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Analysis of the strain rate dependence on the mechanical properties of polypropylene

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Abstract: Since the end of the 20th century, the use of plastics has undoubtedly been expanding, not only in technical applications, but also in food industry, medicine, and many other sectors. The mechanical behaviour of polymeric materials is significantly influenced by temperature, strain-rate and their processing. This paper investigates the effect of strain rate on the mechanical properties of polypropylene filled with 12% talc. Bending, DMA and uniaxial tensile tests at three strain rates were carried out as part of the material testing. The obtained stress-strain data were adjusted to align Young's modulus with the storage modulus by modifying the curve slopes. This methodology can be applied for evaluating mechanical properties to input into material models for FEM simulations.

Keywords: polypropylene; viscoelasticity; strain rate; mechanical properties; mechanical testing

1 Introduction

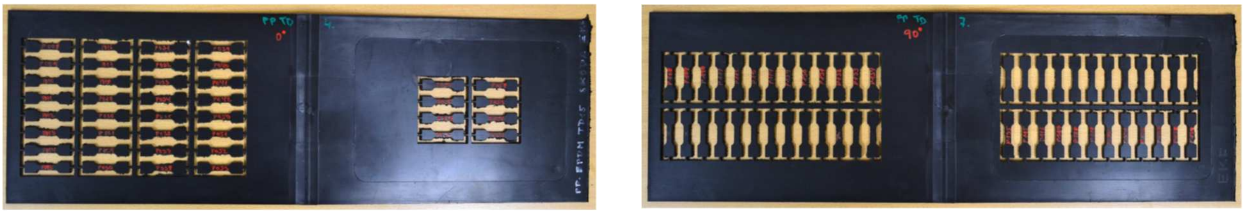
The same parameters are used to characterise the mechanical properties of plastics as for metals, i.e. Young's modulus, Yield stress, Ultimate strength, Poisson's ratio, but their mechanical behaviour differs considerably to metals. In comparison to other materials, the mechanical response of plastics varies to a much greater extent depending on the strain rate, temperature, and the external environment [1-3]. Polymers at high strain rate or low temperature behave like glassy substances, while at low strain rate or high temperature polymers behave like rubbery materials. In the first case, the mechanical properties are higher, but the polymer becomes brittle, while in the second case the mechanical properties are lower and the polymer becomes ductile [4].

The investigated material was polypropylene filled with 12% talc (PP_TD12). Polypropylene is a semi-crystalline thermoplastic produced by the polymerisation of propylene. Polypropylene has high strength and stiffness. There is a wide range of different applications for polypropylene, from automotive parts to packaging foils [5][6].

Dynamic mechanical analysis (DMA) is a method for determining mechanical properties of viscoelastic materials. Applying an oscillating (sinusoidal) stress to a material, its response can be measured as function of frequency. From phase lag between applied stress and measured strain is determined tendency of material to flow (viscosity), while the sample recovery reflects material's stiffness (modulus). Since modulus equals to stress/strain ratio, the complex modulus can be calculated. Then the storage modulus and loss modulus can be derived as components of complex modulus using measured phase lag between two sine waves. The storage modulus is the elastic component, and it is directly related to the stiffness of the sample. Loss modulus is the viscous component, which is dependent on the material's ability to dissipate mechanical energy through molecular motion [7].

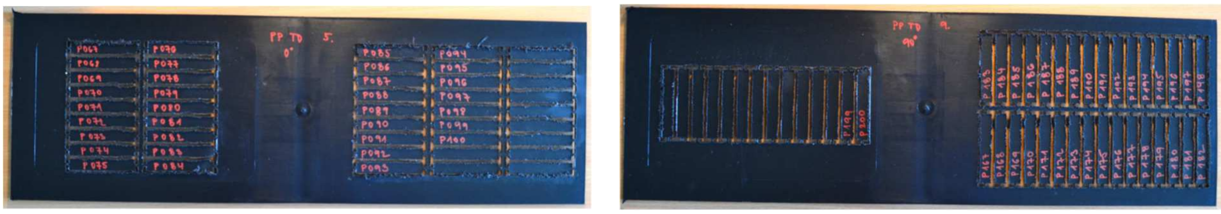
2 Experimental investigation

Polypropylene PP_TD12 was tested in two perpendicular directions, 0° and 90° according to the cutting orientation from the base plastic plate made by injection. It was necessary to verify whether the material can be considered homogeneous and isotropic due to the talc filler. Fig. 1 shows tensile specimens and Fig. 2 shows the specimens for DMA and bending tests.



a) b)

Fig. 1 Tensile test specimens: a) 0°; b) 90°.

