ADVANCED SENSOR FOR ENHANCEMENT OF ELECTROMAGNETIC IMAGING OF IMPACTED CARBON FIBERS-PPS COMPOSITES

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Abstract: *Carbon fiber reinforced plastics (CFRP) have applications among most different domains due their low density, high elastic modulus and high ultimate strength along the carbon fibers direction, no fatigue and the expansion coefficient is small. CFRP is a paramagnetic composite, with electrical conductivity relatively high in the fibers plan, 10^2-10^4S/m. CFRP samples with matrix from Polyphenylene sulphide (PPS) reinforced with woven carbon fibers 5 harness satin fabrics have been impacted with energies between 2 and 12J at different temperatures of the samples. Due to the plastic deformation following the impacts, the transversal electrical conductivity is modified, allowing electromagnetic procedures for evaluation. An advanced transducer with metamaterials lens assures the manipulation of the evanescent waves that appear between the carbon fibers. This method has been applied for investigation of CFRP in order to determine the influences of temperatures and impacts energies over the area of delaminated surface.*

Key words: *CFRP, metamaterials lens, sensor, impact damage, temperature*

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1. Introduction

Fiber Reinforced Polymer Composites (FRPC) materials continue to be used in a large number of applications ranging from aerospace systems to automotive, industrial and consumer products. FRPC have evolved both in reinforcement and matrix. Matrices used in polymer composites are typically epoxy, polyester polyphenylene sulphide (PPS) while the reinforcements can be carbon fibers, glass fibers or Kevlar (Kaw, 2006). From the point of view of reinforcements, the tendency is to pass from pre-preg laminas, where carbon fibers are parallel, to laminas that contain woven of different types of carbon fibers, leading to the improvement of composite’s formability.

It is known (Grimberg et al., 2000) that the fibers have an average electrical conductivity around 10^3-10^4S/m and relative magnetic permeability is 1 (Morgan, 2005). Because the mechanical properties of epoxy resin are influenced by the moisture content and due to the relieves of dangerous vaporous at temperature exceeding thermal destruction, the trend is to replace it with polyphenylene sulphide (PPS), that has better behavior at impacts at high temperature (Vielle &Taleb, 2011). PPS offers a promising alternative to thermosetting resins such as epoxies: high degree of chemical resistance, excellent damage and impact resistance, and they may be used over a wide range of temperatures. Due to their increasing use in structural applications, the nondestructive evaluation (NDE) of FRPC continues to receive attention for research and development (Hentschel et al., 2010), (Solodov et al., 2012), (Hirsekorn et al., 2013). The shapes of defects in composites are very often different from those typically formed in metallic materials and the fracture mechanisms are more complex (Elmarakbi et al., 2013), due to the heterogeneous nature of composites (Nemes et al., 2004). PPS used as thermoplastic matrix presents a series of major advantages reported to the matrix from epoxy resin, because the gas released due to ignition of matrix is substantially low (Tencate website), the effect of water adsorption is reduced, and the composites carbon fiber woven – PPS have increased strength to impact, the area of delamination surface being smaller.

The specific degradations of FRPC are delaminations due to impacts (Dogaru& Udroiu, 2009), even at low energies, or overloading of the structure, excessive porosity, and water absorption (Morgan, 2005). Visible damage can be clearly detected and repairing can be done in order to maintain structural integrity. But, a major problem consists is the growth of undetected, hidden damages caused by low velocity impacts. These damages are known in aerospace applications as Barely Visible Impact Damages (BVID). Failure to detect BVIDs may result in a catastrophe (Staszewski et al., 2009).

