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Dynamic Analysis of 3D Printed and Moulded Composites with Carbon Microfibers

KULHAVÝ Petr[1,a], FLIEGEL Vítezslav[1,b], LEPŠÍK Petr[1,c] and SRB Pavel[1,d]

[1] Technical University of Liberec, Faculty of Mechanical Engineering, Studentska 2,

461 17, Liberec 1, Czech Republic

[a] Petr.Kulhavy@tul.cz, [b] Vitezslav.Fliegel@tul.cz, [c] Petr.Lepsik@tul.cz, [d] Pavel.Srb@tul.cz

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Abstract. Using of fused deposition modelling rapidly expands due to the still decreasing costs of the machines and main materials. However, the main disadvantage is still the diametrically lower strength of the printed plastic parts, especially in the direction normal to the laid plies. Therefore, the new trend in recent years was to improve the material properties by adding fibre reinforcement. In this work, two kind of samples made from the same base material (carbon reinforced ABS) but using different manufacturing technology, one made by injection moulding and second by the 3D printing have been compared. Because for real condition the basic static test is not sufficient enough, the samples were tested on the dynamic mechanical analyzer (DMA). The chosen method was 3point bending, with constant strain and various frequency and temperature. In this study, the storage and loss modulus, of the plastic samples were determined.

Introduction

3D printing is a type of additive manufacturing that can be used to fast creation of usually prototype components with highly customizable geometries. 3D printing is rapidly attracting interest the scientific, manufacturing and even public community, because of its potential for enabling low-cost, highly flexible, low- and mid-scale manufacturing [1].
A lot of worldwide companies has been producing 3D printers and printable materials enhanced for printing carbon fiber-reinforced parts for customers in almost unlimited industries [2]. A very advantageous technology for prototypes is the printing of polymers. However, the strength of this way created parts is not equivalent to that by the conventional e.g. the injection moulding processes. In the work of Nakagawa [2] and Whitwam [3] could be read about the tensile and bending strength of printed ABS samples with and without fiber reinforcement and it is stated that the strength could be significantly increased by being reinforced with carbon fibres. About dependency of the mechanical parameters on the conditions such as layer thickness, orientation, raster angle, raster width, and air gap on the tensile, flexural, and impact strengths could be read in the work of Sood [4].

Shofner [5] compounded cut nanofibres into an ABS and increased the strength by about 20%. Tensile testing of the materials shows that a material with aligned fibers have higher elastic modulus and ultimate tensile stress than with the randomly oriented fibres. Really interesting research in this field conducted Nanya [6], she studied the simultaneous printing of continuous fibre with the polymer, mutually connected in the printing head. She tested the mechanical strength and thermodynamic properties of this way prepared parts with using dynamic mechanical analyzer. Mori [7] mentioned next advantageous of the additional improving of mutual fibre/resin connection by heating – thermal bonding. He also mentioned that it is desirable to develop approaches for increasing the volume ratio of carbon fibres and the bonding force between the carbon fibres and plastic and for controlling the orientation of carbon fibres. According to Whitwam [3] the printing of thermoplastic reinforced by fibres has the potential to replace the basic alloys in industrial applications.

Materials

The 3D printing of plastic materials is relatively easy, but the resulting parts do not have sufficient durability for long-term use. Parts from the same material created by moulding injection could exhibit up to 20 times more durability and 10 times more rigidity compared to standard printed parts made from ABS. Even if the price of 3D printers is steadily declining, the possibilities of their use do not differ much from the time when their price ranged in the order of thousands of dollars. Finally, nowadays comes a solution of carbon-fiber reinforced nylon that could compete to carbon-alloys or some cheaper steels.

When replacing conventional materials by composites it is important to know the mechanical properties of the composite [8]. Whereas metal materials show one failure mode i.e. cracking, composites can exhibit one or a combination of failure modes, including fiber rupture, matrix cracking, delamination, interface debonding and void growth [9].

Thermoplastic materials, which could be repeatedly melted and formed into their shapes are nowadays one of the most commonly used materials in 3D printing. As has been already mentioned the fiber-reinforced plastics (FRP) have recently gained attention for their potential use in 3D printing to enhance the mechanical strength and elasticity of manufactured parts. Spackman [10] and Mallick [11] aimed their study to systematically studying the effect of key processing parameters e.g. fiber alignment, area coverage, and surface energy of the fiber carrier substrate, on the tensile properties and failure mechanisms is heavily influenced by the types of plastic resin selected, as well as the length and loading of the carbon fibers seen in 3D and even 4D printed polymers. In the presented work, the samples made of ABS reinforced with carbon micro fibres randomly distributed in the matrix has been used (Fig. 1).

