

The Effects of Strain Rates on the Mechanical Properties of Thermoplastic Polyurethane

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ABSTRACT

Thermoplastic polyurethane (TPU) has a wide range of uses, including automotive panels, cast wheels, power tools, sports equipment, medical equipment, driving belt systems, clothing, inflatables, and a wide variety of extruded film, sheet, and profile systems. The material has unique properties like high abrasion resistance and elasticity, enhance the material efficiency at low temperatures and has a high shear resistance, make the TPU highly popular in the industry today. Nonetheless, the other researchers have not performed any study for the effects of different strain rates on TPU systematically. In this study, three strain rate values are applied to the specimens, which is 0.1 s^{-1} , 0.3 s^{-1} and 0.5 s^{-1} to study the effects of different strain rates applied on the mechanical properties of TPU. Furthermore, the research task is include the finite element analysis (FEA) to simulate the tensile test of TPU by using different strain rates. From the results, the material shows that the yield stress and ultimate tensile strength of the specimens increased proportionally to the strain rates from 0.1 s^{-1} to 0.5 s^{-1} . However, the ultimate tensile strain of the specimen decreased when higher strain rates applied to the specimen. Thus, the increasing strain rates values improve the mechanical properties of the TPU, such as yield stress and ultimate tensile strength but will reduce the ultimate tensile strain value as well.

Keywords: *Thermoplastic polyurethane, tensile test, FEA, strain rate.*

Introduction

The thermoplastic Polyurethane (TPU), due to the material properties such as elasticity, durability and resistance to grease, oil and abrasion, is commonly used in the automotive, the building construction, the aerospace and the medical industries. The TPU is also biodegradable, environmentally-friendly, and fully recyclable, making the material an appropriate alternative to polymer PVC and various other polymers. This is one of the main factors that made the material much preferable.

The main applications for the TPU mostly used for various industries such as industrial plates, transducer belts, laminates, and medical packaging. Besides, due to the growth of the end-use industries, the demand for the thermoplastic polyurethane is expected to increase during the forecast period. Moreover, the constant growth of the medical and healthcare industry is expected to increase demand for this material further, due to a rise in population, income level, and awareness as well as technological advances in the industries.

The study of the effects of strain rate to the specimen under tensile loading is very popular among researchers. This study has been done on carbon fiber-reinforced thermoplastic (CFRT), glass fiber-reinforced thermoplastic, Al-Mg-Si-Cu alloy, etc. [1]–[3]. The research work stated that thermoplastic polyurethane (TPU) is a strain-dependent material [4]. However, there is still no researchers who dedicated their study on the effects of strain rate on thermoplastic polyurethane (TPU).

In several studies, the effects of strain rates on the mechanical properties of short glass fiber reinforced thermoplastic (SGFRT) were investigated [5]–[7]. The strain rate-dependent tensile behaviour under tensile loading of the continuous GFRT composite was studied. Brown et al. [8] reported the effects of strain rates over a strain range of $10^{-3} \text{ s}^{-1} - 10^{-2} \text{ s}^{-1}$ on the tensile, shear, and compression behaviour of continuous GFRT composites. The result discovered that with the increase on strain rates, the tensile and compression modulus and strength increased. Nevertheless, with the increasing strain rates, the ultimate strain, the shear modulus and strength were discovered to decrease, and the strain rate effects in the material appeared to be mainly affected by matrix viscoelasticity, fiber-matrix interfacial properties, composite woven reinforcement design, and time-dependent existence of damage accumulations. Duan et al. [9] addressed the effects of strain rates on hot-moulded continuous GFRT composite tensile properties. Results showed that the composite was prone to strain rates, and with rising strain rates, the ultimate strength value increased.

Theory of the Model

The typical shape of a tensile specimens are flat dog bone. Both of the specimen end are enlarged for gripping purpose. The cross-sectional area of the gauge section is reduced relative to that of the remaining specimen to identify deformation and failure of the specimens. The gauge length is the area where measurements are performed and based inside the reduced portion. The distances between the ends of the gauge section and the shoulders should be sufficiently wide to prevent the larger ends from constraining deformation within the gauge section, and the length of the gauge should be long relative to its cross-sectional area. Otherwise, the state of stress would be more complicated than mere tensioning.

ABAQUS/CAE software was used to model the study of tensile test on the TPU. The standard dimensions of the specimen are obtained from the American Society for Testing and Materials (ASTM). Type IV dimensions of the specimen from the ASTM D638 standard, which is used for standard test method on thermoset and thermoplastic material is chosen for the specimen modelling. Figure 1 and Table 1 shows the standard dimensions of the specimens. The dimensions of the specimens are constant for all the testing in this research.

