ARCHIVES OF ACOUSTICS
11, 1, 97-116 (1986)

ASSESSMENT OF ULTRASONIC WELDING PROCESS OF POLYCARBONATE BY EMPLOYING THERMAL EMISSION ANALYSIS

JANUSZ ŁOZIŃSKI

Institute of Fundamental Technological Research Polish Academy of Sciences
00-049 Warsaw, Świętokrzyska 21

The thermal effects of ultrasonic welding of polycarbonate foil were considered. A contactless method of measuring temperature was developed, applying the emission of infrared radiation from the zone welded ultrasonically. The distributions of the thermal emission in the weld zone were observed on the oscilloscope screen and registered by a 16-mm camera, by recording the stages of the process every 1/32 sec.

Measurements were performed of the maximum temperature of the ultrasonic welding zone of the polycarbonate foil for three vibration amplitudes of the wave-guide instrument: 30, 35 and 40 μm. The wave-guide instrument was under static pressure ranging from 4.21 MPa to 9.64 MPa. The tensile strength of the weld was measured. It was shown that the static pressure and the vibration amplitude influence strongly on the contributions of the internal friction and the friction between the faces of welded polymer to the thermal emission observed.

1. Introduction

Despite many investigations undertaken in various scientific centres, polymers ultrasonic welding up to now has not been fully described and explained. The character of the process caused by a strong ultrasonic field is the main difficulty. These effects are nonlinear and the general ultrasonic wave propagation laws in elastic media can not be applied.

Many scientists have applied thermocouples and other thermo-sensitive elements. They introduced them into the weld zone, what falsified the measured values due to a strong ultrasonic field. An additional temperature rise at the boundry of both media was the cause of the falsification.

Due to a mismatch of the acoustical impedance of the detector and the studied medium, absorption and diffraction effects occur, forming a thermal energy source wich adds up with the heat emitted during the propagation of an ultrasonic wave in the investigated polymer. Therefore the readings of the temperature detector are indeterminate resultants falsifying the measurement results.

According to S. S. Wołkow [11], the process of joint forming during ultrasonic welding of plastics can be divided into two stages. In the first stage the materials are heated up, and in the second, joints are formed between the surfaces heated up to a temperature ensuring a visco-fluid state. The forming of these joints condition a uniform connection.

The mentioned above author states, that the maximum welding temperature of polyethylene is 473 K. This author also adds that at this temperature the sample with a thermocouple placed in it was extruded from the weld zone during ultrasonic welding.

Wołkow considers the amplitude damping coefficient β, and not the modulus of elasticity E, as the decisive factor of the ultrasonic welding of polymers. This coefficient characterizes the absorption effect of mechanical vibrations propagating in the medium, and can be defined by the formula:

$$\xi_x = \xi_0 e^{-\beta x}, \tag{1}$$

where ξ_0 and ξ_x – displacement amplitudes for $x = 0$ and a wave propagating along the x axis.

In the above reasoning the author completly overlooks the fact that formula (1) can be applied only for very small amplitudes and for plane waves,

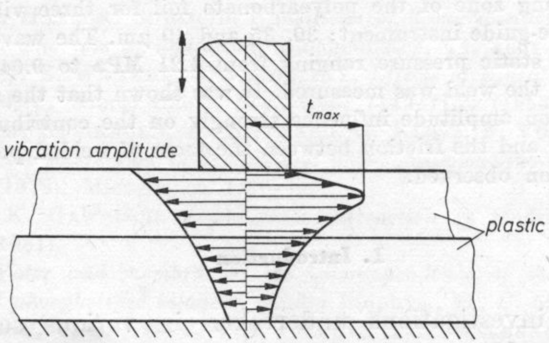

Fig. 1. Distribution of temperature and vibration amplitude in plastic during the process of ultrasonic welding, according to W. A. Neitzert [19]

what is not the case during welding, which is a markedly non-linear process. Wołkow also does not pay any attention to the falsification of the temperature measurement results, what was explained at the begining of the paper.

A very interesting diagram of the temperature distribution in an ultrasonically welded plastic was included in W. A. Neitzerts paper [15]. As it can be seen the greatest temperature rise occurs near the welding instrument.

This work would have been of great significance, because it was a trial of a quantitive localization of thermal emission sources in a polymer under an ultrasonic field. Unfortunately the author does not mention the method of deriving this relation and does not motivate in detail the suggested temperature distribution.

B. MENGES and H. POTENTE [18] have conducted very detailed studies on the ultrasonic field and the energetic processes occuring during ultrasonic welding of thermoplastics. Their paper brings results of experiments on the propagation of an ultrasonic wave in bars made from cold hardened epoxy resin. The photo-elastic method was applied. The geometry of the models was so designed, that a standing wave was formed in them. A significant influence of the length of the bars on the vibration amplitude and the amount of transferred acoustical energy, was found.

The same authors in another paper [14] stated the theoretical foundations, supported by experiments, maintaining that energy transfer in thermoplastic bars depends signiticantly on the length of the system: welded element, support.

Owing to the applied contactless measurement method, the obtained results are objective and constitute a valuable information source for acoustic theory, as well as for designers of thermoplastic fittings appropriate for ultrasonic welding.

The work does not include heat measurements, which would allow the determination of the source position of transfer of ultrasonic wave energy into thermal energy, which is the direct cause of polymer melting and the formation of a stable connection.

Basing on the fundamental dependences of wave motion, J. G. STEGER [19] proves that the air at the end of a wave-guide bahaves as an acoustical isolator for an ultrasonic wave propagating in metals.

Through existing surface roughness, two media adjoin, but the contacting surfaces do not lie perpendicularily to the direction of propagation of the ultrasonic wave. These quantities of the ultrasonic field, acting on every point, have two components. One in the direction tangent to the element surface, the second — perpendicular to it. This effect is summed up on the whole boundary surface, giving a motion component of this surface. This component gives rise to a friction force, called the friction of the boundary surfaces. According to the author, this friction is of a fundamental importance the conversion of the ultrasonic energy into heat. H. POTENTE [16] carried out an analysis of the existing state of information on energy conversions occuring in thermoplastic polymers during ultrasonical welding and reached a conclusion that there is no uniformity of views on this problem. Therefore, theoretical trials of estimating the ultrasonic weldability of thermoplasts should be conducted.

