, the author had used the test samples with geometry of energy director : height of h = 1 mm, angle of $\alpha = 90^{\circ}$ and method of welding by absolute distance. Firstly, the author had determined the effect of welding pressure on the joint strength and the resulting dimension of workpiece (see Figure 4). The test samples were welded under technological parameters as follows : maximum welding time of t_w = 7 s, holding pressure of p_h = 200 kPa, holding time of t_h = 8 s, welding amplitude of A_w = 45 μm and welding pressure of p_w = 1-210 kPa with a step of 30 kPa. The measured results showed that the used welding pressures had great effects on the joint strength and the resulting dimension of workpiece. The highest mean value of the joint strength and the best resulting dimension of workpiece were R = 965 N and H = 8.13 mm at p_w = 1 kPa, respectively. With increasing welding pressure occurred a decrease in the joint strength and an increase in the resulting dimension of workpiece. At p_w = 210 kPa, the joint strength was already so low that the joint was damaged during removal from the fixture and therefore the value of the joint strength could not be measured. In this case, movability of energy director also decreased and an attenuation of ultrasonic oscillations occurred. The increase in the initial contact area and the attenuation of ultrasonic oscillations resulted in a decrease in the heat generated at the interface and only a small amount of the material was melted. Contrarily, the optimal melting was achieved at the interface and the formation of the small flash at the edge of the weld area at p_w= 1 kPa.

Secondly, the author had determined the effect of holding pressure on the joint strength and the resulting dimension of workpiece. The test samples were welded under technological parameters as follows : welding pressure of p_w = 1 kPa, maximum welding time of t_w = 7 s, holding time of t_h = 8 s, welding amplitude of A_w = 45 μm and holding pressure of p_h = 1-320 kPa with a step of 40 kPa. The measured results showed the apparent effect of holding pressure on the joint strength and the resulting dimension of workpiece. The highest mean value of the joint strength was R = 965 N at p_h = 200 kPa and the best resulting dimension of workpiece was H = 8.12 mm at p_h = 280 kPa. When using values of holding pressure lower than 160 kPa and higher than 200 kPa, it resulted in reducing the joint strength. Furthermore, it could be stated that the magnitude of holding pressure almost did not have any effect on the created flash.

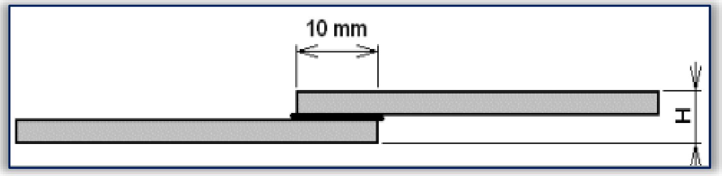


Figure 4. Dimension of joint H after welding

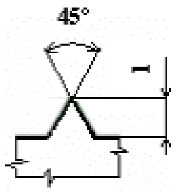
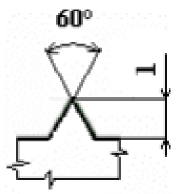
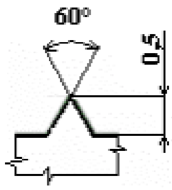
Thirdly, the author had determined the effect of holding time on the joint strength and the resulting dimension of workpiece. The test samples were welded under technological parameters as follows : welding pressure of p_w = 1 kPa, maximum welding time of t_w = 7 s, holding pressure of p_h = 200 kPa, welding amplitude of A_w = 45 µm and holding time of t_h = 0.5-8 s. In the first step, the holding time increased by 0.5 s and from value of t_h = 1 s, the holding time was always extended by 1 s. The measured results showed that the highest mean value of the joint strength and the best resulting dimension of workpiece were R = 965 N and H = 8.13 mm at t_h = 8 s, respectively. The effect of holding time on the melt at the interface was apparent. This is due to the fact that the melt still flowed during solidification in small extent at the interface through holding time. With solidification of the molten material, this phenomenon gradually slowed down until the material was completely solidified. During welding, the optimal melting at the interface and the formation of the small flash at the edge of the weld area were achieved. The magnitude of holding time almost did not have any effect on the created flash, as in the previous measurement.

