

A Review of Studies on Ultrasonic Welding

Thang Nguyen Vo¹ and Petr Lenfeld²

^{1,2}Department of Engineering Technology, Technical University of Liberec, Czech Republic

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

I. 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.

II. 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 Fig. 1 [1].

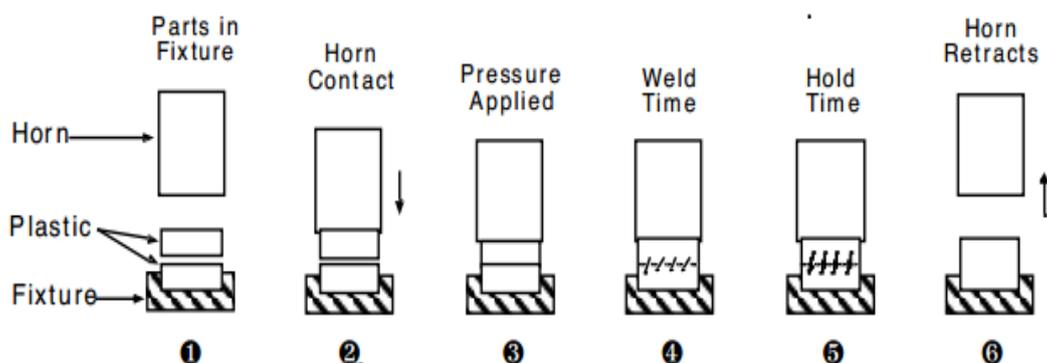


Fig. 1. Phases of ultrasonic welding

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 occurred, 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.

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].

III. 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 Fig. 2). 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 $A_w = 45 \mu\text{m}$ 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 $A_w = 45 \mu\text{m}$ 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.

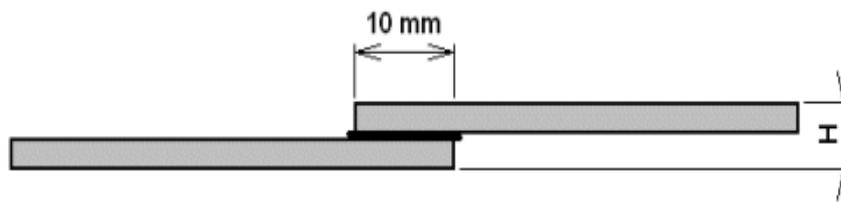


Fig. 2. Dimension of joint H after welding

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 $A_w = 45 \mu\text{m}$ 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

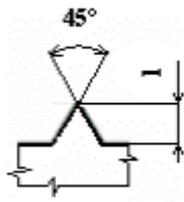
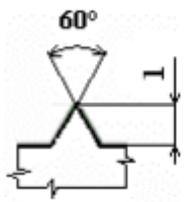
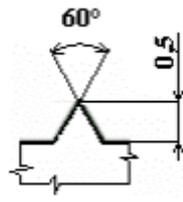
always extended by 1 s. The measured results showed that the highest mean value of the joint strength and the best resulting dimension of workpiece were $R = 965 \text{ N}$ and $H = 8.13 \text{ mm}$ at $t_h = 8 \text{ s}$, respectively. The effect of holding time on the melt at the interface was apparent. 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 $p_w = 1 \text{ kPa}$, maximum welding time of $t_w = 7 \text{ s}$, holding pressure of $p_h = 200 \text{ kPa}$, holding time of $t_h = 8 \text{ s}$ and welding amplitude of $A_w = 25\text{-}45 \text{ }\mu\text{m}$ with a step of $5 \text{ }\mu\text{m}$. The measured results showed that the highest mean value of the joint strength and the best resulting dimension of workpiece were $R = 965 \text{ N}$ and $H = 8.13 \text{ mm}$ at $A_w = 45 \text{ }\mu\text{m}$, 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 Frejtoová [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 $h = 1 \text{ mm}$, angle of energy director $\alpha = 45^\circ$, welding time of $t_w = 1 \text{ s}$, welding pressure of $p_w = 23 \text{ kPa}$, pressure during cooling of the joint $p_c = 70 \text{ kPa}$, cooling time of the joint $t_c = 1 \text{ s}$, welding amplitude of $A_w = 85 \text{ }\mu\text{m}$ and welding frequency of $f_w = 20 \text{ kHz}$ was $R = 46.69 \text{ MPa}$. The lowest mean value of tensile strength was achieved by pure copolypropylene at the following welding parameters : height of energy director $h = 0.5 \text{ mm}$, angle of energy director $\alpha = 60^\circ$, welding time of $t_w = 1 \text{ s}$, welding pressure of $p_w = 23 \text{ kPa}$, pressure during cooling of the joint $p_c = 80 \text{ kPa}$, cooling time of the joint $t_c = 1 \text{ s}$, welding amplitude of $A_w = 80 \text{ }\mu\text{m}$ and welding frequency of $f_w = 20 \text{ kHz}$ was $R = 26.15 \text{ MPa}$. 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 $R = 42.8 \text{ MPa}$ at $h = 1 \text{ mm}$ and $\alpha = 45^\circ$.