C-scan or top view ultrasound, Lamb waves using noncontact transducers (Su et al. 2006), with Hertzian contact (Grimberg et al., 2009a) or compression waves generated by normal transducers or phased arrays (Grimberg et al., 2009b) are usually used for NDE of FRPC. Embedding intelligent sensors, Fiber Bragg gratings type, in composites structures, it is possible to effect monitoring and prediction of delaminations apparition in order to estimate its lifetime (Grimberg et al., 2008). Also, active thermography (Hung et al., 2009) is used successfully and for desbonding evaluation, bond tests can be used (Xue et al., 2008). The matrix of FRPC has low electrical conductivity (<10S/m) and is paramagnetic, and the carbon fibers of average conductivity are embedded into this matrix and this has suggested that electromagnetic evaluation methods can be also utilized. The starting point for application of electromagnetic nondestructive evaluation method is the theoretical modelling based on the idea that one lamina can be considered as an anisotropic electric conductive plan, having different conductivity along the direction of carbon fibers and perpendicularly on them (Sabbagh &Sabagh, 1984). The composite can be modelled as a succession of thus planes, in thickness, having the direction of anisotropy axis according to the composite layout (Circiumaru et al., 2008), (Bria et al., 2011). But the reality shows that the carbon fibers are not arranged parallel in composite; electrical contact might succeed between fibers that form a lamina and between different laminas, it is schematically shown in Figure 1.

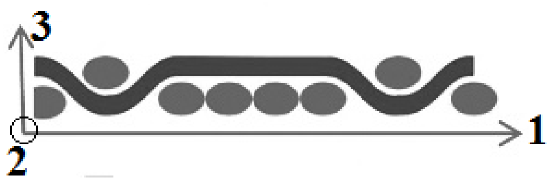


Fig. 1. Carbon fibers layout in FRPC

This situation modifies the electrical conductivity local and completely randomly both in the plane of the fibers and perpendicularly on fibers.

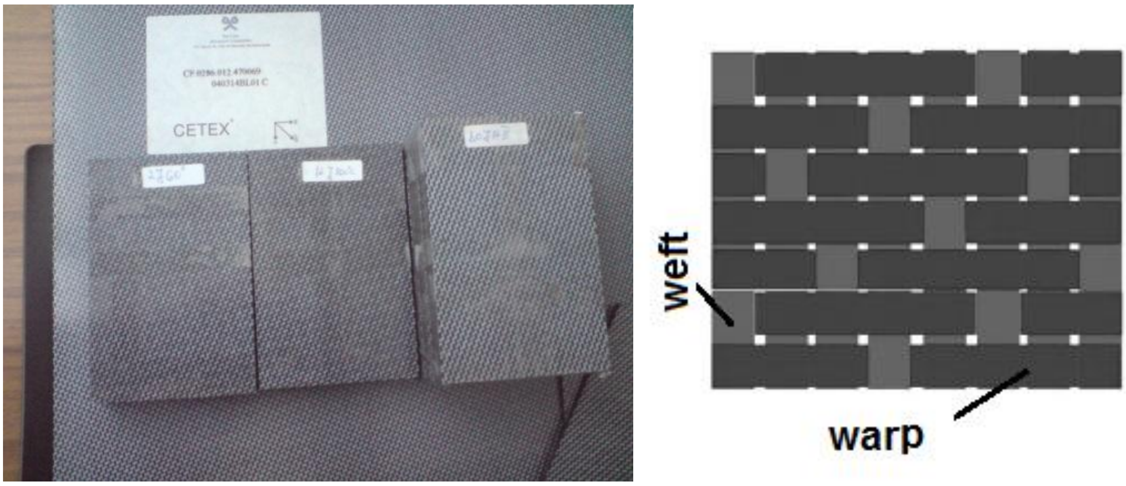
Another possibility for electromagnetic NDE of FRPC consists in utilizing the method described in (Grimberg et al., 2011) and (Grimberg et al., 2001). This paper proposes the electromagnetic NDE of FRPC with polyphenylene sulphide matrix reinforced with carbon fibers woven fabric using special electromagnetic transducers used for effective visualization of the delamination of FRPC created by impacts with low energies, occurring at different temperatures.

2. Studied samples

Plates of FRPC made by Tencate, the Netherlands (Tencate website) having the dimensions 150 mm×100 mm×4.2 mm have been taken into study. The composite plate contains 12 layers of carbon fibers 5 Harness satin woven type as reinforcement and the matrix is PPS –CETEX. The carbon fibers volume ratio is 0.5±0.1. The carbon fibers are T300JB type. This composite has been used in the construction of Airbus and Boeing aircrafts (Hawk, 1987). In Figure 2 are presented the studied samples and the layout of the 5 Harness satin woven (Akkerman, 2006).

