doi: 10.18323/2782-4039-2023-1-57-67

Statistical dependences of influence of ultrasonic exposure time on the strength and other parameters of a polypropylene welded joint

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Received 30.06.2022 *Accepted 21.03.2023*

Abstract: Polypropylene is one of the most popular thermoplastic materials used in industry. To produce goods from this material, the ultrasonic welding method is often used. However, despite a large number of scientific papers, the influence of some parameters of the ultrasonic welding mode on the strength characteristics of polypropylene joints remains unstudied. The paper presents the results of experimental studies of contact spot ultrasonic welding of plates 3 mm thick made of 01003-26 grade polypropylene. The authors considered the process of gradual penetration of the ultrasonic tool working face into polypropylene to a depth equal to the total thickness of the welded plates. Statistical dependences of the depth of the tool face penetration into the material and the force of material separation on the ultrasound exposure time are obtained. The influence of the depth of the ultrasonic tool working face penetration on the tearing force of welded specimens is determined. A significant increase in the tearing force from 150 to 400 N was found at the tool penetration depth of more than 3.5 mm due to an increase in the nominal area of mutual mixing of the material between the welded plates caused by the flow of molten material into the gap. The authors proposed a hypothesis about the flow of the molten material in the direction opposite to the direction of penetration of the working tool by forming traveling Rayleigh waves. However, its confirmation requires additional studies of the influence of the ultrasonic welding mode parameters and the size of the gap between the parts to be joined on the rate of the molten material flow into the gap.

Keywords: ultrasonic welding of plastics; polypropylene; welded joint strength; welding tool working part; ultrasonic welding time; depth of penetration of an ultrasonic tool face.

For citation: Murashkin S.V., Selivanov A.S., Spiridonov N.G., Savina E.B. Statistical dependences of influence of ultrasonic exposure time on the strength and other parameters of a polypropylene welded joint. *Frontier Materials & Technologies*, 2023, no. 1, pp. 57–67. DOI: 10.18323/2782-4039-2023-1-57-67.

INTRODUCTION

Today, various polymeric materials begin actively to displace metals due to some of their technical and economic indicators. First of all, this refers to significant corrosion resistance, high mechanical properties at a relatively low density and lower cost than that of metals and alloys [1; 2]. According to the scale of production, among thermoplastic polymeric materials, which are characterized by the ability to pass when heated to a viscous and then liquid state, polyolefins occupy the leading place. This group includes low-density and high-density polyethylene, polypropylene, etc. In terms of the production growth rates, these materials surpass all other polymeric materials, and at present, polyethylene ranks first in world production, and polypropylene is the fourth [3]. The mass use of polyolefins for manufacturing various products involves the improvement of technological processes for their joining. Ultrasonic welding of polymeric materials remains one of the most popular methods for joining parts when assembling products and building structures [4; 5].

However, due to the complexity of ultrasonic equipment and ignorance of the influence of various welding mode parameters and additional factors (welding time, welding force, substrate material, soaking time, energy concentrator shape, etc.) on the strength characteristics of a resulting joint, manufacturers of plastic goods made of polypropylene and polyethylene encounter the problems of determining the ultrasonic welding optimal modes, which would provide the required strength indicators of a finished product.

The studies presented in [6] are aimed at searching for optimal modes of ultrasonic welding of polypropylene. The authors emphasize the influence of variable welding parameters, namely, welding time, soaking time, and vibration amplitude, on the strength characteristics of H110MA grade polypropylene specimens. Based on the results of the experiments, the optimal values of technological variables were determined to ensure maximum tearing strength: the welding time – 1200 ms, the soaking time – 900 ms, and the vibration amplitude – 75 %.

In [7], the optimal modes for ultrasonic welding of polypropylene filled with 10 % glass fiber were found.

The results of the experiments showed that the maximum breaking force of about 2.3 kN is achieved with a welding force of 1.5 bar, a vibration amplitude of 32 microns, and a welding time of 0.4 s.

The authors of [8] investigate the influence of the amplitude and welding time on the strength characteristics of polypropylene, arguing that they are the most important parameters of the weld joint strength. Ultrasonic welding of the specimens was performed using a pyramidal energy concentrator, which made it possible to ensure the welded joint shear strength equal to 22.36 MPa (319 % of the initial strength).

The authors of [9] state that it is the shape of the energy concentrator that has the greatest effect on the strength of the joint, and the pyramidal energy concentrator allows obtaining the most durable joint made of pure polypropylene.

In the work [10], the authors state that the main factors affecting the strength of a welded joint made of polypropylene are the welding time and the welding force. According to the results of the experiments, it was found that the welding time of less than 2 s and the welding force of less than 2 N do not provide a monolithic joint, and the welding time of 8 s and the welding force of 8 N lead to the formation of pores and defects in the weld. The optimal modes for ultrasonic welding of polypropylene specimens with a thickness of 4 mm are: the welding time is 4–6 s, the welding force is 5–7 N.

