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METHODS AND MEANS FOR NONDESTRUCTIVE STUDY OF THE DAMAGEABILITY OF COMPOSITE MATERIALS

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ABSTRACT

Changes in the properties of composite materials and their structural imperfections are closely associated with physical parameters dealing with acoustic, thermal, electric, etc. To disclose these interrelations, the method of nondestructive testing of composite materials may be used. A number of these methods will be discussed.

INTRODUCTION

Conventional methods of studying the formation and accumulation of microcracks and flaws include X-ray dissipation, infrared spectroscopy, electromicroscopy and acoustic emission. However, damageability in the broader sense is connected with the variations of material structure due to loading, aging, technological imperfections, etc. Our studies of less known methods used in fracture mechanics associated with the emission of acoustic, thermal and electric energy show that in some cases these methods are more effective than the conventional ones. Their main advantage lies in the nondestructive evaluation of the integral characteristics and variations of numerous composite materials.

A. Basic Studies of the Physical and Mechanical Properties

Experience has shown that all composites are inhomogeneous and vary significantly in their composition and properties even in the absence of gross defects. The range of variability of mechanical properties is illustrated in Table 1. The quantities in Table 1 are defined as:

σ_{11}, E_{11} - longitudinal strength and modulus of elasticity along the fiber direction;

σ_{22}, E_{22} - longitudinal strength and modulus of elasticity transverse to the fibers;

τ_{31} - interlaminar shear strength along the fiber direction;

τ_{32} - interlaminar shear strength transverse to the fibers.

TABLE 1 - THE VARIABILITY OF MECHANICAL PROPERTIES OF REINFORCED PLASTICS (max value/min value)

Material	Mechanical Properties					
	σ_{11}	σ_{22}	E_{11}	E_{22}	τ_{31}	τ_{32}
Unidirectional GFRP						
AG-4-S	2.3	2.3	1.3	2.0	2.6	-
33-18-S	1.9	1.5	1.7	2.4	1.5	2.0
27-63-S	2.0	-	1.7	-	-	3.1
P-2-1S	1.9	-	2.6	-	-	-
GFRP with two-dimensional reinforcement PPN	1.4	1.3	1.6	1.7	1.6	1.6
GFRP with fabric reinforcement	2.0	2.7	1.8	1.3	1.3	1.4

Evaluation of the in-service performance reliability of composite materials during loading requires nondestructive testing (NDT). Careful study on the detailed physical and mechanical properties of typical reinforced plastics provided by M. Z. Medvedev and A. V. Sandalov shows a highly definite correlation between the physical parameters and mechanical properties. We could therefore set up an equation as follows:

$$P \text{ and } F = f(S,K,T)$$

$$P \text{ and } S = f(F,K,T)$$

where P is the parameter of strength or reliability; F is the physical parameter which can stand for the velocity of ultrasonic waves, thermal conductivity, dielectric constant, dissipation factor, ratio of light penetration, etc., S is the parameter of structure such as fiber volume fraction, fiber orientation, distribution of reinforcement, porosity content, interlaminar adhesive strength; K is the mechanical characteristics of components; and T is the processing characteristics such as winding tension moulding pressure, temperature of polymerization and others. The equation shows that to assure high durability the NDT physical methods must be combined with technological control.

Investigations conducted by V. D. Shtrauss and J. Matison disclose correlation between the strength and some physical parameter during the process of artificial aging of GFRP. Figure 1 shows the correlationship between bending strength and the physical parameter. Both parameters are presented in relative units:

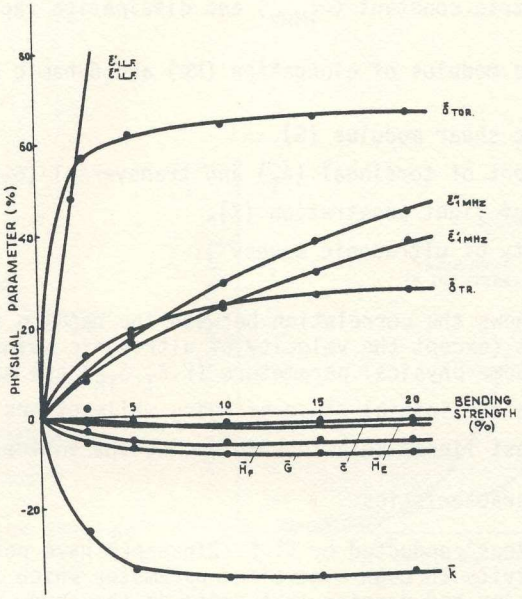

Fig. (1) - Correlation between the physical parameter and bending strength during the composite aging

$$\bar{\sigma} = \left| \frac{\sigma_{b,s}}{\sigma_{o,b,s}} \right| \cdot 100\% \qquad \text{(bending strength)}$$

and the physical parameter

$$\bar{y} = \left| \frac{y}{y_o} \right| \cdot 100\%$$

where $\sigma_{o,b,s}$ is the bending strength of the initial specimen; $\sigma_{b,s}$ is the bending strength of the specimen under aging; y_o is the physical parameter of the initial specimen; y is the physical parameter of the specimen under aging.

In our investigation the emphasis was placed on the following physical parameters:

1. Dielectric constant (ε'_{ILF}) and dissipation factor (ε''_{ILF}) at the infra-low frequency ranging from 0.001 up to 1 Hz.

2. Dielectric constant (ε'_{1MHz}) and dissipation factor (ε''_{1MHz}) at 1 MHz frequency.

3. Dynamic modulus of elongation (He) and dynamic modulus of flexibility (H_F).

4. Dynamic shear modulus (G).

5. Decrement of torsional (δ_T) and transversal (δ_{TR}) oscillations.

6. Ratio of light penetration (K).

7. Velocity of ultrasonic waves.

Figure 1 shows the correlation between the bending strength and different physical parameters (except the velocity of ultrasonic waves and dynamic modulus of flexibility). Some physical parameters (K, δ_T, δ_{TR}) are more sensitive to the bending strength in the initial stage of aging while others ($\varepsilon'_{ILF}, \varepsilon''_{ILF}, \varepsilon'_{1MHz}, \varepsilon''_{1MHz}$) have an almost linear relationship during the entire aging process.

B. Thermal Characteristics

Investigations conducted by V. F. Zinchenko have noted high sensitivity of the thermal activity through a combined parameter which incorporates thermal conductivity, capacity and density that arise in the study of the damageability of composites. The thermal activity was determined from the experimentally determined thermal flux diagram in which the difference between the thermal flux in the material under investigation and in the standard material is plotted. The relationship obtained from the flux diagram provides information with regard to material inhomogeneity owing to imperfections, microcracks, unbonded areas of the laminated structure, etc. The cracks size and their location depth can be determined as well. Figure 2 exhibits the thermal flux diagram obtained for materials with different microporosity and for materials with macro imperfections. It can be seen from the graphs in Figure 2 that the quantity of microporosity determines the amplitude of the curve, while the presence of imperfections determines the curves variation rate.

C. Acoustic Emission Study

The approach proposed by M. J. Tutans complies formation of the output signal by summing the amplitudes of individual acoustic impulses during the loading test. The experiments show that this approach is very helpful in studying the microcrack formation and accumulation. The relationship between the output signal and the continuous load (Figure 3), and the relationship between the output signal and the tensile load (Figure 4) indicate that the fracture of the composite material starts from the very onset of loading and continues during the entire loading process. It should be noted that correlations in Figure 4 correspond to the exponential function. It is attractive to assume that under recurrent loads of identical magnitudes acoustic emission is decreasing after each cycle (Figure 5). A further increase in load leads to the exponential correlation as in the previous experiment.