On these plates, delaminations due to impacts with different energies have been induced using equipment FRACTOVIS PLUS 9350-CEAST-Instron USA with a hemispherical bumper head having 20 mm diameter and 2.045 kg weight. The samples were impacted with energies of 2 J, 4 J, 6 J, 8 J, 10 J, and 12 J at temperatures of 20^0 C, 60^0 C and 100^0 C.

Above ambient temperatures, 60^0 C and 100^0 C, were selected as around the maximum surface temperature reached, for example, during the aircraft cleaning process, and the maximum service temperature for this resin for structural applications, respectively (Vielle &Taleb, 2011).



a b

Fig. 2. Studied samples: a) composite plates; b) 5 H satin layout

The elastic properties of the composite plate were determined by Dynamic Mechanical Analyzer DMA 242C Netzsch Germany - for evaluation of elasticity moduli along the principal directions and by ultrasound method described in (Grimberg et al. 2009b, Grimberg et al. 2001) - for determination of shear moduli and Poisson coefficients. The direction “1” (Figure 2b) corresponds to the warp direction, the direction “2” coincides with the weft direction and the direction “3” is perpendicularly on the surface of the composite.

The principal mechanical characteristics of the studied composites are presented in Table 1.

E_1 [GPa]	E_2 [GPa]	E_3 [GPa]	G_{12} [GPa]	G_{21} [GPa]	$G_{13} = G_{23}$ [GPa]	υ_{12}	υ_{21}	$\upsilon_{13} = \upsilon_{23}$
16.2	15.1	4.3	3.1	3.1	2.8	0.3	0.3	0.03

Tab. 1. The principal elastic characteristics of the studied composites

DMA measurements have allowed to determine the glass transition temperature, defined as the temperature where tan(δ) exhibits a maximum, as shown in Figure 3.

With DMA, the components of complex elastic modulus can be determined

$$E^* = E' + jE'' \quad (1)$$

$$\tan\delta = \frac{E''}{E'} \quad (2)$$

where $j = \sqrt{-1}$.

From data presented in Figure 3 it is clear that the glass transition starts at onset temperature of 112.8^0 C. E" presents a peak at 125.5^0 C and maximum of tanδ is reaching at 128.5^0 C and 287.1^0 C.

