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Effect of Ultrasonic Techniques on Welding Technologies

Abstract: The article discusses selected physical properties of industrial ultrasonic equipment utilising the magnetostrictive or electrostrictive effect. Particular attention was paid to equipment enabling the ultrasonic welding of various metals and thermoplastics. The research involved the comparison of various designs and operation of technological equipment, taking into account selected energy, control and environmental aspects. Based on reference publications it was possible to determine and categorise general features concerning the application of ultrasonic technologies as well as to indicate factors responsible for the formation of imperfections during the ultrasonic welding process.

Keywords: ultrasonic testing, non-destructive testing, ultrasonic equipment

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Introduction

The contemporary development of manufacturing technologies favours the application of new materials and the replacement of traditional materials with those capable of satisfying new requirements. As a result, various plastics are used alongside metals and ceramics. The processing and welding of plastics using traditional devices and methods frequently prove ineffective, costly and difficult. One of the methods enabling the joining of such materials is welding involving the use of ultrasonic vibration. Depending on the design of the welding machine and the shape of the sonotrode, it is possible to make spot, seam or ring welds. The performance of such welding processes requires appropriate equipment, knowledge and practical skills. The number of reference publications concerning this subject is growing not only overseas but also in Poland (see [1–4]). The above-named issues are also addressed works by Russian-speaking authors [5–8]. The aforementioned publications inspired the Author to classify and compare ultrasonic equipment and technologies involving the use of magnetostriction and electrostriction transducers. The article presents selected designs of equipment and characteristics of processes enabling the welding of metals and thermoplastics. The study also indicates the vast applicability of such equipment and technologies in modern industry.

Selected properties of ultrasonic equipment

Time-related changes of electric current flowing through the winding of the induction coil with the ferromagnetic changes are accompanied by changes of magnetic induction. These, in turn, trigger changes of the geometrical dimensions of the core, which is referred to as magnetostriction. Metallic materials characterised by the highest magnetostriction are alloys of iron

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with cobalt or nickel. When using alloys containing between 20% and 40% of Ni, it is possible to obtain the maximum magnetostriction coefficient amounting to $24 \cdot 10^{-6}$. In turn, the magnetostriction coefficients of modern materials can reach up to $2000 \cdot 10^{-6}$.

Similarly, time-related changes of voltage applied to capacitor plates (with dielectric elastomer or piezoelectric placed between them) are accompanied by changes in electric field induction. These, in turn, trigger changes in the geometrical dimensions of the dielectric elastomer or piezoelectric (referred to as electrostriction). Piezoelectric include monocrystals of inorganic substances characterised by favourable mechanical and heat resistance properties (e.g. quartz or tourmaline). However, such substances are difficult to obtain both in laboratory and technological conditions. It is more convenient to use polycrystalline substances, the polarity of which is ordered by the external electric field or directional stress. The aforesaid substances include ceramic ferroelectrics (barium titanate, lead zirconate titanate or PZT type ceramics). The electrostriction coefficient of modern piezoelectric materials reach the value of $3 \cdot 10^{-8}$. The above-named materials are used to make converters of electric energy into mechanical vibration:

– magnetostriction transducers with ferromagnetic materials,
– electrostriction transducers with piezoelectric materials.

In technological applications, the most favourable range of frequencies of generated ultrasonic vibration is $f = 1.5 \cdot (10^4 – 10^5)$ Hz. Magnetostriction transducers work at lower frequencies, whereas electrostriction transducers work at higher frequencies (which is connected with internal losses of energy). A disadvantage of magnetostriction transducers is their low efficiency amounting up to 40%. In turn, the efficiency of electrostriction transducers may reach 80%. The use of specific frequency depends on the type of material and the dimensions of a welded element.

The magnetostriction transducer contains the closed ferromagnetic core with copper winding. In turn, the segmented electrostriction transducer is composed of the cascaded pile of piezoceramic transducers and metallic loading masses referred to as the reflector and the emitter (enabling the reduction of vibration frequency) [5]. The elements are coupled mechanically with a bolt, usually passing axially along the segmented transducer. The system of bolts located around the circumference is used less frequently [4].