H. Potente criticizes the measurements of the temperature of the weld zone done with the application of thermocouples, as not reproducible. To this aim he uses a set of sensitive to heat points.

His work is particularily valuable, because it contains temperature measurements of the weld zone, done with the application of a more objective method. The shortcoming of this method is the impossibility of conducting temperature measurements in dynamic conditions, i. e. investigating the temperature growth in the weld zone in the course of a 1–2 sec process. But we have to admit, that this method gives much more credible measurement results then those obtained with the application of detectors sunk into the bulk of the welded polymer.

Those, interested in a more detailed discussion of the literature in this domain, may find it in the authors doctors thesis [12].

1. 1. Conclusions of the critical literature survey

On the basis of the mentioned papers it can be concluded that investigating thermal effects in the welded zone are a very important source of information on the process of ultrasonic welding of thermoplasts. But these methods were most frequently based on the temperature measurements done with the aid of thermocouples placed directly in the polymer, being under the influence of an ultrasonic field. Moreover it can be found, that up to now there is no uniform view on the thermal effects taking place during ultrasonic welding of thermoplasts. On one hand, there are trials of explaining thermal energy formation on the basis of sound absorption, namely mechanical losses due to internal friction; on the other hand, some authors consider that the effect consists in the friction of the boundary surfaces in the joint point.

The experimental problem resolves itself into the development of a proper method of measuring the temperature of the weld zone during the welding process. This is a rather difficult problem, because it has to be solved considering the following fundamental conditions:

a) Temperature measurements will be conducted by the contactless method.

b) The reaction of the detector to temperature changes should be possibly immediate.

c) The measurement will be done by succeeding, linear searching of the whole weld zone.

In the last years research has been conducted at the IFTP on the application of infrared radiadion detection in temperature measurements in the zone of ultrasonic welding [1]–[4], [7]–[11] and also the process of welding of thermoplasts was investigated [5], [6].

The method allowed the observation of the thermal effects taking place during the welding process, without an adverse effect of the meter on the studied object.

The intention of the author was to analyse experimentaly the thermal effects occuring in the ultrasonic weld zone and to study the influence of fundamental physical parameters on the technological process of welding of a chosen amorphous polymer on the basis of the obtained results. Furthermore, the author wanted to undertake a trial of explaining the reasons of melting of the polymer during the process of welding. A polycarbonate, i. e. poly (4,4 dioxidiphenyl-2,2 propanocarbonate) was chosen as the subject of investigation. It is a typical amorphous polymer [17], what minimalizes the thermic disturbances, resulting from phase changes of the individual crystalline forms.

In the investigations of the process of ultrasonic welding of a polycarbonate, a polymer in the form of a foil, produced by BAYER, and called *Makrofol N*, was chosen. The thickness of the foil was 0.2 mm.

2. Temperature measurement on the basis of infrared radiation detection

Every body which has a temperature above O K radiates electromagnetically. The intensity and spectrum of this radiation is determined by the Planck law:

$$m_{\lambda cc} = \frac{2\pi hc^2}{\lambda^5 (e^{hc/(\lambda kT)} - 1)}, \tag{2}$$

where $m_{\lambda cc}$ – the power of radiation to a hemisphere of a unit surface, adequate to a unitary interval of wave length, for a given wave length, λ – radiation wave length, h – Planck constant $= 6.6\ 10^{-34}$ Js, T – temperature in K, c – light velocity $= 3 \cdot 10^8$ ms^{-1}, k – Boltzmann constant $= 1.4 \cdot 10^{-23}$ JK^{-1}.

In a general form, the radiation distribution function of a black body, is an equation with three coordinates: λ, $m_{\lambda cc}$ and T.

The total radiation power emitted to a hemisphere by an unitary surface of a black body equals:

$$M_{cc} = \int_0^\infty m_{\lambda cc}\, d\lambda = \sigma T^4, \tag{3}$$

where σ – Stefan constant $= 5.67 \cdot 10^{-8}$ Wm^{-2}K^{-4}.

The power of the emitted radiation is a temperature function, so its measurements can be applied in the contactless method of determining the temperature of the studied object.

Usually the studied object is a real body, in which apart from absorption, transmission and reflection, occur.

Therefore, a method of applying a spectrum, where the thermoplastic foil behaves as a black body, i. e. where the reflection and transmission effects practically do not occur, was chosen. In order to find such a range, a characteristic of the infrared absorption spectrum for a *Makrofol N* polycarbonate foil was made. This spectrum is presented in Fig. 2. There is a narrow range in this spectrum, where the absorption equals 100%, so transmission is 0. According to the KIRCHOFF law, the material will behave as a black body in this range.

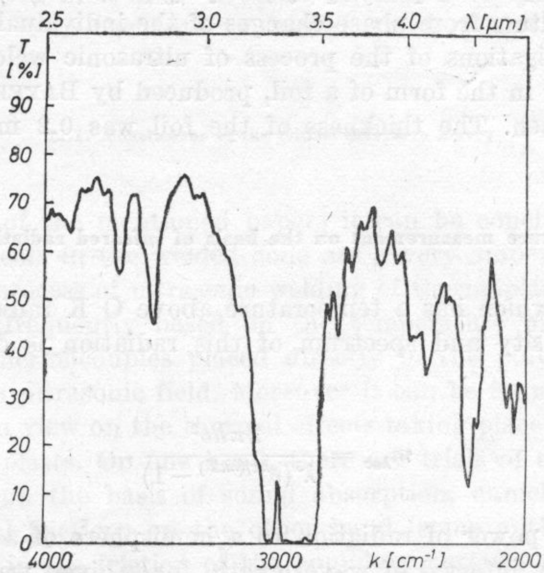

Fig. 2. Characteristic of the *Macrofol N* polycarbonate foil absorption spectrum; T – transmission in %; λ – wave length in μm; k – wave number in cm^{-1}. Beckman Instruments Inc. spectrophotometer

The mentioned conditions are fulfilled for a polycarbonate by the radiation of wave length $\lambda = 3.43$ μm. A signal generated by such radiation on the output of the detector is a function of only the surface temperature of the studied polymer

$$S = F(T_0), \tag{4}$$

where S is the value of the output signal from the detector.

