A METHODOLOGY TO CALCULATE MANUFACTURING COSTS OF INNOVATIVE CARBON NANOTUBE-BASED POLYMER COMPOSITES

Nikolaos D. Alexopoulos[1,2,*], Ilias G. Tapeinos[1], Angelos Miaris[3], Peter Mitschang[3], Zaira Marioli-Riga[2]

[1]Department of Financial Engineering, University of the Aegean, 41 Kountouriotou str, 82100, Chios, Greece
[2]Research and Development Department, Hellenic Aerospace Industry, GR 320 09, Schimatari, Greece
[3]Institut für Verbundwerkstoffe GmbH, Verarb Fungstechnik, Erwin-Schroedinger Strasse 58, 67663, Kaiserslautern, Germany
**nalexop@aegean.gr*

Keywords: Carbon nanotubes, Glass fibers, Mechanical properties, Rheology.

Abstract

In the present work, a methodology was devised to calculate manufacturing costs of the newly-developed carbon nanotube reinforced polymer composites. Glass fiber reinforced – epoxy composite plates were produced on Hellenic Aerospace Industry based on different parameters: (a) manufacturing process, (b) various geometrical dimensions, (c) variable carbon nanotubes concentration in the matrix and finally (d) modified resin infusion temperature. In addition to manufacturing costs, the tensile mechanical properties of the produced materials were evaluated. It is noticed that almost 20% added manufacturing cost is paid to increase the strength ability of the composite at the expense of ductility and attain multi-functionability via piezo-resistivity of the composite.

1 Introduction

During last decades, there has been strong demand increase for composite materials; in the aerospace industry. Critical parameters are their high specific strength and advanced mechanical properties. Glass fiber reinforced polymers are widely used in aeronautics; however, it is essential to combine manufacturing quality with respective cost.

A significant drawback for the widespread use of GFRPs is their high manufacturing cost; several models have been developed to simulate various manufacturing processes and calculate respective manufacturing cost. Aircraft manufacturers aim to design aircrafts with the lowest possible operating cost, incorporating depreciation costs, insurance, landing fees and fuel consumption [1]. Additional focus has been given on creating GFPRs with a balanced cost to weight ratio. However, investigation should not be focused on ‘pure’ weight reduction, but rather on a combined minimization of manufacturing cost and structural weight [2]. A methodology for a combined cost/weight optimization of aircraft components, thus inputting the weight penalty parameter has been described explicitly in [3].

Use of carbon nanotubes (CNTs) in polymer composites has attracted great attention nowadays due to their excellent mechanical and electrical properties, e.g. [4]-[5]. Using resin reinforced with CNTs, a non-conductive GFRP composite can now become electrically conductive. Therefore, exploiting the methodology of Baron and Schulte [6] with the electrical resistance change of the electrically conductive CFRPs, GFRPs can now be monitored by measuring simultaneously surface electrical resistance change of a coupon during mechanical loading. The addition of electrically conductive CNTs offers to non-conductive GFRP composites the potential for sensing capabilities through changes in electrical resistance on the onset of damage [7] and enhanced fracture properties e.g. [8]-[9].

Research on these newly-developed, multi-functional materials is mainly focused on the enhancement of their mechanical performance as well as measurements of electrical resistance change simultaneously recorded from stress/strain variances of the testing specimens, e.g. [10]. However, critical parameters of rheological properties of the epoxy resin reinforced with CNTs and their effects on processing and mechanical features of these composites have been scarcely treated [11]-[12]. Nevertheless, a complete study on the global benefits of the addition of the CNTs in the composites by means of quality to cost ratio has not yet reported.

In the present work, an assessment of GFRPs reinforced with different percentages of CNTs in their epoxy matrix was performed by means of mechanical and economical point of view. Fully-parametric cost models for different manufacturing processes and governing parameters of composite plates' manufacturing were developed and the quasi-static mechanical properties of the produced GFRP specimens were evaluated. Optimal manufacturing parameters were identified, with regard to enhanced mechanical performance and low cost, produced through the most efficient manufacturing methods known so far.

