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INVESTIGATION OF KNITTED FABRIC REINFORCED GF/PP COMPOSITES BY ACOUSTIC EMISSION AND INFRARED THERMOGRAPHY

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Abstract

The damage zones in three different knitted glass-fabric (GF) reinforced polypropylenes (PP) were studied on SEN-T specimens simultaneously by acoustic emission (AE) and infrared thermography (IT). The composites have different fiber contents and additives. The fracture toughness, the size of damage zone and the acoustic events were measured and calculated. The results showed that the effect of additives was bigger than the increase of the fiber content.

Keywords: knitted fabric, glass fiber, polypropylene (PP), acoustic emission, infrared thermography, fiber content, additive.

1. Introduction

A characteristic feature of the present modern technique is the wide-range application of reinforced and mated polymers as engineering materials. Reinforced plastics can be regarded as engineering materials shaped up from several elements forming structures (matrix, reinforcement) providing certain but different tasks. The load carrying element is the more rigid reinforcing material, depending on external effect it is tensioned or compressed, while the tasks of the softer matrix material are partly the load transmission, partly protection of the reinforcing structure and assuring the co-working of the reinforcing fibers. This efficient "task-sharing" makes impossible the quick damage of composite structures.

The main reason of wide-spreading fiber reinforcement is that a given material shows higher strength as a fiber than in any other form. The finer the fiber, the higher the probability of the improvement in strength [1]. It is possible to control the beneficial effects on improvement of the mechanical characteristics of the different structures prepared from reinforcing fibers, that is both the value and the direction of the strengthening effect can be influenced. In the case of random distribution of the chopped fibers the system can be handled as an isotropic one. The situation is the same in the case of mat reinforced systems. The fabric-reinforced materials show orthogonal anisotropy as their characteristics in two directions perpendicular to each other are equal. Composites reinforced with fibers oriented are anisotropic as well as the systems reinforced by knitted material. The characteristics are direction-dependent what can be seen in the polar diagram given in *Fig. 1* [2].

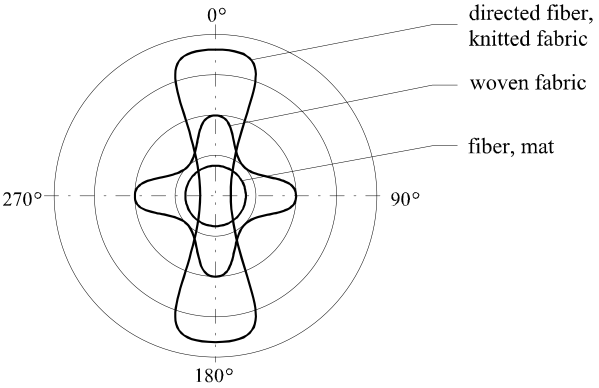


Fig. 1. Tensile strength of reinforced systems presented in polar diagram

The most frequent reinforcing materials are fibers and their combination as mats, the woven and the knitted fabrics (*Fig. 2*). The difference between woven and knitted fabrics presents oneself in the type of connection among the rovings shaping the fabric. The two systems of rovings at woven fabric cross each other perpendicularly and their dense texture results in a relatively rigid fabric while the knitted fabric is shaped up by a system of rovings in loose connection describing highly curved paths. This is why the knitted fabric shows far bigger elongation than the woven one. This fact makes the knitted fabric suitable to follow more closely the spatial surfaces than the woven one which can follow the same surfaces only by breaking of series of elementary fibers.

Mechanical characteristics of knitted fabric reinforced thermoplastic composites (PET, PEEK, PEMA) have already been investigated previously [3, 4, 5]. This paper sets out to present characteristics of polypropylene (PP) systems, reinforced by knitted glass-fiber fabrics tested by acoustic and thermographic methods.