The application of a selective filter, passing the radiation of wave length $\lambda = 3.43$ μm, allowed us to consider the material under research to be a black body.

3. Experimental ultrasonic apparatus and research set-up

The instrument for ultrasonic welding consisted of high frequency ultrasonic lamp generator, which generated a continuous wave of frequency 18.7 kHz, with maximum power of 600 W. The generator with an ultrasonic transducer worked in a feedback loop, securing an automatic tuning during the frequency changes of the free vibrations of the instrument.

The constant time of welding foil samples, equaling 1.3 sec, was ensured by an electronical time-measurer included in the circuit of the generator. It measured time with the accuracy of 0.1 sec.

A nickelic magnetostrictic transducer, connected to a transformer of acoustical vibrations of a sixtuple degree of amplitude transformation, was used as a vibration source.

An aluminium instrument wave-guide was fastened to the acoustical transformer. This wave-guide had a cylindrical section changing into a wegde and with a point at the end, which enables us to obtain a weld of dimensions 1.6 ×10.2 mm.

The process of welding was carried out on a steel support provided with special holders, making spontaneous movement of the foil during the process impossible.

The transfer of the static pressure to the instrument was done with the aid of weights with the accuracy of ±10 g.

The amplitude of the vibrations of the wave-guide tip was accepted as an indicator of the ultrasonic energy supplied to the instrument wave-guide. The amplitude was measured by a capacitive meter of the vibration amplitude [18]. The amplitude was maintained at a constant level for every series of measurements.

In the generator of ultrasonic vibrations an electronic system was applied, which stabilized the amplitude of the vibrations of the welding instrument under load changes of the instrument [20].

4. Experiment methods leading to the determination of the temperature distribution in the weld zone in dynamic conditions

Results of experiments conducted on a model set-up have given rise an idea of adapting a serial thermograph "AGA" for the measurements of thermal emission from the weld zone.

The Swedish thermograph – "AGA" 680, enables, the visualization of the surface distribution of the radiation emitted by the investigated zone.

The characteristic of the spectral transmission of the "AGA" thermograph optic system allows to measure the temperature of the weld in the polycarbonate. In order to take advantage of this feature a special filter was designed and produced. Its pass band lied in the range of total absorption of the polycarbonate. Fig. 3 presents the spectral characteristic of this filter.

The signal at the detector output in the "AGA" thermograph, proportional to the intensity of the infrared radiation, is amplified and utilized to modulate the electron flux in the picture tube. This permits us to obtain on the tube screen the image of the intensity of the infrared radiation emitted by the investigated surface.

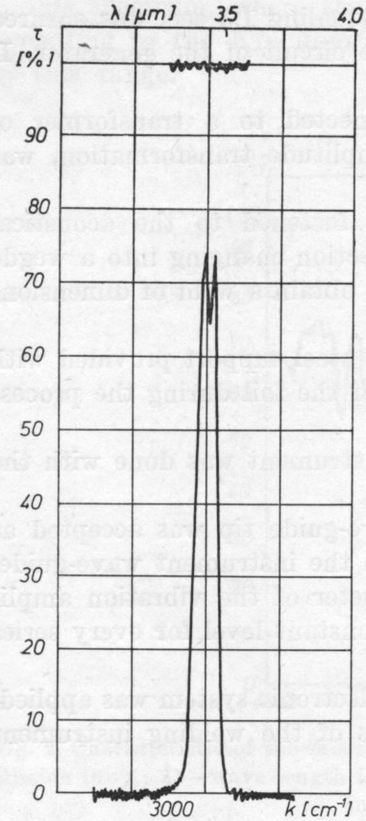

Fig. 3. Characteristic of an infrared filter, being applied in the measurements of the maximal temperature of the ultrasonically welded polycarbonate zone: λ — radiation wave length; k — wave number; τ — radiation transmission

The temperature of the zone very near the object changes in an uncontrol able manner.

This has a significant influence on the signal amplitude at the output of the detector, because the amplitude is a function of the difference between the temperature of the investigated surface of the object and the temperature of the region next to the object. In order to slove this problem, a resistance wire with a constant temperature is introduced in to the field of view of the camera. A holder for the resistance wire is fastened to the support appropriated for sample welding. A signal from the thermistor, fixed to the surface of the wire, controlled the supply source of the wire in such a manner, that the temperature of the wire was constant during temperature changes of the surroundings – negative feedback. The wire can be deflected, what secures a constant distance of the edge of the foil mounted in the holders. In a position ready for measurement, the wire was 0.4 mm away from the bottom edge of the foil layer lying on the anvil. The measuring system is shown in Fig. 4.

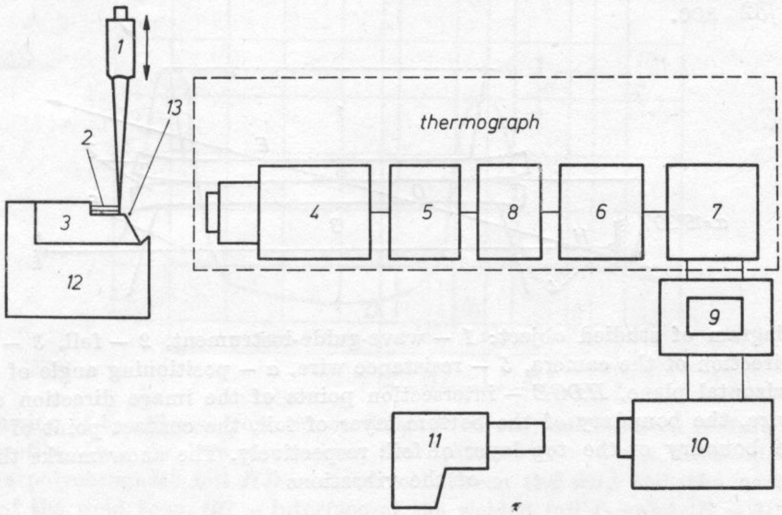

Fig. 4. Measuring system accomodated to the measurement of the temperature distribution in the weld zone in dynamic conditions: *1* – wave-guide instrument, *2* – foil, *3* – anvil, *4* – microscope, *5* – mechanic-optical analyser, *6* – detector, *7* – amplifier, *8* – filter, *9* – monitor, *10* – oscilloscope, *11* – film camera, *12* – support, *13* – resistance wire

4. 1. Description of the weld zone and method of its localization on the osciloscope screen

The tip of the wave-guide was a plaue in the shape of a rectangle, 0.16 cm^2 of surface and with dimentions: 1.6 ×10.2 mm. Therefore, the investigated object was a thickness weld zone 0.4 ×10.2 mm in dimention. The process required microscope optics.