2 Manufacturing of composites

GFRP plates were manufactured using three different manufacturing processes; the first process was Hand Lay-up Method, the second was Vacuum Assisted Resin Infusion (VARI), and the third was Resin Transfer Moulding (RTM). GFRP plates were manufactured at various geometrical dimensions (e.g. plate edges: 300 mm, 400mm, 500 mm, 600 mm, 800 mm and 1000 mm), either with neat epoxy resin or resin reinforced with CNTs at different concentrations (e.g. 0.5 wt.%, 0.75 wt.%, or 1.00 wt.%, etc). Resin injection inside the mould was carried out from the centre of the mould at various temperatures (e.g. 40°C up to 80°C with a grid of 10°C) to alter its viscosity value which affects the mould filling time.

Tensile specimens were machined out of manufactured plates according to ASTM D3039 specification. Various tensile tests were applied to GFRP specimens reinforced with CNTs at different concentrations and produced from the three different manufacturing processes, in order to obtain results and isolate the effect of CNTs on specimens' mechanical properties. The electrical response for monitoring purposes of GFRP coupons with CNT reinforcement was investigated through attaching electric cable connectors on the specimen surface.

3 Cost modeling

A cost model was developed to simulate the manufacturing cost of GFRP composite material, incorporating different cases: (a) percentage of CNTs in the doped resin, (b) resin infusion temperature and (c) plate's geometrical dimensions. Cost estimation approach in the present work was based on the Activity Based Costing (ABC) method [13]. ABC theory lies on identification of all activities that generate costs during product development (sub-processes and main processes), assignment of respective cost drivers and summation of costs of all sub-processes. As a result, the three different processes are divided into non-automated (Hand Lay-up) and automated processes (VARI, RTM), regarding the fashion at which resin transferred into the mould.

3.1 Hand Lay-up: Non-Automated GFRP manufacturing process

Hand Lay-up is an open moulding manufacturing method and doesn't involve use of machinery throughout the fiber impregnation and therefore it is a labour intensive process. Resin impregnation as well as curing costs were calculated using the equation below:

$$C_{st2} = C_{mat} + C_{Labour} + C_{depr}, \tag{1}$$

where C_{mat} is the cost of consumables used throughout the stage (as calculated in Eq.2), C_{Labour} is the labour cost for resin impregnation by the technician (as calculated in Eq.3) and C_{depr} is the fixed depreciation charges of the used fixed asset throughout curing. C_{mat} is:

$$C_{mat} = \left[\left(\frac{RUA \cdot C_{resa}}{RWA} + \frac{RUB \cdot C_{resb}}{RWB}\right) + F_{scrap}\right], \tag{2}$$

where RUA and RUB are the resin base and hardener used accordingly (in weight), RWA and RWB are the resin base and hardener cases weight respectively, C_{resa} and C_{resb} are the resin base and hardener cost of cases accordingly and F_{scrap} is the cost of resin scrap:

$$C_{Labour} = t_{imp} \cdot C_{wm}, \tag{3}$$

where t_{imp} is the fiber impregnation time for the Hand Lay-up method and C_{wm} is the technical personnel cost per minute. C_{depr} is calculated as:

$$C_{depr} = \frac{PP}{L_f \cdot N_{pc}}, \tag{4}$$

where PP is the purchase price of the fixed asset used throughout curing sub-process, L_f is the estimated life of the fixed asset and N_{pc} determines the number of produced GFRP plates per year, by using Hand Lay-up method. Total cost of GFRP plate manufacturing using the Hand Lay-up method was calculated as the summation of costs from all employed stages:

$$C^{1}_{TOTAL} = C_{CNT} + C_{st1} + C_{st2} + C_{st3}, \tag{5}$$

where C_{CNT} is the CNT mixing stage cost, C_{st1} is the preparation stage cost, C_{st2} is the main process cost (as calculated from Eq.1-4) and C_{st3} is the post-process stage cost.

