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Effect of Temperature and Strain Rate On The Mechanical Behavior Of Discontinuous Glass Fibre Reinforced Thermoplastic Composite

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Résumé

L'utilisation de composites thermoplastiques renforcés par des fibres de verre discontinues se développe aujourd'hui dans de nombreux secteurs (automobile, marine, biomédical, aéronautique) en raison de leurs bonnes propriétés mécaniques et de leur caractère éco-responsable (recyclabilité). Bien que ces types de matériaux présentent de nombreux avantages, leur sensibilité à la température et à la vitesse de déformation rend leur étude complexe. Au cours de leur mise en forme (thermoformage, moulage par compression...), les composites thermoplastiques peuvent être soumis à des conditions sévères : vitesses de déformation et températures élevées, chemins de déformation complexes, pouvant entraîner des changements significatifs des propriétés mécaniques. Dans cette étude, le comportement mécanique du polypropylène renforcé de fibres de verre longues est évalué en réalisant des essais de traction uniaxiale à des vitesses de déformation allant de $0,001s^{-1}$ à $10s^{-1}$ pour des températures allant de l'ambiante jusqu'à $120^{\circ}C$. Sur la base de ces résultats expérimentaux, un modèle phénoménologique du comportement du matériau utilisé dépendant de la vitesse de déformation et de la température est identifié. Ces essais uniaxiaux sont alors considérés comme une étape préliminaire pour préparer une caractérisation mécanique plus complexe au moyen d'essais de traction biaxiaux sur des éprouvettes de forme cruciforme, intégrant en plus des effets température et visqueux, l'effet du chemin de déformation.

Abstract

The use of discontinuous glass fibre reinforced thermoplastic composites is nowadays increasing in many fields, e.g. automotive, marine, industrial, biomedical and aircraft structures due to their good mechanical properties and environmentally-friendly nature (recycleability). Although such types of material show many advantages, their sensitivity to temperature and strain rate complicates their study. During manufacturing processes (thermoforming, compression moulding...), the thermoplastic composites may be subjected to severe conditions : high strain rates and temperatures, complex strain paths, resulting in significant changes of their mechanical properties. In this study, the mechanical behaviour of long glass

fibres reinforced polypropylene is evaluated by performing uniaxial tensile tests at strain rates ranging from $0.001s^{-1}$ to $10s^{-1}$ under different temperatures starting from ambient up to $120^{\circ}C$. On the basis of the experimental results, a phenomenological material behavior model that depends on temperature and strain rate is identified. The uniaxial tests are then considered as a preliminary step to prepare for more complex mechanical characterization by means of biaxial tensile tests on cruciform shaped specimens, integrating the effect of strain path in addition to temperature and viscous effects.

Key words : long glass fibre reinforced composites, strain rate, temperature, mechanical properties.

1 Introduction

Discontinuous fiber reinforced thermoplastics are composite materials consisting of a thermoplastic polymer matrix reinforced with short or long fibers. The average fiber length before injection is usually less than 1mm for short fiber reinforced thermoplastics and 10-12mm for long fiber reinforced thermoplastics. A reduction in the average fiber length value is expected in the molded part due to fibers breakage occurring inside the barrel of the injection molding machine [1, 2]. Such composites have been widely used in various applications due to their good mechanical properties represented by a favorable strength-to-weight ratio, excellent processability, recyclability, corrosion resistance, vibration damping, durability and moderate cost [3]. These properties have enabled their use as advanced lightweight engineering materials, particularly within the transportation sector [4], as they can have promising performance when compared to conventional metallic structures.

