Theoretical and Experimental Contributions Regarding the Influence of Technological and Mechanical Parameters over the Quality of Ultrasonic Welds of Various Material Combinations

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The paper presents the parameters of the ultrasonic welding process of some combinations of materials. These parameters can be divided intro three categories: technological, mechanical and acoustical. A particular attention has to be paid to the technological and acoustical parameters, since they influence the quality of the welds.

Keywords: welding horn, energy director, near field, far field, static force

Welding various combinations of materials is a high complex technology due to several elements in the material processing that needs to be welded and the technological , mechanical and acoustical parameters that influence in a way the welding process.

The main elements to be taken into account are the nature of the comprising elements of the materials to be welded; the geometrical configuration of their surfaces; the dimensions of the surfaces to be welded; the properties of each material components and the properties of the global system; the methodology of materials processing, the required productivity, etc.

The main technological parameters of the welding process are: the nature of materials; the state of the surfaces to be welded; the thickness of the materials to be welded; the conditions required by their functional role; the method of welding; the number of acoustical energy concentrators etc.

The mechanical parameters with strong influence over the welding process are: the static force of pressing; the local contact pressure of the surfaces that need to be welded; the duration of the ultrasonic activation, etc.

The optimization of the ultrasonic welding process of several materials combinations assumes the establishments of an objective function comprising all the influence factors and determining the minimum cost of the process of maximum productivity while still achieving the desired quality of welds.

The influence of the technological parameters over the quality of obtained ultrasonic welds of several materials combinations

The technological parameters influence direct the shape, dimensions and characteristics of the welds, according to functional role of the desired part.

The nature of the welded materials

The experimental results obtained have demonstrated that weldability of several combinations of materials depends only on the hardness of the components that need to be welded and their elasticity Module.

The materials with a relatively small hardness can be welded very well, with a lower limit in the sense that soft materials, that can be very easyly deformed can be destroyed by the influence of the ultrasounds. On the other hand, the hard and breakable materials, have the tendency of breaking due to fatigue under the cyclic action of the ultrasonic waves. Thus, the welding is easier to be executed between different materials, with hardnesses not very different. The attenuation capacity is also influenced directly by the hardness. Materials with a high coefficient of attenuation can be welded very well.

Materials with a low attenuation coefficient of amortization present a tendency of breaking under stress and have a low capacity of welding.

One can observe that the interior waste are smaller directly porportional with the elasticity module and allow maximum transmitting of ultrasonic energy in the welded area with a high efficiency.

Furthermore, one can see that the welding of various material combinations depends essentially of the: melting temperature; resistance at shocks; the friction coefficient between the surfaces that need to be welded and their thermal conductibility.

According to some authors the criteria for the determination of the welding behaviour of a material is the k_r ratio:

$$k_r = \frac{\sigma_c^0}{\sigma_c^s} \cdot 100 \quad [\%] \qquad (1)$$

where:

σ_c^0 is the curing resistance of the material at room temperature;

σ_c^s - the curing resistance of materials at the dominant temperature at the area of surfaces that need to be welded.

It is considered that the materials have the same welding capacity when k_r = 0.3...0.25 (weldabilities decreases with the ratio).

Geometrical configuration of the welded surfaces

The realization of high quality, repeatable ultrasonic welds requires some general design rules to be followed:

- the initial area of contact between the surfaces that need to be welded must be small in order to concentrate the energy and minimize the total energy and the duration required for starting and finishing of melting the components in the are of welding. By decreasing the time in which the sonotrode remains in contact with the components one can decrease the possibility of its friction

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wearness and can obtain de displacement of a smaller quantity of material;

- ensuring a correct positioning of the component that needs to be jointed. Features such as pins and sockets, steps, or tongues and grooves, should be used for alignment rather than the vibrating horn and/or fixture, to ensure proper, repeatable alignment and to avoid marking;

-the contact with the sonotrode and the positioning of the contact area must be taken into consideration to ensure the required pressure in the joint area, in order to direct the energy and mechanical force without being necessary the contact surface marking.

There are two important categories of ultrasonic welds of plastic materials: welds with energy directors and welds with shear joint. All other types of welds can be included in these general categories or are combinations of the above.

The welds realized with acoustical energy directors are characterized by the fact that the direction of ultrasonic oscillation is perpendicular on the contact surface of the component in the joint area.