2. Experiments

The investigated PP composites have been manufactured by pressurisation of knitted fabric, made by the German Buck Maschinenbau GmbH, and it was prepared from mixed rovings. The essence of this technology is that both the matrix and the reinforcing material are present as elementary fibers built into one roving what is used at knitting to produce the basic fabric. By pressurisation of this basic fabric the composite plate is prepared. The cycle of pressurisation, having been optimized, was the following:

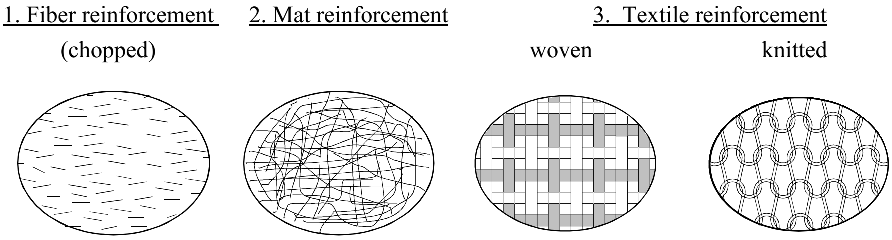


Fig. 2. Reinforcement

i.) heating the pressure plates up to 200 °C;
ii.) increasing the pressure up to 40 bar;
iii.) keeping the 40 bar pressure for 5 minutes;
iv.) cooling down slowly till 100 °C, then quickly.

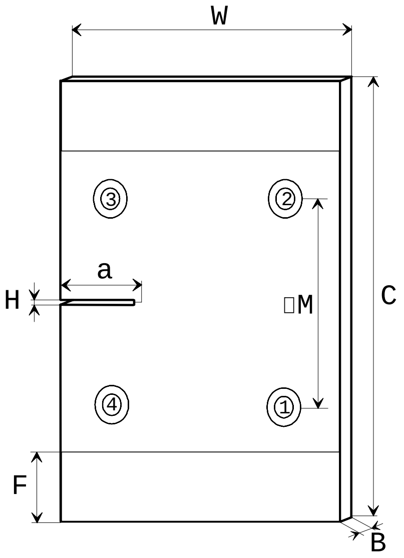
There were used 10 layers of reinforcing material to keep on the required strength and another mechanical characteristic. During the investigation 3 composites different from each other in their characteristics were tested in order to follow the effects of glass-fiber content and the adhesion between fiber and matrix on mechanical characteristics. The effects were possible to follow partly by treatment of the fibers, partly by modifying the matrix material with maleicanhydride. The investigated composites were:

No. 1 PP + 70 wt.% glass-fiber,
No. 2 PP + 50 wt.% glass-fiber and treating both the fibers and the matrix material to improve adhesion,
No. 3 PP + 70 wt.% glass-fiber and treating both the fibers and the matrix material to improve adhesion.

The knitted fabrics applied were plain weft systems in normal (non-elongation) condition having 20 ribs per 10 cm in wale and 15 ribs per 10 cm in course direction.

The aim of the investigation was to compare the characteristics of the three different composites using acoustic emission (AE) and infrared thermography (IT). The results of tests with composites No. 1 and No. 3 show the adhesion improving effect of the additive having equal percentages of reinforcing content in these materials, while the different results obtained with composites No. 2 and No. 3 show the effect of the amount of reinforcing materials. To determine by tests these differences razor-blade notched SEN-T (single edge notched – tensile) specimens presented in *Fig. 3* were applied for fracture-mechanics investigation load in wale and course directions. The tensile tests were carried out on ZWICK 1485 type tensile machine applying 1 mm/min crosshead speed, at room temperature. The tolerances of the specimen sizes were ± 0.1 mm.

During loading of the SEN-T specimens the acoustic emission (AE) was monitored by a microprocessor controlled AE device (Defectophone NEZ-220,



SEN-T
specimen
[mm]

W = 70
a = 20+1
B = 3
C =140
F = 25
H = 1
M = 50x60

Fig. 3. Geometric sizes and positions of acoustic sensors on SEN-T specimen

Atomic Energy Research Institute, Budapest, Hungary). The acoustic events were picked up by a wide bandwidth heat-proof transducer in the frequency range 100 to 600 kHz (peak sensitivity -70dB/V/bar, type Micro-30D of Dunegan Co.). The output signal of the transducer was amplified logarithmically. The transfer function for the whole measuring system (including the logarithmic amplifier and acquisition unit) was:

Peak amplitude = 100 + 20 lg(Uinp/0.4) [dB referred to V].

Parallel to tensile tests there were taken photos and video films, using Hughes Thermal Video System type camera for infrared thermography from the vicinity of crack tip.