The authors [11] believe that the level of deterioration in the mechanical and thermal properties of polypropylene goods after ultrasonic welding depends on the change in the crystalline structure, glass transition temperature, and the weight loss, since polypropylene undergoes crystal reorientations during melting. As a result, a phase is formed that has an intermediate crystalline order and differs from the normal phase. After welding polypropylene, the glass transition temperatures tend to change from 5 to 10 K/min.

Studies allowing a more detailed understanding of the degree of impact of ultrasonic vibrations on the polypropylene structure are presented in [12]. The authors identified that after ultrasonic welding, the strength of welded joints after 300–600 h of aging reaches 90–100 % of the base material strength. However, significant strength instability is observed, which can be traced even on one product, when the strength of various sections of a weld ranges from 50 to 100 % of the base material strength. It is explained by complex wave processes during the ultrasound propagation in welded plastic parts, which leads to an uneven change in the structure of the weld material [13].

A more detailed analysis of the effect of ultrasonic vibrations on the formation of a polypropylene welded joint using modern techniques, such as differential scanning calorimetry, thermogravimetric analysis, Fourier transform infrared spectroscopy, and scanning electron microscopy, was carried out in [14]. The analysis of the degree of stretching of samples after ultrasonic welding allowed concluding that an increase in the main parameters of the process (pressure, time, and vibration amplitude) leads to an increase in the strength of the weld, to the contrary, a decrease in plasticity was noted. Using scanning electron microscopy, the authors revealed the formation of voids, which is closely correlated with the amplitude of vibrations.

The works [15–17] present evidence that the strength of a welded joint during ultrasonic welding directly depends on the amount of melt located between the contact surfaces. In this case, the amount of melt is determined by a whole complex of ultrasonic welding modes and depends on the amplitude and frequency of vibrations, welding force, the depth of the coupler end face penetration into the material, the time of exposure to ultrasound, and other parameters [18].

Based on the analysis of scientific publications, it can be concluded that the influence of welding time, vibration amplitude, welding force, energy concentrator geometry on the strength characteristics of polypropylene samples and the structure of the resulting weld is well studied in the literature. All these factors directly determine the amount of melt formed between the parts during the welding process. However, the amount of melt in the gap is also influenced by the working tool end face penetration depth, which directly depends on the time of exposure to ultrasound. This issue has not been addressed in the scientific literature.

The study aims at the improvement of the strength of polypropylene welded joints obtained in the process of ultrasonic welding by adjusting the time of exposure to ultrasound on the welding zone and the depth of penetration of the welding coupler end face into polypropylene.

METHODS

Ultrasonic welding of samples was carried out using a technological complex for ultrasonic welding of plastics consisting of a welding device and an UZG-2M ultrasonic generator. The device for ultrasonic welding consists of an ultrasonic vibrating system (USVS) placed inside a metal case. The ultrasonic vibrating system contains a magnetostriction converter of electrical energy into the energy of mechanical extension vibrations and an ultrasonic coupler rigidly connected to the end face of the converter. The ultrasonic coupler working part has the form of a cylindrical rod with a flat end 5 mm in diameter.

The ultrasonic welding technological complex was installed on an FHV-50PD universal milling machine using specially designed equipment. The equipment includes:

– a device for orienting and fixing sample plates during ultrasonic welding, made in the form of a prism with a square base, on the upper end of which there are two mutually perpendicular slots-lodgments for sample plates;

– a unit for fastening the USW device to the quill of the machine is a bracket with two terminal clamps for clamping the quill and USW device, respectively;

– a device for creating a constant static pressure of the ultrasonic coupler working end face on the welding zone includes a calibrated load mounted to the steering wheel of the lever-rack mechanism of the machine spindle head;

– a device for measuring the pressing force of the ultrasonic coupler working end face to the contact surface of the sample plates consists of a 7039-2023 spring according to the ГОСТ 13165-1967 standard and a rectangular prism with a blind cylindrical hole located in the center of one of its faces.

During calibration, the spring was installed in the prism hole until it stops. The result of the calibration is a straight line equation

$$\Delta(F) = b \cdot F \,, \tag{1}$$

where $\Delta(F)$ – is the dependence of deformation on the force of compression of the spring;
b – is the proportionality coefficient, b=0.122 mm/N;
F – is the spring compression force, N.

Rectangular plates cut from 01003-26 sheet polypropylene 3 mm thick according to the ГОСТ 26996-1986 standard were used as samples (Fig. 1).

Contact spot ultrasonic overlap welding of samples was carried out according to the scheme shown in Fig. 2.

The welding cycle consisted of sequential execution of the following actions:

– applying a constant static pressure P_{st} equal to 1.32±0.10 MPa, which corresponds to a spring compression force F equal to 26±2 N;

– exposure for 3 s for pre-compression of sample plates under pressure P_{st};

– turning on the ultrasonic vibrations (without relieving pressure);

– switching off the ultrasonic vibrations after a time t_i=1.2…3.6 s;

– exposure of the welded joint sample under a pressure P_{st} for 3 s;

– removal of static pressure P_{st}.