The primary parameters concerning the electromechanical transducer include the frequency of free vibration, the coefficient of electromechanical coupling, maximum working power and electroacoustic efficiency. The transducer is connected with the concentrator and the sonotrode (constituting mechanical waveguides and tasked with the supply of mechanical energy to the load). The concentrator (waveguide) is used as a system adjusting the mechanical impedance of the load to the impedance of the transducer. The sonotrode is an element supplying mechanical energy to the load [4]. Each of the above-named elements has its own frequency of resonant vibration. The maximum amplitude of radiant surface vibration is obtained in the state of the conformity of resonant frequencies of the transducer and those of the concentrator. The adjustment of the above-named elements requires the correction of geometrical dimensions.

An exemplary welding device with the magnetostriction transducer is presented in Figure 1. The joining process involves the effect of static force and dynamic force (changing synchronically along with vibration).

Ultrasonic transducers with piezoelectrics are built as the half-wave electromechanical Langevin system having the even number of piezoceramic elements and connected with the half-wave concentrator. An example of the above-named system is presented in Figure 2. The lengths of the pin elements (transformer

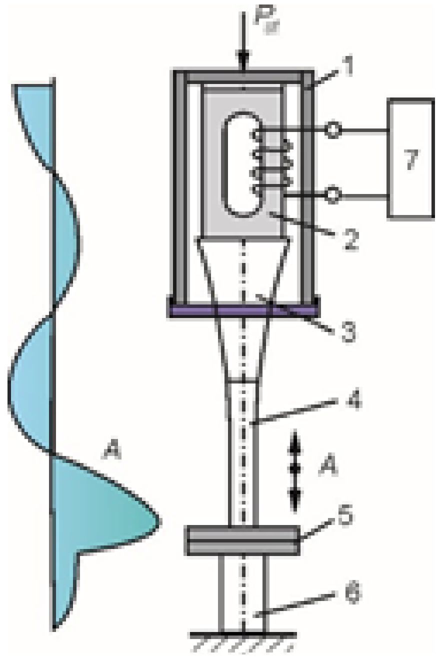

Fig. 1. Welding machine with the magnetostriction transducer (1 – transducer housing, 2 – magnetostriction transducer with the winding, 3 – transformer of elastic vibration, 4 – waveguide, 5 – welded elements, 6 – anvil, 7 – electronic generator, A – amplitude of vibration) [6]

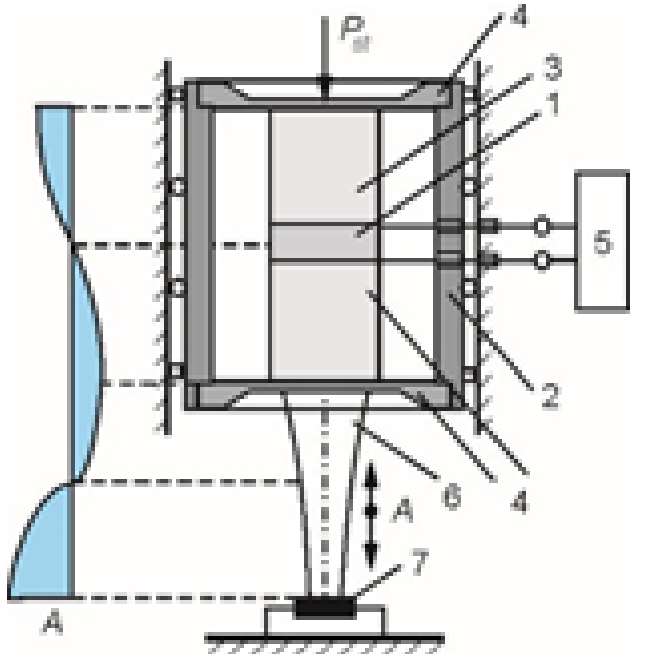

Fig. 2. Welding machine with the electrostriction transducer: a) schematic diagram of the machine, b) diagram of changes in vibration amplitude (1 – piezoelement, 2 – housing, 3 – plates, 4 – elastic membranes, 5 – generator, 6 – concentrator, 7 – sonotrode, A – amplitude of vibration) [7]

and waveguide) of the vibrant system should be commensurable with the length of the elastic wave in the material of the pins.