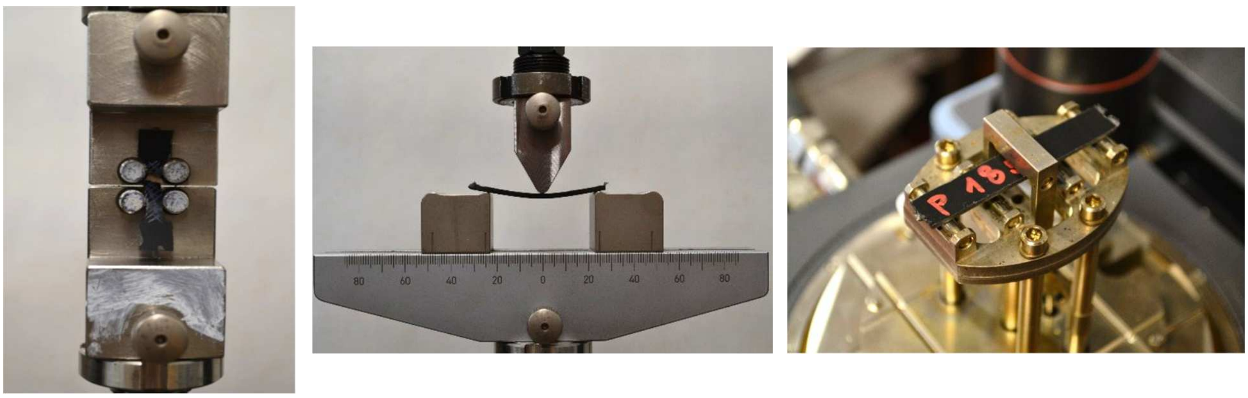


a) b)

Fig. 2 DMA and bending test specimens: a) 0°; b) 90°.

Uniaxial tensile tests were performed on the universal machine LabTest 5.050ST at strain rates of 10^{-2}, 10^{0} s^{-1}. Impact tensile test on drop tester was used as technique for measurement of high strain rates and specimens was loaded with strain rate 10^{2} s^{-1}. Seven specimens was measured for each strain rate and results was averaged to obtain representative curves. Tensile tests were carried out to obtain material characteristics (stress-strain curves) up to the failure. Three-point bending tests were performed on the same machine as tensile tests to determine the flexural modulus at a strain rate of 10^{-2} s^{-1}. This test was performed to verify the results of the DMA tests. DMA analysis was performed on a DMA Q800 device in a three-point bending test at four frequencies of 0.04, 0.4, 4.0, and 40 Hz to find the frequency dependence of the storage modulus. Bending tests, including DMA, was realized on five specimens.

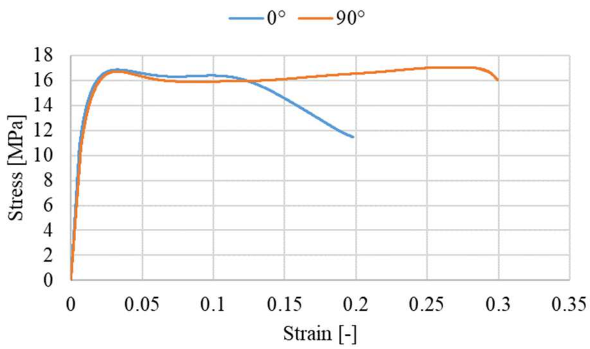
The test specimen for the tensile tests was in the shape of a conventional "dogbone" specimen with a thickness of 2.5 mm and the specimen for the flexural and DMA tests was in the shape of a rectangle with the same thickness. The specimens were small in size to avoid some undesirable effects due to the high loading rates. The tensile, flexural and DMA tests are shown in Fig. 3.