The static pressure P_{st} is applied before the ultrasonic vibrations are turned on (the pre-compression time t_{p} is 3 s), it is considered constant throughout the entire welding cycle and is removed with a delay of t_{d}. The delay time is 3 s. The time of exposure to ultrasound t_{i} varies from 1.2 to 3.6 s.

Before the first cycle and every 15 USW cycles, the spring compression deformation was measured and, using the equation (1), the pressing force value was calculated, which was controlled within the specified limits of 26±2 N.

Sample plates having glossy (with low roughness) flat surfaces on both sides (Fig. 1) were installed in the corresponding lodgments (Fig. 3), evenly fixed and pressed together with screws.

The USW mode: generator output power is 330±10 W, amplitude and frequency of vibrations are 67±3 μm and 21915±5 Hz, respectively; the force of pressing the welding tool (WT) working end face to the samples was applied in the direction perpendicular to their joint plane and was maintained within the range of 26±2 N using a calibrated load mounted to the steering wheel of the lever-rack mechanism of the machine spindle head. After each completed cycle, the WT surface temperature was controlled by immersing it for two minutes in a container with cold water, then blown with compressed air at a temperature of 22±2 °C and wiped with a napkin. The time of ultrasound exposure to the welding zone was set according to the generator timer in the range of 1.2...3.6 s with a step of 0.2 s. At each time value, five experiments were performed (five welded joint samples were created). The joint samples were marked with Arabic numerals as they were created (Fig. 3) and prepared for measuring the depth of coupler working end face penetration into polypropylene.

The depth of ultrasonic coupler penetration into the material was measured using a stand equipped with measuring heads of the C-IV ГОСТ 10197-1970 type according to the scheme (Fig. 4). The welded joint thickness H was measured with an ABSOLUTE Digimatic 547-401 thickness gauge having a measurement range from 0 to 12 mm, a resolution of 1 μm, and a precision of ±3 μm.

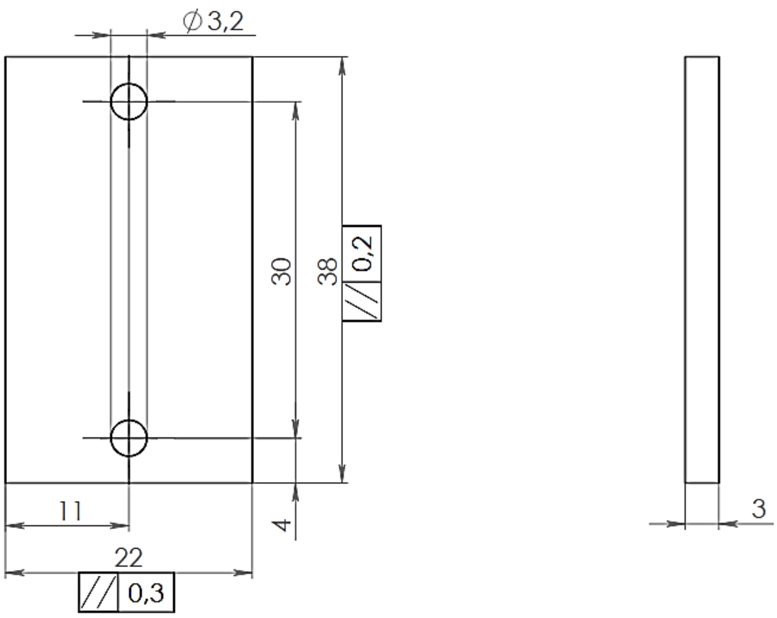


Fig. 1. *A sample plate*
Рис. 1. *Образец-пластина*

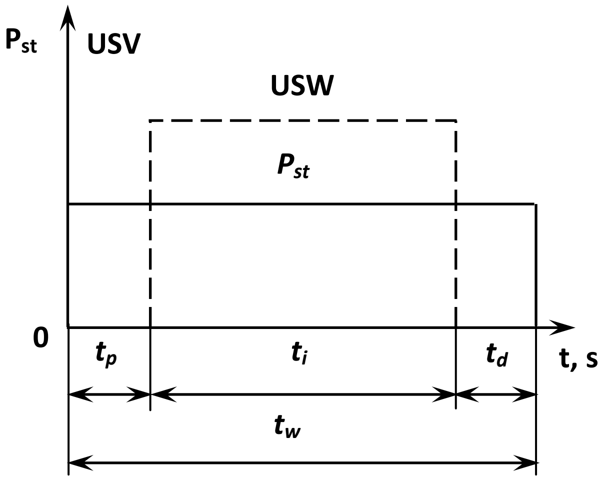


Fig. 2. *"Static pressure – ultrasound" USW working cycle:*
P_{st} – static pressure; USV – the ultrasonic vibrations; t_p – the time of preliminary pressing of samples;
t_i – the ultrasonic vibration exposure time; t_d – the static pressure-off delay time; t_w – the welding time
Рис. 2. *Рабочий цикл УЗС «статическое давление – ультразвук»:*
P_{st} – статическое давление; USV – ультразвуковые колебания; t_p – время предварительного сжатия образцов;
t_i – время воздействия УЗК; t_d – время задержки снятия статического давления; t_w – время сварки