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.

Tab. 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 $p_w = 15 \text{ kPa}$ and

welding amplitude of $A_w = 100 \mu\text{m}$ caused decrease in the welding speed v_w (the arithmetic average of the mean values from all series was between $v_w = 1.29 \text{ mm/s}$ at $K = 3$ and $v_w = 0.097 \text{ mm/s}$ 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 $P_w = 321 \text{ W}$ at 6 wt% of nanoclay and a minimum mean value was $P_w = 367 \text{ W}$ 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 $E_w = 114.1 \text{ J}$ at $K = 3$ to $E_w = 1082.9 \text{ J}$ 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 $F_d = 625.4 \text{ N}$ for unfilled homopolypropylene at $K = 15$ and $F_d = 122.3 \text{ N}$ 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 $p_w = 15 \text{ kPa}$ to 600 kPa at a constant degree of braking ($K = 3$) and welding amplitude of $A_w = 100 \mu\text{m}$, it caused increase in the welding speed. The arithmetic average of the mean values from all series was between $v_w = 1.29 \text{ mm/s}$ at $p_w = 15 \text{ kPa}$ and 2.553 mm/s at $p_w = 600 \text{ kPa}$. 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 $P_w = 596.5 \text{ W}$ for unfilled homopolypropylene at $p_w = 600 \text{ kPa}$ and $P_w = 320.5 \text{ W}$ for homopolypropylene with 6 wt% of nanoclay at $p_w = 15 \text{ kPa}$. The mean value of the welding energy decreased with increasing welding pressure. With increasing concentration of nanoclay occurred a slight decrease in mean value of welding energy except energy at $p_w = 15 \text{ kPa}$. The mean value of the welding energy decreased from a value of $E_w = 109.3 \text{ J}$ for unfilled homopolypropylene to a value of $E_w = 55.9 \text{ J}$ 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 $F_d = 271.4 \text{ N}$ for unfilled homopolypropylene at $p_w = 15 \text{ kPa}$ and $F_d = 77 \text{ N}$ for homopolypropylene with 6 wt% of nanoclay at $p_w = 600 \text{ kPa}$.

Determination of the effect of amplitude when welding homopolypropylene with various concentrations of nanoclay was performed at $A_w = 70 \mu\text{m}$ and $100 \mu\text{m}$ under the following welding conditions : $K = 3$, $p_w = 50 \text{ kPa}$; $K = 6$, $p_w = 15 \text{ kPa}$ and $K = 9$, $p_w = 15 \text{ kPa}$. 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 $v_w = 0.352 \text{ mm/s}$. 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 $A_w = 100 \mu\text{m}$ and $70 \mu\text{m}$ for 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 $A_w = 70 \mu\text{m}$ and 2.57 at $A_w = 100 \mu\text{m}$. 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 $A_w = 100 \mu\text{m}$ and $70 \mu\text{m}$ 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 6 wt% was 3.37 at $A_w = 70 \mu\text{m}$ and 1.98 at $A_w = 100 \mu\text{m}$. 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 $A_w = 100 \mu\text{m}$ and $70 \mu\text{m}$ 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 $A_w = 70 \mu\text{m}$ and 2.21 at $A_w = 100 \mu\text{m}$. 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 $A_w = 100 \mu\text{m}$ and $70 \mu\text{m}$ 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 $A_w = 70 \mu\text{m}$ and 1.49 at $A_w = 100 \mu\text{m}$. 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 $A_w = 100 \mu\text{m}$ and $70 \mu\text{m}$ 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 $A_w = 70 \mu\text{m}$ and 1.16 at $A_w = 100 \mu\text{m}$. 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 $A_w = 100 \mu\text{m}$ and $70 \mu\text{m}$ 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 $A_w = 70 \mu\text{m}$ and 1.08 at $A_w = 100 \mu\text{m}$. 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 $A_w = 100 \mu\text{m}$ and $70 \mu\text{m}$ for individual concentrations of nanoclay ranged from 1.31 to 1.48.

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 $\alpha = 60^\circ$ and height of $h = 0.65$ mm, angle of $\alpha = 75^\circ$. Firstly, the measurement was carried out on the samples with $h = 1$ mm, $\alpha = 60^\circ$ when monitoring the trigger force. The welding parameters for this case were shown in Tab. 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.

Tab.2. Welding parameters during monitoring of trigger force for samples with $h = 1$ [mm], $\alpha = 60$ [°]

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

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 $\alpha = 75^\circ$. The welding parameters for this case were shown in Tab. 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 %.