Temperature changes in time were determined through the analysis of the amplified signal generated by the radiation emitted from points of the investigated surface, lying on a chosen line, i. e. the signal of the thermovision image line. Positioning the camera suitably in relation to the studied object, the line was chosen in such a way, that it intersected the weld zone, like it is shown in Fig. 5.

Due to the positioning of the camera under an angle of 15°30′, a rectangular zone along the diagonal 1.5 mm in length, was analyzed.

In such a case the output signal of the detector was proportional to the radiation emitted by points lying on the contact of two welded foils, and between the weld line and the foil surface, a like. By switching out a prism with a horizontal axis of rotation a signal of a 1600 Hz frequency is obtained. This signal was observed on the oscilloscope screen. To register signal changes during the welding process a photographic camera was used.

The film moved with the speed of 32 frames per second. On following film frames the signal corresponding to the temperature profile was registered every 1/32 sec.

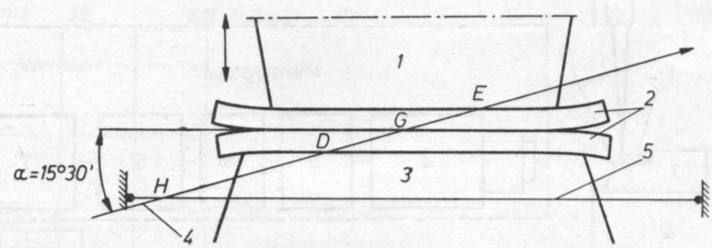

Fig. 5. Diagram of studied object: *1* – wave-guide-instrument, *2* – foil, *3* – anvil, *4* – analysis direction of the camera, *5* – resistance wire, *α* – positioning angle of the camera in the horizontal plane, *HDGE* – intersection points of the image direction and the resistance wire, the boundary of the bottom layer of foil, the contact point of the welded layers, the boundry of the top layer of foil, respectively. The anow marks the direction of the vibrations

The confrontation of the temperature profiles, registered on following frames of the film show, how, both the value and the distribution of the temperature, change in the foil during the process. On the basis of the optical system parameters of the thermograph and the camera, each point of the temperature profile was assigned to a point in the weld zone. This permitted the determination of the position of the heat source in relation to the boundary surfaces of the welded layers.

The described above method refers of course only to those cases, when both of the welded edges of the welded foil are optically accessible. In a general case, when the weld zone is surrounded from all sides by the welded material, a slight distortion in the temperature pattern may occur, due to a difference of the heat conduction of the material and air. However in the authors opinion, these errors are reduced to minimum and can be neglected, because of the instant reaction of the detector of thermal radiation, which has a propagating velocity uncomparably greater than the heat conduction velocity of the polymer.

4. 2. Determining the value of temperature in the weld zone

The temperature value of the wire did not have to be known. It only served as a constant reference level. A typical temperature profile along the line intersecting the heated wire and the foil weld zone is presented in Fig. 6.

The left side of the diagram corresponds to the heated wire, the right side – to the foil. The difference between the left peak and the other points of the right part of the profile, expressed in volts, is a temperature measure in the individual points of the weld.

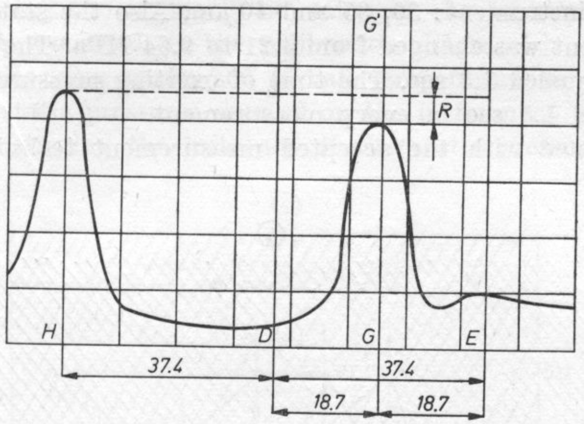

Fig. 6. Drawing of the filmed from the oscilloscope screen thermovision picture of the temperature profile along the line intersecting the heated wire and the ultrasonically welded zone of the polycarbonate foil *HD* – distance between the wire and the sample, DE – thickness of the weld zone, *GG* – interface of the welded foil samples, *R* – difference between the signal level from the heated wire, and a chosen point of the welded zone is the measure of the maximal temperature in a given profile; a difference *R* of 1 mm corresponds to 13.5 mV on the oscilloscope scale HDGE line dimensioning in mm. Sample boundries, broken line, dimensioning and letter denotation have beee drawn in for easier interpretation

In order to determine the absolute temperature value of the foil, the calibration of the mentioned difference *R* was conducted. The error of determining the temperature did not exceed 7 K.

5. Measurement results

5. 1. Strength measurements

An optimization of the technological parameters of the ultrasonic welding process was done on the basis of the strength measurements of the obtained joints. Tensile failure strength was the fundamental strength criterion of the weld for plastic foils.

The strength was measured on testing machine INSTRON, model 1115. Its measurement accuracy is $\pm 0.5\%$. Research results were registered by a recorder on paper fed with the velocity of $v_p = 30$ cm/min. The action velocity of the tensile force was $v_z = 5$ cm/min. The tensile strength of the foil was 177 N.

5. 2. Measurement of the maximum temperature value of the weld zone of the polycarbonate foil, as a function of the vibration amplitude and static pressure

Measurements were conducted for three amplitudes of the vibrations of the welding instrument: 30, 35 and 40 μm. Also the static pressure acting on the instrument was changed from 4.21 to 9.64 MPa. The welding time was constant and equaled 1.3 sec. The time of exerting pressure was slightly longer and equaled 1.5 sec in every measurement.