The ultrasonic device can work effectively only in resonant states as only in such states it is possible to obtain sufficiently high amplitudes of vibration, necessary for technological purposes. Ultrasonic machines are usually tuned in the no-load state, assuming the possibility of ignoring the effect of the technological load. However, the technological load leads to changes of resonant frequencies and non-linear distortions of amplitude-frequency characteristics.

Ultrasonic welding machines are used to join elements made of metals and plastics. Typical schematic diagrams of such devices are presented in Figure 3. Ultrasonic welding machines differ in terms of the method used to supply periodically alternating forces. In Figure 3a they are consistent with the direction of force P, which leads to changes in plastic viscosity. According to Figure 3b, the aforesaid forces are perpendicular to each other, inducing the periodic transverse vibration of the pin with the sonotrode attached to it. The vibration is transferred (via the contact) to the lower metal element (subjected to welding), triggering friction, heating and, ultimately, resulting in weld formation.

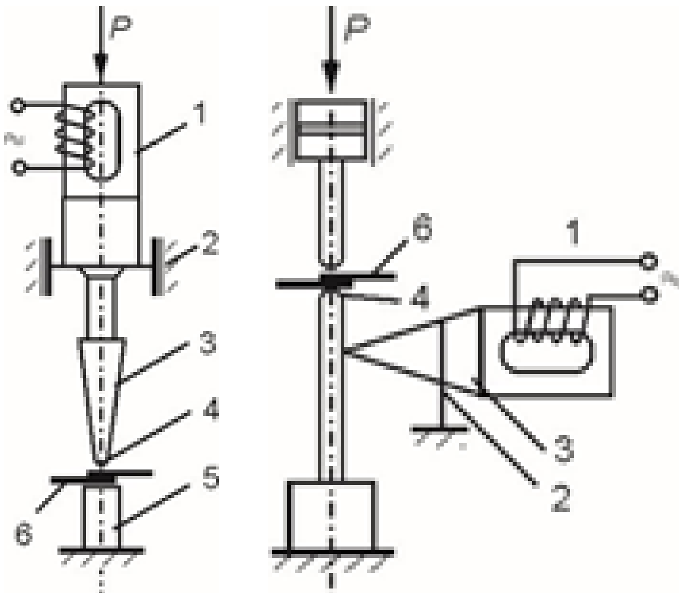

Fig. 3. Schematic diagrams of magnetostriction welding machines for the welding of: a) plastics and b) metals (1 – magnetostriction transducer, 2 – machine housing, 3 – wave transformer, 4 – sonotrode, 5 – anvil, 6 – elements, P – force) [5, 8]

Generate ultrasonic vibration should be characterised by specific parameters including direction, frequency and amplitude. Usually, perpendicular vibration is used in welding machines. Only in certain applications (welding of thin foils), more favourable results are obtained using tangential vibration. The ultrasonic welding of metals is accompanied by the reduction of vibration amplitude triggered dissipating load generated as a result of dry friction. In the above-presented case, the effect of the working process on resonant frequencies is insignificant. Ultrasonic devices for the welding of plastics can be classified according to the presence or lack of static pressure and the type of energy supplied to welded elements (thermal, thermomechanical or mechanical processes) [6].

Elastic forces play an important role in the problem of plastic deformation, An increase in (electrode) force leads to the reduction of vibration amplitude not only because of thermal energy dissipation in the working area but also due to changes of the system resonant frequency triggered by non-linear distortions resulting from the effect of the vibrant system (ending with the sonotrode and an element subjected to welding). To provide energy to polymers quickly and effectively, it is necessary to obtain high vibration amplitude, i.e. restricted within the range of 50 μm to 90 μm.

The primary parameters of the ultrasonic machine include vibration amplitude, (electrode) force as well as the frequency, time and the cyclicity of operation. The maximisation of energy supplied to the system is obtained when the grips of the acoustic transducer are located in the nodes of the wave responsible for the maximum amplitude of vibration and when the length of the pin subjected to processing amounts to ¼ of the wavelength. The transformation of the mechanical energy of ultrasonic vibration into heat takes place through friction occurring in the contact area between the elements. As a result, the temperature in the contact area rises, the material subjected to processing absorbs energy, the temperature of the material increases and the material itself becomes viscoplastic. The manner in which vibration energy is supplied to the welding area depends on the coefficient of elasticity of the material and the coefficient of the damping of mechanical vibration having ultrasonic frequency.