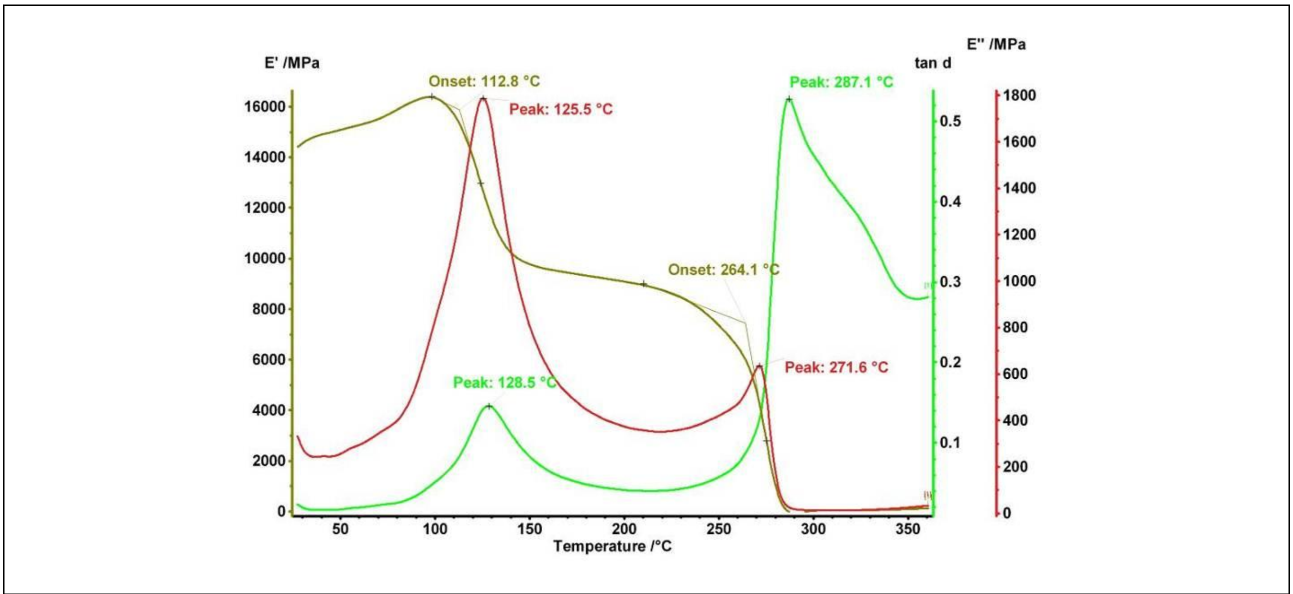


Fig. 3. DMA results

The temperatures at which the impacts were made are smaller than glass transition temperature, giving the warranty that during the heating, the vitreous phase does not appear.

In order to be sure that the entire mass of the composite has reached the prescribed temperature, the impaction has been effectuated after 30 minutes from the moment when the heating system has indicated the prescribed temperature.

3. Experimental set-up

The samples were placed on a fixture device. The impact equipment and the sample's fixture are presented in Figure 4. The impact data were recorded with acquisition system DAS16000-Instron USA, having sampling frequency of 1 MHz.

The plates were examined by means of electromagnetic procedure presented above using the transducer that contains a metamaterial lens for detection (Figure 5). The lens is constructed from two Conical Swiss rolls (CSR) (Grimberg et al., 2012), with large basis face to face. The rectangular frame used for the generation of TM_z polarized electromagnetic field has 20 mm × 60 mm dimensions from 1.2 mm diameter Cu wire. The conical Swiss rolls have 20 mm base diameter, 3.2 mm top diameter, the aperture angle 20^0, height of 55 mm and 2.5 turns made from 18 µm thickness copper foil adhesiveless laminated with 12 µm thickness polyimide foil (LONGLITE^{TM}200 produced by ROGERS CORPORATION USA), in order to decrease the losses at high frequencies.

The transducer is coupled with a Network/Spectrum/Impedance Analyzer 4395A –Agilent USA. The FRPC has been fixed on a XY motorized stage Newmark USA. The displacing system is commanded by PC through RS 232 Interface. The equipment 4395A is coupled with PC through IEEE 488.2 interface. The programs for command and data acquisition were developed in Matlab 2011b. The equipment is presented in Figure 6.