Automotive components made of thermoplastic composites can be manufactured by thermoforming [5]. During this process, the composite part (originally a sheet or plate) is subjected to various strain paths, strain rates and temperatures. The sensitivity of an unreinforced thermoplastic polymer to these mentioned factors [6, 7] is also expected to be a part of the overall mechanical behavior of a fiber reinforced thermoplastic polymer. Atmani et al. [7] performed an experimental and numerical study to describe the behavior of an unreinforced thermoplastic polymer (high impact polystyrene) during its plug-assisted thermoforming (a plug is used to force the softened sheet down into the mould before by applying a pressure to stretch it around the cavity walls). In the experimental part of their study, elastic properties were investigated by performing uniaxial tensile tests at different temperatures (from $80^{\circ}C$ to $140^{\circ}C$) and strain rates ($0.0167 s^{-1}$, $0.033s^{-1}$, and $0.167 s^{-1}$). The influence of these factors was obvious on the elastic modulus and the yield strength which increased by 67% and 50%, respectively, as the strain rate increased by a factor of 10. Also, a temperature increment of $20^{\circ}C$ at the lowest strain rate, caused a decrease in the values of Young's modulus and yield strength by 67% and 54%, respectively. The authors also conducted plug-only tests at high velocities (impact with aluminum plug) to study the material's behavior under multiaxial and large deformation loading in order to give a close estimation of the real thermoforming conditions. The selected forming temperature range was $110^{\circ}C$ to $140^{\circ}C$ and the testing velocities were 200mm/s, 500mm/s and 1000mm/s. The curves of the plug force as a function of the plug stroke showed a rigid and brittle behavior of the sheet at a temperature of $110^{\circ}C$, contrary to the curves at $130^{\circ}C$ and $140^{\circ}C$ showing a rubbery and ductile behavior. The maximum force and the slope of the curves decrease significantly, when the temperature increases. Tests conducted at different plug velocities and a temperature of $130^{\circ}C$ showed that increasing the velocity intensifies the rigidity of the sheet.

Duan et al. [8], investigated the effect of strain rate on the mechanical properties of a long glass fiber reinforced thermoplastic polymer used as an automotive structural component that undergoes various environments while being loaded in different strain rates. Their experimental results of uniaxial tensile tests performed at strain rates ranging from $0.001s^{-1}$ to $50s^{-1}$ showed that increasing the strain rate of $0.001s^{-1}$ by a factor of 10^4 increases the ultimate tensile strength and the maximum strain by 84% and 120%, respectively, while having a negligible effect on Young's modulus. Cui et al. [9], studied the effect of strain rate on the behavior of long glass fiber reinforced polypropylene used in automotive parts by carrying out tensile tests at strain rates ranging from $0.001s^{-1}$ to $400s^{-1}$. Results showed that the ultimate strength, fracture strain, and Young's modulus increase by 77%, 39%, and 40%, respectively, by increasing the strain rate of $0.001s^{-1}$ by a factor of 10^5 . Wang et al. [10], studied the effect of temperature ($20^{\circ}C$ up to $100^{\circ}C$) and strain rate (quasi-static conditions) on the mechanical behavior of short glass fiber reinforced polyamide-6. Based on their experimental data, they concluded that both tensile strength and tensile modulus of the composite decrease with increasing temperature and increase with increasing strain rate.

Material models used to predict the mechanical behavior of fiber reinforced polymers must embed material-related mechanical characteristics, such as non linear viscoelasticity and plasticity along with strain rate and temperature dependency. Over the years, several studies have been carried out on polymers as well as their corresponding composites (keeping in mind that the strain rate and temperature dependency of a fiber reinforced polymer is typically a characteristic of the matrix material not the reinforcement) as an effort to model their mechanical behavior specifically for thermoforming applications. Mooney-Rivlin is an example of hyperelastic models that can predict the behavior of polymeric materials. Pham et al. [11] predicted the strain rate and temperature dependent stretching behavior of a thermoplastic polymer (polyethylene terephthalate PET) using a visco-hyperelastic model based on Mooney-Rivlin whose parameters were determined by means of a non-linear curve fitting based on data obtained from a biaxial characterization technique. Afterwards, the model was applied to simulate the stretch blow molding of PET which was successfully validated experimentally. Viscoelastic models such as Maxwell can also be adopted to model the thermoforming behavior of polymers or their corresponding composites. Peng et al. [12] proposed a non-linear thermo-viscoelastic constitutive model to describe the strain rate and temperature dependent behavior of a polypropylene wood composite. The model's parameters were identified through curve fitting to the experimental data from uniaxial compression tests at different temperatures and strain rates. The model was used in thermoforming simulation of a car interior part made of polypropylene wood composite. Polymers or reinforced polymers might also exhibit complicated viscoplastic behavior (temperature and strain rate dependency). Cowper-Symonds, which is a simple viscoplastic model, originally designed for metals, was applied in some studies to model the behavior of fiber reinforced polymers [13, 14]. Another popular viscoplastic model, G'Sell and Jonas, was designed in the first place for modeling the mechanical behavior of semi-crystalline polymers [15]. This model gave acceptable results describing the mechanical behavior of fiber reinforced polymers. In the work of Schossig et al. [16], the influence of strain rate and fibers concentration on the mechanical behavior of glass fiber reinforced thermoplastics was experimentally investigated. G'Sell and Jonas model was used to describe the strain rate dependent behavior of the materials. Additionally, this model was used to represent the deformation behavior during thermoforming applications. The numerical part of Atmani et al. [7] discussed previously, consisted in modeling the thermoforming of a yogurt container by the elasto-viscoplastic G'Sell and Jonas model with thermal considerations.