The acoustical energy director is usually a portion of material of a triangular shape placed on one of the components that need to be jointed. Its primary functions is to focus the energy in order to quickly initiate “softening” and melting of the components in the joint area.

The diagrams in figure 1 show time-temperature curves for a common butt joint and the more ideal joint incorporating an energy director. The energy director permits rapid welding while achieving maximum strength; material within the director generally flows throughout the joint area. These types of joints are the most commonly used for plastic amorphous materials, but can also be used for semi-crystalline materials.

The basis elements regarding the design of some welds done with ultrasonic directors are depicted in figure 2. It is very important to take into account that the size and position of the acoustical energy director on the joint interface depends on the component materials, the requirements and the thickness of the components.

The tip of the acoustical energy director has to be as sharp as possible. The directors with round or flat tips will not be softened and melted as efficient as those mentioned above.

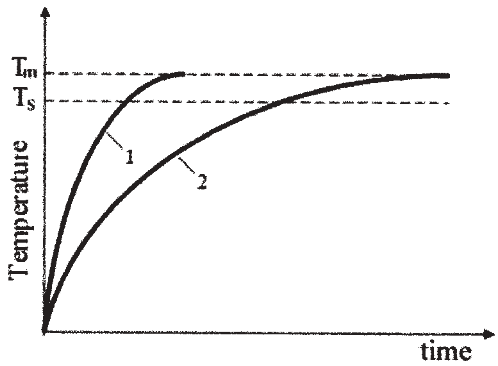

Fig.1. Temperature variation in the joint area
1- joints without acoustical energy director 2- joints with acoustical energy director;T_m– melting temperature; T_s–softening temperature

When a plastic material relatively easy to be welded (e.g., polystyrene) that has a high elasticity modulus (hardness) and a low melting temperature is used , a minimum height of 0.25 mm is recommended, while a semi-crystalline or amorphous resin with high melting temperature requires a minimum height of 0.4 mm.

Usually, an angular opening of 90^0 is used for amorphous resins, while an angular opening of 60^0 is used for semi-crystalline resins. The angular opening may vary function of the material, filling, geometry of the component or other requirements.

In the case of plastic semi-crystalline materials welding (e.g., acetal, nylon) with ultrasonic director, the maximum resistance of the obtained joined is determined in general only by the dimensions of its base.

As a general rule, it does not matter which components of the joint contains the energy director. In special situations, such as the case of welding some component of different materials, the rule is to place the energy director on the component with the lowest melting temperature and hardness.

The energy director must be designed so it will ensure the required positioning of the components that need to be jointed with features such as pins and sockets, guiding lines or by using some placing devices.

A step joint (fig. 2b) is used for positioning the components and for applications in which excessive

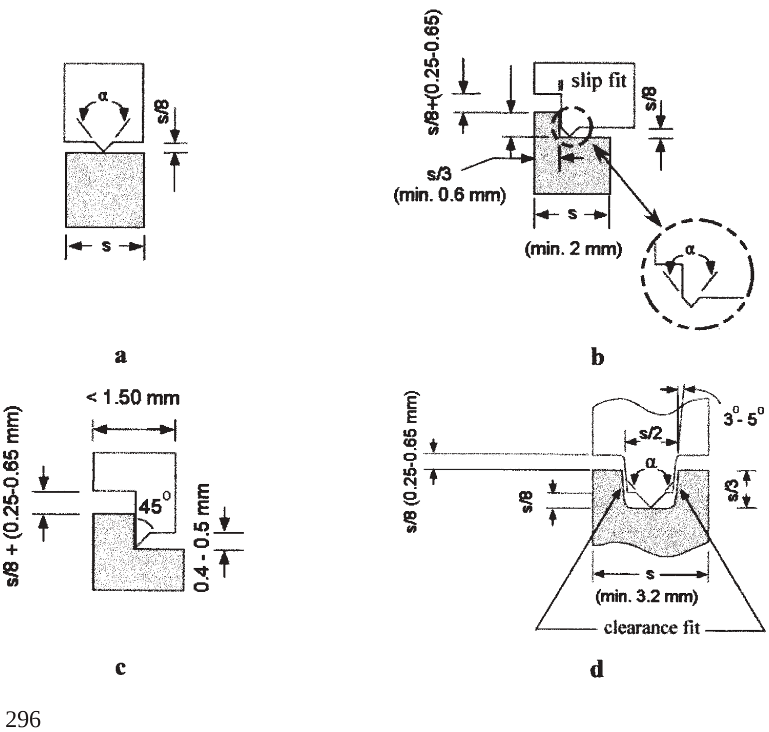

Fig. 2. Types of ultrasonic welds with acoustical energy directors
a - basic energy director ; b - step joint;
c - chisel energy director ; d - tongue and groove

melting or displacement of material in the joint area is unacceptable.

