ULTRASONIC WELDING OF COMPOSITE MATERAILS. ULTRASONIC BOOSTER DESIGN AND FEM SIMULATION

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Abstract: The paper proposes a new research point of view about the ultrasonic welding which uses the finite element modeling. In the first there are presented some analytical aspects for the booster design and the second part presents the ANSYS modal analyze that offers good information about the ultrasonic system vibration modes and frequency that are used forward to optimize the welding process.

1. THEORETICAL ASPECTS

The paper presents some analytical aspects regarding the design of the active part of the ultrasonic welding system that covers the piezoceramic active elements and the ultrasonic booster.

In the case of a symmetrical (fig.1) compound piezoceramic transducer formed by two piezoceramic disks with the diameter 2 a_1 and high h_p, acoustic characteristic impedance $\rho_1 \cdot v_1 \cdot s_1$, two identical metallic elements h with the diameter 2 a_2 and acoustic impedance $\rho_2 \cdot v_2 \cdot s_2$, the elasticity modulus for the metallic parts Y_z^m and Y_r^m have the relations:

$$Y_z^m = \left[\frac{1}{Y}\left(1+\frac{2\nu}{n_1}\right)\right]^{-1} \tag{1}$$

$$Y_r^m = \left[\frac{1}{Y}\left(1-\nu^2\right)+\nu(1+\nu)n_1\right]^{-1} \tag{2}$$

Where: Y is the Young modulus; ν - Poisson coefficient and n_1 – is given by the relation:

$$n_1 = -\frac{T_z}{T_r} = -\frac{T_z}{T_\theta} \tag{3}$$

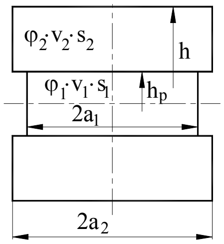

Fig. 1 Simmetrical compound piezoceramic transducer

For the piezoceramic disks we get:

$$Y_z = \left[s_{33}^E \left(1 + \frac{2\nu_{31}}{n} \right) \right]^{-1} \tag{4}$$

$$Y_r = \left\{ s_{11}^E \left(1 - \nu_{12}^2 \right) + \nu_{13} \left(1 + \nu_{12} \right) n_2 \right\}^{-1} \tag{5}$$

Were ν_{12} is the Poisson coefficient and has the relation:

$$\nu_{12} = -\frac{s_{12}^E}{s_{11}^E} \tag{6}$$

and

$$\nu_{13} = -\frac{s_{13}^E}{s_{11}^E}; \quad \nu_{31} = -\frac{s_{13}^E}{s_{33}^E}; \quad n_2 = -\frac{T_z}{T_r} = -\frac{T_z}{T_\theta} \tag{7}$$

The resonance condition for the passive elements is
:

$$k_r^m a_2 J_0 \left(k_r^m a_2 \right) = (1 - \nu) J_1 \left(k_r^m a_2 \right) \tag{8}$$

Were:

$$k_r^m = \omega_0 \sqrt{\rho_2 / Y_r^m;} \quad \omega_0 = 2\pi f_0 \tag{9}$$

Considering the relation (8) the following relation is available:

$$\omega_0 a_2 \sqrt{\frac{\rho_2}{Y} = R_1^m \left(1 - \nu^2 \right) + n_1 \nu (1 + \nu)}^{-\frac{1}{2}} \tag{10}$$

Where R_1^m is the first solution of the equation (8).

The resonance condition for the piezoceramic elements has the form:

$$k_r a_1 J_0 \left(k_r a_1 \right) = \left(1 - \nu_{12} \right) J_1 \left(k_r a_1 \right) \tag{11}$$

Were:

$$k_r = \omega_0 \sqrt{\frac{\rho_1}{Y}} \tag{12}$$

From the relation (11) it follows:

$$\omega_0 a_1 \sqrt{\rho_1 s_{11}^E = R_1 \left\{ \left(1 - \nu_{12}^2 \right) + n_2 \nu_{13} \left(1 + \nu_{12} \right) \right\}}^{-\frac{1}{2}} \tag{13}$$

The resonance condition for the compound transducer becomes:

$$tg\left(k_1 l_1 \right) tg\left(k_2 l_2 \right) = \frac{\rho_1 v_1 S_1}{\rho_2 v_2 S_2} \tag{14}$$

Were:

$$k_1 = \frac{\omega_0}{v_1}; \quad v_1 = \sqrt{\frac{Y_z}{\rho_1}}; \quad k_2 = \frac{\omega_0}{v_2}; \quad v_2 = \sqrt{\frac{Y^m}{\rho}} \tag{15}$$

and l_1, l_2 S_1 and S_2 are the piezoceramic material dimensions respective passive elements.
The resonance condition (14) may be written as:

$$tg(k_1 y_0 h) tg[k(1 - y_0)h] = \frac{\rho_1 v_1 a_1^2}{\rho_2 v_2 a_2^2} \tag{16}$$

From the experiments it resulted that in the assembly ceramic material – reflector longitudinal and transversal oscillations appeared instead the longitudinal oscillations transmitted by the ceramic to the radiant element. These oscillations are independently transmitted (according to Hooke law) and the characteristic impedance of the radiant element is a total of the characteristic impedances of each generated radiations type.

