Dubravko Rogale[1], Snježana Firšt Rogale[1], Željko Knezić[1], Siniša Fajt[2]

Functional relationships between the breaking forces of ultrasonic welds and the speed in relation to the electrical power of the ultrasonic generator

[1]University of Zagreb Faculty of Textile Technology
[2]University of Zagreb Faculty of Electrical Engineering and Computing

Abstract

Welding thermoplastic polymer materials with ultrasonic welding machines (UWM) and an ultrasonic rotary sonotrode (URS) is a high-tech, long-term process welding technology with fast welding speed, high weld breaking forces, low energy consumption, and simplicity of operation. Many writers have concentrated on a few characteristics, primarily the welding duration, welding speed, and ultrasonic generator power. This study present s43 parameters grouped into three categories : polymer material parameters, acoustic parameters and technological parameters. Functional correlations are provided between ultrasonic weld breaking forces and the speed at which specimens are welded utilizing a rotary ultrasonic sonotrode in relation to the electrical power of the ultrasonic generator

***Keywords**: process parameter, welding, ultrasonic, rotary sonotrode*

1. Introduction

Thermoplastic polymer ultrasonic welding is becoming increasingly common. It is characterized by comparatively low energy consumption per welded joint, welding speed, high weld breaking force, ease of use, and environmental friendliness. Airtight and watertight ultrasonic welds can also be approved. Since weld tightness is a critical property, ultrasonic technology is most commonly used for long welds in continuous mode in the manufacture of face masks, protective clothing, disposable hospital gowns, filters, aerospace, sails, marine, automotive and other applications.

The three parameters most frequently discussed in scientific papers are the power of the ultrasonic generator for the URS, the compression force of the URS on the material, and the welding duration.

Many scientists list power welding mode, amplitude, pressure, and URS or anvil gap as welding parameters. E. Sancaktr specifies amplitude, welding speed, power and frequency parameters [1]. Z. Kiss et al. specify amplitude, compression force, frequency and welding time [2]. A. K. Makawana and V. R. Patel specify amplitude, welding pressure, and welding duration as the most important process parameters [3]. W. Shi and T. Little specify welding duration, power, speed, amplitude, and compression force as process parameters [4]. O. Atalay et al. give only strength and compressive force as process parameters [5]. V. N. Kmelev et al [6] provide the greatest overview of the process parameters for the plunge technique, particularly in terms of the thermal characteristics of the materials.

2. Ultrasonic welding parameters

Tab.1 displays the ultrasonic welding parameters of thermoplastic polymer materials. They are thermoplastic polymer material properties, acoustic parameters, and technical parameters that are governed by the UWM.

3. Mathematical correlation of parameters

A counter roller is located at the bottom of the welder and has a specified density of the material from which it is manufactured as well as the speed of sound waves in it. In the URS, ultrasonic vibrations of high intensity are generated to introduce heat into the thermoplastic polymer material. Since reflection occurs at each discontinuity of acoustic impedances encountered by an ultrasonic wave, an ultrasonic wave of intensity is also partially reflected at the discontinuity (URS/material) with an intensity, while a larger part penetrates the material with an intensity of (I_1). Equation (1), proposed by E. Dieulasaint and D. Royer [16], may be used to represent the intensity of the ultrasonic oscillations (I0) of the URS, i.e., the average power of the ultrasonic wave:

$$I_0 = 2 \cdot \pi^2 \cdot f^2 \cdot A_0^2 \cdot Z_0 \qquad (1)$$

where is:

f - frequency of ultrasonic vibrations of the sonotrode [Hz]

A_0 - sonotrode vibration amplitude [m]

Z_0 - acoustic impedance of the ultrasonic rotary sonotrode [kg/m^{2}s]