Finally, the author had determined the effect of amplitude on the joint strength and the resulting dimension of workpiece. The test samples were welded under technological parameters as follows : welding pressure of p_w = 1 kPa, maximum welding time of t_w = 7 s, holding pressure of p_h = 200 kPa, holding time of t_h = 8 s and welding amplitude of A_w = 25-45 µm with a step of 5 µm. The measured results showed that the highest mean value of the joint strength and the best resulting dimension of workpiece were R = 965 N and H = 8.13 mm at A_w = 45 µm, respectively. Since the test material was blend of two amorphous polymers with low attenuation of ultrasonic oscillation and welded in the near field, the effect of amplitude on the joint strength and the resulting dimension of workpiece in the given experimental extent was minimal. The welding time increased with decreasing value of amplitude, because less heat was generated at the interface. And there was a significant increase in the magnitude of the flash when increasing the welding amplitude.

Lenka Frejtová [4] had presented the results of study on the effects of ultrasonic welding technological parameters on the joint strength of long glass fiber reinforced copolypropylene. In this work, the author had selected three levels of weight percentages of long glass fiber filler to compare the joint strength: pure copolypropylene, 30 wt% and 45 wt% of fibers. The two methods of ultrasonic welding: welding by time and by absolute distance were compared during the experimental measurements and welding by absolute distance was only for PP-GF45. The experimental results showed that when welding by time, the highest mean value of tensile strength achieved by PP-GF30 at the following welding parameters : height of energy director h = 1 mm, angle of energy director α = 45 °, welding time of t_w = 1 s, welding pressure of p_w = 23 kPa, pressure during cooling of the joint p_c = 70 kPa, cooling time of the joint t_c = 1 s, welding amplitude of A_w = 85 μm and welding frequency of f_w = 20 kHz was R = 46.69 MPa. The lowest mean value of tensile strength was achieved by pure copolypropylene at the following welding parameters : height of energy director h = 0.5 mm, angle of energy director α = 60 °, welding time of t_w = 1 s, welding pressure of p_w = 23 kPa, pressure during cooling of the joint p_c = 80 kPa, cooling time of the joint t_c = 1 s, welding amplitude of A_w = 80 μm and welding frequency of f_w = 20 kHz was R = 26.15 MPa. The most significant welding parameters from the viewpoint of welding method by absolute distance were geometry of energy director, its height and angle. When welding by method of absolute distance, the highest mean value of tensile strength was R = 42.8 MPa at h = 1 mm and α = 45 °.

The reason for the low joint strength was percentage of glass fibers in the matrix (increasing percentage of filler in the matrix, caused reduction in the joint strength owing to small amount of matrix), fiber orientation anisotropy and short welding time. Owing to the high welding speed, could not arrange the fibers in such a short time and thus resulted in a negative orientation. The fibers were arranged in the plane of the welded joint perpendicular to the pressure direction of the horn, which was the plane perpendicular to the direction of force F_{max} (the maximum force required to break the joint), so the joint had a lower strength than the base material of the composite. The advantage of high welding speed was that there was no formation of the material layer affected by the surrounding environment (oxygen, moisture), which would reduce the ability to join the welded materials. Experimental measurements were evaluated on the basis of Taguchi statistical method. The selected statistical method contributed to evaluate the importance of the welding parameters for the test materials. Table 1 listed the most suitable welding parameters, which based on the performed experiments and their evaluations.