2. FINITE ELEMENT ANALIZE OF THE ULTRACOUSTIC SYSTEM USED IN COMPOSITE MATERIAL WELDING

2.1 THEORETICAL CONSIDERATIONS

The ultraacoustic system is the most important asssembly of an ultraacoustic welding machine because it offers the acoustical parameters (acoustic intensity, acoustic energy density, oscillation amplitude, oscillation frequency, vibration type) and the mechanical parameters (static pression and pression force).

The ultra acoustic system used at the ultrasonic welding consists in the piezoceramic assembly, booster and concentrator (fig.2).

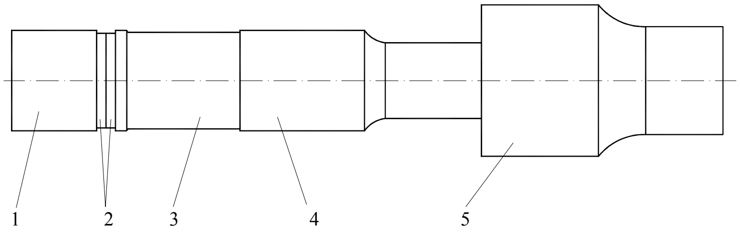

Fig. 2 Ultrasonic system

1. - Reflector; 2. -Piezoceramic elements; 3. -Radiant element; 4. – Booster; 5. – Concentrator.

The piezoceramic assembly is set to frequency f = 20 KHz, and generates the ultrasonic waves (usually longitudinal waves). The ultrasonic energy concentrator (5) is coupled to the piezoceramic assembly by the booster element (4). The booster is an ultrasonic system element, which is an interface element between the transducer and concentrator and has the role to increase the transmitted concentrator vibration amplitude up to the superior limit of the transducer.

The ultrasonic concentrator element is designed as a function of its material properties in such a way that its length is equal to a wave half-length and has to work in resonance condition. Its role is to amplify the oscillations and to transmit the ultrasonic energy in the working zone.

For a maximum efficacy the concentrator must be accorded with an approximation of a few periods with the calculated frequency of the ultrasonic transducer. In this condition the whole oscillating system has to work in the resonance condition for maximum vibration amplitude at the tool peak zone as a result of a high acoustic intensity.

The ultra acoustic system geometrical dimensions for the welding machine are presented in the fig. 3.

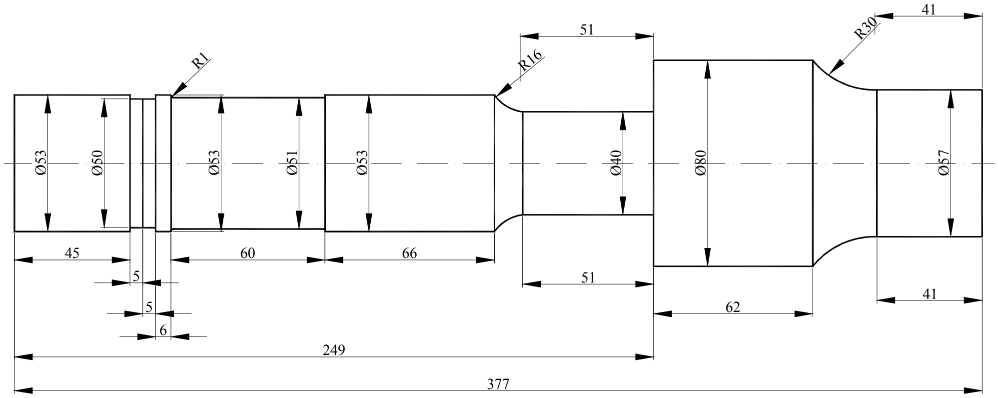

Fig. 3. The ultra acoustic system geometrical dimensions

An isometric view of the ultrasonic system is presented in the figure 4.