The ultrasonic power (P_α) developed in the thermoplastic polymer material is calculated by the product of the intensity of the ultrasonic waves converted into the heat of the polymer material (I_α) and the effective area of the URS, which consists of the width (w_s) and length (l_s) of the URS imprint on the polymer material:

$$P_\alpha = I_\alpha \cdot w_s \cdot l_s \qquad (2)$$

When equation (1) is supplemented with the reflection and absorption coefficient, the resulting equation (3) is:

$$P_\alpha = 2 \cdot \pi^2 \cdot f^2 A_0^2 \cdot Z_0 \cdot w_s \cdot l_s \cdot (1-R_1) \cdot (1-e^{-4 \cdot \mu_A \cdot d} + R \cdot e^{-4 \cdot \mu_A \cdot d} - R \cdot e^{-8 \cdot \mu_A \cdot d}) \qquad (3)$$

R_1 – ultrasound intensity reflection coefficient between the URS and the polymeric material to be welded

μ_A – acoustic damping factor of the material [m^{-1}]

d – material thickness [mm]

R – coefficient of reflection of ultrasound intensities on the discontinuity

Tab. 1. The parameters of thermoplastic polymer ultrasonic welding

Ultrasonic welding parameters		
Polymer material parameters	**Acoustic parameters**	**Technological parameters**
1. intensity of ultrasonic oscillations	1. intensity of ultrasonic oscillations	1. frequency of ultrasonic vibrations of the URS
2. reflection of ultrasound pressures coefficient	2. coefficient of reflection of ultrasound pressures	2. specified electrical power of the UWM generator
3. ultrasound intensity absorption coefficient	3. ultrasound intensity absorption coefficient	3. electrical power of the UWM generator
4. ultrasound intensity reflection coefficient between the material to be welded and the counter roller	4. ultrasound intensity reflection coefficient between the material to be welded and the counter roller	4. effective power of the URS
5. ultrasound intensity reflection coefficient between the URS and the material to be welded	5. ultrasound intensity reflection coefficient between the URS and the material to be welded	5. force with which URS act on two layers of thermos-plastic polymer materials with total thickness
6. ultrasound intensity absorption coefficient on the discontinuity of URS/material	6. ultrasound intensity absorption coefficient on the discontinuity of the URS/material	6. specific density of URS material
7. ultrasound intensity absorption coefficient on the material/counter roller discontinuity	7. ultrasound intensity absorption coefficient on the material/counter roller discontinuity	7. speed of ultrasound propagation in the URS
8. functional dependence of the decrease in ultrasound pressure in the material to be welded depending on the thickness of the material	8. functional dependence of the decrease in ultrasound pressure in the material to be welded depending on the thickness of the material	8. URS vibration amplitude
9. ultrasound pressure	9. ultrasound pressure	9. acoustic impedance of the URS
10. functional dependence of the decrease in ultrasound intensity in the material with thickness of the material	10. functional dependence of the decrease in ultrasound intensity in the material with thickness of the material	10. specific material density from which the counter-roller is made
11. coefficient of reflection of ultrasound intensities on the discontinuity	11. coefficient of reflection of ultrasound intensities on the discontinuity	11. speed of ultrasound propagation of the backing material for welding
		12. acoustic impedance of the backing material for welding
		13. URS ultrasound intensity
		14. radius of the URS
		15. width of the URS
		16. length of the imprint of the URS on the material
		17. angular velocity of the rotation of the URS
		18. linear speed of the edge of the URS
		19. ultrasonic welding time depending on the ratio of the length of the imprint of the URS
		20. linear speed of the sonotrode edge
		21. delay time of the start of welding due to heating the beginning of the welded joint

When ultrasonic energy is delivered into a thermoplastic polymeric material for the first time, the temperature begins to rise as the energy is used to raise the temperature of the material from its starting temperature to its melting point. The density of the material (ρ), the thickness of the two layers of material with individual material thickness d, the width (w_s) and length (l_s) of the URS imprint on the polymer material, the specific heat of the material (c), and the difference between the melting temperature and the initial temperature are the factors that determine the energy required to reach the melting temperature of the material [7].