a b

Fig. 4. Experimental set-up: a) the impact equipment; b) fixture device

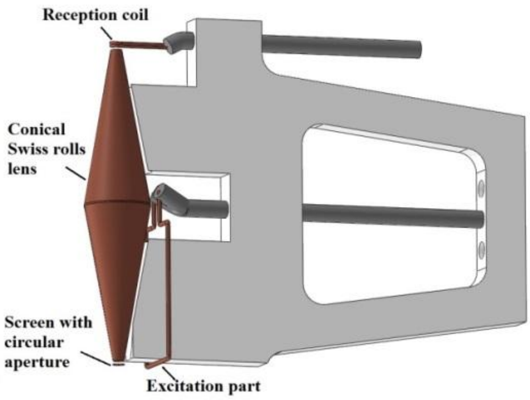


Fig. 5. The electromagnetic transducer with metamaterial lens

Fig.6. The experimental set-up

4. Experimental results

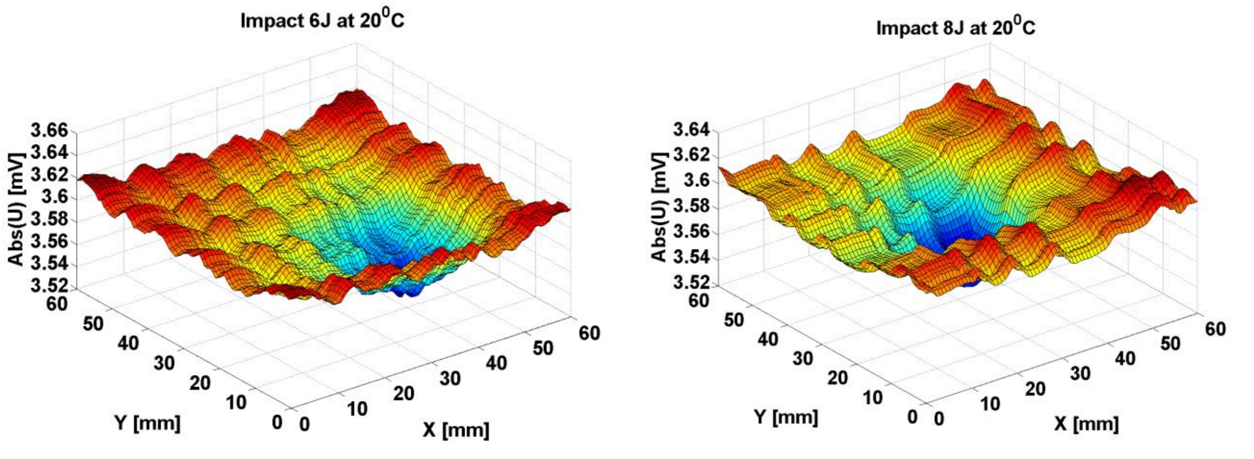
The impacted plates were examined through electromagnetic nondestructive method described above.

A region of 60 x 60mm for each sample has been scanned, the scanning step on both direction being 1 mm. The examination had place at the following frequencies 100 MHz, 200 MHz, 300 MHz, 400 MHz and 500 MHz, respectively, the real and imaginary component of the signal induced in the reception coil of the transducer being measured. The lift-off has been maintained constant at 0.2 mm from the material to be examined, that is practically in the plane of the aperture of the transducer, and the reception part is in the focal plane of the metamaterial lens. The diameter of the focal spot of the metamaterial lens is given by (Sutherland & Soares, 2005) and is equal to the diameter of the small base of the CSR (i.e 3.2 mm).

The samples taken into study were analyzed from two points of view: the influence of increasing impact energy over the area of delamination at constant temperature and the influence of temperature at which the impact take place over the area of delamination when the temperature increase till near the temperature of glass transition (128^0 C, Fig. 3), respectively 100^0 C. In Figure 7 are presented the signals delivered by the transducer at the scanning of a region of composite which contain delaminations due to impact with energies of 6 J, 8 J, 10 J and 12 J induced at 20^0 C.

It can be observed that the delamination is net visible from the signal due to the woven structure, the energy absorbed by the composite increase with the increasing of the impact energy, so the area of the delamination increase in the same manner. On the borders of the electromagnetic image, the structure of the woven can be observed; in the central zone, the delaminated region is emphasized.

This zone becomes electromagnetically detectable due to the modification of the electrical conductivity on the normal direction to the woven plane as a consequence of the impact.



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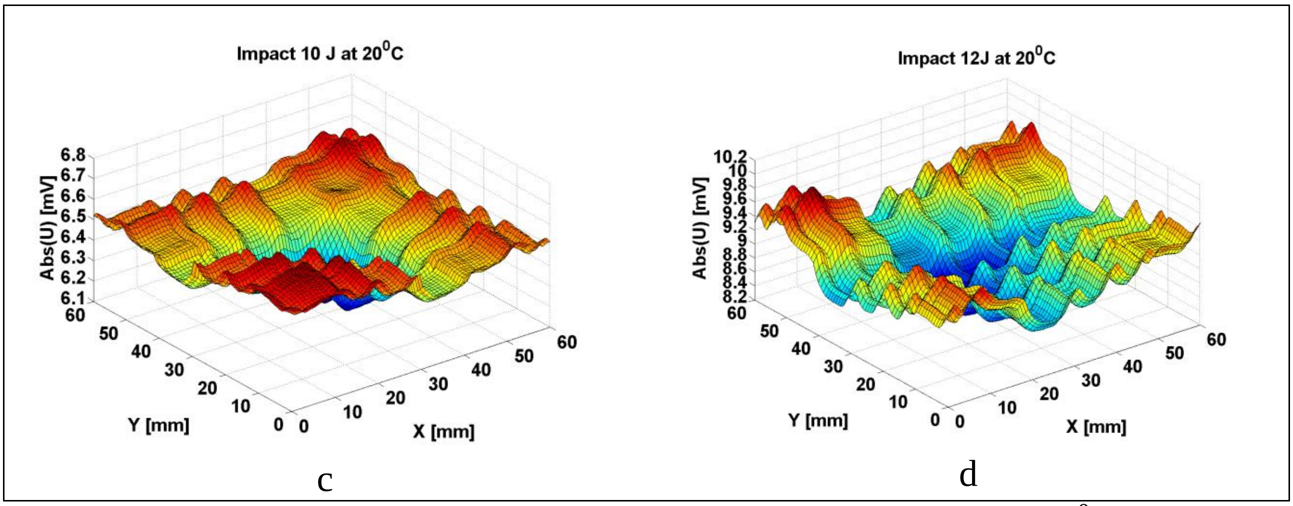