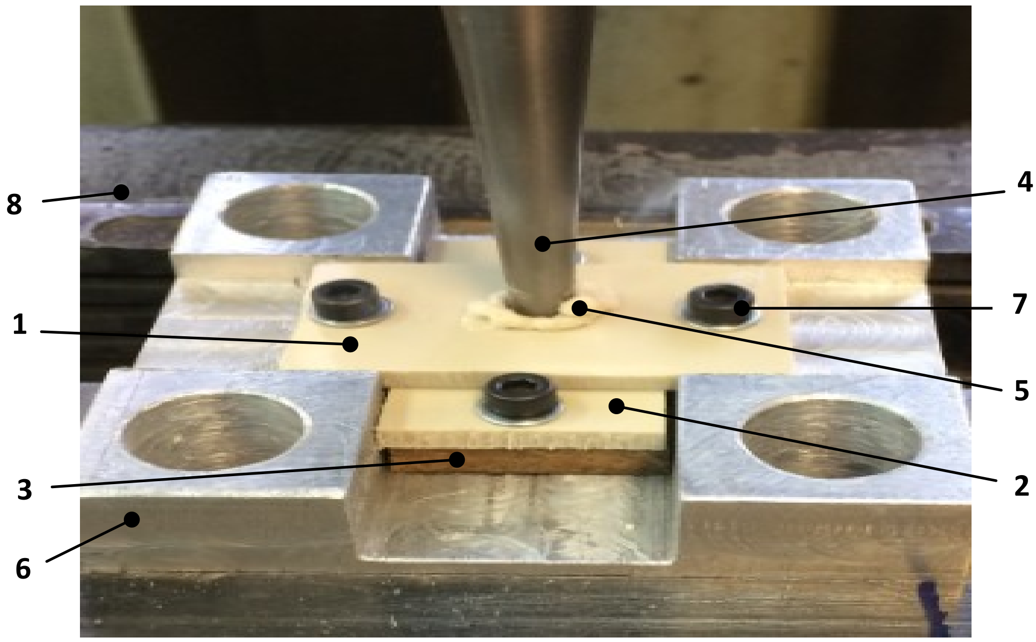


Fig. 3. *The creation of a sample of a polypropylene welded joint on a milling machine:*
1 and 2 – the upper and lower plates-samples respectively; 3 – the heat insulating substrate;
4 – the welding tool; 5 – the overlap of a pressed-out melt;
6 – the lodgments' prism; 7 – screws and washers for sample fixation; 8 – the machine-tool clamps
Рис. 3. *Создание образца сварного соединения полипропилена на фрезерном станке:*
1 и 2 – верхний и нижний образцы-пластины соответственно; 3 – термоизоляционная подкладка;
4 – сварочный инструмент; 5 – наплыв выдавленного расплава;
6 – призма ложементов; 7 – винты и шайбы для крепления образцов; 8 – тиски станочные

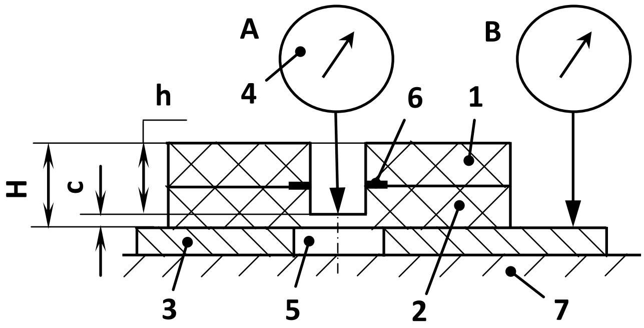


Fig. 4. *The scheme for measuring the thickness of the "bottom" using a C-IV type stand:*
1 and 2 – the upper and lower welded joint plates respectively; 3 – the metal plane-parallel plate;
4 – ICh-10 type detecting head rigidly fixed on the C-IV type stand; 5 – a hole in the plate;
6 – a welded joint; 7 – the support table of the C-IV type stand;
H – total thickness of the plates in a welded joint; h – the depth of WT working face penetration; c – the "bottom" thickness;
A – measurement location; B – the location of "zero" setting
Рис. 4. *Схема измерения толщины «дна» при помощи стойки типа С-IV:*
1 и 2 – верхняя и нижняя пластины сварного соединения соответственно;
3 –металлическая плоскопараллельная пластина;
4 – индикаторная головка типа ИЧ-10, жестко закрепленная на стойке типа С-IV; 5 – отверстие в пластине;
6 – сварной шов; 7 – опорный столик стойки типа С-IV; H – общая толщина пластин в сварном соединении;
h – глубина внедрения рабочего торца СИ; c – толщина «дна»; A – положение измерения; B – положение установки «нуля»

The depth of coupler penetration into the material was determined by the formula (Fig. 4)

$$h = H - c,$$

where h – is the depth of WT working end face penetration into polypropylene, mm;
H – is the total thickness of the plates included in a welded joint, mm;
c – is the "bottom" thickness, mm.