Table 1. The best welding parameters

Parameter	PP-GF45	PP-GF30	Pure copolypropylene
Geometry of energy director			
Welding time (s)	1	0.8	1
Welding pressure (kPa)	25	23	20

Daniel Hušek [5] investigated near field ultrasonic welding of homopolypropylene filled with nanoclay, welding by method of absolute distance with using a hydraulic braking to improve the joint strength. The work focused on the effect of nanoclay concentrations in the matrix and of the welding parameters (such as : degree of braking K, welding pressure and amplitude) on the joint strength. In this work, the author had selected four levels of the weight percentages of nanoclay filler: pure homopolypropylene, 2 wt%, 4 wt% and 6 wt% of nanoclay.

The experimental results showed that the increase in degree K (K=3 after three units up to a value K=15) at constant welding pressure of p_w = 15 kPa and welding amplitude of A_w = 100 µm caused decrease in the welding speed v_w (the arithmetic average of the mean values from all series was between v_w = 1.29 mm/s at K = 3 and v_w = 0.097 mm/s at K = 15), which led to an increment in welding energy and more energy was delivered to the weld interface to increase melting of the material in the weld area and causing an increase in the joint strength. The mean values of the maximum instantaneous power P_w at K = 3 were highest in comparison with values at the other higher degrees of K, a maximum mean value was P_w = 321 W at 6 wt% of nanoclay and a minimum mean value was P_w = 367 W at 0 wt% of nanoclay. The mean value of the welding energy E_w did not show a dependence on the concentration of nanoclay. The arithmetic average of the mean values of the welding energy from all concentrations of nanoclay was increased from E_w = 114.1 J at K = 3 to E_w = 1082.9 J at K = 15. An increase in percentage of nanoclay caused a decrease in the value of destructive force. The calculated mean value of destructive force was F_d = 625.4 N for unfilled homopolypropylene at K = 15 and F_d = 122.3 N for homopolypropylene with 6 wt% of nanoclay at K = 3.

The mean value of v_w did not show a dependence on the concentration of nanoclay and when increasing the welding pressure from value of p_w = 15 kPa to 600 kPa at a constant degree of braking (K = 3) and welding amplitude of A_w = 100 µm, it caused increase in the welding speed. The arithmetic average of the mean values from all series was between v_w = 1.29 mm/s at p_w = 15 kPa and 2.553 mm/s at p_w = 600 kPa. The effect of changes in pressure on the destructive force, welding energy and maximum instantaneous power was tied to characteristics of hydraulic braking. After achieving a specific welding pressure, there was no increase in the welding speed and so dependence of the welding speed on the welding pressure was lost. The mean value of maximum instantaneous power showed a slight decrease in dependence on increasing concentration of nanoclay. However, the mean value of power increased with increasing welding pressure. The calculated mean value of power was P_w = 596.5 W for unfilled homopolypropylene at p_w = 600 kPa and P_w = 320.5 W for homopolypropylene with 6 wt% of nanoclay at p_w = 15 kPa. The mean value of the welding energy decreased with increasing welding pressure. With increasing concentration of nanoclay occured a slight decrease in mean value of welding energy except energy at p_w = 15 kPa. The mean value of the welding energy decreased from a value of E_w = 109.3 J for unfilled homopolypropylene to a value of E_w = 55.9 J for 6 wt% of nanoclay. The mean value of destructive force decreased with increasing the welding pressure and percentage of nanoclay. The mean value of destructive force was F_d = 271.4 N for

