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CONCENTRATOR DESIGN USED IN PLASTIC AND COMPOSITE MATERIALS ULTRASONIC WELDING

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Abstract: Composite materials have been a successful challenge for several decades and will continue to represent particularly innovative solutions and of very important application value in many avant-garde fields with particular applicability, such as the aerospace, automotive, medical, consumer goods industries, and more. Much has been written and will be written about the characteristics of composite materials from now on, characteristics that are sometimes clearly superior to structural materials. One of the problems that needs to be solved and which is at a relatively early stage, refers to the joining of two composite materials or plastics between them. At present, the only viable method, and this under certain conditions, refers to ultrasonic welding. The present research refers to the design of an ultrasonic concentrator, part of an ultrasonic transducer used for welding by this method. For this, determining the geometric shape of the ultrasonic concentrator is extremely important, and as such, it was considered innovatively the use a 3rd degree equation whose coefficients were determined. Further, using this equation, the corresponding curve was drawn using the MATLAB software, the curve used in the practical realization of the ultrasonic concentrator, which in this case also represents the tool used in the welding system.
Keywords: ultrasonic, welding, composite materials, concentrator, mathematical model.

1. INTRODUCTION

Ultrasonic welding is a less well-known welding method, but it is used predominantly in certain very important technological situations, especially in high-end industries, in Fig. 1, the principle diagram of this method is presented. This diagram presents the most important elements of the ultrasonic system, namely: the ultrasonic transducer, the ultrasonic amplifier and concentrator, and possibly a pneumatic system that applies a force to the tool in the case of larger welding systems. In the case of ultrasonic welding, portable systems can also be used in which the pressing force is exerted by the human operator. In most work situations, ultrasonic welding is applied to join plastic materials, but more and more recent research also shows the advantages of joining other types of materials using this method. ultrasonic welding is applied to join plastic materials, but more and more recent research also presents the advantages of joining other types of materials using this method.
These refer to the medical, pharmaceutical, automotive or aeronautical industries. A possible classification of non-detachable joining methods for these industries is shown in Fig. 2. Among all these, ultrasonic welding has several benefits, such as:
- welding of different thermoplastic materials depending on their compatibility with the polymer, such as PVC, PET, ABS, PP, PE composites, fabrics, non-wovens, or films;
- welding of thin metal wires such as gold on different metallic or non-metallic supports;
- very short working time;
- welding of materials can be performed without very good cleaning of their surfaces, as there may be surfaces with traces of oils, fibers, or water;
- in case of changing the type of welded parts, changing the tools associated with them can be done very easily;
- no defects such as cracks or fissures are found on the surface or inside the welded parts;
- the welding method is performed at room temperature;
- ultrasonic welding does not require high energy consumption;
- the welded parts can be recycled if the joint was not performed properly;
- does not require filler materials;

- it is a welding method that does not produce side effects on the environment;
- the welding system does not require initiation periods, temporary stops, or cooling at the end of work cycles;
- the shape of the welded joint is defined on the surface of the tools;
- the reproducibility of the welded joint is 100%, all parts obtained in this way having the same shape seam;
- the process of controlling the welding parameters is very accessible and digitalized;
- the welded joint is hermetic, which does not allow the passage of water or gases;
- when the welding process is accidentally stopped, the welded parts do not lose their properties;
- the quality of the welded joint is very good, while also having an attractive appearance

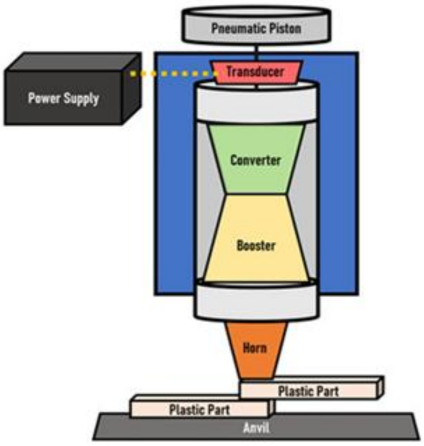

Fig. 1. Schematic of the ultrasonic welding system, [1]

In the following, one of the possible classifications for permanent joining methods will be presented, among which ultrasonic welding is one of the important technologies (Fig. 2).