Energy can be supplied to the working area using one of the following methods:

- contact method – where energy is propagated across the entire cross-section of the element (used in relation to macromolecular plastics and foils);
- transmission method – vibration excited at several points concentrates in the joint area (used in relation to materials characterised by the high coefficient of elasticity).

Typical schematic diagrams of ultrasonic welding systems are presented in Figure 4. In relation to the manner of weld formation, the aforesaid systems differ as regards the space coordination of (pressure) force and forces of the periodic vibration of the sonotrode. The case presented in Figure 4c is used in ring welding. The remaining cases can be used in spot welding.

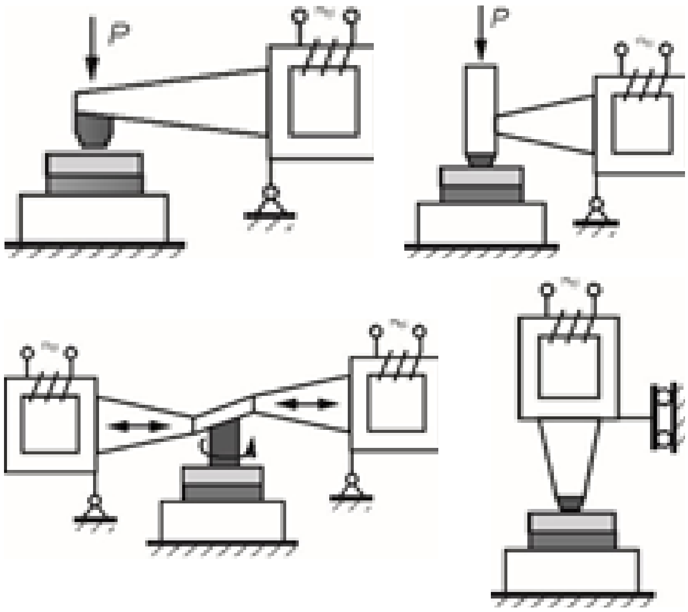

Fig. 4. Kinematic schematic diagrams of ultrasonic welding systems: a) longitudinal, b) longitudinally transverse, c) torsional and d) longitudinally vertical [6, 9]

Publication [6] presents and discusses the following examples of welding systems:

- with normal setting into vibration,
- providing additional binding agents,

- with the inclined tool,
- with torsional and longitudinal-torsional vibration of the concentrator,
- with two-sided collection of vibration energy from the inverter,
- with two-sided energy supply by means of two welding heads,
- with multi-sided supply of energy to the product.

In terms of energy concentration in the welding area, ultrasonic welding systems can be divided as systems where energy is concentrated [6]:

- using artificial concentrators of stresses,
- by increasing the roughness of surfaces being in contact,
- by sprinkling the surface with welded material grains,
- using additional external clams of a separate mechanism outside the concentrator,
- by additional local heating the welding area,
- using the combination of the above-named solutions.

Machines enabling the ultrasonic welding of thermoplastics can be classified according to:

- method used to supply mechanical vibration to the element,
- transfer of mechanical energy in the welding area,
- concentration of energy in the welding area,
- dosage of supplied energy,
- movement of the tool and the welded element (in relation to each other) to obtain seams of appropriate length and configuration.

Ultrasonic devices can be manual and stationary. As regards the method of energy supply, they can be divided into one or two-sided machines. In relation to the manner of concentrator movement, ultrasonic devices can be divided into machines of pulsed (short impulses emitted along with every step of concentrator movement) or continuous (continuous travel rate in relation to the material) operation. The amount of energy supplied to the joint can be identified in relation to the time of effect, the state of upsetting (penetration of the material by the sonotrode), the width of the gap or the kinematic component (ultimate amplitude of the movement of the support-anvil). If the excitation of welded elements leads to resonant vibration, the quality of the weld may be affected. In such a situation it is necessary to change the position of elements or use additional damping masses on the anvil side.

Additional losses of mechanical energy are generated at the contacts of the vibrant system with the elements of the sound box housing and at the contacts of the grips used for supporting elements subjected to welding. The losses of mechanical energy can be minimised by the acoustic decoupling of sound box grips in the nodes of the standing wave with the minimum amplitude of grip vibration and by the acoustic decoupling of half-wave acoustic reflector grips in the nodes of the standing wave with the minimum amplitude of grip vibration.