3. Results and Discussion

3.1. Tensile DMA Spectra

First of all the DMA tests of composites were carried out. Specimens of 70 × 13 mm sawn from plates were subjected to load-controlled sinusoidal tensile load with frequency 10 Hz in a dynamic-mechanical thermoanalyzer (DMTA; Eplexor 150 N of Gabo Qualimeter). The complex tensile modulus (E^*) as well as its components (the loss and storage modulus $E^* = E' + i\,E$) were monitored from -100 °C to

+170 °C at 1 °C/min heating rate. The static and oscillating loads were 80 and ±50 N. In *Fig. 4* the changes of the complex tensile modulus as a function of the temperature are presented showing clearly the significant effect both of the glass-fiber content and the treatment to improve the adhesion as well as the effect of additives. Significant differences can be observed into different directions. That is the three investigated composites form three systems, easy to differentiate from each other.

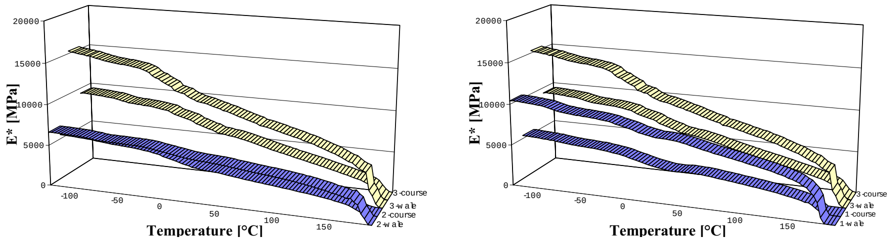


Fig. 4. Complex rigidity modules as a function of temperature for materials No. 2 & No. 3 and No. 1 & No. 3 in wale and course directions

3.2. Fracture Toughness

The SEN-T specimens under monotonously increasing load can be characterised by the load – elongation ($F - \Delta L$) curve being the basis to calculate fracture toughness factor

$$K_c = \frac{F_{\max}}{B \cdot W} \cdot a^{1/2} \cdot f(a/W),$$

where: $F_{\max}$ – upper limit force on $F - \Delta L$ curve
B – thickness of the specimen
W – width of the specimen
a – total length of slot prepared by saw and blade
$f(a/W) = 1.99 - 0.41(a/W) + 18.7(a/W)^2 - 38.48(a/W)^3+$
$+53.85(a/W)^4$
correction factor of geometry

5 specimens of each material were investigated. To calculate the fracture toughness factor all the necessary geometric sizes (a, W, B) were measured individually on each specimen. Out of the five results the minimum and the maximum values were neglected while the average of the remaining three gave the value presented in table. The inclination of the values in table from average values were assigned by 95% confidence interval that according to math-statistics can be calculated as:

$$\bar{s} = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n-1}},$$

where: $\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i$ – average of individually measured values
x_i – an arbitrary measured value
n – number of measurements.

The values of fracture toughness factor calculated according to the method above can be seen in *Table 1*.

Table 1. Values of the fracture toughness factor in wale and in course directions

	Fracture toughness factor K_c[MPam$^{1/2}$]	
	Wale direction	Course direction
1	15.9 ± 0.62	3.9 ± 0.21
2	19.8 ± 1.01	5.1 ± 0.14
3	38.3 ± 2.14	12.5 ± 0.38

The results show that material No. 3 is the strongest followed by material No. 2 and finally comes material No. 1. This result testifies that the effect of the adhesion improving treatment together with the additive material is higher than the effect of +20 wt.% glass-fiber.

3.3. Determination of the Size of the Damage Zone by Acoustic Emission (AE)

The acoustic emission test is based on the fact that solids loaded mechanically or by heat emit stress waves from the areas where physical events had happened. Stress waves are generated in solids when the strains and elementary breakings allow to emit energy. The AE is basically the result of the local unstable condition within the solid block and it is independent of material tested as well as from circumstances. The material under load gets into lower and lower energy levels, as a result of the ever increasing local unstable conditions the material step-by-step loses its energy and finally it reaches the total unstable condition (e.g. the fracture).

The acoustic emission is a sound wave or more precisely stress wave running through the material. The process itself is a quick energy evolution caused by stress. The stress itself is not a hearable phenomenon but the result is. The damages can be local breakage of elementary fibers, pull out of fibers, deformation or cracking of the matrix.

The technique of AE aims to detect the sound waves generated in the material, then to analyse them and to determine their origin. To detect these signals sensors sensitive in ultrasonic band of sounds were fitted on the specimens. The detected acoustic signals were amplified and handled electronically by suitable systems to make them suitable for registration and for analysis.