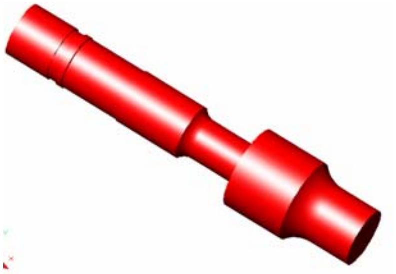

Fig. 4 Welding machine ultrasonic system

System analytical calculus and design is done in such a way that this has to work in resonance regime, but this problem is very difficult to be resolved and the finite element model method is a good method to be used. Because the modal analyze for this system is very complex, the method will be applied for each ultrasonic system acoustic element. The piezoceramic element modal vibrations results will be input data for the concentrator element modal analyze.

3. FEM OF THE PIEZOCERAMIC MATERIALS

The ultraacoustic active elements are the piezoceramic disks made from PZT 4 material. The geometrical dimensions are presented in the figure 5.

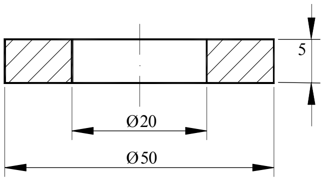

Fig. 5 Geometrical dimensions of the piezoceramic plates

In the figure 6 there are presented the piezoceramic plates geometry and the meshed structure.

Fig.6 Piezoceramic plates geometry and the meshed structure.

With the repect of reality the common nodes in the common areas are set to zero displacements (fig. 7) and on the free areas and common area of the piezoceramic plates is U = 2000 V. The two corrresponding images are presented in the figure 7 and 8.

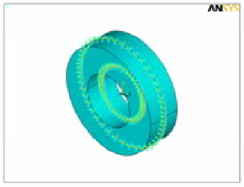

Fig. 7 Zero displacement on the common area

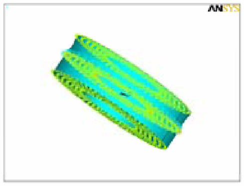

Fig. 8 Applied of the electrical voltage an piezoceramic disks areas

For this analyse type the most important result is the displacement of piezoceramic plates free surfaces For the case of positive electrical voltage on the exterior surfaces, the result is presented in the figure 9.

Fig. 9 Piezoceramic disks displacements at applied positive voltage on exterior surfaces

In the case of negative electrical voltage on the external surfaces the displacements of the piezoceramic disks are presented in the figure 10.

Fig. 10 Piezoceramic disks displacements at applied negative voltage on exterior surfaces

Performing an armonic analise for the frequency f = 20 kHz the result is the nodal displacement that represents the input attac value for ultrasonic concentrator. The results of this anlize in the case of different voltages applied on the piezoceramic surfaces are presented in the table 1.

Tabelul 1. The dependence of the oscilating amplitude as a function of the applied voltage.

Applied voltage on the piezoceramic surfaces [V]	Oscillation amplitude [µm]
0	0
100	0.94
200	1.877
300	2.82
400	3.75
500	4.72
600	5.63
700	6.57
800	7.50
900	8.44
1000	9.38
1200	11.26
1400	13.14
1600	15.01
1800	16.89
2000	18.692

The grafic presentation of the displacement values is presented in the figure 11.

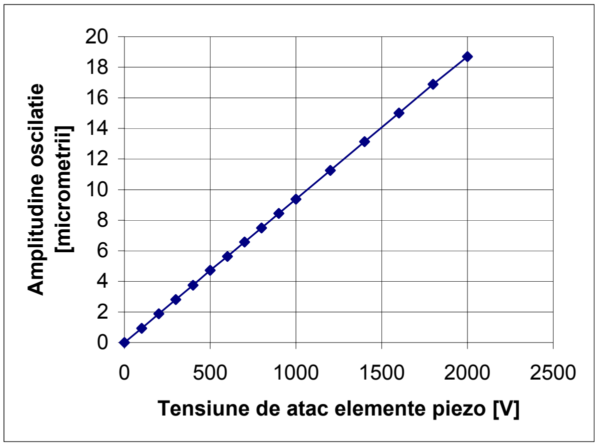

Fig. 11 Linear variation of the oscillations amplitude as a function of applied voltage.

3. FEM OF THE PIEZOCERAMIC ASSEMBLY

The active element of the system is the piezoceramic transducer that transforms the electrical oscillations in to mechanical displacements.

The transducer was composed by two piezoceramic plates that are fixed between tow different blocks (like materials and dimensions) named reflector and radiant (fig.12). Modeling using FEM offers information about structure deformations and stress.