The ultrasonic welding machine consists of several component elements:

- electric energy supply source,
- electronic inverter (increasing frequency),
- welding head containing the ultrasonic transducer,
- transformer (waveguide) and the sonotrode,
- anvil,
- sonotrode force system,
- control system.

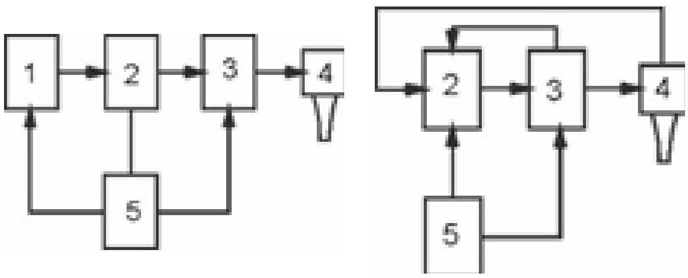

Fig. 5. Flowcharts of ultrasonic generators: a) with independent excitation and b) with self-excitation (1 – presetting generator, 2 – preliminary amplifier, 3 – power amplifier, 4 – transducer, 5 – network rectifier) [6, 8]

The designs of welding systems can be relatively simple. Exemplary flowcharts of ultrasonic generators are presented in Figure 5.

Energy supplied to the welded element can be dosed by presetting [6]:

- time of supplying ultrasonic impulses,
- upsetting dimensions,
- restrictions in transducer (sonotrode) movements,
- gap size,
- limited temperature of the material,
- minimum anvil movement.

The primary welding process control methods include the control of preset welding time and the control of preset deformation (gap width). The welding process can be destabilised by changes in the resistance of load influencing the vibrant system (affected by the sonotrode), changes in the ability to transfer energy between the sonotrode and elements being welded, changes of the thermomechanical state of the welded material because of the lower or higher ability to absorb energy as well as changes of the parameters of electronic generators and changes in the concentrator system.

The repeatable strength of joints depends on sonotrode vibration amplitude stability. Ultrasonic welding machines feature the stabilisers of vibration amplitude, vibration frequency and (pressure) force [10]. The operating and power efficiency of ultrasonic welding machines can be obtained by increasing the quality factor of the vibrant system and the tuning (adjusting) of the system to resonance in the load state. The dynamic properties of the ultrasonic welding machine can be fully utilised by means of the autoresonant excitation system with the positive feedback circuit.

The ultrasonic welding machine control system enables changes within permissible ranges of such parameters as the amplitude and frequency of vibration, the travel rate and the time of effect of impulses, static pressure, preheating temperature and the length of the sonotrode adjusted to dimensions of elements being welded. In relation to the welding process automation level, ultrasonic welding machines can be divided into manual, mechanised and automated [9]. In turn, generators of ultrasonic vibration can be divided into versatile generators (with the correction of the electronic system structure and with the correction of parameters <frequency and amplitude>) and specialised fixed parameter generators.

General principles of the application of ultrasonic technologies

Ultrasounds (reducing static forces necessary for plastic deformation, crushing or overcoming friction forces) have found applications in numerous areas such as the processing of brittle materials, the surface hardening of metals, the plastic deformation of products, the drawing of wires, the cutting and welding of metals or the cutting and welding of thermoplastics. Ultrasonic welding machines enable the making of overlap, lap and edge joints.

The stages of the practical application of the ultrasonic welding process are the following:

1. Analysis of the structural properties of a product being welded:

- shape and dimensions of the joint,
- ultrasonic vibration damping factor,
- supply of energy to the welding area (contact, transmission).

2. Movement of the vibration system in relation to the joint:

- sliding (continuous),
- stepped,
- one-position,
- multi-position.

3. The selection of the welding state is based on:

- identification of energy supply conditions,
- reflection and attenuation of waves,
- energy dosage conditions (force, rate, and time).