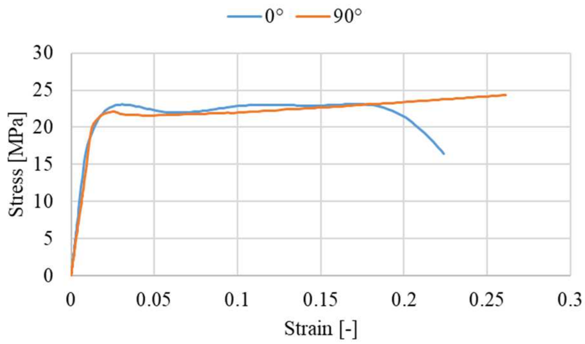
a) b) c)

Fig. 3: Material tests: a) uniaxial tensile, b) three-point bending, c) DMA.

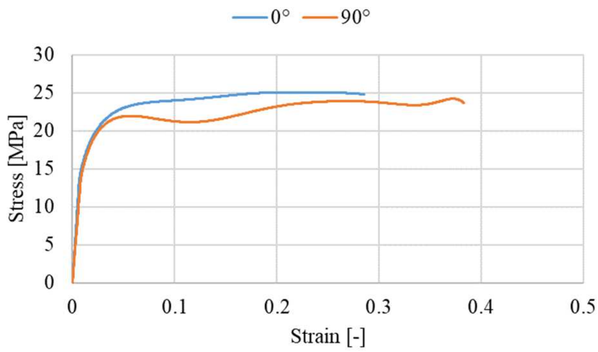
Fig. 4 shows the average stress-strain curves evaluated from tensile tests for both specimen orientations. From the plots can be seen that curves correspond well in the elastic region but differ in the plastic region at failure.



a)



b)



c)

Fig. 4 Average stress-strain curves measured at strain rate: a) 10^{-2} s^{-1}; b) 10^{0} s^{-1}; c) 10^{2} s^{-1}.

In Fig. 4c, can be seen that the strain value at failure is too high, since the samples were measured at the highest strain rate. During impact tensile test on drop tester, only the force as a function of time was measured. It means that the strain values were calculated only as an approximation from the measured time data and the strain rate. For these tests, the curves show significant oscillation. This oscillation is caused by the propagation of the shock wave from the ram impact on the lower grip. The measured curves had to be smoothed and approximated. They were approximated in Matlab software using polynomial functions. For demonstration, evaluated engineering stress-strain curve and the approximated curve from the impact tensile test are shown in Fig. 5.

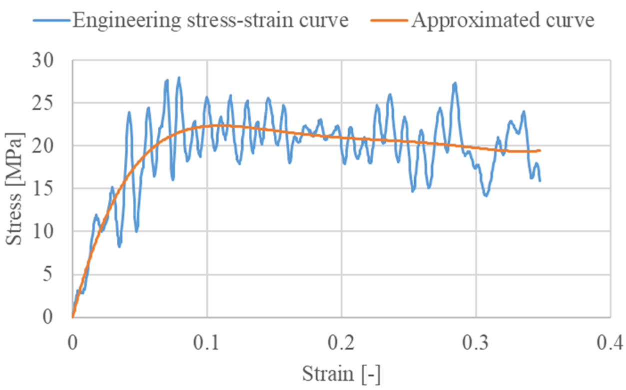


Fig. 5 Engineering and approximated stress-strain curve.

Since the orientation of the talc filler in injection molded components can be arbitrary with respect to the loading direction, the stress-strain curves for 0° and 90° were averaged and the material was further treated as homogenized isotropic. For the same reason, the modulus values obtained from the DMA tests were also averaged. Tab. 1 shows the measured and average value of flexural modulus. The resultant mean flexural modulus is 1599 MPa. The resultant flexural modulus value is in good agreement with the result from the DMA analysis, where the measured storage modulus for a frequency of 0.4 Hz is 1621 MPa. This frequency corresponds approximately to the loading rate of the three-point bending test. The average values of storage modulus and loss modulus measured at the other frequencies are shown in Tab. 2.

Tab. 1 Measured and average value of flexural modulus obtained by three-point bending test.