The welded specimens were tested for tensile strength in accordance with the ГОСТ Р 55142-2012 standard after their holding for 24 h to complete the material polymerization process. The tests were performed on an Instron (USA) 5966 model tensile-testing machine equipped with a force sensor with a measurement range of 10 kN and a measurement tolerance of ±0.5 %. The testing was carried out in the following sequence:

– the tested samples were conditioned for at least 4 h according to the ГОСТ 12423-2013 standard at a temperature of (23±2) °C and relative humidity (50±5) %;

– a welded joint sample was fixed in the device (Fig. 5) and installed in the testing machine so that the upper and lower clamping plates were pressed by the jaws of the machine corresponding clamps;

– the sample was loaded with a tensile force in the direction perpendicular to the joint plane of the welded joint plates, at a speed of 1 mm/min until the plates were completely separated from each other;

the maximum force applied to destruct the welded joint sample was recorded;

– the type of destruction was determined according to the ГОСТ Р 58121.3-2018 standard.

Statistical processing of the measurement results was performed according to the ГОСТ 14359-1969 standard using the STATISTICA software. The MATHCAD software was used to approximate the experimental results and obtain analytical dependencies.

RESULTS

Fig. 6 presents the results of experimental studies of the dependence of the depth of ultrasonic tool end face penetration and the material tearing force on the time of exposure to ultrasound. As follows from the figure, the depth of tool end face penetration is proportional to the time of ultrasound exposure to the welded materials and is determined mainly by the time of melting the material and its displacement under the action of the feed force of the ultrasonic tool. The dependence of the tearing force of the material on the time of exposure to ultrasound has a different nature and is not linear.

Fig. 7 presents a graph constructed according to the experimental values in the "tearing force" – "tool penetration depth" coordinates. As follows from the analysis of the graph, when the tool penetration depth changes to 3.5 mm, the material tearing force changes rather smoothly from 50 to 150 N. With a tool penetration depth of more than 3.5 mm, a significant increase in the tearing force from 150 to 400 N is observed.

During the tests, the authors noted that the deformation in the direction of application of tensile forces increases to the yield point, then almost immediately the destruction of the welded joint occurs. Fig. 8 shows the appearance and the state of the welded joint samples during loading by the tensile force at the moments of its maximum and minimum values. From the figure, it can be observed that at the moment of applying the maximum force, the plates were strongly bent (Fig. 8 a).

The weld is deformed, and with the formation of the neck, the joint is destroyed. The type of fracture is

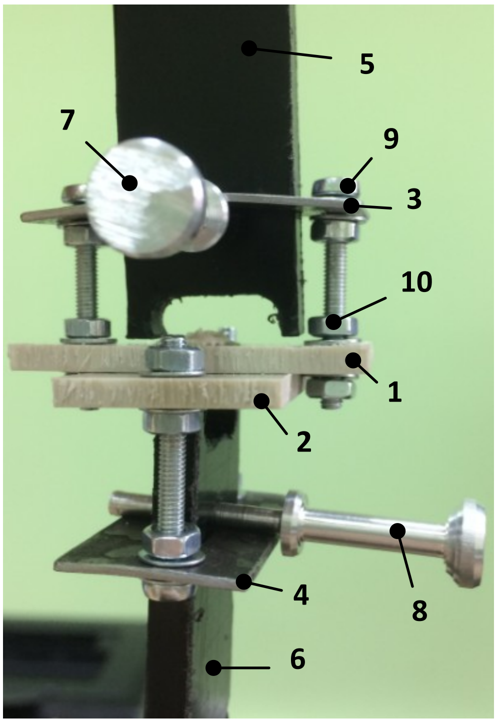
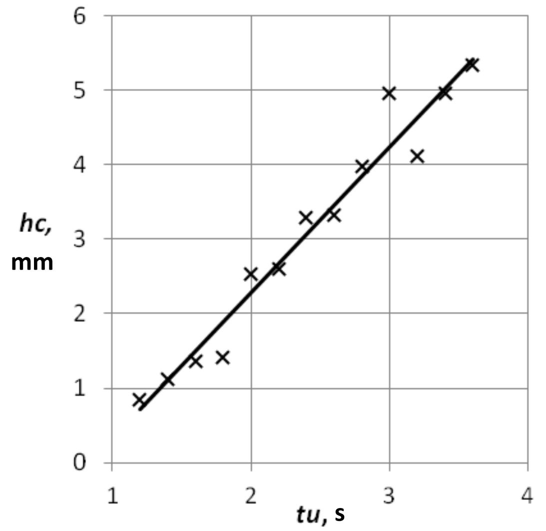
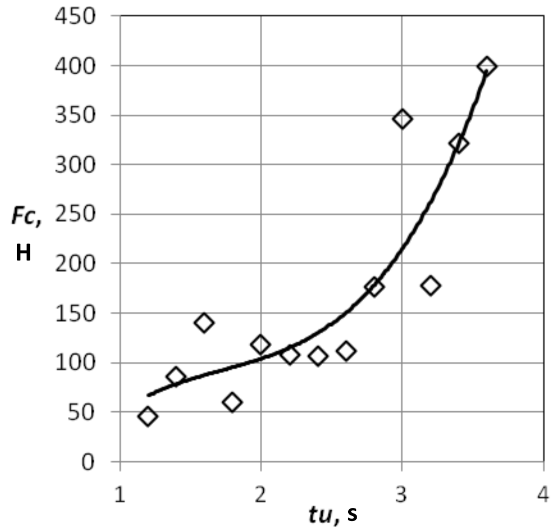