unfilled homopolypropylene at p_w = 15 kPa and F_d = 77 N for homopolypropylene with 6 wt% of nanoclay at p_w = 600 kPa.
Determination of the effect of amplitude when welding homopolypropylene with various concentrations of nanoclay was performed at A_w = 70 μm and 100 μm under the following welding conditions: K = 3, p_w = 50 kPa; K = 6, p_w = 15 kPa and K = 9, p_w = 15 kPa. For lower value of welding energy, the average value of the mean welding speed gradually increased with increasing concentration of nanoclay and was lower for lower welding amplitude. The greatest difference for the individual concentrations was v_w = 0.352 mm/s. The dependence of speed on concentration of nanoclay disappeared at higher levels of energy and lower welding speeds. Destructive force – Welding condition 1: the mean value of destructive force decreased when reducing the welding amplitude. The ratio between the mean value of destructive force at A_w = 100 μm and 70 μmfor individual concentrations of nanoclay ranged from 1.08 to 1.27. The ratio between the mean value of destructive force for series of 0 wt% and 6 wt% was 2.56 at A_w = 70 μm and 2.57 at A_w = 100 μm. Welding condition 2: the mean value of destructive force decreased when reducing the welding amplitude. The ratio between the mean value of destructive force at A_w = 100 μm and 70 μm for individual concentrations of nanoclay ranged from 1.25 to 2.75. The ratio between the mean value of destructive force for series of 0 wt% and 6wt% was 3.37 at A_w = 70 μm and 1.98 at A_w = 100 μm. Welding condition 3: the mean value of destructive force decreased when reducing the welding amplitude and strongly fluctuated for individual concentrations of nanoclay. The ratio between the mean value of destructive force at A_w = 100 μm and 70 μm for individual concentrations of nanoclay ranged from 1.25 to 1.94. The ratio between the mean value of destructive force for series of 0 wt% and 6 wt% was 1.96 at A_w = 70 μm and 2.21 at A_w = 100 μm. Welding energy – Welding condition 1 : the mean value of welding energy decreased when reducing the welding amplitude and the increase in concentration of nanoclay caused a slight decrease in mean value of energy. The ratio between the mean value of welding energy at A_w = 100 μm and 70 μm for individual concentrations of nanoclay ranged from 1.16 to 1.31. The ratio between the mean value of welding energy for series of 0 wt% and 6 wt% was 1.48 at A_w = 70 μm and 1.49 at A_w = 100 μm. Welding condition 2 and 3 : the mean value of welding energy fluctuated owing to the increase in energy, which was supplied to the workpieces, and however the author did not evaluate these welding conditions. Maximum instantaneous power – the mean value of maximum instantaneous power decreased when reducing the welding amplitude. Welding condition 1: The ratio between the mean value of power at A_w = 100 μm and 70 μm for individual concentrations of nanoclay ranged from 1.41 to 1.50. The ratio between the mean value of power for series of 0 wt% and 6 wt% was 1.14 at A_w = 70 μm and 1.16 at A_w = 100 μm.
Welding condition 2: the mean value of maximum instantaneous power varied slightly between the series with various concentrations of nanoclay. The ratio between the mean value of power at A_w = 100 μmand 70 μm for individual concentrations of nanoclay ranged from 1.43 to 1.56. The ratio between the mean value of power for series of 0 wt% and 6 wt% was 1.09 at A_w = 70 μm and 1.08 at A_w = 100 μm.
Welding condition 3: the mean value of maximum instantaneous power varied slightly between individual concentrations of nanoclay. The ratio between the mean value of power at A_w = 100 μm and 70 μm for individual concentrations of nanoclay ranged from 1.31 to 1.48.

Table 2. Welding parameters during monitoring of trigger force for samples with h = 1 (mm), α = 60 (°)

Parameter	Value
Frequency (kHz)	20
Amplitude (%)	100
Trigger force (N)	20-70
Welding speed (mm/s)	1
Holding time (s)	1
Welding distance (mm)	1
Welding time (s)	1

Table 3. Welding parameters during monitoring of trigger force for samples with h = 0.65 (mm), α = 75 (°)

Parameter	Value
Frequency (kHz)	20
Amplitude (%)	100
Trigger force (N)	20-70
Welding speed (mm/s)	0.6
Holding time (s)	1
Welding distance (mm)	0.6
Welding time (s)	1

Dalibor Kopáč [6] performed a study on monitoring of welding parameters (trigger force, welding amplitude and speed) during ultrasonic welding of polyamide, including evaluation of the effect of individual parameters on the joint strength. In this work, the welding process was carried out on both types of energy director: height of h = 1 mm, angle of α = 60 ° and height of h = 0.65 mm, angle of α =