Orientation	0°					90°					Mean
Specimen	PP_01	PP_02	PP_03	PP_4	PP_5	PP_1	PP_2	PP_3	PP_4	PP_5	
Flexural modulus [MPa]	1730	1715	1755	1836	1757	1447	1420	1477	1449	1400	1599

Tab. 2 Average values from DMA test.

Log. Frequency [Hz]	Frequency [Hz]	Storage modulus E' [MPa]	Loss modulus E'' [MPa]
-1.4	0.04	1490	138
-0.4	0.4	1621	113
0.6	4	1756	96
1.6	40	1849	141

The frequency dependence of storage modulus can be seen in Fig. 6, where it is obvious that as the frequency increases, the value of storage modulus also increases.

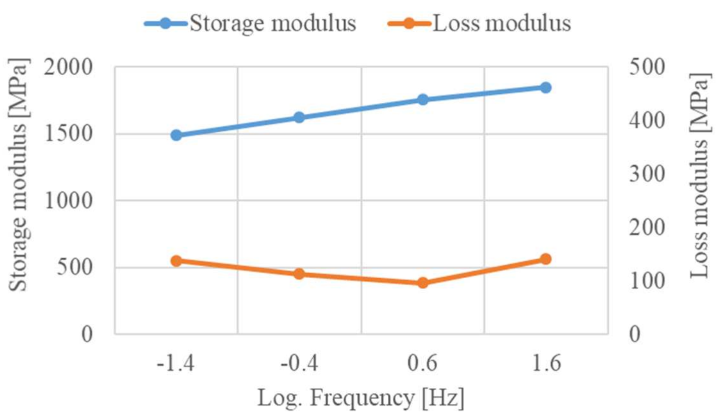


Fig. 6 Frequency dependence of storage modulus.

As it was mentioned, from impact tensile test the strain values were calculated only as an approximation from the measured time data. It means, that the elasticity modulus (slope of the stress-strain curve) is not correct and it needs to be corrected. Storage modulus determined from DMA tests describes elastic region of these curves. By using the following methodology, it is possible to directly adjust the tensile curve to the storage modulus. The method is the following:
The total strain ε_t of the engineering stress-strain curve can be expressed as

$$\varepsilon_t = \varepsilon_e + \varepsilon_{pl} \,, \tag{1}$$

where ε_e is elastic strain of specimen and ε_{pl} is plastic strain. From the stress-strain curve, only the plastic strain needs to be expressed according to the equation

$$\varepsilon_{pl} = \varepsilon_t - \frac{\sigma}{E}, \tag{2}$$

where σ is stress value and E is Young's modulus from tensile test. Using equation (2), all elastic strain values are set to zero, leaving only the plastic strain values. With equation

$$\varepsilon_t = \varepsilon_{pl} + \frac{\sigma}{E'}, \tag{3}$$

where E' is storage modulus, the elastic deformation corresponding to the storage modulus is added to plastic deformation from previous equation. These steps result in a modified tensile curve for the storage modulus. The initial averaged engineering stress-strain curve (blue) with $E = 556$ MPa and the stress-strain curve (red) with storage modulus $E' = 1849$ MPa modified according the eq. (3) are shown in Fig. 7.

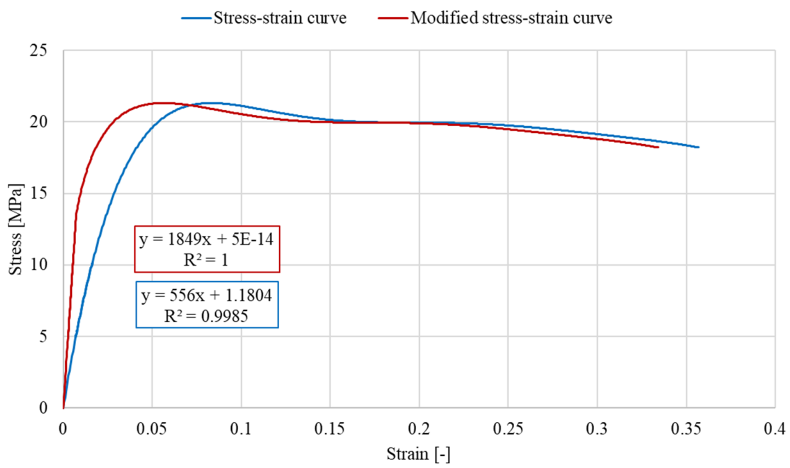


Fig. 7 Tensile and modified stress-strain curve.