One of the biggest advantages of the AE technique is that in the case of applying more sensors at tests and registrating the time differences, the place of the sound source comparing to sensors can be precisely determined. The principle of localisation based on sound events is that the time differences (Δt) are registered by signals at different sensors, the velocity of sound propagation in the material and the known positions of the sensors make possible to determine the precise geometric place of the sound source.

The acoustic measurements have been carried out by using the localisation method. The positions of the four sensors on the specimen are shown in *Fig. 3.* The intensity of the acoustic events registered at loading of the specimens is presented in pictorial view. The meaning of the vertical co-ordinate is a relative value expressing the number of acoustic events detected in a square-millimeter area compared to the total number of acoustic events. The acoustic map in pictorial view for the materials No. 1, No. 2 and No. 3 is given in *Fig. 5* when the specimens were loaded in wale direction.

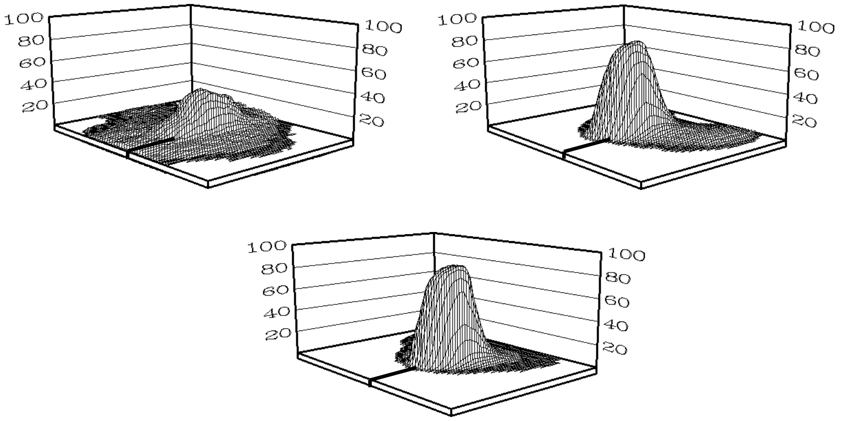


Fig. 5. Pictorial acoustic maps for materials No. 1, No. 2 and No. 3, loaded in wale direction

The pictorial acoustic maps were prepared on the basis of our previous tests [6] so that an $R = 11$ mm circular area was detected along the specimens. The measurements were carried out by using an elliptical area with a major axis 22 mm and minor axis 11 mm, too. This elliptical area is just the half of the circular one mentioned before. The number of detected events as a result of tests is given in *Table 2.*