Tab.3. Welding parameters during monitoring of trigger force for samples with $h = 0.65$ [mm], $\alpha = 75$ [°]

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

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, $\alpha = 60^\circ$ when monitoring the welding amplitude. The welding parameters for this case were shown in Tab. 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.

Tab.4. Welding parameters during monitoring of welding amplitude for samples with $h = 1$ [mm], $\alpha = 60$ [°]

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

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 $\alpha = 75^\circ$. The welding parameters for this case were shown in Tab.

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.

Tab.5. Welding parameters during monitoring of welding amplitude for samples with $h = 0.65$ [mm], $\alpha = 75$ [°]

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

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 Tab. 6. Firstly, the measurement was carried out on the samples with $h = 1$ mm, $\alpha = 60$ ° 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 $v_w = \pm 0.2$ 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/s and 2 mm/s was 2 %.

Tab.6. Welding parameters during monitoring of welding speed for samples with $h = 1$ [mm], $\alpha = 60$ [°]

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

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 $\alpha = 75$ °. The welding parameters for this case were shown in Tab. 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 $t_w = 1 \pm 0.25$ 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 %.

Tab.7. Welding parameters during monitoring of welding speed for samples with $h = 0.65$ [mm], $\alpha = 75$ [°]

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

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 $h = 1 \text{ mm}$, $\alpha = 60^\circ$ when monitoring the speed profile. The welding parameters for this case were shown in Tab. 8. A total of 18 speed profiles were programmed to achieve the welding time of $t_w = 1 \text{ s}$. 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 Fig. 3. 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 value of tensile force was $F_t = 1662.1 \text{ N}$ at the sixteenth speed profile, the second one was $F_t = 1652.3 \text{ N}$ at the fourteenth speed profile and the third one was $F_t = 1639.7 \text{ N}$ at the thirteenth speed profile. The joint strengths were almost identical.

Tab.8. Welding parameters during monitoring of speed profile

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

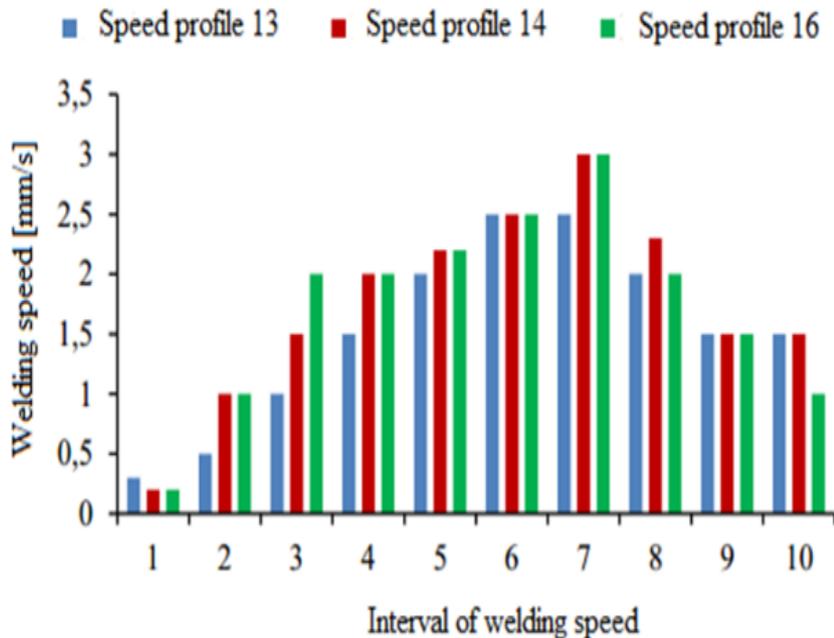


Fig. 3. The three best speed profiles exhibiting the highest joint strengths

IV. 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 parameters 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.

ACKNOWLEDGEMENT

This paper was written at the Technical University of Liberec as part of the Student Grant Contest "SGS 21122" with the support of the Specific University Research Grant, as provided by the Ministry of Education, Youth and Sports of the Czech Republic in the year 2017.

REFERENCES

- [1] Information on <https://www.dukane.com/us/Documents/DesignGuides/Guide%20To%20US%20Plastic%20Assembly.pdf>
- [2] PDL, Handbook of Plastics Joining: A Practical Guide. Plastics Design Library of William Andrew, New York, p. 44, 1997.
- [3] J. Gürtler, Influence of technological parameters of ultrasonic welding on strength of weld joint, Technical University of Liberec, (Master thesis), 2007.
- [4] L. Frajtoová, Ultrasonic welding of the long-fibres PP composites, Technical University of Liberec, (Ph.D. thesis), 2009.
- [5] D. Hušek, Ultrasonic welding of polypropylene with nanoclay filler, Technical University of Liberec, (Ph.D. thesis), 2011.
- [6] D. Kopáč, Monitoring of welding parameters during ultrasonic welding of polyamide, Technical University of Liberec, (Ph.D. thesis), 2012.