In accordance with the accepted measurement technique, the thermal

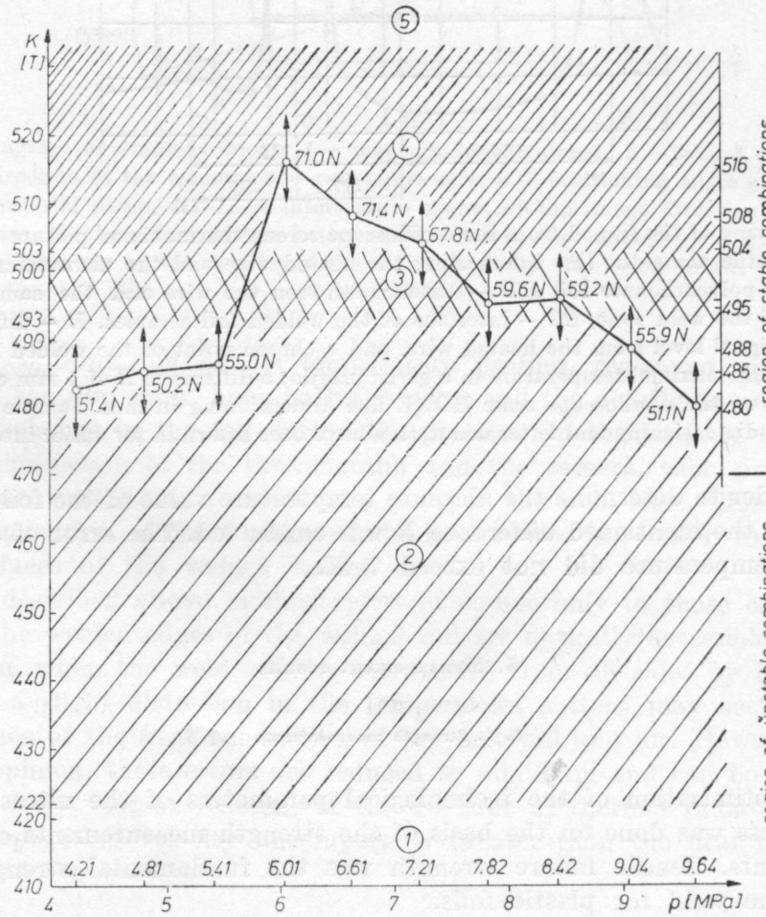

Fig. 7. Influence of static pressure P on the value of the maximal temperature T of the ultrasonically welded zone of the polycarbonate foil, at a vibration amplitude of 30 μm. Digits at the measuring points determine the weld tensile strength: 1) to 422 K – vitrification state, 2) to 493 K – highly elastic state, 3) to 503 K – visco-fluid state, 4) to 533 K – fluid state, 5) above 533 K – decomposition

emission of the wire and the weld zone was visualized at the same time on the oscilloscope screen. These images were documented by a film camera.

The weld zone difference between the peak temperature of the wire and the peak point on the curve of the temperature profile, was measured by employing the previously described measurement method.

After calculating the voltage, the value of the maximum temperature of the weld zone was read of the calibration diagram.

These activities were performed for all temperature profiles, corresponding to different static pressures exerted on the instrument wave-guide. This way diagrams illustrating the influence of the static pressure on the value

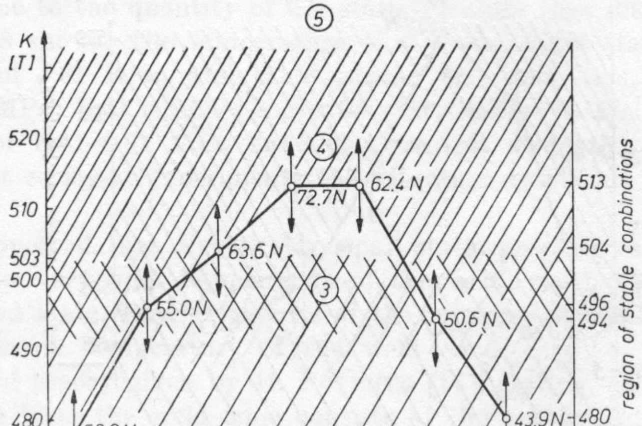

Fig. 8. Influence of static pressure P on the value of the maximal temperature T of the ultrasonically welded zone of the polycarbonate foil, at a vibration amplitude of 35 μm. Digits at the measuring points determine the weld tensile strength: 1) to 422 K – vitrification state, 2) to 493 K – highly elastic state, 3) to 503 K – visco-fluid state, 4) to 533 K – fluid state, 5) above 533 K – decomposition

of the maximum temperature of the weld zone, were obtained and are shown in Figs. 7–9.

On the basis of the measurements performed for an amplitude of 30 μm, it can be seen, that durable welding also takes place in a temperature below the visco-liquid state 3, yet in the top region of the highly elastic state 2 of the investigated polymer. This effect has also been observed for the amplitude of 35 μm. However, the strength of the joints obtained below the 3 state is low. It can be observed particularily when the welding temperature falls below 490 K.