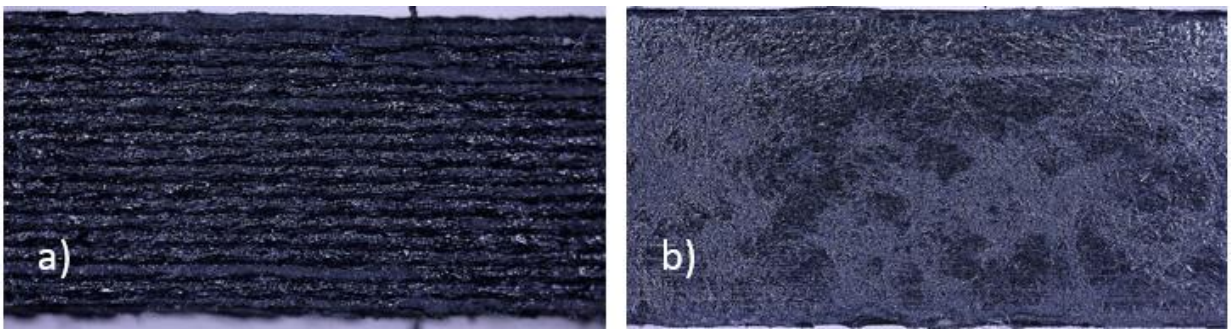

Fig.1 The base reinforced material a) printed b) moulded

Experiment

The aim of the carried experiment was using the dynamic mechanical analyzer (DMA) compare elastic behavior in dynamic loading, during simultaneous external thermal loading. The used test was the conventional 3-points bending (Fig. 2), that is also with the 4-points bend probably the most appropriate method useable for testing layered composites work [8, 9].

The created experiment consist in the various frequency and constant strain amplitude. Because, the plastic materials are really sensitive to thermal changes, simultaneously with the experiment, the temperature was also changed. A frequency sweep may be performed to evaluate the viscoelastic response of a material by the observed changes in the storage and loss moduli and tan δ. The loss tangent is the ratio of loss modulus and storage modulus, which indicate the viscosity and elastic properties of material, respectively.

In the DMA experimental device, the amplitude is defined as the maximum amount of oscillatory motion in micrometers (one half peak-to-peak). According to [6] [12] for composite samples the amplitude of 10 to 50 μm should yield good results and it is recommended to use "Logarithmically spaced" frequencies (*e.g.*, 10, 5, 2, 1) rather than "linearly spaced" frequencies (*e.g.*, 9, 7, 5, 3, 1).

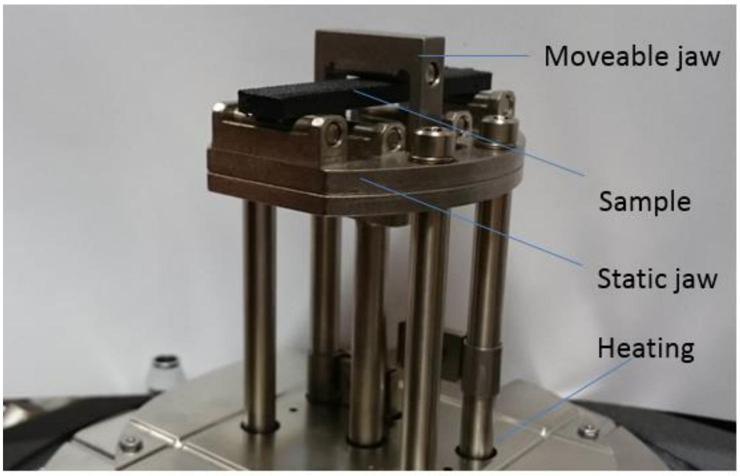

Fig.2 The experimental DMA device

For testing highly elastic material like the plastic one, the force track should be used to circumvent the deformation arising due to the thermal loading. The dynamic force is that which is required to maintain the programmed amplitude at a certain frequency [12]. When force track is activated, the static force is no longer constant, but is dependent on the dynamic force. The ratio of static to dynamic force is essentially for the force track. The following formula (1) is used to maintain the ratio between the preload force and dynamic force (force to drive amplitude).

$$F_S = F_T \times K \times A \tag{1}$$

Where the F_s is the static force [N], F_T the force track [-], the K stiffness [N/m] and A the amplitude [m].

Before the main testing, it is appropriate to set the value of the geometry factor. For the 3-point bending clamps with rectangular samples it is possible to determine the optimal sample size according to (2):

$$GF = \frac{L^3}{48\,I}\left[1 + \frac{12}{5}(1+\mu)\left(\frac{t}{L}\right)^2\right] \tag{2}$$

Where according the Tab. 1 the individual parameters of the tested samples are:

Tab.1 Parameters of the tested samples

Parameter:	*Mould*	*Printed*
L = sample length [mm]	50,000	50,000
I = geometric moment [mm^4]	52,267	53,867
t = sample thickness [mm]	4,000	4,000
h = sample width [mm]	9,800	10,100
ν = Poisson's ratio [-]	0,350	0,380
GF [1/ mm]	49,928	48,447

Results

In the pictures below are the result of dynamic micro 3 point bending test. It is possible to see the comparison of the printed (Fig. 3) and moulded parts (Fig. 4) in dependency on the loading frequency in the range 1 – 10 Hz.