A supplementary space of 0.25 up to 9.65 mm between the components that need to be jointed will have as a result a much more pleasant aspect of the welding. This is due to the fact that the local variations of thickness will be much less visible. Furthermore, the possible non-uniformities produced by the non-uniform melting of the components along the length of the joint contour will be less visible.

Figure 2c presents a joint with chiesel acoustical energy director.This type of joint is used when the wall thickness is of 1.5 mm or less. If a regular energy director is used, this will have a much less height (under 0.25 mm), this resulting in a small resistance of the weld. The height of the director must be 0.4 to 0.5 mm and the angle between two adjacent surfaces is 45^0. Taking into account that the weld resistance will be limitd to its height, one must foreseen a textured surface when this type of joint is used.

Figure 2d presents a joint with a tongue and groove energy director. The main advantage of using such configuration is the decrease in possibility of melted material displacement, both inside and outside and the ensuring the positioning of the components that needs to be jointed. The retaining of material inside the groove increases the possibility of obtaining some sealed joints. Furthermore, due to the reduced area of the welds, it is in general less resistant than the step joint.

The improvment of some quality characteristics of the joints which can be obtained is that the component surface coming into contact with the energy director is textured. Usually, the texture is 0,008 to 0,15 mm deep and varies with the height of the energy director. In the majority of cases, the advantages are the increase of the weld resistance, the reduction of welding time and the possibility of using smaller amplitudes.

Another way of preparing the components for welding is the use of acoustical energy directors on both components, perpendicular on each other, ensuring a minimum initial contact at the interface, while a potential higher volume of material can be involved. This can have as result the increase of the joint resistance. Each energy director must be dimensioned at approximately 60% of the size of only one component, has a director and will have an angular opening of 60^0 as opposed to the regular one of 90^0.

The joints with acoustical energy director can not produce in some cases the desired results when some semi-crystalline resins such as nylon, , polypropylene, polyethylene, acetal and thermoplastic polyester are used. This is because the semi-crystalline resins are rapidly changing from solid to liquid state and the other way around in a relatively narrow temperature interval. The melted material that flows from a energy director can therefore solidify before fusioning with the other component. This is why, when the assembly configuration allows, it is indicated that shear joint to be used (fig. 3).

By using such a configuration, the welding is done through the melting of a small initial contact area and then continuing melting on an overlapping area along the vertical walls, while the components are moving one at each other. This allows the obtaining of resistant joints, sealed that will never come into contact with the surrounding environment. This type of welding is used especially for semi-crystalline resins.

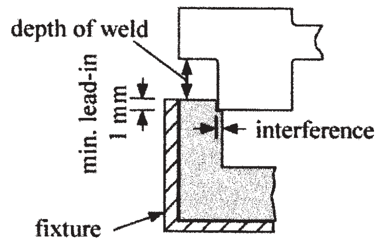

Fig. 3. Shear joint

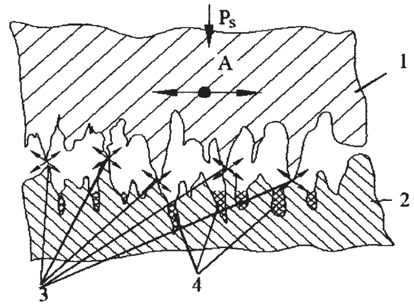

Fig. 4. The profile of the contact area of the joint surfaces
1; 2 – joint component; 3 – first micro-irregularities in contact; 4 – material in the melted state; P_s - static force of pressure; A – amplitude of the ultrasonic oscillations

The profile of the contact area of the joint surfaces

The contact profile has a high practical influence because each micro-irregularity of the surface constitutes an acoustic energy director and first area of melting will appear between micro-irregularities 3, of the highest height (fig. 4). The melted material 4, is expulsed in the lower part component micro-irregularities, thus contributing to the acceleration of the melting process of the other micro-irregularities, process that it is intensified by the ultrasonic energy introduces in the joint area.