Selected properties of the ultrasonic welding of metals

The ultrasonic welding of metals requires the heating of welded elements up to appropriate temperature (0.3–0.5 of the melting point), the exertion of appropriate force and the supply of ultrasonic energy. Depending on required welding process efficiency, the aforesaid temperature can be obtained by using additional heat sources or only by means of the energy of ultrasounds. As the temperature is relatively low, changes of physicochemical properties of metals are minimal. In cases where no additional heat source is used, the value of the contact area temperature depends on the power of the machine as well as on the physicochemical properties of metals subjected to welding. During the ultrasonic welding of metals, the oscillating movements of the waveguide and force are transferred to the upper part subjected to welding (and moving in relation to the lower part attached to the anvil). It is favourable if the weight of the moving part is lighter. As a result, there is friction (of specific frequency and amplitude) between the elements subjected to welding. Ultrasonic welding can be classified as high-frequency mechanical friction welding without supplying current to the welding area. For this reason, the work surface of the sonotrode and that of the anvil should be rough, whereas elements to be joined should be degreased. The quality of joints made of hard-to-weld metals can be improved by using interlayers made of other metals. Zinc, tin and lead coatings impede the process of welding.

During the welding process, the micromovements of the elements in relation to each other lead to the abrasion of roughness, damage to oxide layers and the formation of scuffed nodes. The friction and further deformation of welded elements along with growing temperature in the welding area are accompanied by the increased plasticity of metal surface layers as well as the movement of oxide layers and impurities from the welding area. All this leads to an intense increase in the dimensions of pressure areas, the diffusion of one material in the other, the local melting of the upper atomic layers and the formation of interatomic bonds. The stabilisation of process parameters during the welding of rigid elements includes the amplitude of mechanical vibration, force and operating time. The power of the welding system is adjusted in relation to the thickness of the material on the sonotrode side, the material of the greatest thickness and worse weldability [1].

Selected properties of the ultrasonic welding of plastics

Ultrasonic welding is primarily used in the joining of thermoplastics [10]. The high quality of the welding process depends on the accuracy of acoustic energy dosage (time, vibration amplitude), the accuracy of mechanical energy dosage (force, travel rate, gap width restriction) and on the initial performance of experimental tests.

The criteria of energy dosage include time, deformation, vibration amplitude, force, acoustic resistance and the temperature of the vibrant system with the sonotrode [10]. The principles of the optimum adjustment of the welding state include the power of the electronic generator, the width of the gap between the radiant surface and the resistance surface as well as the amplitude of the mechanical vibration of mechanical resistance.

The amount of energy emitted in the welding zone depends on vibration amplitude, the area of the acoustic contact, the thickness of materials being welded, the acoustic and the thermodynamic properties of welded materials as well as the acoustic and the thermodynamic properties of the backing strip.

The welding of variable products is controlled manually as changes involve the physical properties of elements, the parameters of ultrasonic vibration systems, resonant frequency, quality factor and the amplitude of mechanical vibration. In relation to variable products, the manual control requires taking into account the amplitude of the vibration of the sonotrode radiant surface (depending on the amplitude of the output current of the generator exciting the ultrasonic transducer), values of mechanical force and operating time.

Ultrasonic vibration leads to changes of the state of thermoplastics such as the improvement of the acoustic contact of the radiant surface with the plastic (changing from the viscoplastic state into the viscofluid state). Changes of the mechanical load of the sonotrode correspond to changes of power used by the transducer. This, in relation to stabilised voltage, results in changes of current (Fig. 6).

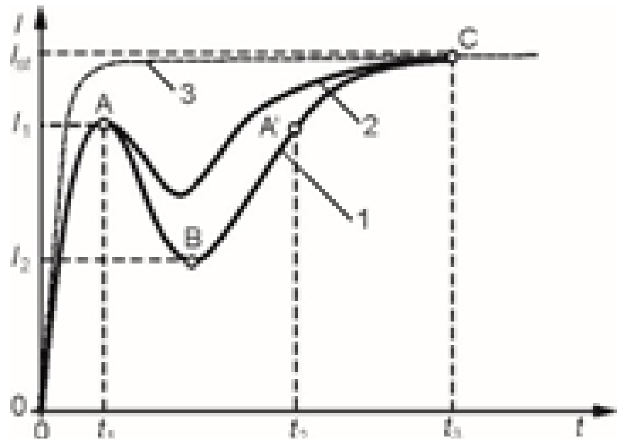

Fig. 6. Dependence of the amplitude of current flowing through the piezoceramic elements during the formation of the joint (1 – greater thickness of the element, 2 – smaller thickness of the welded element, A – beginning of the damping of the vibration of the concentrator pressed by the material, A-B – softening of the polymer material, the improvement of the acoustic contact of the radiant surface and the reduction of the quality factor of the ultrasonic system, B – maximum damping of vibration, B-C – transition of the material from the viscoplastic state into the viscofluid state, the partial escape of the excess material, the reduction of static pressure and an increase in the quality factor of the vibrant system. A' – point of optimum joint quality) [10, 11]

In Figure 6, the diagrams and marked points correspond to the following states:

- dotted line – indicates the lack of changes in the materials affected by ultrasounds (in air),
- full line – indicates changes in the polymer materials (softening → viscoplastic state →viscofluid state).