3.2 VARI & RTM: Automated GFRP manufacturing processes

Apart from Hand Lay-up method, two closed mould processes were employed for manufacturing GFRP plates-VARI and RTM. These are automated processes, which rely on the use of vacuum and compressed air respectively, for the homogeneous resin injection inside the mould. Indicatively resin injection as well as curing costs for an automated GFRP manufacturing process (VARI, RTM) are provided below:

$$C'_{st2} = C_{mat} + C_{inj} + C_{energy} + C_{depr}, \tag{6}$$

where C_{inj} is the resin injection sub-process cost for an automated manufacturing process, C_{mat} is the raw material cost used, C_{energy} is the energy cost of the resin injection sub-process and C_{depr} is the fixed depreciation charges of the used fixed asset throughout resin injection and curing, where t_{fill} is the mould filling time for an automated process [14]:

$$C_{inj} = t_{fill\cdot} \cdot C_{wm} + CAP \cdot CF \cdot C_{ind} \cdot t_{fill} + C_{depr} \tag{7}$$

and

$$C_{energy} = CAP \cdot CF \cdot C_{ind} \cdot \frac{t_{fill\cdot}}{60}, \tag{8}$$

where CAP is the installed electrical capacity of the machinery used throughout resin injection, CF is the ratio of used electrical capacity to installed capacity and C_{ind} is the cost of industrial energy consumption per hour (kWh). Additionally, total cost of GFRP plate manufacturing for VARI method is:

$$C^2_{TOTAL} = C_{CNT} + C'_{st1} + C'_{st2} + C_{st3}, \tag{9}$$

where C'_{st1} is the cost of preparation for VARI method, which involves setup of bagging material on the top of the mould -unlike the other two GFRP manufacturing processes- for effective vacuum application, during resin injection inside the closed mould. Finally, total cost of GFRP plate using the RTM process is:

$$C^3_{TOTAL} = C_{CNT} + C_{st1} + C'_{st2} + C_{st3}, \tag{10}$$

where C_{st1} is the RTM preparation stage cost, C_{st2} is the main process cost (as calculated from Eq.6-8) and C_{st3} is the post-process stage cost.

4 Results

4.1 Experimental Results

4.1.1Viscosity tests

CNTs dispersion inside epoxy resin LY564 affects the matrix viscosity, as it can be seen in Figure 1. As expected, the addition of CNTs at various concentrations increased the dynamic viscosity of the matrix and in the case of 1.0 wt.% CNTs the matrix viscosity was increased by more than 100 times, compared to reference resin viscosity value at 33°C. On the other hand, Figure 1 illustrates that with increasing testing temperature, dynamic viscosity values obtain a diminishing tendency, thus the difference between reference and 1.0 wt.% CNTs resin being one order of magnitude at 80°C.

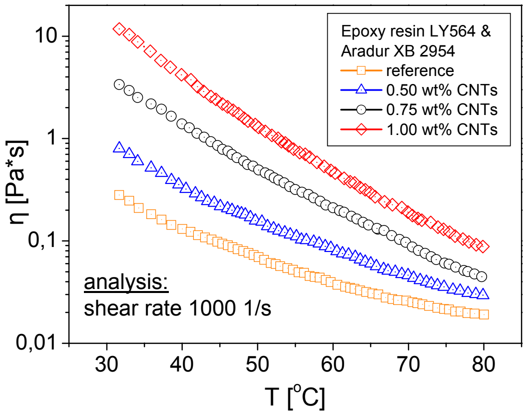

Figure 1: Effect of the addition of different wt.% CNTs on the viscosity of the epoxy resin LY564.

4.1.2 Tensile tests

Tensile test results of manufactured composites with different percentages of CNT doped resin can be seen in Figure 2. The mechanical properties depicted are tensile strength (R_m) and strain energy density (W), in order to investigate the strength increase on the expense of ductility. As expected, tensile strength of nanocomposites was increased with increasing content of CNTs in the resin. Nevertheless, strain energy density - which represents the ability of the composite to absorb mechanical energy up to fracture point - is essentially decreased by almost 40 % for the case of 1.0 wt.% doped resin composite; more details regarding tensile test and results can be found in [10].