The experiments have demonstrated that the micro-irregularities of the contact surfaces are higher as the welding process starts earlier and a higher quality joint is obtained.

The process of joint formation can be divided conventionally in two stages:

- in the first stage, the ultrasonic oscillations start heat development in the contact micro-irregularities; these micro-irregularities are moving relatively one to each other, with an ultrasonic frequency and amplitude A, resulting a high quantity of heat due to contact friction. The majority of thermoplastic materials start to melt in a very short time;
- in the second stage, between the contact surface, heated up the plastic state temperature, links appear that allow the obtaining of a resistant joint, after all irregularities have been melted, creating an homogenous area on all contact surfaces.

The temperature in the joint area must be smaller than the minimum temperature that can produce the destruction of the material in the contact area and higher than the temperature at which a resistant joint is obtained.

Welding method

The welding method has a special influence on the joint because it affects the repartition of the ultrasonic energy introduced in the irregularities of the joint surfaces, the dosing of the ultrasonic energy and the degree of continuity and mechanization of the welding process.

After the repartition character and the dosing of ultrasonic energy in the joint surfaces, there are two welding methods:

- near field welding, when the sonotrode is brought as close as possible to the joint area (fig.5 , a). In this case , the ultrasonic energy is distributed uniformly on all contact

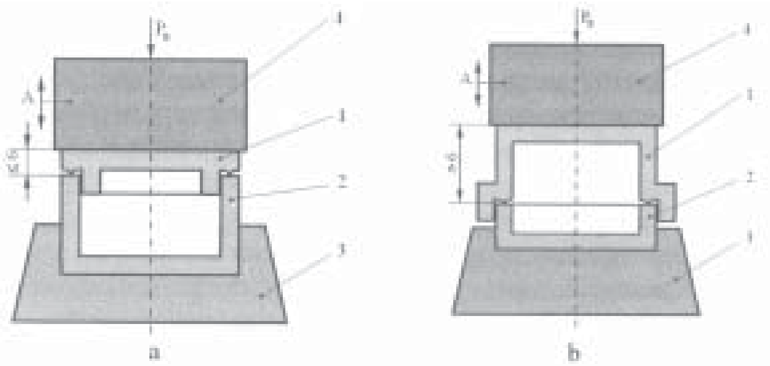

Fig. 5. Welding methods of some materials combinations:a – near field welding; b – far field welding.1 – upper part; 2 – lower part; 3 –acoustic anvil; 4 – sonotrode ;P_s – static force of pushing; A – sonotrode amplitude of oscillation

surface of components that are welded 1 and 2. The frontal part of the sonotrode 4, that comes into contact with the upper part has the surface and shape identical with the welded parts. The method is used for welding soft plastic materials such as polyethylene, PVC and other materials with thickness smaller than 6,0 mm, thus obtaining overlapping joints;

- far field welding, when the ultrasonic oscillation are applied in a certain point or on a small area of the upper part (fig 5,b) and the welding takes place in an area far away from the sonotrode. The uniform transmitting and repartitioning of the ultrasonic energy depends on the plastic materials capacity to convey mechanical vibrations; thus this welding method is highly recommended for hard plastic materials such as : PS, PMMA, PC, ABS.

The influence of mechanical parameters over the quality of the ultrasonic weld of some material combinations

The mechanical parameters are the result of the technological scheme used at designing and realization of the welding system. In general, the welding systems allows more technological scheme, as a function of shape, dimension of the ultrasonic system, that can be fixed or interchangeable. The main mechanical parameters with a particular influence over the ultrasonic welds are the static force of pushing, and the local contact static pressure. The ultrasonic activation duration, the shape of the sonotrode, the shape of the acoustic anvil, the shape factor of the sonotrode and energy director, etc.

The influence of the static force of pushing over the quality of the ultrasonic weld of some materials combinations

The theoretical and experimental results have shown that the value of the static force of pushing Ps influences directly the value of the stress resistance of the welded joints, Fr. As can be observed from figure 6, the results obtained when welding ABS with PMMA, there is an optimum for the static force of pushing, and optimum that depends on the activation time ***t*** and the sonotrode amplitude ***A***.