75 °. Firstly, the measurement was carried out on the samples with h = 1 mm, α = 60 °when monitoring the trigger force. The welding parameters for this case were shown in Table 2.
The measured values showed that a large increase in the joint strength was appreciable when using a greater trigger force. The highest value of tensile force was F_t = 999.6 N at trigger force of F_{trig} = 70 N and the lowest value was F_t = 480.5 N at trigger force of F_{trig} = 20 N. The difference in the strength between trigger force of F_{trig} = 20 N and 70 N was more than 100 %. The greatest increase in the strength was recorded between the values of the trigger force of F_{trig} = 30 N, 40 N and 50 N. The difference in the strength between trigger force of F_{trig} = 50 N and 70 N was only 6 %, whereas between F_{trig} = 30 N and 50 N was almost 40 %. The joint strength was not changed excessively when using higher trigger force than of F_{trig} = 50 N.
Secondly, monitoring of the trigger force was continued by changing the test samples with geometry of energy director as follows: height of h = 0.65 mm, angle of α = 75 °. The welding parameters for this case were shown in Table 3. The measured values showed that a increase in the joint strength was obvious when using a higher trigger force. The highest value of tensile force was F_t = 713.6 N at trigger force of F_{trig} = 70 N and the lowest value was F_t = 400.8 N at trigger force of F_{trig} = 20 N. The largest difference in the strength was 28 % at lower trigger force of F_{trig} = 20 N and 30 N. The difference between trigger forces of F_{trig} = 40 N, 50 N, 60 N and 70 N were moved to 7 %.

Table 4. Welding parameters during monitoring of welding amplitude for samples with h = 1 (mm), α = 60 (°)

Parameter	Value
Frequency (kHz)	20
Amplitude (%)	70-100
Trigger force (N)	50
Welding speed (mm/s)	1
Holding time (s)	1
Welding distance (mm)	1
Welding time (s)	1

Table 5. Welding parameters during monitoring of welding amplitude for samples with h = 0.65 (mm), α = 75 (°)

Parameter	Value
Frequency (kHz)	20
Amplitude (%)	70-100
Trigger force (N)	50
Welding speed (mm/s)	0.6
Holding time (s)	1
Welding distance (mm)	0.6
Welding time (s)	1

Welding amplitude is one of the fundamental parameters, which can significantly affect the welded joint. Monitoring of amplitude also proceeded at similar parameters as for monitoring of trigger force. The amplitude gradually reduced from A_w = 100 % to 70 %. Firstly, the measurement was carried out on the samples with h = 1 mm, α = 60° when monitoring the welding amplitude. The welding parameters for this case were shown in Table 4. According to the measured results of tensile test, the effect of amplitude on the joint strength was demonstrably significant. The highest value of tensile force was F_t = 938.2 N at welding amplitude of A_w = 100 % and the lowest value was F_t = 570 N at amplitude of A_w = 70 %. The overall decrease in strength was 64 % when reducing amplitude from A_w = 100 % to 70 %. The strength decreased by 8 %, 27 % and 19 %when gradually decreasing amplitude from A_w = 100 % to 90 %, 80 % and 70 %, respectively.
Secondly, monitoring of amplitude was continued by changing the test samples with geometry of energy director as follows : height of h = 0.65 mm, angle of α = 75 °. The welding parameters for this case were shown in Table 5. The joint strength decreased exponentially with decreasing value of amplitude. The highest value of tensile force was F_t = 639.8 N at welding amplitude of 100 % and the lowest value was F_t = 495.9 N at amplitude of 70 %. The overall decrease in strength was 24 % when reducing amplitude from 100 % to 70 %. The strength decreased by 11 %, 5 % and 8 % when gradually decreasing amplitude from 100 % to 90 %, 80 % and 70 %, respectively.
The third monitoring parameter was constant welding speed during the cycle, which according to the theoretical assumptions had the largest effect on formation of the weld area as well as on the joint strength. The lower the welding speed, the longer the welding time and thus causing an increase in the joint strength or the energy director melted evenly and the melt had sufficient time to spread completely and so enlarged the weld area. Monitoring of the welding speed proceeded at the parameters, which were presented in Table 6. Firstly, the measurement was carried out on the samples with h = 1 mm, α = 60 ° when monitoring the welding speed. The decrease in the joint strength was the least noticeable at very low welding speeds of v_w = 0.5-0.8 mm/s or conversely at very high ones of v_w = 1.6-2 mm/s. The highest value of tensile force was F_t = 1243 N at welding speed of v_w = 0.5 mm/s, welding time of t_w = 2 s and the lowest value was F_t = 612.3 N at welding speed of v_w = 1.8 mm/s, welding time of t_w = 0.56 s. In the vicinity of welding speed of 1 mm/s, had the largest