The following is the mathematical equation for heating the material from room temperature to melting temperature:

$$Q_H=2\cdot\rho\cdot d\cdot w_s\cdot l_s\cdot c\cdot(T_2-T_1) \tag{4}$$

The latent melting heat of fusion of the welded polymer material (Q_L) is equal to the product of the density of the material (ρ), the thickness of the two layers of material with individual thickness (d), the width (w_s) and length (l_s) of the URS on the polymer material, and the latent heat of the material (L):

$$Q_L=2\cdot\rho\cdot d\cdot w_s\cdot l_s\cdot L \tag{5}$$

The total heat (Q_T) required for welding polymer materials is the sum of specific heating and latent heat of fusion

$$Q_T=2\cdot\rho\cdot w_s\cdot l_s\cdot[c\cdot(T_2-T_1)+L] \tag{6}$$

where is:

T_1 - ambient temperature and melting temperature

T_2 - melting temperature

The necessary welding time (t) for applying ultrasound to thermoplastic polymer materials is provided by equation (7).

Even after removing some action factors, equation (7) retains great accuracy in terms of practical applicability. The intricate structure of Equation (7) indicates that numerous factors influence the welding of polymeric materials. Ultrasonic welding of polymer materials involves complex interdependencies between technical and technological parameters, which are completely explained and revealed by the equation above and all of its derivatives [7].

Based on experience and experiments, it was found that the most important parameters of the comprehensive model are the specified power of the ultrasonic generator and welding times, while other parameters are required to achieve a certain accuracy of the acoustic mathematical model of ultrasonic welding time.

$$t=\frac{\rho\cdot[c\cdot(T_2-T_1)+L]}{\pi^2\cdot f^2 A_0^2\cdot Z_0\cdot(1-R_1)\cdot(1-e^{-4\cdot\mu_A\cdot d}+R\cdot e^{-4\cdot\mu_A\cdot d}-R\cdot e^{-8\cdot\mu_A\cdot d})} \tag{7}$$

4. Experimental and results

The tests were performed using the Pfaff UWM, model 8310 [17] with URS for welding thermoplastic polymer materials, shown in Fig. 1. An InfiniVisions MSO-X 3024A oscilloscope from Agilent Technologies [18] and an MTI-2100 photon sensor [19] were also used for the measurements. The MTI-2100 photon sensor, a dual-channel optical measurement system that performs non-contact measurements of displacements and vibrations, was used in this work. Displacements ranging from 0.25 nm to 5.08 mm can be measured at frequencies from DC to over 150 kHz. The frequency response ranges from DC to 100 kHz. The typical normal sensitivity of the probes is of the order of 0.025 μm/mV [7].

The properties of the PVC material used are: thickness d = 20 μm; specific heat (at T_1 = 289 K and T_2 = 485 K) c = $1\cdot10^3$ J/mm^{3}K; specific melting heat L=$163\cdot10^3$ J/kg; specific density $\rho_0 = 1.4\cdot10^3$ kg/m^3. PVC foil was used to create 15x50 mm measuring specimens. The aforementioned UWM, which has an adjustable electrical power of the ultrasonic generator of 50 – 100 % , or converted to a power of 200 to 400 W, was used to weld the test specimens. Five welding speeds were also used, including 0.077 m/s, 0.097 m/s, 0.125 m/s, 0.146 m/s, and 0.227 m/s.

The acoustic impedance of the sonotrode $Z_0 = 4.1\cdot10^7$ kg/m^2 s, the acoustic impedance of the material to be welded $Z_1 = 3.2\cdot10^6$ kg/m^{2}s, and the acoustic damping factor of the material $\mu_A = 0.37$ m^{-1}.

The ultrasound intensity reflection coefficient between the material to be welded and the counter roller and the ultrasound intensity reflection coefficient between the URS and the material to be welded amount to 0.73.