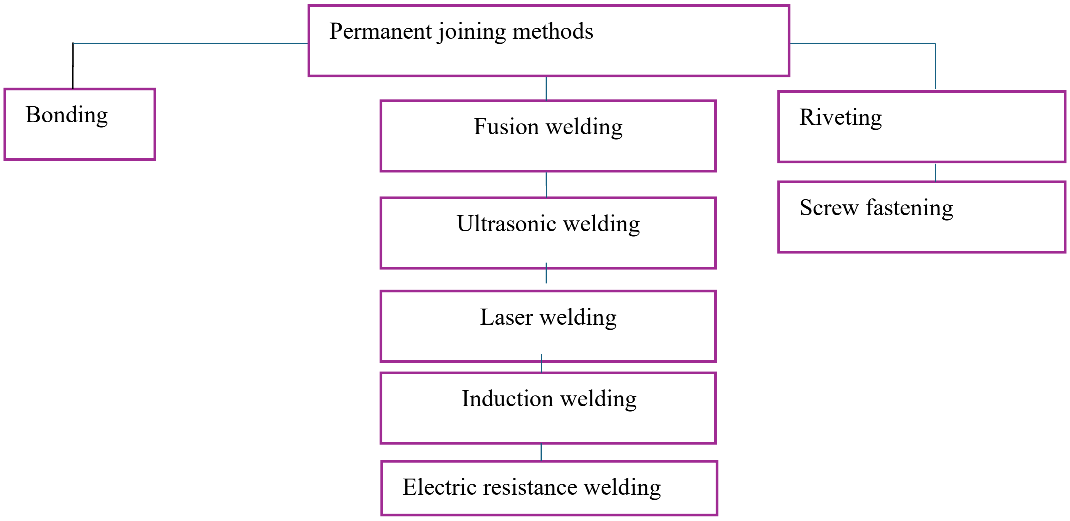

Fig. 2. The main methods of non-removable fastening of composite and plastic materials

As can be seen from Fig. 2, one of the methods for realising permanent joints is represented by ultrasonic welding. Ultrasonic welding is based on the use of an ultrasonic transducer, which, as a constructive and operating principle, is common to many applications of the ultrasonic field. Most of the time, however, the difference between these applications lies in the shape of the ultrasonic concentrator. In the following, a study will be made of the current state of design of different forms of concentrators in order to propose a form of a possible ultrasonic energy concentrator that can be used for ultrasonic welding of plastic and composite materials. This shape is defined as the curve representing a 3rd degree polynomial equation.
Characteristic of an ultrasonic system used for ultrasonic welding of plastic materials or composite materials, in addition to the vibration frequency, the operation of the system depends largely on the vibration amplitude reached at the end of the concentrator. The required operating frequency is provided by an ultrasonic generator from a low-frequency electrical signal (20–90)Hz and converted into mechanical vibrations by the transducer. However, the vibration amplitude achieved by the transducer is not sufficient for machining applications [2].