There is a close link between the static forces of pushing and the amplitude of the active part of the ultrasonic system A, (fig. 7), in the sense that when the force increases, the amplitude decreases. When passing the optimum value of the force, the joint resistance decreases considerably.

The static force of pushing has a high influence over the local static pressure of contact (fig. 8). This increases when the force increases, at various acoustic energy densities.

The static force of pressure is chosen also as a function of the thickness of components that need to be jointed, s. There is an optimum of the joint resistance F_r (fig.9), as a function of thickness and the static force of pressure.

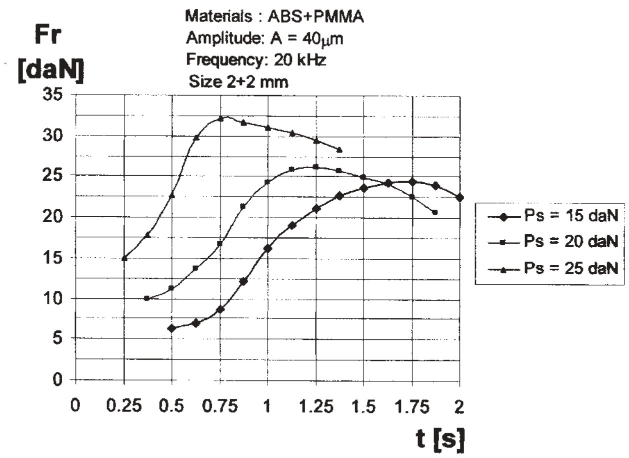

Fig. 6. The influence of the static force of pushing and the activation duration on the welded joint resistance

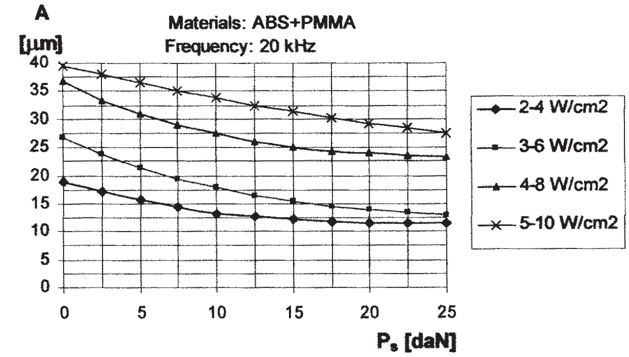

Fig. 7. The influence of the static force of pushing P_s on the amplitude A, at various acoustic energy densities

The influence of the static pressure over the quality of the ultrasonic weld of some materials combinations

The experimental results when welding various combinations of materials has shown that the static local pressure is variable and depends not only upon the static pressure of pushing, but also upon the thickness of the joint parts, size and geometrical configuration of the joint area.

One can see that when passing from stage 1 to stage 2 of the welding process, the contact area increases and the static local contact pressure decreases (fig. 10). Therefore, the joint resistance decreases, up to a limit when the joint cannot be created anymore.

The local static pressure of contact depends also by the configuration of the contact area. Therefore, in order to create the joint, the contact area has a certain shape in the first stage corresponding to the thickness of the parts that need to be welded, the geometrical configuration of the joint area and the functional role of the part. One can see that those acoustic energy directors required to be processed on the contact area, produce not only a

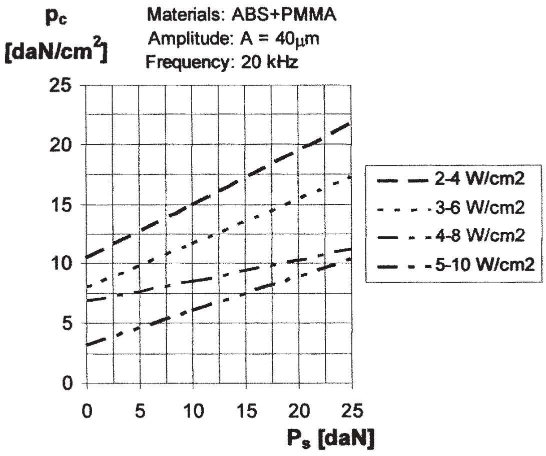

Fig.8. The influence of the static force of pushing P_s on the local contact pressure p_c, at various acoustic energy densities