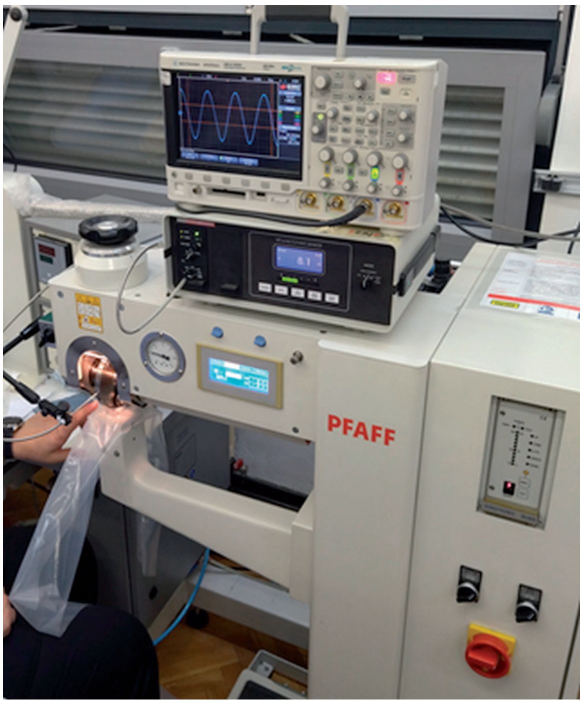

Fig. 1. Measuring set-up on the UWM

The maximum breaking forces (F_p) of the test specimens for the highest welding speeds (0.077 m/s, 0.097 m/s, 0.125 m/s, 0.146 m/s, and 0.227 m/s) are important for validating the mathematical model. For each maximum, the vibration amplitude must be read based on the specified declared power (D_p) of the ultrasonic generator [7]. Based on the data acquired, functional correlations were established between ultrasonic weld breaking forces and the stated claimed power of the ultrasonic generator, as well as the speed at which the specimens were welded with the URS (Fig. 2).

As the applied ultrasonic energy increases, the material melts more and the weld has a larger breaking force. The breaking force of ultrasonic welds first increases as the claimed power of the ultrasonic generator increases. The breaking force can be raised until it reaches its limit, at which point the injected energy becomes too high, resulting in excessive melting of the polymer material, damage to the weld, and a sudden decline in breaking force.

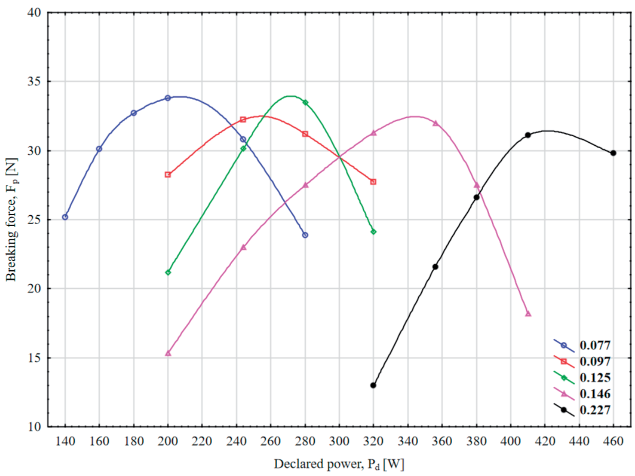

Fig. 2. Functional relationships between the breaking forces of ultrasonic welds and the speed in relation to the electrical declared power of the ultrasonic generator

Fig. 2 shows that the maximum breaking force (F_p) for the polymer material used is between 32 and 34 N for different powers of the ultrasonic generator and welding speeds [7].

5. Conclusion

This study discusses the use of ultrasonic welding. The article presents and discusses the delicate interweaving of technological and technical elements of ultrasonic welding of polymer materials. The optimal welding parameters and typical changes in the functional dependency of breaking forces on the ultrasonic energy introduced into the weld have been determined. The results show that the applied ultrasonic energy resulted in low breaking forces, that there were optimum ranges of applied ultrasonic energy that resulted in maximum joint breaking forces, and that there were ranges with too much applied ultrasonic energy. As a result, the welds deteriorated. The newly established mathematical model and the experimental results agreed well, with minor variations for practical applications.

6. References

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