The ultrasonic amplifier is used to increase the vibration amplitude so that it fulfills their functional role, in this case, to excite the die used for drawing.
Under these conditions, the design of the amplifier and the ultrasonic concentrator is a very important aspect to obtain a higher vibration amplification and operating time. Determining the resonance frequencies is very important, and this problem was also focused on by Seah and his collaborators, who studied conical or stepped ultrasonic concentrators using different types of approximations in this regard.
Other studies on the optimization of the shape of energy concentrators have considered replacing their conical shape with a cylindrical shape in order to reduce the mechanical stress states. For this, Jagadish and collaborators studied stepped concentrators but of exponential shape using FEM to predict the mechanical stress states that occur in it. This exponential shape showed a slight increase in the concentrated power enhancement factor by approximately 69% compared to exponential or conical concentrators. However, the mechanical stresses were found to be lower than those of the stepped, conical, and exponential concentrators. Behavior of the stepped concentrator for ultrasonic welding [3]. Kumar et al [4] analyzed simple and complex concentrator configurations for ultrasonic welding applications to reduce the possibility of cracking of the concentrator, the ultrasonic amplifier attachment area of the horn attachments, and to improve the ultrasonic energy utilization efficiency (Kumar et al., 2018). The main objective is thus to design a new geometry of the ultrasonic concentrator with a high magnification factor in safe conditions from the point of view of the stress state that could cause, under certain conditions, its damage.
The second research direction is to design ultrasonic concentrators with a higher axial vibration frequency, but close to the excitation frequency of the generator, in order to obtain a resonance condition and test their performance. Thus, this was also the objective of work for several researchers to analyze the operation of ultrasonic systems at frequencies very appropriate to that of the ultrasound generator but very slightly located in the upper part of it, from slightly higher frequencies. This research includes determining the proper vibration modes by carrying out modal analyses through which to determine the vibration amplitude, the state of mechanical stresses, as well as the amplification factor. It was observed that the magnification factor achieved by the new concentrator was the highest of all the studied shapes and considered within the limits of safe mechanical stresses. The ultrasonic concentrator should be designed to achieve a higher vibration amplification, while keeping the mechanical stresses as low as possible. Its design depends on the transducer specifications, the vibration amplitude required for the specific applications, etc. To develop the generalized equations representing the ultrasonic concentrator profile, L represents its length, D and d are the diameters in the amplifier area and the free end of the concentrator, respectively, and h is considered the difference in radius at both ends.
For the research on defining a new shape of the ultrasonic concentrator, the expression of a 3rd degree polynomial equation was considered. In equation (1) "y" represents the shape of the ultrasonic concentrator, and "x" represents the position of the variable along the longitudinal axis of the piezoceramic transducer.

$$y = a_3x^3 + a_2x^2 + a_1x + a_0 \tag{1}$$

According to equation 1, the determination of the unknown coefficients that accompany the variable x to the four powers is done by considering the boundary conditions that refer to the diameter of the ultrasonic amplifier that has the ultrasonic concentrator as an extension, to the final diameter of the concentrator that depends on the scope of applicability of the welding system, as well as the slopes corresponding to these diameters.

$$y'_{(x=0)} = 0 \tag{2}$$

$$y'_{(x=L)} = 0 \tag{3}$$

By differentiating equation (1) with respect to x, it results:

$$y'_x = 3a_3x^2 + 2a_2x + a_1 \tag{4}$$

By applying the boundary conditions, it results:

$$y(0) = a_3(0)^3 + a_2(0)^2 + a_1(0)^1 \tag{5}$$

If we consider x = 0, it results:

$$y'_x = 0 \tag{6}$$

$$y'_{(0)} = 3a_3(0)^2 + 2a_2(0) + a_1 \tag{7}$$

$$a_1 = 0 \tag{8}$$

If it is considered that in one of the conditions that the variable x has the length L necessary from the point of view of the functional role of the ultrasonic system, and the value of y at the free end of the concentrator is equal to the useful diameter for making the welded joint, the result is:

$$y_L = a_3(L)^3 + a_2(L)^2 + a_1(L) + a_0 \quad (9)$$

$$a_3(L^3) + a_2(L)^2 + (0)(L) + \frac{1}{2}(D - d) = 0 \quad (10)$$

In the following, it is considered $h = \frac{(D-d)}{2}$. From the construction of the piezoceramic transducer, the diameter D = 22 mm is known. Considering the functional role of the ultrasonic concentrator, which means for welding of the considered parts, the diameter at its extremity is d = 7 mm. According to these, the previous equation can be written:

$$a_3L^3 + a_2L^2 + h = 0 \quad (11)$$

For x = L = 46 mm, the length of the ultrasonic concentrator, if it is considered $y'_x = 0$, equation (6) becomes:

$$y'_L = 3a_3(L)^2 + 2a_2(L) + a_1 \quad (12)$$

$$0 = 3a_3(L)^2 + 2a_2(L) + 0 \quad (13)$$

$$3a_3L^2 + a_2L = 0 \quad (14)$$

$$a_2 = -3a_3L \quad (15)$$

Equation (5) becomes:

$$a_3L^3 - 3a_3L^3 + h = 0 \quad (16)$$

$$a_3 = -\frac{h}{2L^3} = -\frac{(D-d)}{4L^3} \quad (17)$$

Equation (4) becomes:

$$a_2 = -\frac{3h}{2L^2} = -\frac{3(D-d)}{2L^2} \quad (18)$$

Thus, after determining all the parameters, equation (1) becomes:

$$y = \frac{h}{2L^3}x^3 - \frac{3h}{2L^2}x^2 + \frac{D}{2} \quad (19)$$

$$y = \left(\frac{D-d}{4L^3}\right)x^3 - \frac{3(D-d)}{4L^2}x^2 + \frac{D}{2} \quad (20)$$

To visualize equation (20), the MATLAB software was used, and the curve presented in Figure 3 was obtained. Here, the horizontal axis represents the dimensions along the concentrator axis. The vertical axis represents concentrator radius variation. In the construction of the ultrasonic concentrator, only a part of the curve was used. This curve was used to create the ultrasonic transducer shown in Fig. 4.

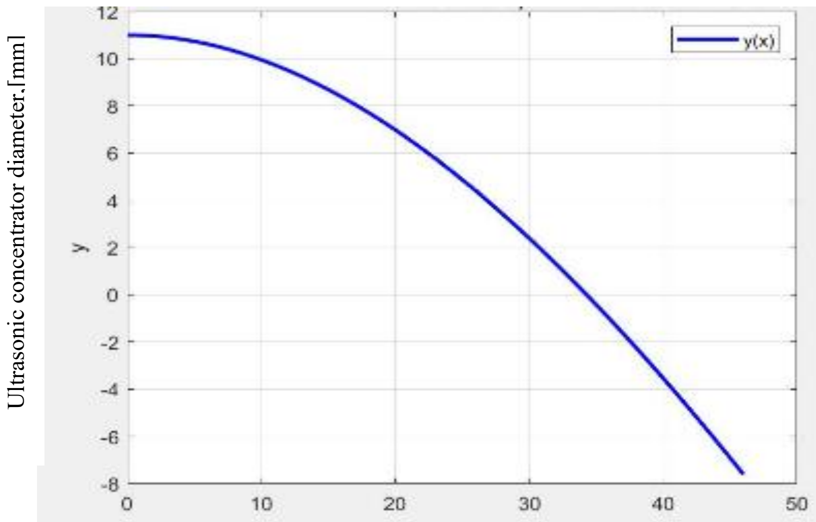

Fig. 3. The geometric shape of the ultrasound concentrator obtained using Matlab software

3. ULTRASONIC TRANSDUCER DESIGN

Apart from the power of the ultrasonic system, which is a function of the thickness of the piezoceramic elements, any such system is composed of the same constructive elements. The generation of ultrasonic oscillations of a certain frequency is achieved in the same way, the differences between them consisting in the design of the ultrasound concentrator. Thus, in Figure 4, an ultrasonic system composed of its classical elements is presented, the only difference being the ultrasonic concentrator. It consists of the following components: 1 – ultrasonic reflector; 2 – four piezoceramic; 3 – cylindrical part of the transducer; 4 – nodal flange; 5 – ultrasonic amplifier; 6 – ultrasonic concentrator. The dimensions of the ultrasonic system are presented in the figure and are adaptable to a small ultrasonic welding system. According to the dimensions of the piezoceramic elements, based on the authors' experience, the power of this ultrasonic system will be approximately 1.500 W.