Table 1: Dimensions of the specimen ASTM D638

Dimensions	Standard measurements
Overall length, LO	115 mm
Overall width, WO	19 mm
Width of narrow section, W	6 mm
Length of narrow section, L	65 mm
Gauge length, G	33 mm
Length of grips, GL	25 mm
Radius of fillet, R	25°

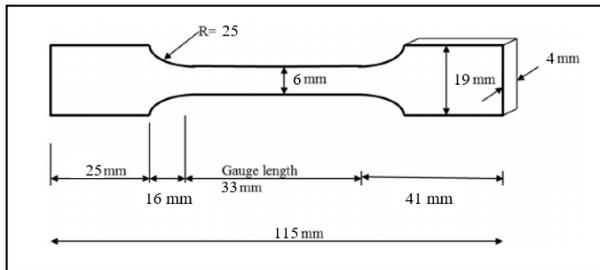


Figure 1: Schematic diagram of the specimen

Methodology

Finite Element Modelling of the Tensile Test

The finite element model of the tensile test is made by using the ABAQUS/CAE software as shown in Figure 2. The types of the body that has been set for this model are solid and deformable. The total number of elements in this model is 208. The number of elements needs to be verified before the analysis to ensure that the model can provide the best tensile test results and contours that viewing the region of stress properly.

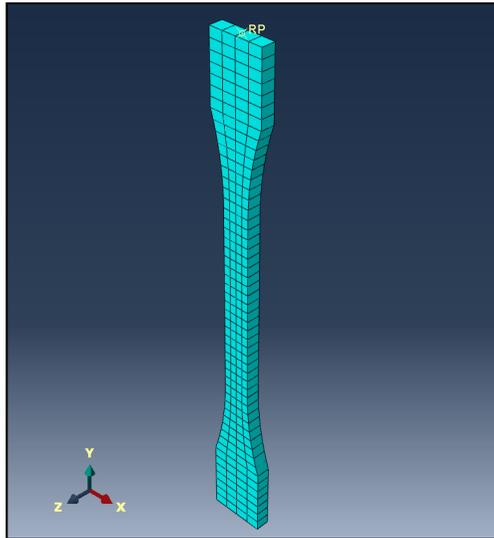


Figure 2: Finite element model of the tensile test specimen

Meshing

The mesh of the TPU test specimen is an important element in modelling the specimen. A poorly meshed part will result in producing not realistic stress on the specimen. If the elements are too large, the stress analysis between each element can be magnified, if the mesh is extremely fine, the part might take up too much memory space and long period processing. A mesh density study was conducted by changing the size of each element, running the analysis and viewing the results to see if the stress changes with the change in seed size. The smallest element size of the specimen in Figure 2 at the gauge region is 3.4 mm, and the total number of elements is 208.

Boundary Conditions

In this study, one end of the test specimen is fixed from displacement or rotation in x, y, and z-direction. The boundary conditions are applied to indicate that the end of the test specimen is fixed from displacement and rotation. Besides, the displacement boundary condition, as shown in Figure 3, is also applied to the opposite end of the first boundary condition. The displacement boundary condition is used to control the displacement of the specimen for every second. This boundary condition is the step that required to apply different strain rate for every specimen. The displacement value is applied to the positive y-axis to ensure the displacement of the material simulates the tension force rather than compression. The value of the displacement is stated in Table 2, along with the corresponding strain rate:

Table 2: Strain rate and displacement boundary condition

Strain rate (s^{-1})	Displacement boundary condition (mm/s)
0.1	11.5
0.3	34.5
0.5	57.5

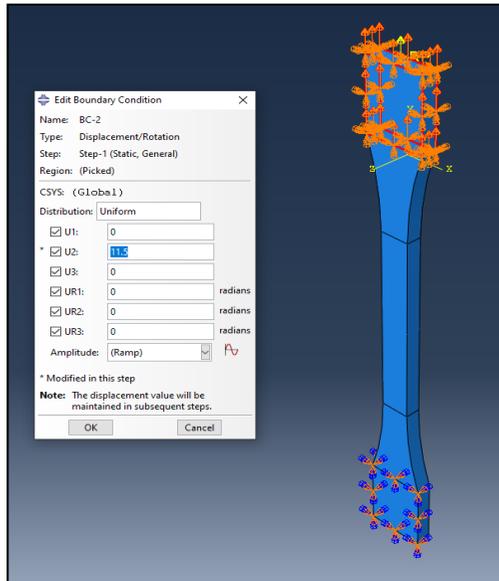


Figure 3: Displacement boundary condition

Simulation Parameters

Three strain rate values that applied on the specimen are 0.1 s^{-1} , 0.3 s^{-1} and 0.5 s^{-1} . The result of FEA by using ABAQUS/CAE software consists of von Mises stress, and load-elongation curves. The properties of the TPU were presented in Table 3.