Fig. 5. *A device for fixing a welded joint sample on a tensile testing machine:*
1 and 2 – the upper and lower welded joint plates respectively;
3 and 4 – the upper and lower bearing metal plates; 5 and 6 – the upper and lower locking plates;
7 and 8 – the support pins; 9 – the adjusting screw; 10 – the anchor nuts
Рис. 5. *Приспособление для крепления образца сварного соединения на разрывную машину:*
1 и 2 – верхняя и нижняя пластины сварного соединения соответственно;
3 и 4 – верхняя и нижняя опорные металлические пластины;
5 и 6 – верхняя и нижняя зажимные пластины;
7 и 8 – опорные пальцы; 9 – регулировочный винт; 10 – крепежные гайки



a



b

Fig. 6. *Experimental values and approximating them graphical dependences*
*of the depth of tool face penetration into the material (**a**)*
*and the force of material separation (**b**) on the ultrasound exposure time*
Рис. 6. *Экспериментальные значения и аппроксимирующие их графические зависимости*
*глубины внедрения торца инструмента в материал (**a**)*
*и усилия отрыва материала (**b**) от времени воздействия ультразвука*

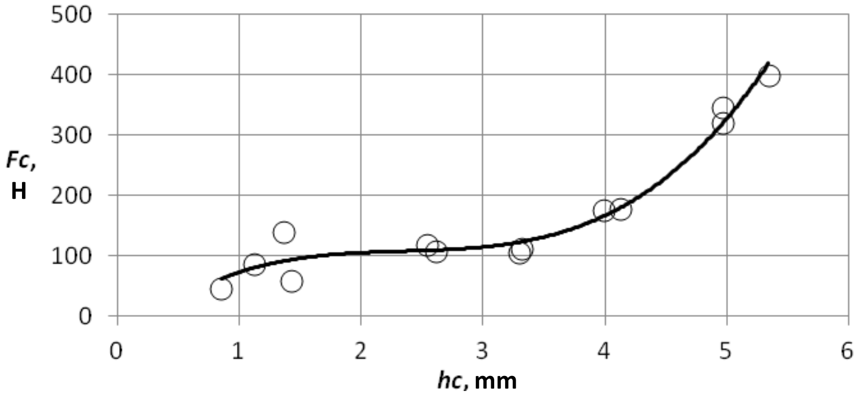
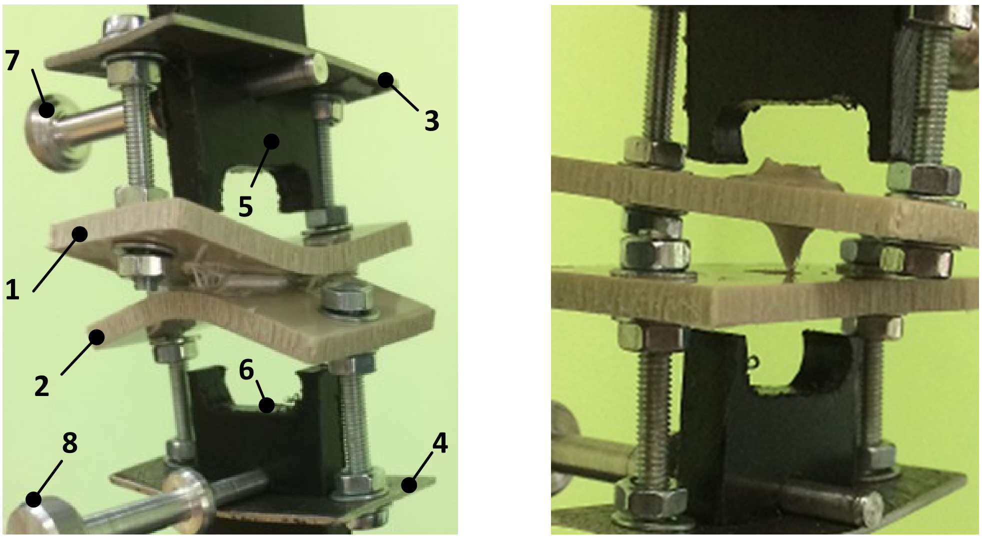


