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Mechanical properties of polymer composites produced by resin injection molding for applications under increased demands for quality and repeatability

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Abstract

The paper analyzes the effect of the cutting angle on the mechanical properties of a fiber composite cut with a water jet cutter applying different speeds. Unlike plasma or laser processing, water jet cutting is a high precision method with no toxic emissions or waste production. The experiments were conducted for a glass reinforced resin matrix composite produced with the Resin Infusion Molding method. The polymer matrix (Polimal 109-32K resin) was reinforced with a two-directional glass fabric (Saertex) with fibers intersecting at an angle of ±45°. The highest efficiency of the 3-dimensional water jet cutting process was reported at the angle of 45°. The composite samples cut with a velocity of 3,000m/s exhibited more stable properties than those cut with velocities of 5,000 and 10,000m/s. The mechanical properties of the material were assessed assuming that there were two layers, each with different physical and mechanical properties, which resulted from different fiber arrangements.

The strength of the composite was analyzed using samples cut with different cutting speeds. It was necessary to determine which layer would fail first. The strength was forecast basing on the distribution of stresses in each layer. It was important to establish the influence of the number and thickness of layers on the mechanical properties of the composite. By calculating the strength of the laminate, it was possible to determine the deformations, loads and residual stresses in each layer as well as the total stress responsible for the material failure.

Key words: resin injection molding (RIM), water jet cutting, laminate, modeling

Introduction

Resin Injection Molding (RIM) is one of the most widely used composite manufacturing methods [1], it is categorized as a closed molding medium volume production. In this process, a viscous resin is injected under pressure into a mold cavity that is gel coated and contains reinforcements. The reinforcements and core material are placed in the mold and the mold is hot, closed and clamped and transfers heat to the moving viscous resin. The reinforcements are preformed in a separate process and can be quickly positioned in the mold. RIM can be done at a room temperature and can be assisted by vacuum (however, heated molds are required to achieve fast cycle times and product consistency) [2, 3].

There are two issues of great concern in RIM modeling:

- accurate prediction of the temperature history to prevent the resin from turning into gel before the cavity is filled or from curing too fast degrading the composite [4-6]; (the formation of the flow front in resin injection process will affect the quality of the finished formation).
- prediction and measurement of permeability which are essential tasks in the efficient design and operation of RIM [7, 8]. Permeability needs to be determined accurately in order to predict temperature and velocity of the resin with a reasonable accuracy.

On the other hand increasing industrial demands with regard to quality and repeatability of the products lead to the development of new technologies regarding material treatment using a water jet and a laser beam [9-11]. Laser cutting is an alternative to oxygen, plasma and mechanical cutting. All these methods are being further developed and modernised offering a higher quality of cutting at relatively lower costs of devices.

The aim of the paper is to try to determine the impact of manufacturing technology, dimensional shaping methods (the water jet) and structural architecture on the mechanical properties of the investigated composite produced using RIM.

Methodology and experimental procedure

The polymer composite produced with RIM in the Composite Center of the Bella company was the focus of the investigation. The composite technological parameters obtained with the injection technique were presented in [13, 14]. Samples were cut according to the standard PN–EN 10002–1+AC1 from the laminate plate (with Polimal 109-32K epoxy and reinforced with the two – directional glass mat $\pm 45^0$ of $800 g/m^2$ produced by SAERTEX) whose height was ca. 1.8÷2,0 mm. Cutting was conducted with the water jet with the produced water – wear suspension (Fig.1). The diameter of the water jet with the treated wear material under a high pressure (ca. 4 000 bar) was 0.2÷0,4mm. The samples from the laminate were cut at the velocities of 3000, 5000 and 10000m/s. The water jet is currently the most modern and very accurate method of material treatment with 0.1 mm accuracy.

The high pressure water or water – wear jet treatment is the most ecological technique in comparison to the conventional methods (using acetylene, plasma, laser, which cause toxic gaseous emissions, etc). Water used in the cutting process can be reused many times (closed water circulation) and there is no waste.