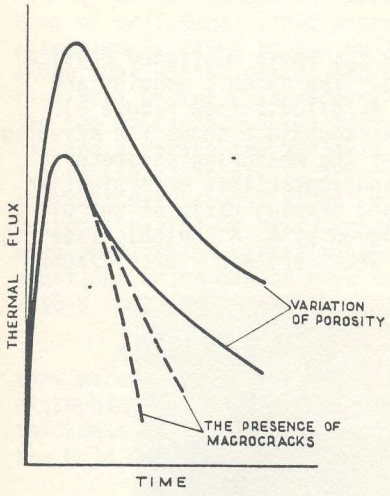

Fig. (2) - Thermal flux diagram

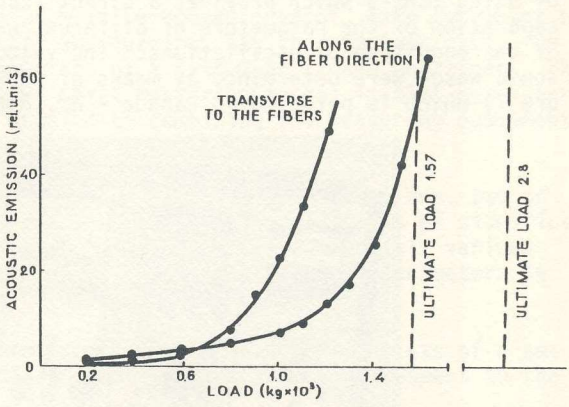

Fig. (3) - Relationship between the acoustic emission and a continuous load

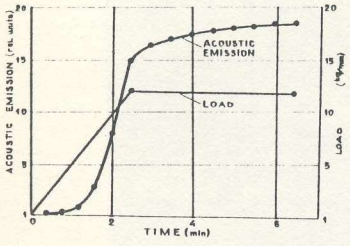

Fig. (4) - Relationship between the acoustic emission and a tensile load

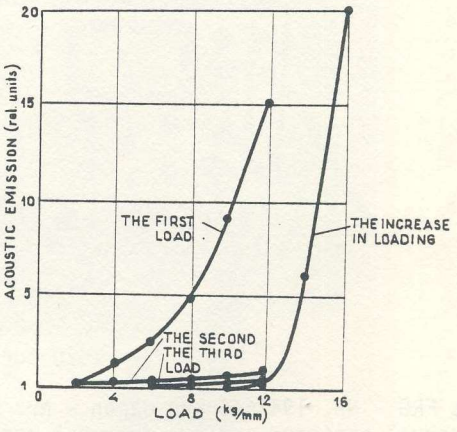

Fig. (5) - The effect of recurrent loads on acoustic emission

D. NDT Technique

In order to characterise damageability by the above mentioned physical parameters, a special test equipment was designed. The dynamic modulus and decrement were measured by ICHZ-9 designed by A. A. Balodis (see Figure 6). Comparison between our device and the conventional technique shows the advantage of using ICHZ-9 which provides a direct reading of the measuring parameters, separation of the parameters of different waves and contactless determination of the magnitude of oscillations. The velocity and damping ratio of the ultrasonic waves were determined by means of ISZU designed by A. A. Balodis (see Figure 7) which is patented in Canada - Nr. 896138, Great Britain - Nr. 1277065,