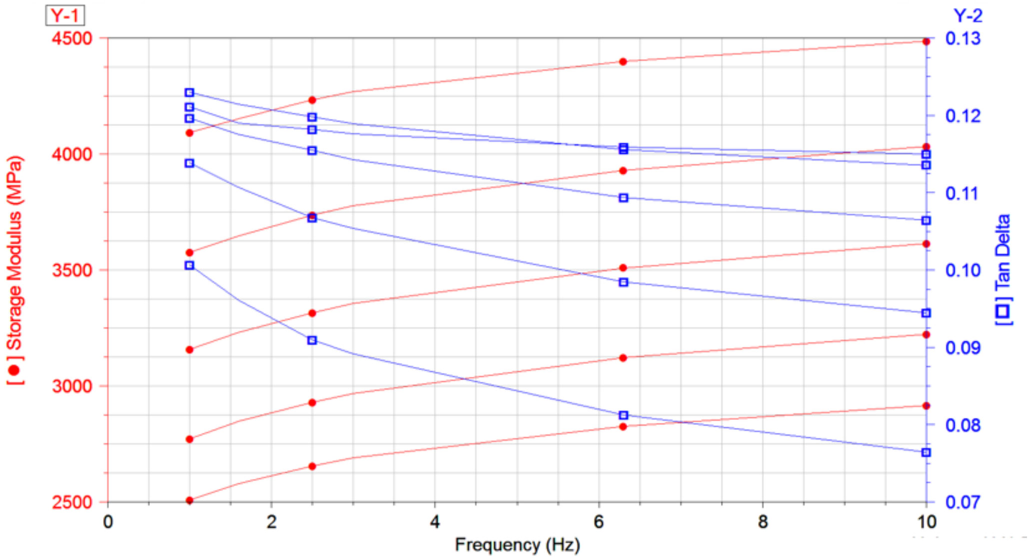

Fig.3 Experimental result of the modulus in dependency on frequency of the printed part

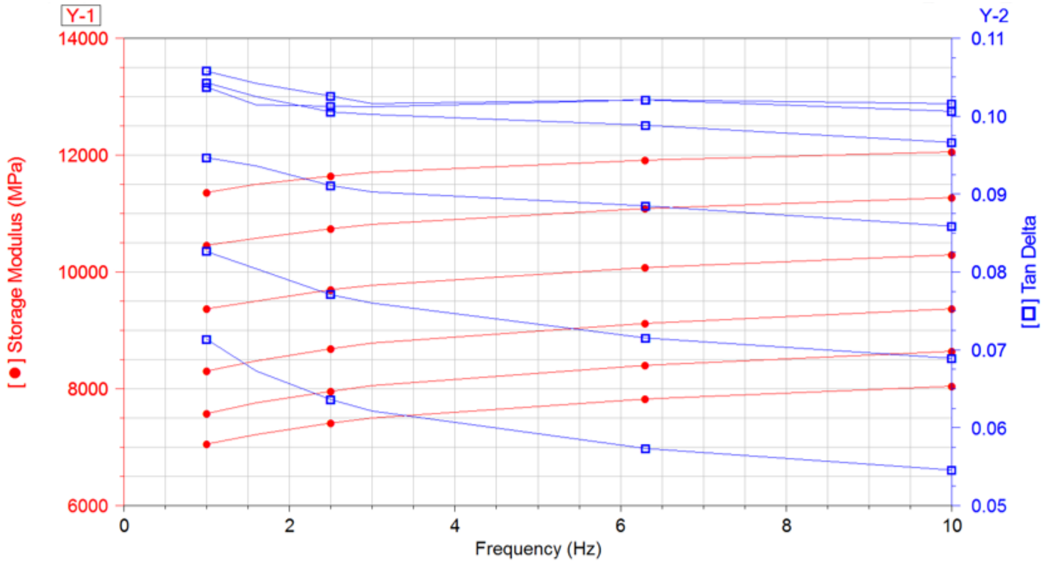

Fig.4 Experimental result of the modulus in dependency on frequency of the moulded part

Because the mechanical properties of plastic materials are really sensitive to the temperatures even within the values near their usual working conditions, it was necessary to asses also the Modulus dependency on the temperature in the range 30 – 50 °C. In the Fig. 5 there are results measured on the printed parts and in the Fig. 6, from the moulded parts.