Fig. 7. *Experimental values and approximating them graphical dependence of the force of material separation on the depth of tool face penetration into the material during ultrasonic welding*
Рис. 7. *Экспериментальные значения и аппроксимирующая их графическая зависимость усилия отрыва материала от глубины внедрения торца инструмента в материал при ультразвуковой сварке*



a ***b***

Fig. 8. *The state of the sample during testing:*
a *– at the moment of maximum force tearing the welded joint plates from each other;* ***b*** *– at the moment of tearing off.*
In the figure: 1 and 2 – the upper and lower welded joint plates respectively; 3 and 4 – the upper and lower bearing metal plates; 5 and 6 – the upper and lower locking plates; 7 and 8 – the support pins
Рис. 8. *Состояние образца при испытании:*
a *– в момент максимальной силы, отрывающей пластины сварного соединения друг от друга;* ***b*** *– в момент отрыва.*
На рисунке: 1 и 2 – верхняя и нижняя пластины сварного соединения соответственно; 3 и 4 – верхняя и нижняя опорные металлические пластины; 5 и 6 – верхняя и нижняя зажимные пластины; 7 и 8 – опорные пальцы

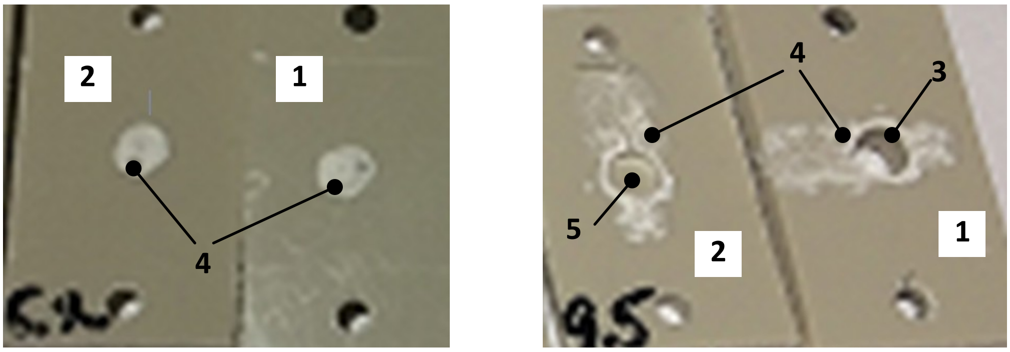
plastic over the entire separation surface. After separation, the tensile force disappears, the bending deformations are removed, and the plates return to their initial position (Fig. 8 b).

The three-dimensional surface, along which the destruction of the welded joint occurs as a result of the separation of the plates from each other, visually represents a group of many pimples and dimples of arbitrary shape and size.

Fig. 9 shows the appearance of the welded joint fracture surfaces for samples when the tool face penetration depth does not exceed the plate thickness (Fig. 9 a) and when it exceeds (Fig. 9 b). In the first case, the tool end face penetration depth is 2.64 mm, the tearing force was 146.80 N, and the fracture surface is limited by a circle with a diameter almost equal to the WT end face diameter. In the second case, the tool end face penetration depth was 3.93 mm, the tearing force was 233.68 N, and the fracture surface diameter was much larger. Fig. 9 b shows traces of the melt flow even beyond the plate.

DISCUSSION

The analysis of the results states that with an increase in the exposure time, an increase in the tearing force occurs which is caused by an increase in the nominal area



a *b*

Fig. 9. *Typical view of the welded joint fracture surface after separation of the plates from each other:*
a *– welded joint sample No. 6.2 (t_i=2.2 s; h=2.64 mm; F=146.80 N);*
b *– welded joint sample No. 9.5 (t_i=2.8 s; h=3.93 mm; F=233.68 N).*
In the figure: 1 and 2 – the upper and lower welded joint plates respectively;
3 – the surface of a through hole formed as a result of WT face penetration to a depth of 3.93 mm;
4 – joint fracture surfaces; 5 – a dimple in the form of a recess hole
Рис. 9. *Характерный вид поверхности разрыва сварного соединения после отрыва пластин друг от друга:*
a *– образец сварного соединения № 6.2 (t_i=2,2 с; h=2,64 мм; F=146,80 Н);*
b *– образец сварного соединения № 9.5 (t_i=2,8 с; h=3,93 мм; F=233,68 Н).*
На рисунке: 1 и 2 – верхняя и нижняя пластины сварного соединения соответственно;
3 – поверхность сквозного отверстия, образовавшегося в результате внедрения торца СИ на глубину 3,93 мм;
4 – поверхности разрыва соединения; 5 – углубление в виде глухого отверстия

of material intermixing. This increase in the strength of welded joints was noted in many works [15–17], however, in them, an increase in the amount of melt occurs due to the application of energy concentrators of various shapes and sizes, which increase the roughness of the surfaces to be joined [18; 19].