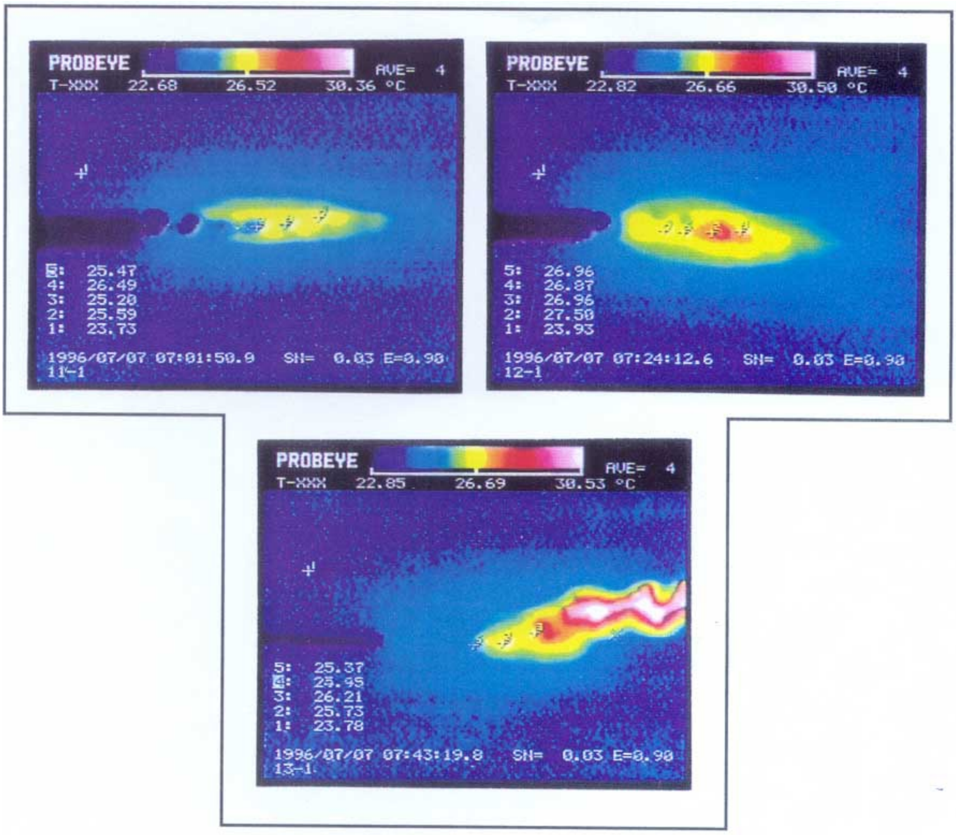


Fig. 6. Photos taken by thermocamera for materials No. 1, No. 2 and No. 3, loaded in wale direction

It is proved for knitted fabric reinforced systems, too, that behaviour experienced at other reinforcements, namely the damage zone is elliptical, as the total number of acoustic events over the ellipse is about equal to the total number of acoustic events over the circle having double the area of the ellipse. The number of events was significantly influenced by the additives. Actually, not only the amount of additives but the treatment of fibers, too, helps the better adhesion. The results clearly show that the number of events parallel to glass-fiber content reduced as less glass-fibers were deformed and broken. This fact can be interpreted by the geometry of the reinforcing structure. It can be observed, too, that the measure of

Table 2. Number of detected events and results of measurements over circular and elliptical areas

	Cumulative events [piece]		Relative frequency [%] circle ($D = 22$ mm)		Relative frequency [%] ellipse ($a = 22$, $b = 11$ mm)	
	Wale direction	Course direction	Wale direction	Course direction	Wale direction	Course direction
1	9950	9000	44	46	39	40
2	4000	3500	87	89	82	86
3	5500	5200	91	88	85	85

the adhesion in the fiber-matrix significantly influences the size of the damage zone.

3.4. Determination of the Damage Zone by Thermocamera

Parallel to other measurements SEN-T specimens at the vicinity of the crack tip were tested by thermocamera, too. The aim of these investigations was to determine the correlation between the value of heat energy generated at energy emission and the measure of the changes in matrix parameters and/or in strengthening structure, whether results of this method can be compared with the results of acoustic measurements. The essence of infrared thermography is that heat conduction capacity of the polymers is extreme low and the possibilities for movement of molecules are limited as well, that is the mechanical energy input that during the crack propagation practically turns into heat can be detected very well. Using the thermocamera it was possible to determine the temperature maximum at the point of the cracking pick comparing to room temperature, as the temperature of the specimen could be regarded as equal to ambient temperature at the beginning of the tests. Point 1 as a reference was chosen on the specimen far enough from the damage zone (heat generating zone). *Fig. 6* shows the state just before breaking for the materials No. 1, No. 2 and No. 3 loaded in wale direction. The three images present that material No. 1 without treatment generates far less heat energy than materials No. 2 and No. 3. The reason of this fact can be deduced from processes of damages as in the case of less adhesion the dominant character of damage is the fiber-matrix separation coming into being at lower loads and consequently the energy emission is less. In the case of strong adhesion between fiber and matrix the typical form of damage is cracking or breaking of the fibers what happens at higher loads so the energy emission is greater.

4. Conclusions

The aim of this investigation was to detect the damage zone on three different knitted glass fabric reinforced polypropylene composites. The conclusions are as follows:

i.) The mechanical strength of composite is far more significantly influenced by adhesion improving additives, helping the fiber-matrix co-working, than by increase of the amount of strengthening materials.

ii.) The sizes of the damage zone detected by thermocamera are 20-30% smaller than sizes of damage zone determined by acoustic emission measurements. The reason of this inclination is that events resulting in big noise effect came into being in the close vicinity of the crack tip that can be well detected by thermocamera as well because the increase of temperature is high owing to energy emission. Investigating the damages of this material, coming farther from this zone, the more typical forms of damages are first the pulling out of the fibers, second the fiber-matrix separation. These latter ones are damages acoustically active, but thermally passive. This is why in previous publication of us [7] it was invented the differentiation of active and passive zones within the total damage zone.

Acknowledgements

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