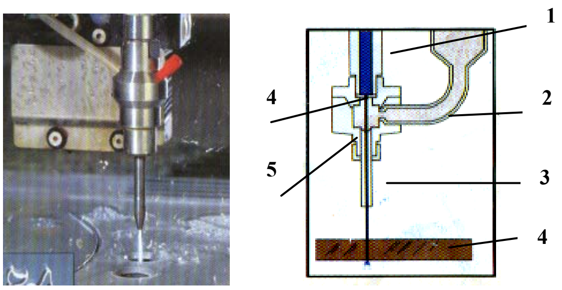


Fig..1. **Schematic of water with fine wear material jet cutting of the composite: 1 – high pressure water supply; 2 – abrasive powder; 3 – mixing nozzle; 4 – workpiece; 5 – water nozzle; 6 – water - abrasive mixture**

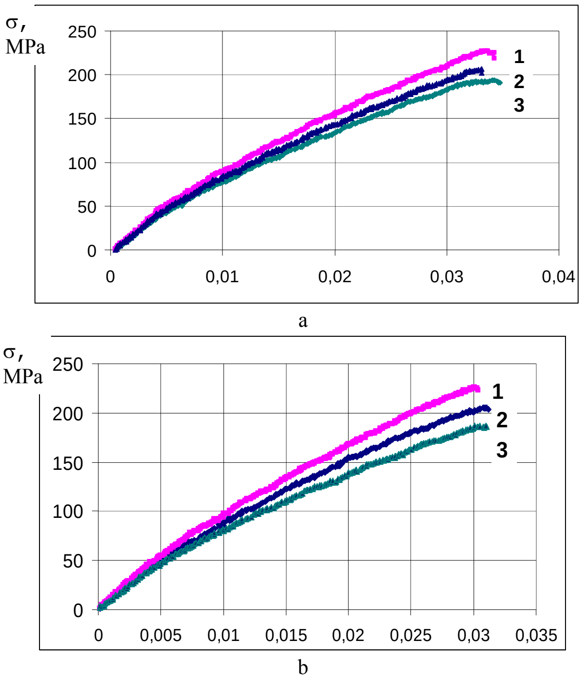
The height of the cut materials is undoubtedly one of the biggest advantages of the water cutters in comparison to the laser of plasma technologies. In fact no one has determined the maximal height of the cut materials. During water cutting there is no worry of material warming and its deformation or melting on the edges, etc. The temperature of the treatment area increases but only marginally. The produced samples underwent static tensile strength tests, which were carried out on the strength machinery INSTRON 4502 in the laboratory of Material Strength of Centers Lasers Technology Metal in Kielce University of Technology. The elastic modulus (E), the tensile strength (σ_{max}) and the breaking point (ε_{max}) were determined. The tests on samples were carried out with increasing cracking sounds of glass fibers in the mat.

The analysis of the impact of the kind of treatment on the structure was performed with the metallographic methods with the use of quantity metallography. The obtained samples were cut using the metallographic cutter produced by BUEHLER model IZOMET LS applying the cutting discs for composite materials type 15HC. Then the samples were abraded and polished using aluminum oxide. The quantity characteristics of the produced composite structures were determined basing on the image of the structure on the IMS-5400 microscope at the magnification of 150 times.

The impact of the cutting angle on the mechanical properties of the composite formed with RIM method

The tensile strength tests with the velocity of 3 mm/min resulted in the destruction of the samples. The recorded dependences of σ-(Δl) for the samples of fibers located at ±45^0 for different cutting angles are presented in Fig. 2.

The character of curves for different angles and velocities of laminate cutting is the same, while the values of σ and Δl are different (Table 1), which result, among others, from volume defects in the samples. The arithmetic mean of the tests was taken as the final result, where the numerator consists of the mean value of 4 measurements, while the denominator of a range from the minimal to the maximal values of the test results. The variation of the strength characteristics caused by the technological aspects of the RIM method resulted in accumulation of defects in the structures of the obtained materials. It is visible in Fig. 3, where microcracks are present in the microstructure (Fig 3a).



a

b

Fig. 2. **Curves σ-(Δ*l*) of the composite polymer cut with the water jet along fibers (2), at angles 45° (1) and 90° (3) at different cutting velocities: 3000 m/s (a) and 10000 m/s (b)**

Table 1. **The mechanical properties of the composite produced with the infusion method**

Property	σ_{max} [MPa]	*E* [MPa]
at the cutting	velocity 3000 m/min	
0^0	179.18 154.10 ÷ 206.19	5992.64 5153.85 ÷ 6895.98
45^0	214.61 192.24 ÷ 227.23	6770.00 6526.33 ÷ 7035.32
90^0	180.19 180.16 ÷ 193.99	5678.37 5509.71 ÷ 6151.82
at the cutting	velocity 5000 m/min	
0^0	193.01 182.92 ÷ 205.45	5997.82 5684.28 ÷ 6848.33
45^0	193.40 177.82 ÷ 220.20	6340.98 5830.16 ÷ 7219.67
90^0	162.23 164.77 ÷ 181.96	5565.35 5652.49 ÷ 6242.19
at the cutting	velocity10000 m/min	
0^0	188.71 173.46 ÷ 205.48	6552.43 6022.92 ÷ 7134.72
45^0	200.40 189.01 ÷ 217.86	6295.29 5937.49 ÷ 6843.77
90^0	179.65 175.72 ÷ 187.21	5988.33 5857.33 ÷ 6240.33

They produce local stress concentrations, which result in cracking of nearby fibers and a reaction that leads to the destruction of the composite. The water – wear material jet of the laminate is mainly concerned with cracking of composite components, although in the area of hitting a wear particle plastic deformations can be observed. The analysis have proven that the maximal treatment efficiency of brittle materials is obtained during the laminate cutting angle of 45^0. The samples of the composite which are cut with the velocity of 3000m/s have more stable properties than those cut with the velocities of 5000 and 10000m/s with a different structural architecture.