change in the joint strength. The change in welding speed of v_w =±0.2 mm/s in this region caused an increase in the joint strength by 17 % and a decrease by 20 % respectively. When welding speeds were greater than v_w = 1.6 mm/s, there was almost no change in the joint strength. The difference in strength between the speeds of v_w = 1.6 mm/sand 2 mm/s was 2 %.

Table 6. Welding parameters during monitoring of welding speed for samples with h = 1 (mm), α = 60 (°)

Parameter	Value
Frequency (kHz)	20
Amplitude (%)	100
Trigger force (N)	50
Welding speed (mm/s)	0.5-2
Holding time (s)	1
Welding distance (mm)	1
Welding time (s)	0.5-2

Table 7. Welding parameters during monitoring of welding speed for samples with h = 0.65 (mm), α = 75 (°)

Parameter	Value
Frequency (kHz)	20
Amplitude (%)	100
Trigger force (N)	50
Welding speed (mm/s)	0.2-1.2
Holding time (s)	1
Welding distance (mm)	0.6
Welding time (s)	0.5-3

Secondly, monitoring of the welding speed was continued by changing the test samples with geometry of energy director as follows : height of h = 0.65 mm, angle of α = 75 °. The welding parameters for this case were shown in Table 7. The effect of welding speed on the joint strength was clearly visible. The greatest joint strength was achieved at the lowest welding speed, meaning the longest cycle time and contrarily. The highest value of tensile force was F_t = 917.5 N at welding speed of v_w = 0.2 mm/s, welding time of t_w = 3 s and the lowest value was F_t = 542 N at at welding speed of v_w = 1.2 mm/s, welding time of t_w = 0.5 s. The increase in strength was not uniform, extending the welding time from t_w = 1 s to 2 s caused increase in strength by 25 %, whereas a futher extension of welding time by t_w = 1 s caused rising in the joint strength by 14 %. At welding speeds corresponding to welding time of t_w = 1±0.25 s, the joints showed almost the same strength, the difference between speed of v_w = 0.5 mm/s and 0.8 mm/s was 8 %. A further increase in welding speed by v_w = 0.2 mm/s resulted only in a slight decrease in strength by about 2-6 %.

One of the main advantages of Dukane 43S220 iQ Series ultrasonic welder is Melt-Match technology, which can be welded by both constant welding speed and variable speed during welding (speed profile). The speed profile can be programmed at 10 intervals during one welding cycle, whereas various values can be set for each interval. The result is production of stronger joints using lower energy in comparison with pneumatic systems. The measurement was only carried out on the samples with h = 1 mm, α = 60 ° when monitoring the speed profile. The welding parameters for this case were shown in Table 8. A total of 18 speed profiles were programmed to achieve the welding time of t_w = 1 s. However, only three profiles (13, 14 and 16) were selected from the analyzed speed profiles, which showed maximum joint strengths. The setting of individual speed intervals was shown graphically in Figure 5. In the beginning of welding cycle, very low welding speeds were programmed, namely v_w = 0.2 and 0.3 mm/s. Gradually, the speeds were increased until reaching the maximum values of v_w = 2.5 and 3 mm/s at the sixth and seventh interval, respectively. At the end of the cycle, the energy director was fully melted and the speeds were again reduced to v_w = 1 and 1.5 mm/s at the ninth and tenth interval, respectively. The first highest