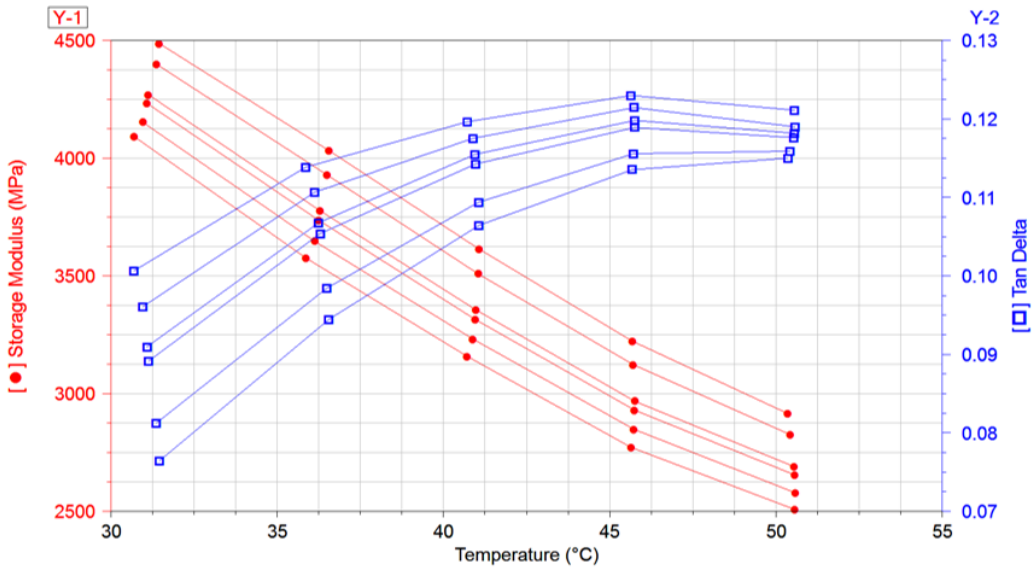

Fig.5 Experimental result of the modulus in dependency on temperature of the printed part

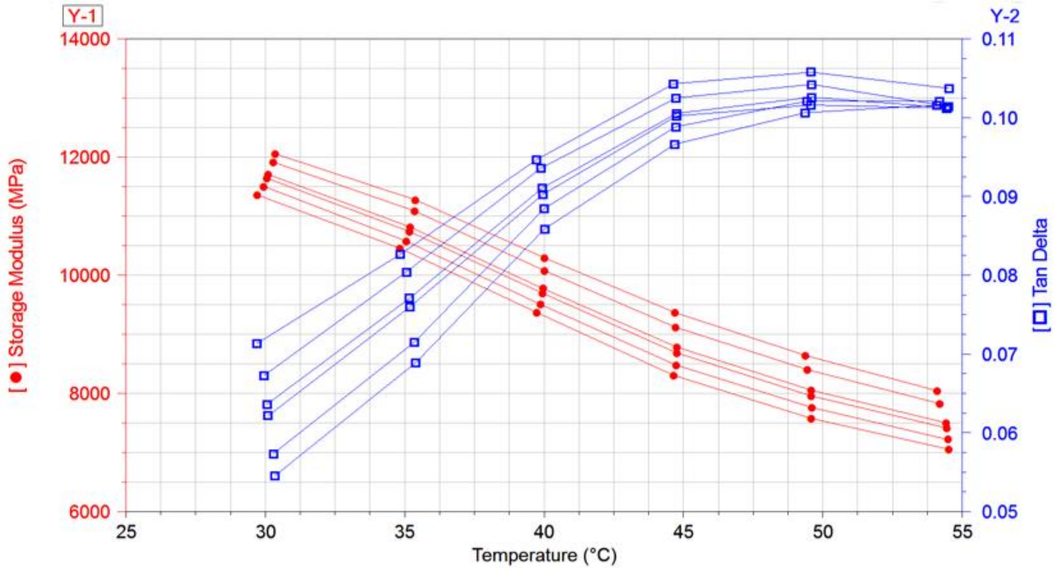

Fig.6 Experimental result of the modulus in dependency on temperature of the moulded part

Conclusions

It has been found that the resultant modulus of elasticity of the printed part reaches approximately one third of the value achieved on the injected and moulded part. Even if this value is still small, it is possible to mention significantly higher values of the material strength compared to conventional printed materials, those have the strength usually many times lower compared to the moulded parts.

Further, for the printed part, even if the increase in E is noticeable with increasing frequency of the loading, from the point of view to the thermal degradation of the material, there is no significant difference between the printed and the injected material.

As the future aim of our work it could be advantageous to study, whether the optimal layout of the printed part (angles, stacking sequence of individual plies etc.), could be optimized and computed according to the classical laminate theory.

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