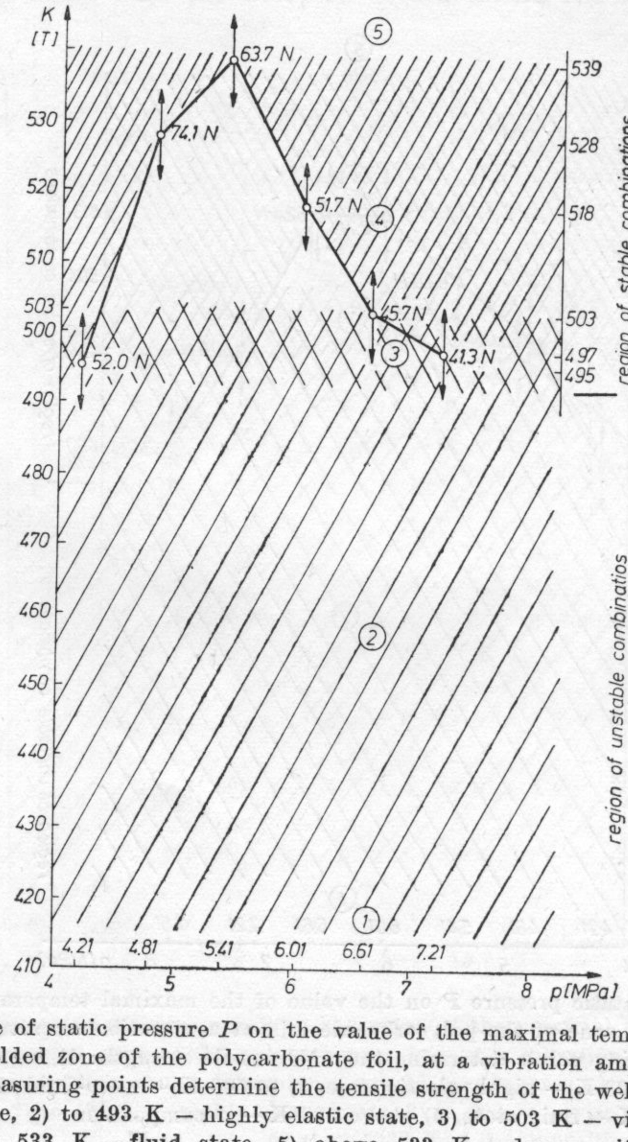

Fig. 9. Influence of static pressure P on the value of the maximal temperature T of the ultrasonically welded zone of the polycarbonate foil, at a vibration amplitude of 40 μm. Digits at the measuring points determine the tensile strength of the weld: 1) to 422 K – vitrification state, 2) to 493 K – highly elastic state, 3) to 503 K – visco-fluid state, 4) to 533 K – fluid state, 5) above 533 K – decomposition

As it can also be seen from Fig. 7, the increase of the pressure initially results in a very small rise of the maximum temperature of the weld and a small strength of the joints. This effect is characteristic for smaller vibration amplitudes. Pressures above 9 MPa cause a distinct deterioration of the joints strength in the latter part of the curve.

This is due to the braking of the amplitude by the pressure. Under pressures above 9.64 MPa the joints was not formed, in spite of the temperature of the weld zone exceeding the point of softening of the polymer.

As it can be seen the figure, in order to reach the highest strength of the welds the pressure must be 6.01–6.61 MPa for an amplitude of 30 μm.

At a higher amplitude the "sensitivity" of the maximum temperature of the weld zone to the quantity of the static pressure rises distinctly, as the curve in Fig. 8 shows. The temperature of the visco-fluid state is achieved at a pressure of 4.81 MPa, while at a smaller amplitude this effect occured at about 5.60 MPa; that is under a greater static pressure. Welds done under the pressure of 5.41–6.61 MPa have the greatest strength.

In the last series of experiments the vibration amplitude was increased to 40 μm.

Then it appeared that a relatively small static pressure causes a sudden attainment of a very high temperature of the weld, much above the state of the visco-fuid state. Further increas of the pressure over 5.40 MPa decreases the maximum temperature of the weld zone.

The general theory given by H. POTENTE [16], stating, that the thermal energy emitted from the weld zone consists of the energy coming from the friction between the welded surfaces and the energy of internal friction, was confirmed. Mutual shares of these two energetic processes yet depend on the vibration amplitude of the instrument and the exerted static pressure. And so, at the amplitude of 30 μm, for most of the applied pressures from 4.21 to 8.42 MPa, the friction energy generated between the contacting surfaces is the main thermal energy source. Increasing the pressure to 9.04, and then to 9.64 MPa liberates greater amounts of energy from internal friction. At a higher amplitude, the friction between the contact surfaces of the foil, cause now the generation of thermal energy only for four following increasing pressures, i. e. from 4. 21 to 6.01 MPa. Further increas of the pressure causes the rise of the energy share coming from internal friction.

The increase of the amplitude to 40 μm, at nearly all pressures, gives the dominant share of the internal friction energy, generated through the change of the supplied energy of acoustical vibrations. Solely under the lowest pressure of 4.21 MPa, the occurence of thermal emission due to the friction between the welded surfaces, was observed.

According to the theory of J. STAGER at al. [19], the heat causing ultrasonic welding of plastics is generated only from friction between the welded surfaces. The results of conducted by the author investigations on the distribution of the thermal energy in the weld zone, prove, that both the energy from the friction between the contacting surfaces and the internal friction energy take part in the welding process.

Due to a quick attainment of a high temperature, the process of welding is shorter and thanks to smaller pressures the thickness of the joints differ less from the thickness of the welded material. The highest strengths are obtained at a pressure of 4.81 to 5.41 MPa.

5. 3. Influence of the static pressure on the thermal emission distribution in the weld zone and its dependency on the vibration amplitude of the instrument wave-guide

The investigations of the thermal emission in the weld zone were conducted through the analysis of following thermographs of the temperature profiles. The weld zone, marked on the thermographs, shows the position of