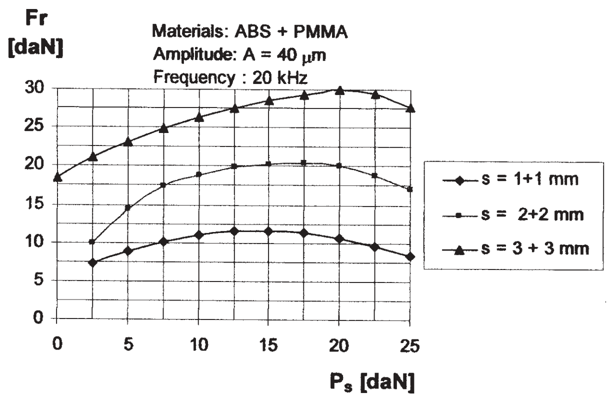

Fig. 9. The influence of the static force of pushing P_s over the joint resistance F_r, at various thickness

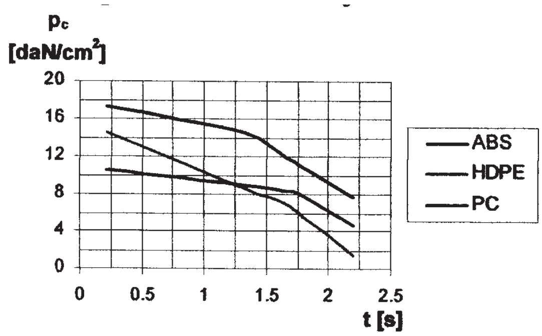

Fig.10. The influence of the welding process duration t_s, on the contact pressure p_c, for various plastic materials

concentration of thermal energy in the local areas of the joint, but also a static pressure of contact much larger in these areas, pressure that decreases when the energy directors are used or are starting to be plasticaly deformed, thus increasing the contact area. The number, size and distance to which these acoustic energy directors are placed depends on the geometrical configuration of the joint and the nature of the materials that need to be welded.

The influence of the welding duration over the quality of the ultrasonic weld of some materials combinations

The welding duration, or the duration of the ultrasouns waves action on the contact area has a particular influence not only on the creation of the welding, but also on its quality and on the welding resistance.

Experimental results have shown that there is an optimum value for the welding duration as a function of the material thickness (fig.11). The maximum welding

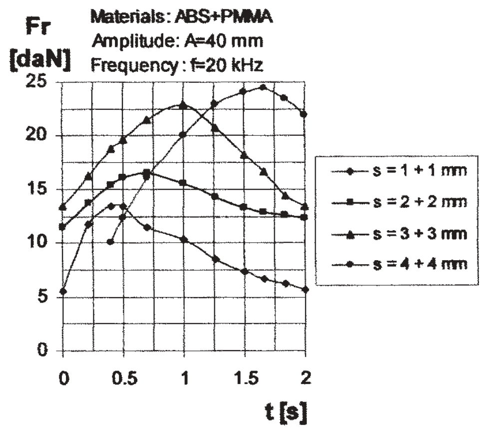

Fig. 11. The influence of the welding duration t on the weld resistance F_r, as a function of the materials thickness

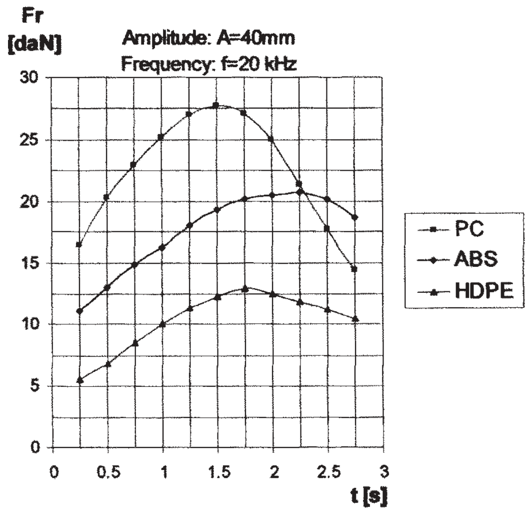

Fig. 12. The influence of the welding duration t on the weld resistance F_r, as a function of the nature of the materials that need to be jointed