In our case, ultrasonic welding of polypropylene plates with a flat glossy contact surface having a low roughness was performed. Taking into account that the thickness of the welded samples was 3 mm, and the tool penetration depth was more than 5 mm, i.e., above the interface between the samples, the increase in the intermixing area, and, accordingly, in the tearing force, can only be associated with the flow of molten material into the gap between the contact surfaces of the specimens to be joined during welding.

Although polypropylene is a polycrystalline material, it is very soft and capable of forming a mechanical surface joint even at poor melting [20]. This provides good adhesion of the molten material in the gap between the surfaces of the plates, and, consequently, an increase in the tearing force. On this basis, it would be very useful to carry out a similar experiment using other materials, for example, an amorphous material such as polystyrene and a harder polycrystalline material such as polyphenylene sulfide.

Moreover, the work did not study the effect of the size of the gap between the parts to be joined on the amount and distribution of the material melt flowing into it, which is of practical interest from the point of view of assembling parts before ultrasonic welding.

The flow of molten polypropylene up the working tool walls in the direction opposite to the direction of its penetration, and the material flow into the gap between the plates being joined, is apparently associated with a decrease in the friction force due to high-frequency vibrations, which contribute to the formation of surface traveling Rayleigh waves. The observed phenomenon can be applied in practice for ultrasonic welding of polypropylene products without using the energy concentrators, which will simplify the design of the parts to be joined, and, consequently the methods of their production. However, this issue requires a more detailed study and determination of quantitative dependences of the material flow rate on the amplitude, vibration frequency, and other ultrasound parameters.

MAIN RESULTS

1. The dependence of the ultrasonic tool end face penetration depth is directly proportional to the time of exposure to ultrasound when welding polypropylene.
2. The dependence of the tearing force of the welded joint of materials welded by ultrasonic with overlap on the time of ultrasound exposure is non-linear and increases sharply when a certain time of ultrasound exposure is reached.
3. With an increase in the depth of the tool end face penetration to the interface between the plates, the strength of a welded joint gradually increases, and beyond the interface, the strength growth rate increases.
4. The welded joint strength increases with an increase in the amount of melt located between the contacting surfaces of the plates.

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Статистические зависимости влияния времени воздействия ультразвука на прочность и другие параметры сварного соединения полипропилена

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Поступила в редакцию 30.06.2022 *Принята к публикации 21.03.2023*

Аннотация: Полипропилен является одним из наиболее востребованных термопластичных материалов, применяемых в промышленности. Для изготовления изделий из данного материала зачастую применяется способ ультразвуковой сварки. Однако, несмотря на большое количество научных работ, влияние некоторых параметров режима ультразвуковой сварки на прочностные характеристики соединений полипропилена остается неизученным. В работе представлены результаты экспериментальных исследований контактной точечной ультразвуковой сварки пластин толщиной 3 мм из полипропилена марки 01003-26. Рассмотрен процесс постепенного внедрения рабочего торца ультразвукового инструмента в полипропилен до глубины, равной общей толщине свариваемых пластин. Получены статистические зависимости глубины внедрения торца инструмента в материал и усилия отрыва материала от времени воздействия ультразвука. Определено влияние глубины внедрения рабочего торца ультразвукового инструмента на усилие отрыва сваренных образцов. Обнаружено значительное увеличение усилия отрыва с 150 до 400 Н при глубине внедрения инструмента свыше 3,5 мм, обусловленное ростом номинальной площади взаимного перемешивания материала между свариваемыми пластинами, вызванного затеканием расплавленного материала в зазор. Предложена гипотеза о течении расплавленного материала в сторону, противоположную направлению внедрения рабочего инструмента, путем формирования бегущих волн Релея. Однако ее подтверждение требует проведения дополнительных исследований влияния параметров режима ультразвуковой сварки и величины зазора между соединяемыми деталями на скорость затекания расплавленного материала в зазор.

Ключевые слова: ультразвуковая сварка пластмасс; полипропилен; прочность сварного соединения; рабочая часть сварочного инструмента; время ультразвуковой сварки; глубина внедрения торца ультразвукового инструмента.

Для цитирования: Мурашкин С.В., Селиванов А.С., Спиридонов Н.Г., Савина Е.Б. Статистические зависимости влияния времени воздействия ультразвука на прочность и другие параметры сварного соединения полипропилена // Frontier Materials & Technologies. 2023. № 1. С. 57–67. DOI: 10.18323/2782-4039-2023-1-57-67.