Fig. 7. Signal delivered by the transducer vs the position at impact at 20^0 C:
a) 6 J; b) 8 J; c) 10 J; d) 12 J

The analysis of data from Figure 7 shows that the shape of delamination is visible. From the mechanics of composite materials (Morgan, 2005) is known that due to an impact normally on the surface of the composite, delamination can appear, of whom shapes are approximately conical.

In the region of impact appears a plastic deformation of FRPC that leads to the increasing of electrical conductivity of the area. Fibers in electrical contact, desbonding of fibers from the matrix can appear with consequences over the mechanical strength of the structures made from this composite. The entire layout of the composite can be modified and therefore, the electromagnetic image of the composite, obtained with the described above transducer is essentially modified reported to the image of the intact zones of the composite.

The energy absorbed by the composite serves at the plastic deformation of the composite in the contact zone; it is dissipated through internal friction between the matrix's molecules, carbon fibers, and matrix -carbon fibers as well as at the apparition of delaminations.

This is more visible on the data obtained from the scanning of zones from the composites impacted with 12 J energy at the temperature of 60^0 C and 100^0 C presented Figure 8.

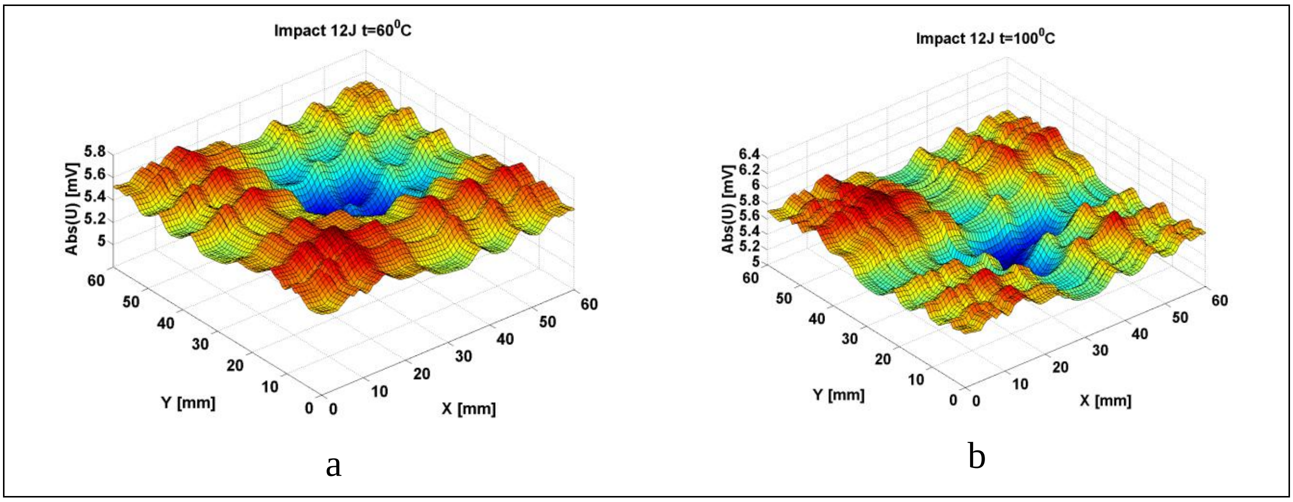

Fig. 8. Signal delivered by the transducer vs. the position at 12J impact:
a) 60^0 C; b) 100^0 C

At the largest impact energy taken into study, the delamination is propagated into the composite, mainly because of the undulation of warp fibers below weft fiber bundles, warp fibers being overstressed and fail first, resulting in failure surfaces oriented along the weft direction.