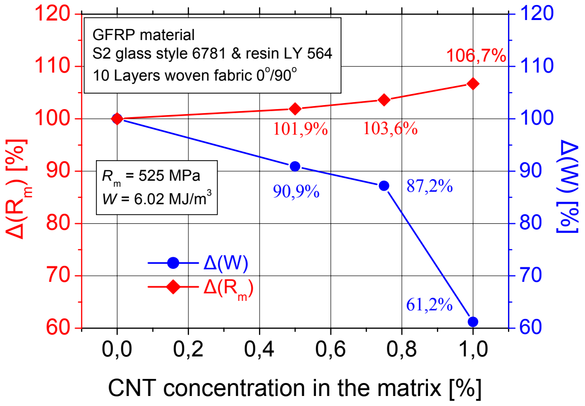

Figure 2: Percentage change of axial mechanical properties tensile strength R_m and strain energy density W due to the addition of CNTs in the resin matrix.

4.2 Cost Modeling Results

4.2.1 Different manufacturing processes

A cost model was developed for each manufacturing process, in order to obtain optimal values for major manufacturing parameters, driving force being the mechanical properties of interest as well as their low manufacturing cost. Figure 3 illustrates the total manufacturing costs and cost distribution of all processes for manufacturing of a 300 mm x 300 mm GFRP plate using a neat epoxy resin. It can be shown that the least expensive GFRP manufacturing process is the Hand Lay-up method, mainly due to the absence of machinery throughout the fiber impregnation with resin. On the other hand, RTM is the most expensive but precise at the same process time, while VARI is the second least expensive process.

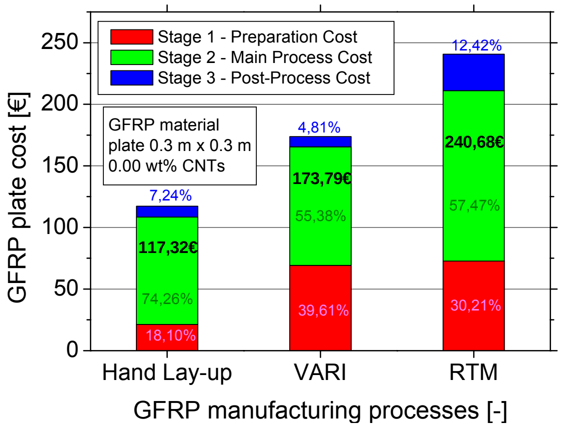

Figure 3: Total cost and its distribution for (a) Hand Lay-up, (b) VARI and (c) RTM process for manufacturing of a reference 300 mm x 300 mm GFRP plate.

In high-mass production conditions, RTM is considered worldwide the most cost-efficient manufacturing method, mainly due to significant reduction on mould seal time and mould filling time [15]. Nevertheless, the results of the present work were the outcome of manufacturing GFRP plates under strict Laboratory conditions, and therefore Hand Lay-up and VARI methods are considered to require less time for machine setup for the manufacturing of a single GFRP plate.

4.2.2 Different geometrical dimensions

Figure 4 illustrates a comparison between Hand Lay-up, VARI and RTM on the basis of cost-per-kilogram of GFRP plates of various geometrical dimensions. It can be seen that as GFRP plate area grows, cost-per-kilogram of each manufacturing process obtains a significant decreasing trend, which can be accounted as a measure of the cost tendency when potentially manufacturing significantly larger GFRP plates. Coupons originated from GFRP plates with larger plate dimensions present lower cost when manufactured with higher resin injection temperature. However, the option of manufactured 1000 mm x 1000 mm GFRP plate is considered by the authors as non-valid, as it is difficult to maintain high quality (absence of structural faults) all over the plate. Figure 5 shows a correlation among mould filling time for various resin injection temperatures against varying coupon costs.

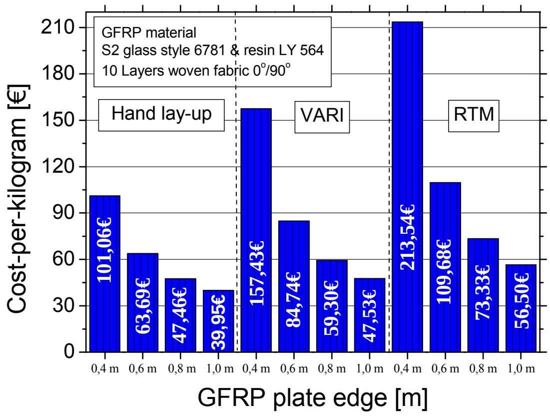

Figure 4: Cost per-kilogram analysis for different manufacturing processes as well as geometrical dimensions.