In addition, there is correlation I1 ∞ $(P)^{-1}$, where P – initial static force.

The moment of the transition of the thermoplastic material into the viscofluid state depends on force – the higher the force, the faster the transition (see Figure 7).

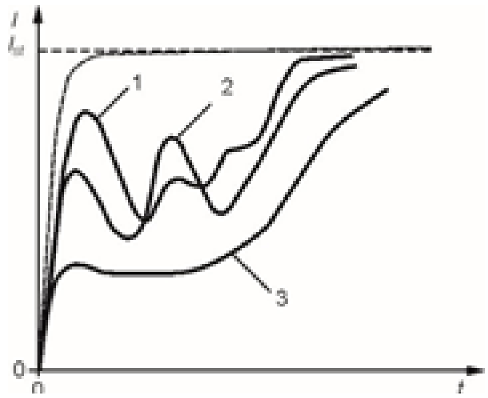

Fig. 7. Dependence of the amplitude of current flowing through the piezoceramic elements during the formation of the hermetic welded joint (1, 2, 3 – increasing values of static pressure) [11]

The measurement of the wave resistance of welded materials can be performed by the monitoring of the voltage and current of the ultrasonic transducer. Related correlations are presented in Figure 8.

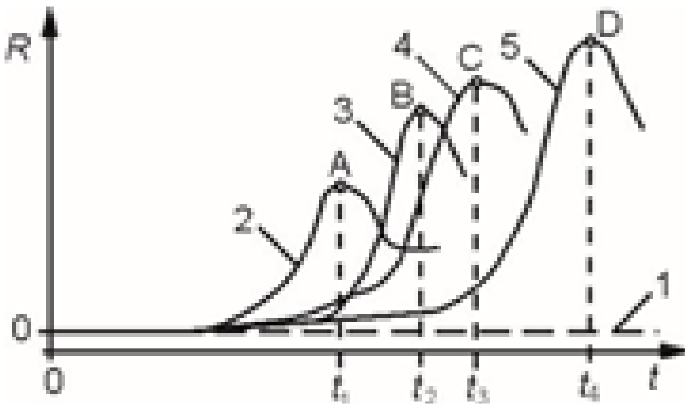

Fig. 8. Dependence of wave resistance R of polypropylene in the welding process with various values of force and the same welding power (1 – no-load state, 2, 3, 4, 5 – degrees of static pressure increase, A, B, C, D – thresholds of the transition of the material into the viscoplastic state) [11]

During the welding process, topochemical reactions take place at three stages:

1) formation of the physical contact,
2) activation of contact surfaces,
3) volumetric development of interaction.

Times of the above-named reactions affect the mechanical strength of the joint (see Figure 9).

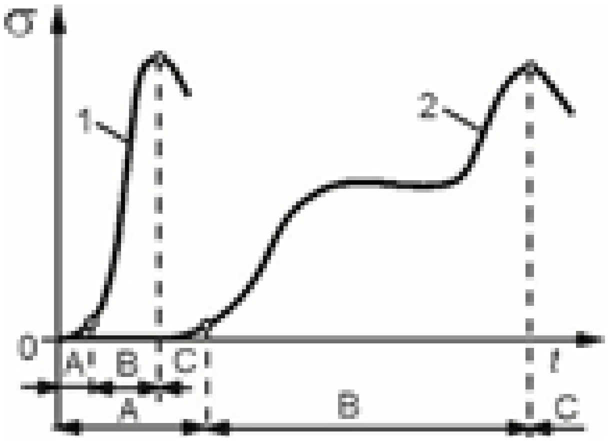

Fig. 9. Change of joint strength σ in relation to the duration of the welding process t if the process is fast (1) and slow (2) (A – development of physical contact formation, B – activation, C – volumetric interaction) [6]

Figure 10 presents the correlation between welding rate v and the amplitude of sonotrode vibration A in one and two-sided welding processes. The Figure reveals that the use of two-sided welding not only speeds up the process but also reduces requirements concerning the amplitude of both sonotrodes.