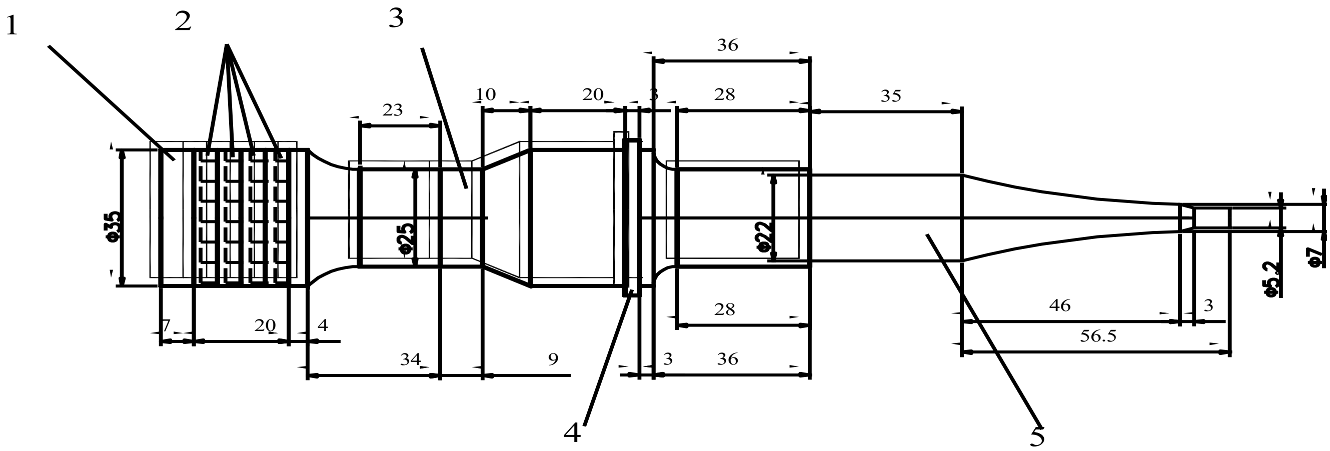

Fig. 4. Components of the transducer designed for use in ultrasonic welding of plastics and composites; 1 – ultrasonic reflector; 2 – elements; 3 – transducer body; 4 – nodal flange; 5 – ultrasonic amplifier; 6 – ultrasonic concentrator

In accordance with the function graph presented, the ultrasonic concentrator was practically realized, which is attached to the ultrasonic transducer that will be used in the ultrasonic welding system that will be practically realized. Fig. 5 presents the experimental realization of the ultrasonic system.


Fig. 5. Ultrasonic system designed for plastic and composite materials welding

4. RESULTS AND DISCUSSIONS

The design of the ultrasonic system for any type of application is the most important step necessary to obtain optimal results. The design of this system is much more complex and includes the analytical design of the system's operating characteristics, the finite element method design of the useful vibration modes, steps that are not the subject of this research. The presented article dealt with the first part of the realization of an ultrasonic welding system. Thus, the concentrator that will be used for this purpose was designed and realized. To increase the amplification of the oscillations, the free end of the concentrator is continued with a cylindrical portion of diameter d = 5.2 mm. In the continuation of the research, the support structure of the ultrasonic system and the welding table will be realized. All these elements will be the subject of another presentation.

5. CONCLUSIONS

The presented work performs the analytical calculation of the ultrasonic energy concentrator, marked with 5 in the principal diagram in Figure 4, to obtain good quality welded joints of materials, but not only. The ultrasonic concentrator is defined by a 3rd degree equation whose gr d =aph is presented in Figure 3. In the continuation of the research, the analytical calculation of the ultrasonic system will be performed, and then the determination of the free vibration modes of the system by the finite element method. This simulation will help to use those vibration frequencies and those vibration modes useful for the proposed purpose. This article presents only the first part of the design activity of an ultrasonic system used for ultrasonic welding of plastics and composite materials. The ultrasonic concentrator, as it was mathematically designed, was also practically realized by machining as can be seen in Figure 5. The authors further propose to conduct experiments in this regard. The validation of the shape of the ultrasonic concentrator will be done through practical experiments that will follow the realization of several types of welded joints, both in terms of the materials that will be used, from the range of plastics and composite materials, and in terms of their geometric shape in the joint area. This geometric shape in the joint area must contain energy concentration areas that manifest themselves through local heating capable of welding the two pieces.

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