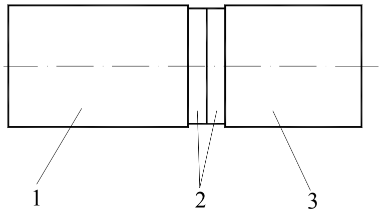

Fig.12. Piezoceramic assembly
1 – radiant; 2 – piezoceramice elements; 3 – reflector.

In the figures 13 and 14 there are presented the steps in design and meshing the model.

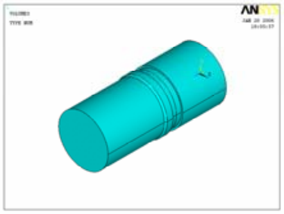

Fig. 13 Piezoceramic assembly geometry

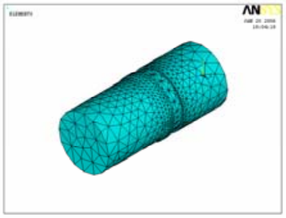

Fig. 14 Meshed model

The way to resolve the problem is to choose an harmonic analyse that is able to predict the structure dinamic, fatigue behavior, to verify if the model reach the resonance. In the same time, the harmonic analize is used to find the structure liniar and stationary responce when the load varies in a sinusoidal form. The ideea is to calculate the structure responce for a few frequencies and to make a grapf frequency – displacement. The analize was performed at frequency f = 20 kHz. That corresponds to resonance frequency of the both piezoceramic assembly and whole ultrasonic system. In the figure 15 it is presented the deformed shape of the piezoceramic at the vibration frequency f = 20 kHz.

Fig. 15 Deformed shape of the piezoceramic at the vibration frequency f = 20 kHz.

The analyze results that presents the deformed shape of the piezoceramic assembly are presented in the table 2.This contains the amplitude vibrations as a function of Z coordinate of the points on the system axis.

On the nodal plane between the piezoceramic plates the vibration aplitude is zero (Z = 50 mm.)

Table 2. Vibration amplitude for the points that belongs to system axis.

Z Coordinate [mm]	Amplitude [μm]	Z Coordinate [mm] [mm]	Amplitude [μm]
0	-17.68	50	0
8.08	-17.52	53	6.88
10.17	-17.08	56	16
16.01	-16.24	56	15.68
21.86	-15.04	61.64	14.6
26.11	-14.08	67.09	16.04
30.36	-13.08	73.54	21.24
33.19	-12.52	79.98	26.08
36.02	-12.12	86.8	30.68
37.91	-12.04	93.62	34.32
39.8	-12.32	98.68	36.44
41.06	-12.92	103.75	37.96
42.32	-13.84	107.12	38.64
43.16	-14.68	110.5	39.08
44	-15.68	112.75	39.12
44	-16	115.02	39.12
47	-6.44	118.8	39.16
		121	39.16

Graphic representation of the vibration amplitude on the Z-axis is presented in the figure 16.

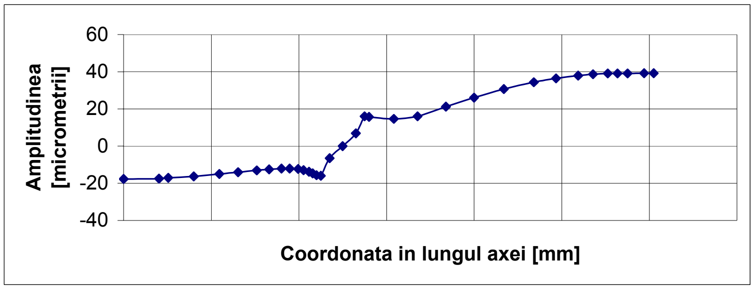

Fig. 16 vibration amplitude on the Z axis

4. FEM OF THE ULTRASONIC SYSTEM

The ultrasonic system consists in an assembly formed by an electromechanically transducer (usually piezoelectric transducer), booster and concentrator. It is the most important assembly in an ultrasonic manufacturing machine because it controls the ultrasonic parameters (acoustic intensity, density of the acoustic energy, vibration amplitude, wave type, vibration frequency) and mechanical parameters.

The general scheme of an ultrasonic device is presented in the figure 17.

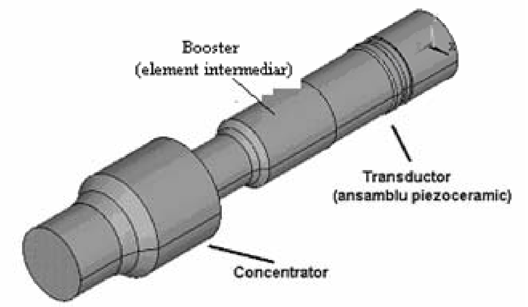

Fig. 17 Ultrasonic system

In the figure 18 it is presented the meshed geometry of the system and the applied loads (electric potential and displacement).