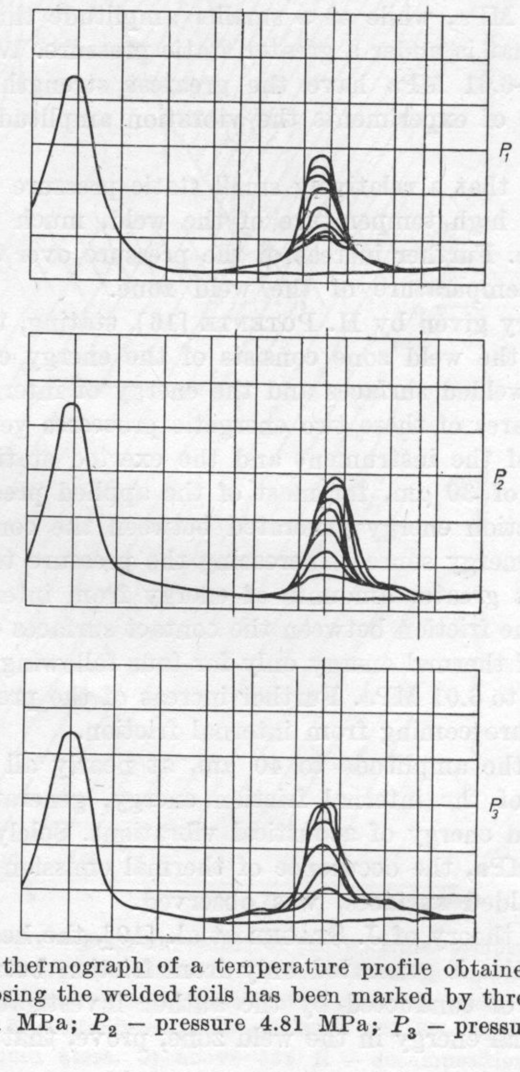

Fig. 10. Examples of thermograph of a temperature profile obtained at an amplitude of 30 μm. The zone enclosing the welded foils has been marked by three vertical lines: P_1 – pressure 4.21 MPa; P_2 – pressure 4.81 MPa; P_3 – pressure 5.41 MPa

the heat emission sources in relation to the contact surface of the welded foil samples.

At the amplitude of 30 μm, the first 8 following thermographs Fig. 10 showed, that the heat was generated in the region of contact of the welded samples. Only at pressures of 9.04 and 9.64 MPa, the heat source moves away from the contact surface.

The thermal emission from the sample joints points to a big share of the energy generated by friction of the two adjoining surfaces. At an adequatly high pressure, the share of the energy generated by internal friction of the polymer macromolecules, in the emitted thermal energy increases.

Welding at an amplitude of 35 μm presented a similar distribution of the thermal energy. However, at a higher amplitude the energy generated

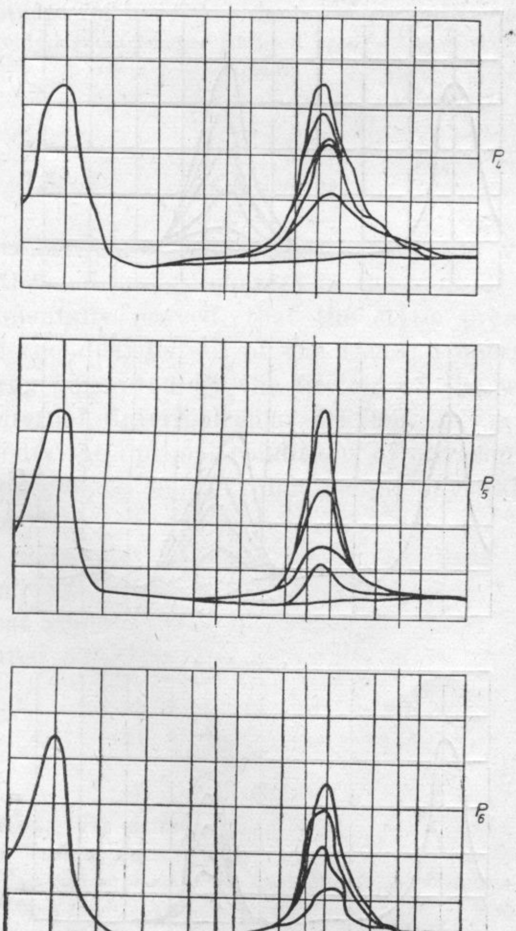

Fig. 11. Examples of thermograph of a temperature profile obtained at an amplitude of 35 μm. The zone enclosing the welded foils has been marked by three vertical lines: P_4 – pressure 6.01 MPa; P_5 – pressure 6.61 MPa; P_6 – pressure 7.21 MPa

by the friction of the welded surfaces has a dominating influence in the first four thermographs. Higher pressures, i. e. 6.61, 7.21 and 7.82 MPa, cause the increase of the share of the thermal energy generated by internal friction (Fig. 11).

Thermographs of the thermal energy distribution at the amplitude of 40 μm, showed that the thermal energy sources were moved away from the contact surface of the foil samples (Fig. 12). Solely thermograph P_1 done at the smallest pressure, i. e. 4.21 MPa, proved a certain share of the heat coming from the friction between the welded surfaces of the foil.

Fig. 13 presents a comparison of the shares making up the total thermal emission from the weld zone in dependence on the vibration amplitude and the static pressure on the instrument wave-guide.

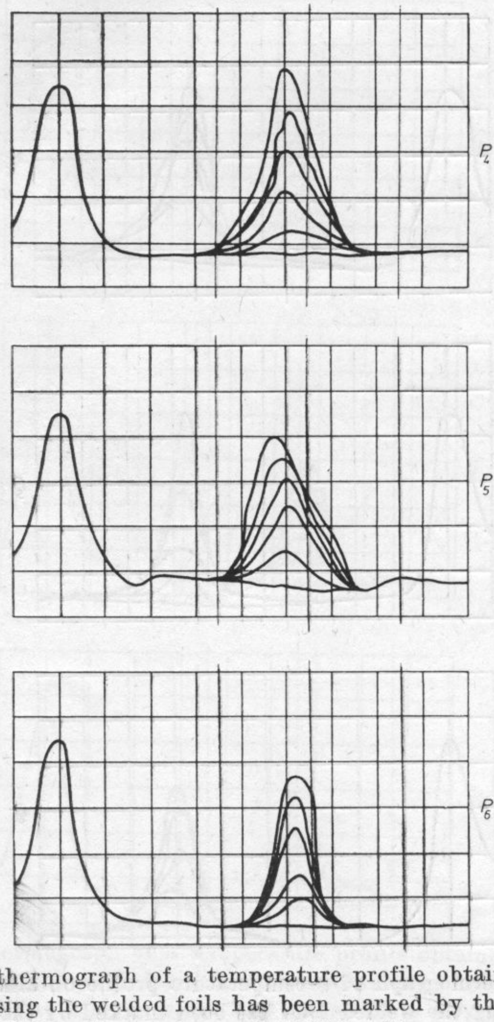

Fig. 12. Examples of thermograph of a temperature profile obtained at an amplitude of 40 μm. The zone enclosing the welded foils has been marked by three vertical lines: P_4 – pressure 6.01 MPa; P_5 – pressure 6.61 MPa; P_6 – pressure 7.21 MPa

The experiment results presented above confirm the theory of H. Potente [16], saying that the heat generated during the ultrasonic welding of polymers partially comes from the losses due to internal friction.