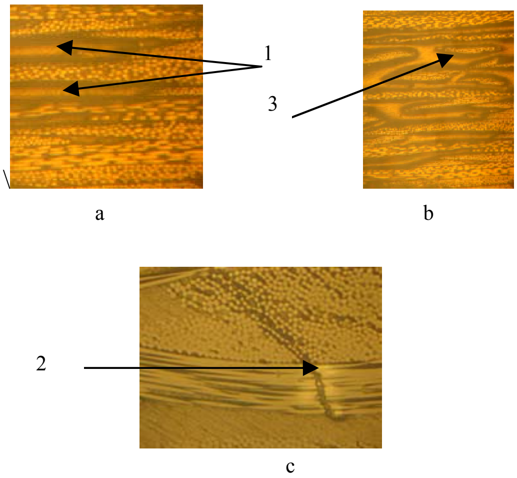


Fig.3. **Microstructures with defects in the laminate: 1 – microslots; 2 – microcracks of composite components; 3 – voids in the polymer coating for the sample cut with the water jet (a, b) and mechanical treatment (c)**

The loading time of the material during the process of hitting of the wear particle is very small, while the material is displaced immediately. Consequently, free propagation of cracks in the composite components is eliminated, which cannot be ensured by the mechanical cutting (Fig.3c), in which the values of σ and E decreased by 8% and 19%, respectively [14]. Thus, the stress waves between the layers of the composite caused by hitting can be considered as the reason for their existence. Disadvantageous microcracks and voids in the polymer coating are produced due to differences in the Young's module of the composite components (fibers and coating). As a result the strength parameters determined during the static tensile strength tests along the reinforcement direction are worsened. Apart from the properties of the components (fibers and coating), the impact of the interfacial layer should also be considered. The composite deformation, from which the separation of fibers from the coating occurs (Fig.3), increases with the rise in the strength of the interfacial layer.

Modeling of the composite strength

The knowledge of the mechanisms and criteria of the destruction of polymer composites enables to predict mechanical properties of the composite. Using the possibility of designing the composite materials microstructure and, thus, their final properties the strength properties of composite materials of different structure were modeled. Deformations and stresses that occur is composite layers were considered as technical constants [15] ($a_{11}=1/E_{11}$; $a_{22}=1/E_{22}$; $a_{16}=1/G_{12}$; $a_{12}=\mu/E_1=a_{21}=\mu/E_2$) for the orthotropic system. The modules (E_x, E_y, E_{45^o}) as well as strength in a certain direction are different. The maximal value of the stress which transfers stress values on the no effective fiber length in microvoids on the surrounding composite components are calculated according to the following equations:

$$\sigma_{krx} = \frac{\sigma_{kry}}{\Omega\cos^4\theta + 2B\sin^2\theta + \sin^4\theta}, \tag{1}$$

where:

$$\Omega = \frac{\sigma_{ky}}{\sigma_{kyx}} \tag{2}$$

$$2B = \left[4\frac{E_y}{E_{45^o}} - \left(1 + \frac{E_y}{E_x}\right)\right] \cdot \left(1 + \frac{E_y - \Omega E_x}{E_x - E_y}\right). \tag{3}$$

The impact of the angle of layers arrangement in relation to the tensile direction on the values of stress and the Young modulus has been analyzed. The tests results in this paper deal with the influence of the number of layers and the layer height on the mechanical properties of the composite. Basing on the strength results of the composite with different angles of layer arrangement the deformation value of the destruction of each layer was determined separately as well as loadings under which each layer in the composite operates, stress acting in particular layers and the total stress under which the material is destroyed (Table 2).