A precise full range of von Mises equivalent stress $\bar{\sigma}$ (Eq. (1)) - equivalent plastic strain $\bar{\varepsilon}$ (PEEQ defined by Eq. (2)), termed as von Mises stress-strain curve, is significant for simulation to accurately capture elastoplasticity behaviors of materials.

$$\bar{\sigma} = \sqrt{\frac{1}{2}[(\sigma_z - \sigma_r)^2 + (\sigma_z - \sigma_\theta)^2 + (\sigma_\theta - \sigma_r)^2]} \quad (1)$$

$$\bar{\varepsilon} = \sqrt{\left[\frac{2}{3}\varepsilon_z^2 + \varepsilon_r^2 + \varepsilon_\theta^2\right]} \quad (2)$$

where three subscripts z, r and θ are axial, radial and hoop directions, respectively.

Table 1: Properties of TPU [10]

Material	Mass density (kg/m ³)	Young's Modulus (GPa)	Poisson ratio	Maximum principal stress (MPa)	Elongation at break
TPU	1×10^{11}	50	0.3	40	0.5

Results and Discussion

Von Mises Stress

Von Mises stress is to develop a ductile material yield criterion that works for any complex 3D loading conditions irrespective of the normal-shear stress mix. This is achieved by boiling the complex stress state to the same number of scalars relative to the yield strength of a component, which often requires a single scalar numerical value dependent on a uniaxial strain check on the material in a laboratory. Figure 4, 5 and 6 shows the Von Mises stress of the specimens. The colour of the contours on the specimen indicated the region that exhibits the stress value listed in the legends at the top left corner of the figure.

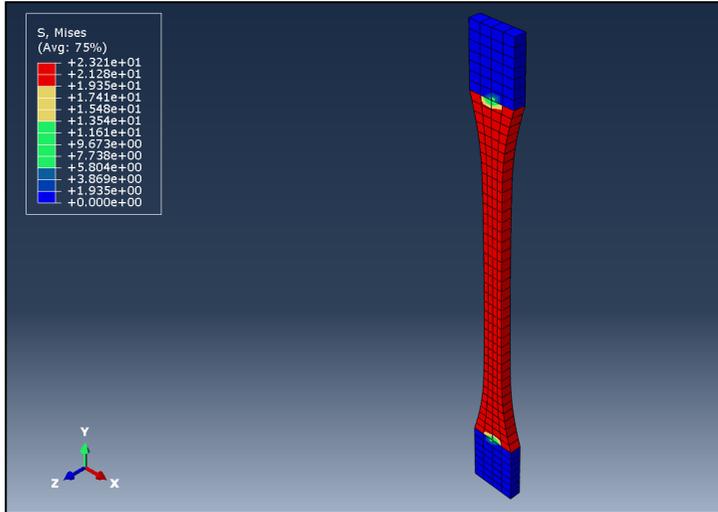


Figure 4: Von Mises Stress (0.1 s⁻¹)

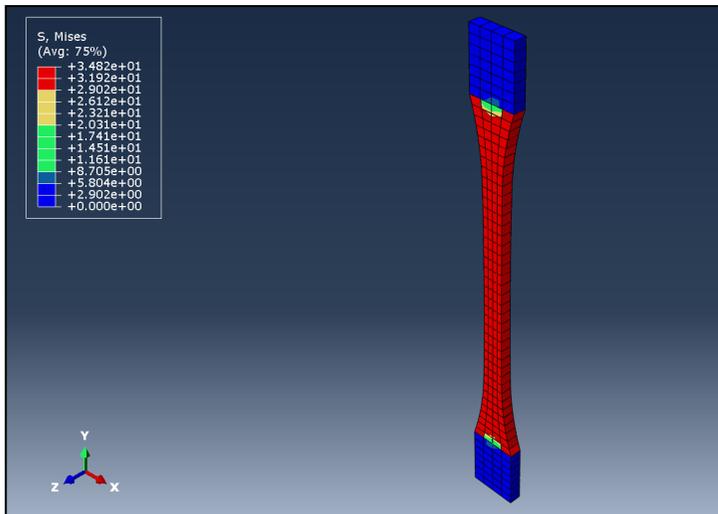


Figure 5: Von Mises Stress (0.3 s⁻¹)