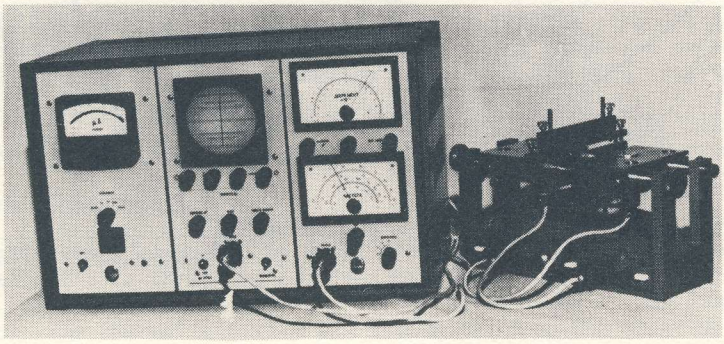

Fig. (6) - ICHZ-9 for vibration inspection of composites

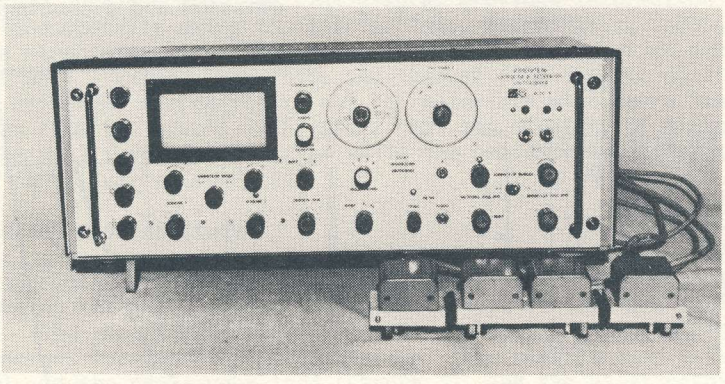

Fig. (7) - ISZU for ultrasonic inspection

the FRG - Nr. 1947646 and Japan - Nr. 4712828. The scanning is performed by two external exciters and two internal receivers of ultrasonic waves disposed symmetrically on one line. Each of the receivers receives the signal which covers different distances in the material. The analysis of these signals from both receivers provides high accuracy of measurement due to the exclusion of the main disturbing factors which take place in the measuring process.

NDT of electric characteristics of composites is based on the application of unilateral capacitance transducers. In our development program great attention is given to the multiparameter measuring technique. Experiments have shown that variations of the distribution of electric field energy over the active area of the transducers face offer one of the greatest potentials for forming the multidimensional signal. In order to analyze the multidimensional signal and separate the variables, special mathematical blocks were used. According to the algebraic interpretation of multiparameter control, each component of the multidimensional signal represents an equation. In the simplest case, the mathematical block must provide a solution of a system of linear equations. The more complicated cases (high accuracy, great measuring range) involve nonlinear equations which can be more easily handled by combining the measuring equipment with a computer.

Multiparameter control provides simultaneous measuring of one, two or more parameters or the measuring of one parameter under conditions of significant disturbing factors such as uneven or rough surfaces of the material, various thickness of thin plates, etc. The variation of the electrical parameters in the bulk of the material can be determined as well.

The general construction of a capacitance transducer consists of a set of coplanar electrodes connected in different combinations with respect to the given field distribution.

On the bases of the above described principles, several two-dimensional measuring equipment was designed: IDP-7 for controlling the dielectric constant of objects with uneven surface (see Figure 8) and DP-201 for controlling the dielectric constant of thin plates (see Figure 9). The basic principles of these

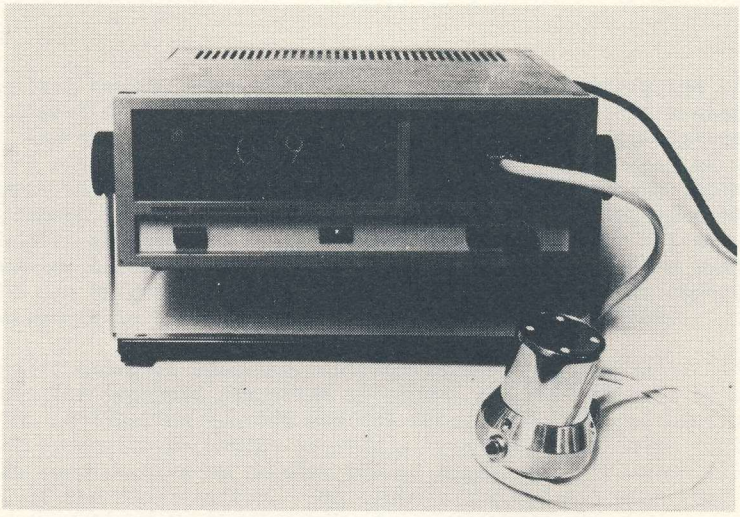

Fig. (8) - IDP-7 for measuring the dielectric constant of objects with uneven surface

Fig. (9) - DP-201 for measuring the dielectric constant of thin plates

devices have patented in the USA - Nrs. 3671857, 3694742), Great Britain - Nrs. 1260359, 1275324, 1277334 and France - Nrs. 2047332, 2067519).