4.2.3 Resin injection temperature and mould filling time

A significant parameter governing the manufacturing cost is the mould filling time. It is well-known that mould filling time is directly influenced by resin viscosity; viscosity of the resin mixture varies with injection temperature and CNTs concentration values-as shown in Figure 1- and thus strongly influences mould filling time. Since the injected resin's viscosity is increasing, its diffusion rate inside mould is decreasing and thus mould filling time increases.

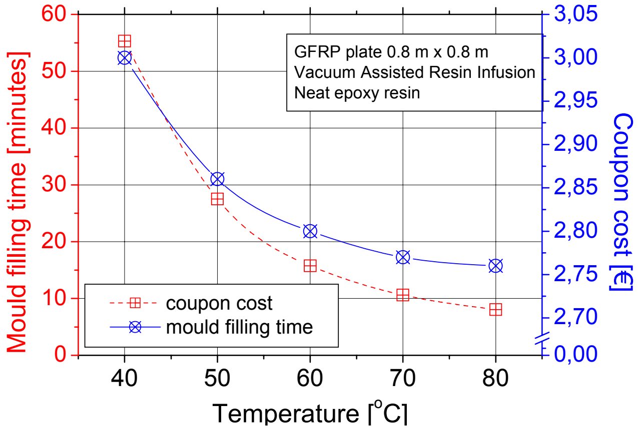

Figure 5: Correlation of mould filling time with coupon costs for various resin injection temperatures for 800 mm x 800 mm GFRP plate.

Infusion temperature of 80°C was also rejected since it exceeds the gelation point threshold and it will quite degrade composite manufacturing quality. Therefore, the combination of resin injection temperature (70°C) that minimizes mould filling time and doesn't lead to resin gelation and larger possible GFRP plate (800 mm x 800 mm) is considered to be the most promising for the specific case. More details regarding this section can be found in [14].

4.2.4 Cost-to-attain piezo-resistivity

Despite the fact that the addition of CNTs deteriorates the mechanical performance (ductility) and adds manufacturing cost, this can be counter-balanced by the new, added function of the composites, which is the ability to be monitored via electrical resistance change (piezo-resistivity).

Addition of CNTs consists of the CNT dispersion, which involves material, labour, energy and depreciation costs. Figure 6 shows the added cost –expressed in percentage unit- for each of the processes for the manufacturing of a 800 mm x 800 mm plate, for the case of 70°C as the injection temperature. In specific, for the case of 0.5 wt% CNTs, the added cost in order to attain piezo-resistivity would be 21.92 %, 18.34 % and 15.37 % for the different manufacturing processes, respectively. Stepping up to higher wt.% CNT content inside the matrix the added cost for piezo-resistivity increases negligibly (from 1 % to 3 %). By employing the automated manufacturing processes VARI and RTM, it can be seen that added cost is much lower (varying from 15 % to 19 %).

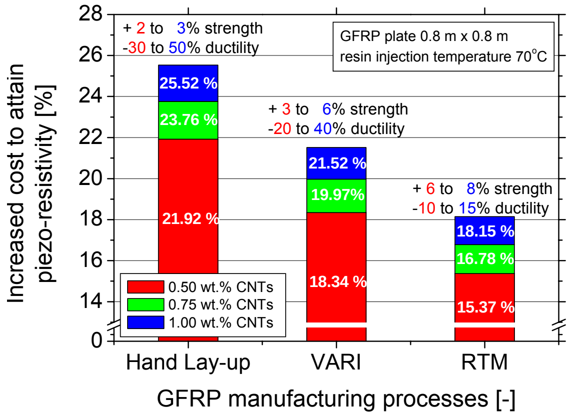

Figure 6: Added percentage cost to attain piezoresistivity via the addition of CNTs in epoxy resin of GFRP.