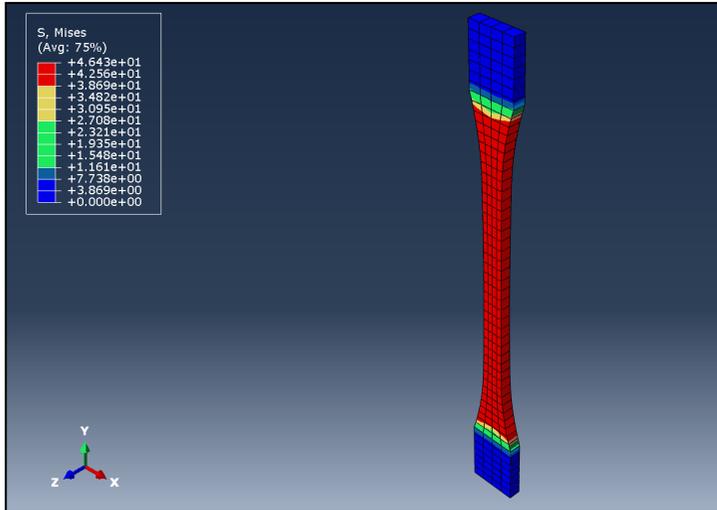


Figure 6: Von Mises Stress (0.5 s^{-1})

Force-Elongation Graph

There are a few results that can be highlighted on the effects of strain-rate towards the TPU material under tensile loading in Figure 7. The first aspect that was affected by the various strain rates applied to the specimen was the force needed to reach the yield point. The TPU specimen that undergoes tensile test with the strain rate of 0.5 s^{-1} required the largest force, which is 2.30 kN to reach the yield point. The second perimeter with 0.3 s^{-1} strain rate, the force needed to reach the yield point is 1.73 kN. The specimen with the strain rate of 0.1 s^{-1} needed the smallest force to reach the yield point, which is 1.15 kN.

Besides, the maximum elongation of the specimens is also affected by the various strain rates applied. The specimen with 0.5 s^{-1} strain rate produced the maximum elongation of 15 mm. The value is the lowest value for maximum elongation compared to the other two perimeters. The second specimen, which applied with 0.3 s^{-1} strain rate produced the maximum elongation of 21.1 mm. The specimen with 0.1 s^{-1} strain rate produced the 30.9 mm maximum elongation. Compared with the other specimen, the value of maximum elongation of the specimen with 0.1 s^{-1} strain rate is the highest.

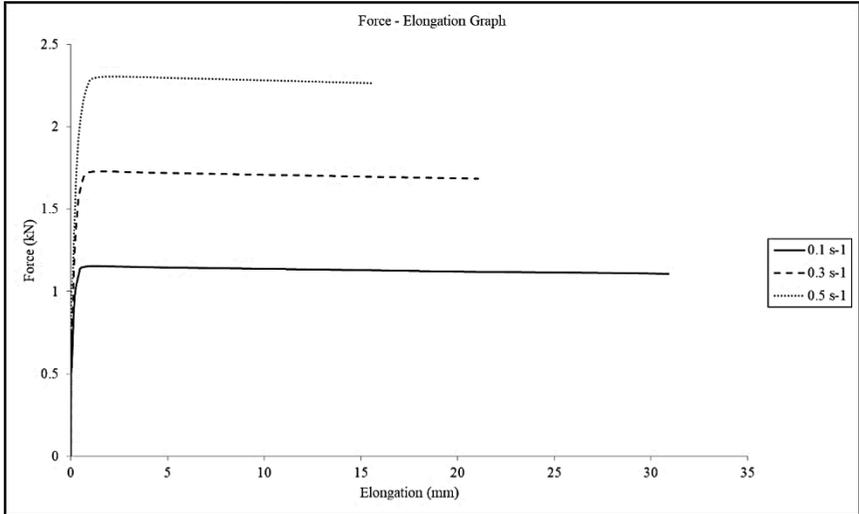


Figure 7: Force-elongation graph

Conclusion

In this study, different strain rate values applied to the TPU tensile specimen influence the changes in mechanical properties of the specimen. Three values of strain rates have been applied to the specimens of TPU for this study which are 0.1 s^{-1} , 0.3 s^{-1} and 0.5 s^{-1} . After completing the analysis, the results show that the increasing values of strain rates applied on the TPU specimens improved some mechanical properties of the TPU specimens such as the yield stress and ultimate tensile strength and. However, the ultimate tensile strain of the specimens is declining when the strain rates values are multiplied. Both of these phenomena occurred because the increases of strain rates values changed the behaviour of the TPU specimens from ductile to brittle behaviour. Thus, it made the slope at the elastic region of the specimens become steeper proportionally with the increasing values of strain rate applied.

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