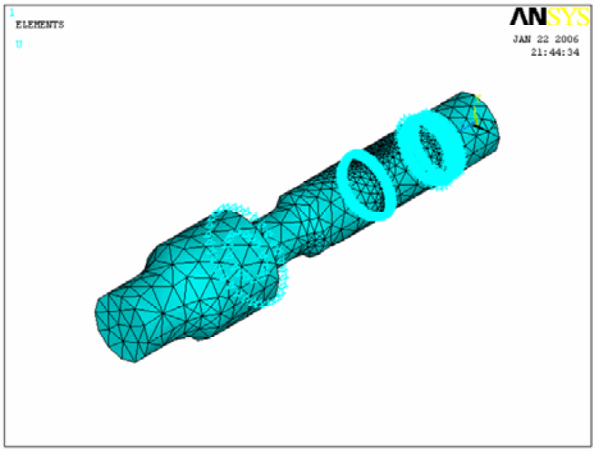

Fig. 18 Aplied loads on the ultrasonic system; electric potential and displacement

Performing a modal analyze, in the figure 19, 20, and 21 there are presented the ultrasonic system deformed shape and the frequency f = 20 kHz.

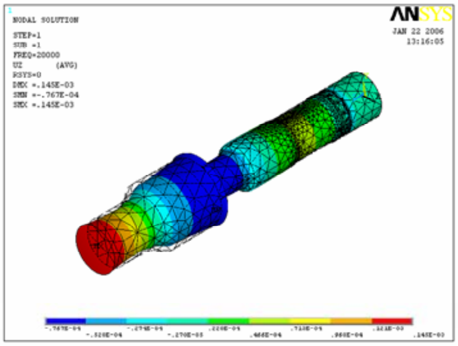

Fig. 19 The isometric view of the ultrasonic system at the frequency f = 20 kHz.

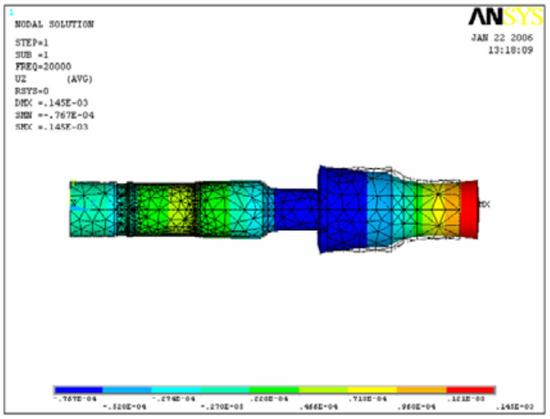

Fig. 20 The lateral view of the ultrasonic system at the frequency f = 20 kHz

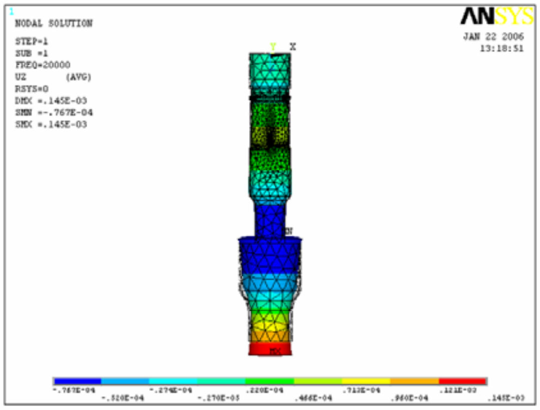

Fig. 5.47 The front view of the ultrasonic system at the frequency f = 20 kHz

4. CONCLUSIONS

The article presents analytical and finite element analyze of an ultrasonic system used in composite materials ultrasonic welding. Using the modal analyze it was found and is presented the vibration mode at f = 20 kHz used in experiments that offers maximum vibration amplitude a the lower consumption energy.

5. BYBLIOGRAPHY

1. Gheorghe Amza, Dănilă Barb; Florica Constantinescu,; Sisteme Ultraacustice; Editura Tehnică, Bucureşti 1988.
2. Jan Soderkvist; Electric Equivalent Circuit for Flexural Vibrations in Piezoelectric Materials; IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Controls, 1990.
3. Nesbitt W, Andrew McFarland , Piezoelectric Materials for Ultrasonic Wave Applications, IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Controls, 1997
4. Qing – Ming Wang, Eric Cross, Constitutive Equations of Symetrical Triple Layer Piezoelectric Benders, , IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Controls, 1999;