5 Conclusions

- Evaluation of different manufacturing parameters was performed by means of mechanical performance and manufacturing cost to identify optimum processing parameters for the production of the newly-developed carbon nanotube reinforced polymer composites.
- The optimal GFRP manufacturing process would be the Vacuum Assisted Resin Infusion (VARI), since it attains relatively high dimensional accuracy and low manufacturing cost criteria.
- Tensile test results on composites showed increase the strength properties (R_m, E) on the expense to the ductility properties (W, A_m). Therefore 0.75 wt.% CNTs was selected as the optimum resin reinforcement concentration as it was shown that ductility properties of the composite material were not so heavily downgraded.
- The real merit of the CNTs addition seems to be the added function of piezo-resistivity; almost 20 % of the nano-reinforced composite's total cost is attributed to

attain this new function, when manufactured with the automated RTM process. Added costs for manufacturing the same nano-reinforced product are approximate 25 % and more than 30 % for the VARI and hand lay-up processes, respectively.

References

[1] Kaufmann M., Zenkert D., Ekermo M. Cost/weight optimization of composite prepreg structures for best draping strategy. *Composites Part A*, **41**, pp. 464–472 (2010).

[2] Kaufmann M., Zenkert D., Mattei C. Cost optimization of composite aircraft structures including variable laminate qualities. *Composites Science and Technology*, **68**, pp. 2748–2754 (2008).

[3] Kaufmann M., Zenkert D., Wennhage P. Integrated cost/weight optimization of aircraft structures. *Structural Multidisciplinary Optimization*, **41**, pp. 325–334 (2010).

[4] Thostenson E.T., Chou T.W. Real-time in situ sensing of damage evolution in advanced fiber composites using carbon nanotube networks. *Nanotechnology*, **19**, pp. 1-6 (2008).

[5] Thostenson E.T., Chou T.W. Carbon nanotube networks: Sensing of distributed strain and damage for life prediction and self healing. *Advanced Materials*, **18**, pp. 2837–2841, (2006).

[6] Schulte K., Baron Ch. Load and failure analyses of CFRP laminates by means of electrical resistivity measurements. *Composite Science and Technology*, **36**, pp. 349-356, (1989).

[7] Fiedler B., Gojny F.H., Wichmann M.H.G., Bauhofer W., Schulte K. Can carbon nanotubes be used to sense damage in composites. *Annales de Chimie: Science des Materiaux*, **29**, pp. 81-94 (2004).

[8] Boeger L., Wichman M.H.G, Meyer L.O., Schulte K. Load and health monitoring in glass fibre reinforced composites with an electrically conductive nanocomposite epoxy matrix. *Composites Science and Technology*, **68**, pp. 1886-1894 (2008).

[9] Wichmann M.H.G., Buschhorn S.T., Boeger L., Adelung R., Schulte K. Direction sensitive bending sensors based on multi-wall carbon nanotube/epoxy nanocomposites. *Nanotechnology*, **19**, pp. 1-6 (2008).

[10] Alexopoulos N.D., Eleftheriou J., Asimakopoulos A., Georgiou Ch., Marioli-Riga Z. Piezo-resistivity and mechanical properties of glass fiber reinforced coupons using carbon nanotube CNT doped resin. in “Proceeding of *18th European Conference on Fracture (ECF18)*, Dresden, Germany, (2010).

[11] Ivanov E., Kotsilkova R., Krusteva E., Logakis E., Kyritsis A., Pissis P., Silvestre C., Duraccio D., Pezzuto M. Effects of processing conditions on rheological, thermal, and electrical properties of multiwall carbon nanotube/epoxy resin composites, *Journal of Polymer Science Part B: Polymer Physics*, **49**, pp. 341-442 (2011).

[12] Cueto E., Monge R., Chinesta F., Poitou A., Alfaro I., Mackley M.R. Rheological modeling and forming process simulation of CNT nanocomposites *International Journal of Material Forming*, **3**, pp. 1327-1338 (2010).

[13] O’Guin M.C. *The Complete Guide to Activity-Based Costing*. Prentice Hall, Englewood Cliffs NJ (1991).

[14] Tapeinos I.G., Miaris A., Mitschang P., Alexopoulos N.D. Carbon nanotube-based polymer composites: a trade-off between manufacturing cost and mechanical performance. *Composites Science and Technology*, **72**, pp. 774-787 (2012).

[15] Vasile C., Kulshreshtha A.K. Liquid Moulding Process. *Handbook of polymer blends and composites*, **2**, pp. 53-63 (2002).