Table 8. Welding parameters during monitoring of speed profile

Parameter	Value
Frequency (kHz)	20
Amplitude (%)	100
Trigger force (N)	50
Welding speed (mm/s)	profile
Holding time (s)	1
Welding distance (mm)	1
Welding time (s)	1

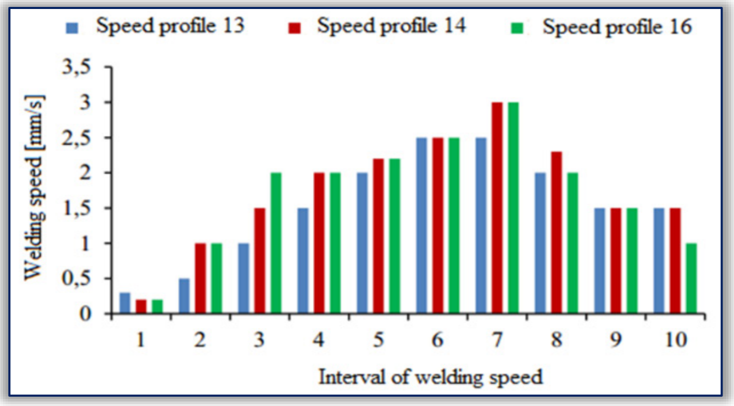


Figure 5. The three best speed profiles exhibiting the highest joint strengths

value of tensile force was F_t = 1662.1 N at the sixteenth speed profile, the second one was F_t = 1652.3 N at the fourteenth speed profile and the third one was F_t = 1639.7 N at the thirdteenth speed profile. The joint strengths were almost identical.

4. CONCLUSION

In the ultrasonic welding, a hydraulic brake was used to ensure a constant welding speed, which was recommended to improve the welding process owing to the effect of ensuring constant melting of the weld area. An increase in degree of braking, caused reduction in welding speed, which was expected. On the other hand, the welding speed was increased by increasing the welding pressure at a constant degree of braking and thus resulted in a decrease in the joint strength. This trend took place up to a certain pressure, where stabilization of speed occurred. In addition, the experimental measurements showed a decrease in the joint strength in dependence on increasing the filler concentration and a slight increase in strength of the filled material. The effect of filler on damaging the contact area of the workpieces from the horn was not significant. The further main factor affecting the properties of joint was geometry of energy director, namely height 'h' and angle 'α'. In the welding process, the volume of energy director should be large enough to cover the contact area of the workpieces as large as possible after melting, and certainly without the flash out of the joint. Finally, the ultrasonic welding parametrs are the most important factors affecting the quality and the joint strength. Extending welding time above the optimum value resulted in the flash around the circumference of the weld. However, the joint strength was not increased. The lower the welding speed, the more time the melt had to achieve a perfect spread over the weld area and thus the joint strength was increased. The welding pressure had the largest effect on the quality of joint. Good welding results were achieved by using lower values of welding pressure. Choosing the holding time and pressure to achieve a high-quality joint had also proved to be important. The holding time and pressure must be sufficient to provide optimal strengthening of the material and solidification of the melt. However, when using high values, could result in high internal tension and thus reducing the joint strength.

The further research directions at our department will be ultrasonic welding of thermoplastics reinforced with natural fibers such as jute, kenaf, flax, etc. The test samples with different energy directors will be fabricated by using injection moulding and then be welded under various welding conditions. Subsequently, the obtained results will be used to evaluate the effect of the main factors on the joint strength and the resulting dimension of workpiece after welding. In addition, the experimental temperature distributions during welding process will be measured by using thermocouples positioned at different points on the workpiece and the obtained results will be compared with the ANSYS simulation results.

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