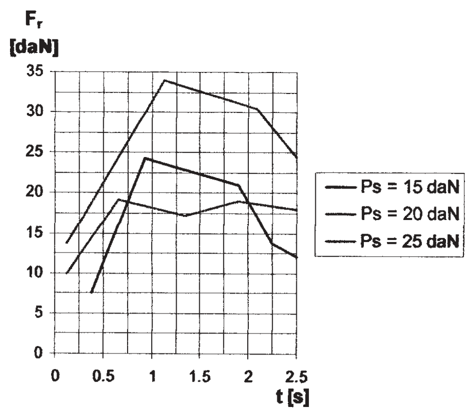

Fig. 13. The influence of the welding duration t on the weld resistance F_r, as a function of the static pressure

resistance depends directly on the decrease of material thickness.

In establishing the optimum value of the welding duration, one must take into account also the nature of the materials that need to be jointed. The activation duration is very different and depends on the properties of the respective materials (fig.12).

The duration of the ultrsounds action in the contact area dependes not only on the nature of the materials, the thickness of the parts that neeed to be jointed, but also on the static force of pressure. (fig.13) and on section shape of the sonotrode in the contact area (fig. 14).

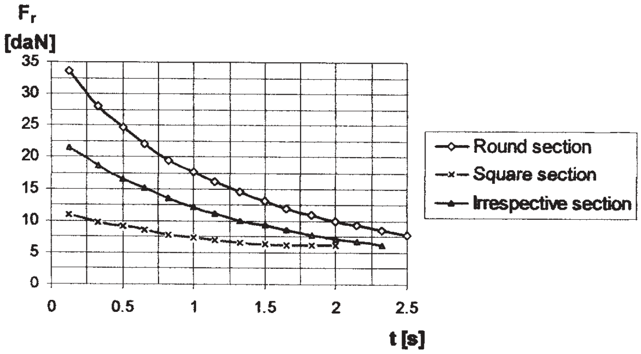

Fig. 14. Influence of the welding duration t on the joint resistance F_r, as a function of the final part section of the sonotrode

The curring plastic speed in the contact areas is in direct correlation with the welding duration, due to the fact that the increase of the curing speed, on short term, based on applying acoustic energy in the joint area, creates favourable conditions for the welding process.

Beside the above mentioned parameters, the quality of an ultrasonic welding depends on several other parameters such as: the nature of the sonotrode material; the state and the quality of the contact area between sonotrode and part; the state of the joint area; the nature of the material of the acoustic anvil; the state and quality of the anvil surface; the physical state of the contact area of the two materials that needs to be jointed; the nature of the environment in which the welding process takes place, etc.

Conclusions

The realisation of various products by ultrasonic welding of some material combinations is a highly complex technology. One must take into account several elements that are directly linked with the processing of the materials that need to be jointed. Furthermore, the welding process is directly influenced by the technological, mechanical and acoustical parameters.

The main technological parameters that need to be optimised in the ultrasonic welding process are the nature of material to be jointed; the geometrical configuration of the surfaces that need to be jointed; the dimensions and size of the contact areas; the thicknesses of the jointed components,; the physical, chemical and mechanical features of the materials that need to be jointed; the global properties of the whole assembly; the method of welding; the required productivity, etc.

The main mechanical parameters of an ultraosnic welding process are: the static force of pressure, the static pressure of contact; the duration of ultrasonic activation; the shape of the sonotrode; the shape of the acoustical anvil; the shape factor of the ultrasonic energy director; the shape factor of the sonotrode; the friction coefficient between the joint components; the elasticity modulus and the hardness of the component materials, etc.

The quality of the ultrasonic welding of some combinations of materials also depends of other parameters, such as: the nature of the sonotrode material; the state and the quality of the contact area between sonotrode and part; the state of the joint area; the nature of the material of the acoustic anvil; the state and quality of the anvil surface; the physical state of the contact area of the two materials that need to be jointed; the nature of the environment in which the welding process takes place, etc.

The optimisation of the ultrasonic welding process of some materials combinations assumes the establishment of an objective function that should include if possible all technological, mechanical and acoustical parameters. This function can be optimised in order to obtain a minimum costs of processing or maximum productivity.

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