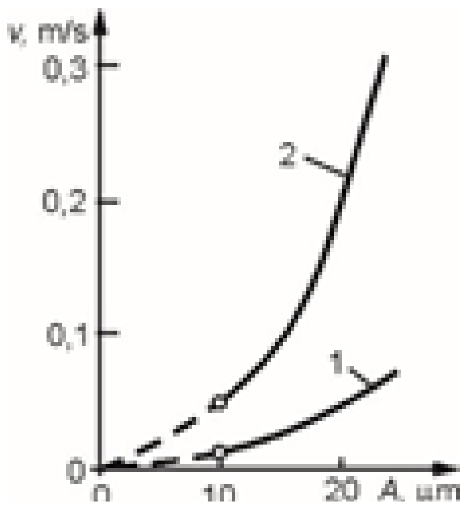

Fig. 10. Correlation between the welding rate and the amplitude of displacement in relation to the one (1) and two-sided (2) welding [6]

Ultrasonic welding can be:

- point-like,
- linear,
- segmented.

Advantages of the ultrasonic welding of metals and thermoplastics

General advantages of ultrasonic welding are the following:

- lack of limitations as to shapes of elements,
- environmental friendliness (very low harmful emission),
- no need for gas shielding,
- no need for filler metals,
- high welding rate and efficiency,
- low energy consumption.

The advantages of the ultrasonic welding of metals are the following [5]:

- possibility of welding various metals (steel-aluminium, aluminium-copper etc.); it is sufficient if one of the metals undergoes plastic deformation,
- possibility of joining plastic metals with hard and brittle metals (e.g. gold or nickel with glass, aluminium with glass ceramics) [3],
- possibility of joining metals characterised by high electric conductivity (e.g. copper or aluminium) or high-melting metals (molybdenum, niobium, tantalum, vanadium, titanium or zirconium),
- possibility of joining metallic details of various thicknesses (even 1:100),
- no need for the preliminary preparation of surfaces of metallic elements to be welded (except for thick layers of impurities and scale),
- only slight effect of generated heat and increased temperature on elements subjected to welding,
- possibility of joining heat-sensitive elements (e.g. thermocouples, bimetals),
- obtainment of excellent electric properties with low contact resistance,
- possibility of joining wires (even without the removal of enamel), possibility of joining wires with electronic elements,
- possibility of welding thin aluminium and copper foils,
- lack of intense heating, enabling the welding of metals characterised by high chemical activity,

- in cases of varying metallic materials it is possible to improve the strength of joints using an interlayer made of aluminium or copper,
- obtained joints are characterised by minimum stresses and strains,
- strength of joints amounting to 70% of the base material strength.

The advantages of the ultrasonic welding of thermoplastics are the following [10]:

- low heating temperature enabling the welding of various thermoplastics at temperatures lower than their melting points,
- possibility of performing the welding process in cases of one-sided access to the joint,
- low force during the process prevents material deformation in the welding area.

Ultrasonic riveting or clinching enables the joining of polymers having various physical properties. The ultrasonic welding of thermoplastics enables the automation or robotisation of the process, the replacement of high-speed (e.g. volume) friction welding and makes it possible to eliminate the use of adhesives. In turn, the disadvantages of ultrasonic welding include the limited thickness of the weld (up to 25–30 cm) and sensitivity to element moistness. Possible defects during welding processes include changes of thicknesses of welded materials, the lack of ultrasonic penetration, the destruction of polymers and the insufficient aesthetics of the product.

Conclusions

The significant variety of the design, operation and industrial application of ultrasonic welding machines necessitates the development of technical education aimed to provide specialists with necessary knowledge concerning the testing, designing and the optimum use of such devices.

Because of physical factors, investment and running costs, the areas of technological applications of magnetostriction and electrostriction ultrasonic devices overlap only slightly. The range of materials which can be subjected to ultrasonic welding is, to some extent, wider than that of other welding methods utilising electric energy.

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