The conditions of the measurements were maintained from the previous test. The specific of the information delivered by the delamination due impact (Grimberg, 2009a) can be observed. The area of delaminated zone has been determined for all impact energies at the three temperatures binarizing the top view of the data obtained for the other energies impacts at different temperatures (Grimberg et al., 2000).

Functions object detection (segmentation, feature extraction), measurement and filtering were used from Image Processing Toolbox –Matlab 2011b (Matlab website).

In Figure 9 is presented the area of delaminated surface function by the impact energies, for the three impact temperatures.

In all situations, the best fitting is a line with equation presented in the legend, the correlation coefficient being better than 0.97. From the data presented in Figure 9 it can be observed the area of delaminations increases with the energy impact and decrease with the increase of the temperature. This can be attributed to a significant presence of plasticization, especially due to the ductile nature of the matrix increasing with temperature (Benli &Sayman), (Majer, 2010).

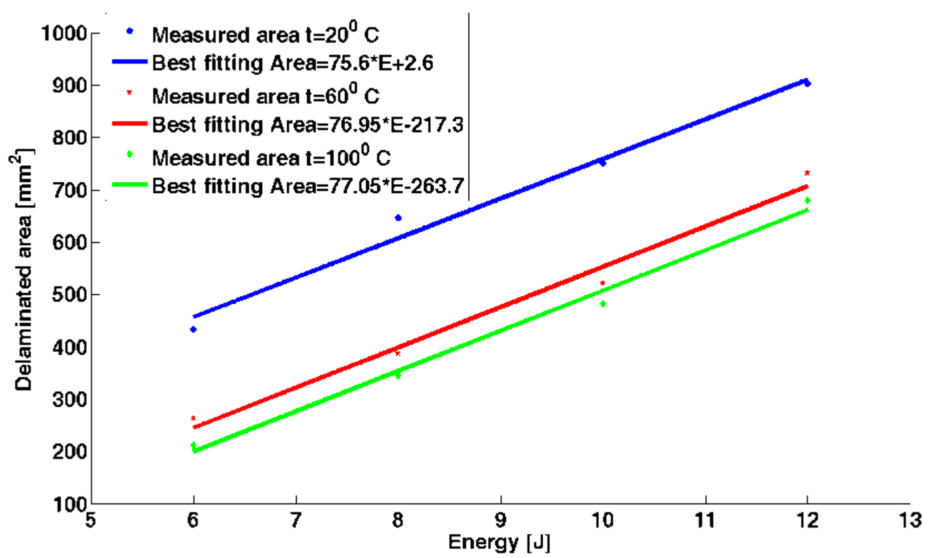

Fig. 9. The area of delamination function of energy

5. Conclusions

Modern FRPC use more and more carbon fibers woven as reinforcement instead of parallel fibers layers. The composite materials from carbon fibers woven, 5 Harness satin type as reinforcement and polyphenylene sulphide is a material relatively sensitive to impact. The principal mechanical parameters as elastic moduli, shear moduli and Poisson ratio were determined by DMA and ultrasound method.

The composite plates were impacted with different energies, at three temperatures, the impact force and the deformations being measured.

After impaction, the samples were nondestructive examined through electromagnetic method with the transducer using metamaterials lens with two Conical Swiss Rolls, working at optimal frequency chosen so the effective magnetic permeability shall be maximum. A linear dependency of the area of delaminated surface function of impact energy has been found, the correlation coefficient being 0.97. The same method has been used for emphasizing the decreasing of the area of delaminated surface with the increasing of the temperature at which the impact took place, due to a more effective redistribution of internal stresses at higher temperature and once again to the more ductile nature of the polymer matrix.

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7. Author Contributions

All authors have equal contributions to this paper.

8. Conflicts of Interest

The authors declare no conflict of interest.

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