In material models used in FEM simulations, it is necessary to transform engineering stress-strain curves to true curves using the volume conservation law

$$\varepsilon_{true} = \ln(1 + \varepsilon_e), \qquad \sigma_{true} = \sigma_e (1 + \varepsilon_e). \tag{4}$$

This law is valid only up to the ultimate strength. The resultant true stress-true strain curve is shown in Fig. 8.

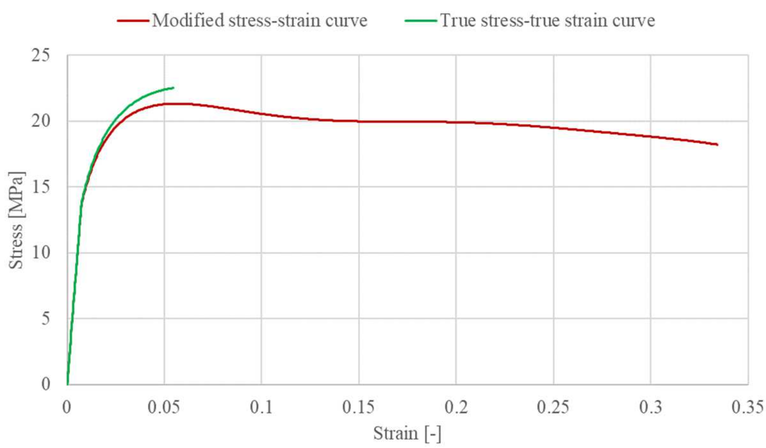


Fig. 8 True stress-true strain curve in comparison with engineering stress-strain curve.

In Fig. 9, the dependence of strain rate on the stress-strain curves can be seen. Due to the increase of strain rate, the material becomes stronger and stiffer. These curves describing the region up to the ultimate strength can be applied in material models for FEM simulations.

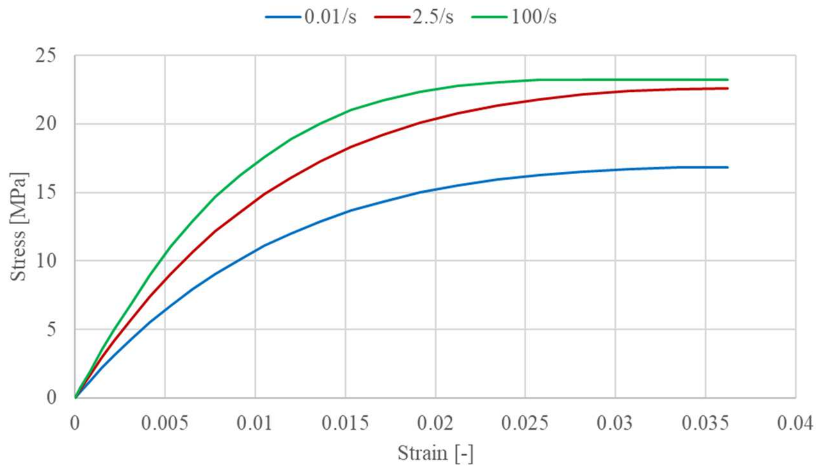


Fig. 9 Resultant true stress-true strain curves for different strain rates..

3 Conclusion

The aim of this paper was to investigate the effect of strain rate on mechanical properties of polypropylene filled with 12% talc. To accomplish the aims of the paper, three types of mechanical tests were performed. The tensile test was carried out to obtain the stress-strain characteristic. The three-point bending test was used as a validation tool for the DMA tests, where the frequency dependence of the storage modulus was measured. The impact tensile tests at a strain rate of 10^2 s^{-1} measured on the drop test machine had to be approximated for further use. After obtaining the stress-strain characteristics for all strain rates, it was further necessary to adjust the Young´s modulus to the storage modulus, i.e. to adjust the slope of the curves. This whole process of evaluating the mechanical properties of the polymer and further curve modifying can be used as a methodology for evaluating mechanical properties for input into material models for FEM simulations.

Acknowledgement

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