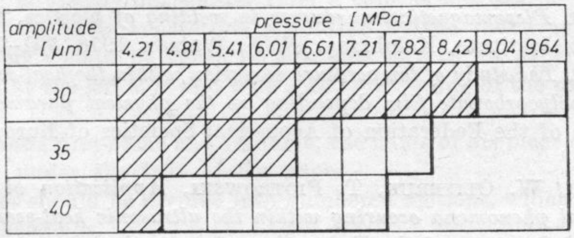

Fig. 13. Influence of static pressure on thermal emission from the weld zone, in dependence on the vibration amplitude. The lined area shows the part of the energy arising from the friction between the welded surfaces, the unlined area – the energy coming from internal friction

6. Conclusions

Conducted thermographic studies have given the visualization of the localization of the thermal energy sources in the zone of ultrasonic welding. It has been experimentally proved, that the static pressure and vibration amplitude influence the distribution of the thermal energy emission, which consists of the energy generated by the friction of the welded surfaces and the engrated by internal, intermolecular friction.

The paper presents the optimal conditions of ultrasonic welding of polycarbonate foil, in dependance on the fundamental physical and technological parameters of the process.

The developed contactless method of investigating thermal effects in the zone of ultrasonic welding with the use of infrared radiation, proved to be useful and of great applicatibility. The absence of the influence of the meter on the investigated object is the main advantage of this method.

References

[1] J. Łoziński, *Contactless method of measuring the temperature of the ultrasonic weld zone*, Proc. of XX Open Seminar on Acoustics, Poznań 1973, 189–190, (in Polish).

[2] J. Łoziński, *Contactless method of temperature distribution monitoring in ultrasonic welded polymers*, The Seventh International Conference on Nondestructive Testing, IFTR, Warsaw 1973, 315–319.

[3] J. Łoziński, T. Piotrowski, *Kinetic and static studies of the temperature distribution in the ultrasonic weld zone in thermoplastic foil*, Proc. of XXI Open Seminar on Acoustics, Rzeszów 1974, 242–243, (in Polish).

[4] J. Łoziński, *Ultrasonic welding oi polyethylene in the view of the observations of the physical parameters of the process*, Proc. of XXII Open Seminar on Acoustics, Wrocław 1975, 517–521, (in Polish).

[5] J. Łoziński, *Ultrasonic welding of thermoplasts*, Polimery – Tworzywa Wielocząsteczkowe, **6**, 294–297 (1975) (in Polish).

[6] J. Łoziński, *Piezomagnetic transducers in welding of plastics*, Proc. of IV Spring School of the Physics Institute, Kołobrzeg, PWN, Warsaw 1978, 751–761, (in Polish).

[7] J. Łoziński, *The study of temperature variation within the heat-seal zone of the ultrasonic heatsealing of polycarbonate film depending on the physical parameters of the process.* The Second Congress of the Federation of Acoustical Societies of Europe, IFTR, Warsaw 1978, 207–211.

[8] J. Łoziński, W. Oliferuk, T. Piotrowski, *Application oi infrared radiation to studying the thermal phenomena occuring within the ultrasonic heat-seal zone of polycarbonate film*, The Second Congress of the Federation of Acoustical Societes of Europe, IFTR Warsaw 1978, 213–218.

[9] J. Łoziński, *Termiczeskije jawlenija w zonie sojedinienja pri ultrazwukowoj swarkie polikarbnatnoj folgi*, Sbornik: Informacionnyje Materiały SEW Instytuta Swarki im. Patona, **1**, 58–72 (1981).

[10] J. Łoziński, W. Oliferuk, T. Piotrowski, *Determination of the temperature distribution in the ultrasonic weld zone in thermoplastic foil, with the application of infrared* radiation detection, Pomiary, Automatyka, Kontrola, **7**, 247–249 (1979), (in Polish).

[11] J. Łoziński, *Study of the influence of static pressure of the thermal emission distribution in the ultrasonic weld zone in thermoplastic foil* in Polish, Proc. of VII Winter School on Molekular and Quantum Acoustics and Sonochemistry, Institute of Fundamen. Technolog. Research, Warszawa 1978, 76–82.

[12] J. Łoziński, *Doctors thesis*, Institute of Foundamental Technological Research, Polish Academy of Sciences, Warsaw 1983, (in Polish).

[13] G. Menges, H. Potente, *Schallfelder und Energieumsetzung beim Ultraschallschweissen von Kunststoffen*, Kunstotoffe, **6**, 369–374 (1969).

[14] G. Menges, H. Potente, *Neue Erkenntnisse beim Schweissen von thermoplastichen Kunststoffen-Ultraschallschweissen*, Plastverarbeiter, **5**, 1–11 (1970).

[15] W. A. Neitzert, *Ultraschall-Verbindungen an Kunststoffen*, Plastverarbeiter, 5, 337–343 (1971).

[16] H. Potente, *Zur Frage der Energieumwandlung beim Ultraschallschweissen von Thermoplasten*, Plastverarbeiter, **8**, 556–562, (1971) and **9**, 653–658 (1971).

[17] D. W. Philips, A. N. North, R. A. Petrick, *Ultrasonic studies of polycarbonate, polysulfone, and polyethersulfone*, Journal of Applied Polymer Science, **21**, 1859–1867 (1977).

[18] B. Peńsko, Z. Toczyski, *The capacity method of distance measurements and its application in the meter of displacement amplitudes of a frequency to 40 kHz*, Proc. of XXII Open Seminar on Acoustics, Wrocław 1975, 565–568, (in Polish).

[19] J. G. Steger, *Einführung in die Ultraschalltechnik*, Kunststofftechnik, **10**, 9, 299–304 (1971).

[20] Z. Toczyski, *Detection oi vibrations of ultrasonic transducers in Polish*, Arch. Akust., **9**, **4**, 403 (1974).

[21] S. S. Wołkow, Ju. I. Orłow, R. N. Astachowa, *Swarka i skleiwanie plastmass*, Maschinostrojennie, **52**, Moskwa 1972.

Received on 3 May, 1985; revised version on 21 November, 1985.