Basing on the calculation results, it can be concluded that increasing the number of composite layers from two (±45°) to twelve ($0^o{}_5 45^o{}_4 90^o{}_3$) at a certain arrangement (keeping the same height of the layers) can, but does not have to, change the value of the breaking stress of the composite. While as the angle of arrangement increased in the range of $0^{\circ} \div 90^{\circ}$ the mechanical properties, e.g. *E* and composite strength decrease. Only loading for the weakest layer rises at the beginning, which causes the destruction of the whole composite component and the fall of the loading of the whole material

Table 2. **Modeling of the mechanical properties of the polymer composite cut with the water jet**

Modelling					
Compo-site	Destruction criterion (the weakest layer)		Breaking stress of the layer, MPa	Loadings in layers, 10^{-3} N	Composite destruction, MPa
$45^o{}_2$	45°	$\varepsilon = 0,0315$	$\sigma_1 = 153,71$	$Q_1 = 596,72$	$\sigma_c = 174,18$
0°45°60°	**0°** 45° 90°	**$\varepsilon = 0,0284$** $\varepsilon = 0,0308$ $\varepsilon = 0,0316$	- $\sigma_2 = 124,34$ $\sigma_3 = 118,52$	$Q_1 = 1022,10$ $Q_2 = 922,38$ $Q_3 = 968,52$	$\sigma_c = 161,83$
$0^o{}_5 45^o{}_4 90^o{}_3$	**0°** 45° 90°	**$\varepsilon = 0,0284$** $\varepsilon = 0,0308$ $\varepsilon = 0,0316$	- $\sigma_2 = 153,73$ $\sigma_3 = 161,42$	$Q_1 = 1362,80$ $Q_2 = 983,87$ $Q_3 = 774,80$	$\sigma_c = 162,58$

Conclusions

Basing on the test and analysis results, one can draw the following conclusions:

- the values of σ and *E* obtained for the composite after cutting with a water jet cutter were 8% and 19% higher, respectively, than those reported in a conventional machining;
- in three-dimensional shaping of the laminate produced by RIM, the maximum efficiency was obtained when the cutting is performed at an angle of 45°;

- composite samples cut with a velocity of 3,000 m/s exhibited more stable properties than those cut with velocities of 5,000 and 10,000 m/s;
- cutting a composite with different fiber arrangements (+/-45) causes changes in the mechanical properties of the particular layers, which are dependent on the forces acting between the layers;
- the proposed model assumes that the properties of the laminate can be assessed by determining the weakest layer;
- the failure (weakest layer) analysis allows one to determine the distribution of stresses in the particular layers as well as forecast the strength of the laminate.

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Polimerinių kompozicinių dervų įpurškimo mechaninės savybės ir kokybės gerinimas

Reziumė

Dervos įpurškimas (RIM), kuris klasifikuojamas kaip uždaras lipdinys, tinkamas vidutinės apimties gamybai, yra vienas iš plačiausiai taikomų sudėtinių gamybos metodų. Čia klampi derva slėgiu įšvirkščiama į formos ertmę, kad galima būtų padengti sutvirtinimus. Į sutvirtinimus ir šerdis medžiagos dedamos kaip į formą ir naudojant uždarą karštą fiksavimą ir šildymą gaunamos judančios klampios dervos. Šis sustiprinimas rengiamas kaip atskiras procesas ir gali būti greitai išdėstomas pagal formą. RIM gali būti atliekamas kambario temperatūroje ir vakuume. Ištirti du darbai, keliantys didelį susirūpinimą:

1. Įpurškimo proceso ir kokybės gerinimas formuojant kompozitus.

2. Pralaidumo prognozavimas ir matavimas, kas yra būtina, norint tinkamai atlikti projektavimo užduotis ir eksploatuoti RIM. Pralaidumas turi būti nustatytas tiksliai, kad būtų galima taip pat tiksliai nustatyti dervos temperatūrą ir greitį.

Darbe nagrinėjami pramonės poreikiai, atsižvelgiant į produktų kokybę ir pakartojamumą, kurie galėtų paskatinti naujų technologijų - medžiagų apdorojimo naudojant vandens srovę ir lazerio spinduliuotę - plėtrą. Pjaustymas lazeriu yra deguoninio, plazminio ir mechaninio apdirbimo alternatyva. Visi šie metodai toliau plėtojami ir modernizuojami, siūlomas aukštesnės kokybės pjaustymo būdas naudojant iš esmės mažesnių sąnaudų prietaisus.

Bandyta nustatyti poveikį gamybos technologijai, matmenų formavimo metodams (vandens) ir struktūrinės architektūros mechaninėms savybėms, taip pat sudėtiniams RIM gaminiams.

Buvo atlikti bandymai ir padaryta irimo mechaninių savybių analizė, pvz., nustatyti technologiniai kompozitų gaminimo būdai, pasiūlyti silpniausi kompozitų sluoksniai ir tai leido analizuoti įtampos paskirstymą sluoksniuose ir prognozuoti kompozitų stiprį.

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