The aim of this work is to investigate the strain rate and temperature dependency of glass fiber reinforced

polypropylene as a first step in understanding their behavior at severe conditions as those encountered in thermoforming. Uniaxial tensile tests are conducted at strain rates of $0.001 s^{-1}$, $1 s^{-1}$, and $10 s^{-1}$ and testing temperatures of $20^{\circ}C$, $70^{\circ}C$, and $120^{\circ}C$. On the basis of the experimental results, the parameters of the isotropic constitutive model of G'Sell and Jonas are calibrated to predict the strain rate and temperature dependent behavior of the material.

2 Mechanical Characterization By Tensile Testing

2.1 Material and Experimental Setup

Discontinuous glass fiber reinforced polypropylene is the composite material used in this work. Injection molded plates were supplied by SABIC (Stamax, 40YM240). The weight fraction of fibers is 40 % whose initial length (before injection) is around 15mm. After injection the length decreases to around 3mm (fibers breakage). The material properties provided by the supplier (technical data sheet) are presented in Table 1. Uniaxial tensile specimens were extracted by means of water-jet cutting machine from the same position with respect to the injection port located in the center of the plate and with the same orientation with respect to the plate. The geometry and dimensions of the tensile specimen are shown in Figure 1. The specimen has a constant cross-section of 50mm gauge length, a section width of 10mm and a thickness of 2mm. Uniaxial tensile tests are performed on the servo-hydraulic tensile testing machine equipped with a

Polymer properties	Value	Unit
Density	1220	Kg/m ³
glass fiber content	40	%
Mechanical properties	Value	Unit
Tensile modulus	8200	MPa
Tensile strength	110	MPa
Elongation failure	2.1	%
Flexural modulus	8200	MPa
Thermal properties	Value	Unit
Heat deflection temperature	180	$^{\circ}C$
Coefficient of linear expansion	40	m/mK

TABLE 1 – Material properties of 40% glass fiber reinforced polypropylene.

heating system and an insulated box where the specimen and the lower and upper grip devices are placed in order to ensure a constant and homogeneous temperature of the specimen at the beginning of the test. To investigate the effect of strain rate, the specimens are subjected to displacement-controlled tension-to-failure tests at $20^{\circ}C$. Three initial loading rates are adopted : quasi-static (0.05mm/s), intermediate (50mm/s) and high (500mm/s) corresponding to strain rates of $0.001 s^{-1}$, $1 s^{-1}$, and $10 s^{-1}$, respectively. The effect of temperature is accounted for by performing uniaxial tensile tests at quasi-static loading rate of 0.05mm/s (i.e., $\dot{\epsilon}_1 = 0.001 s^{-1}$) for three temperatures : $20^{\circ}C$ (ambient), $70^{\circ}C$, and $120^{\circ}C$ (oven temperature). Digital image correlation is adopted as strain measurement technique. The specimen's

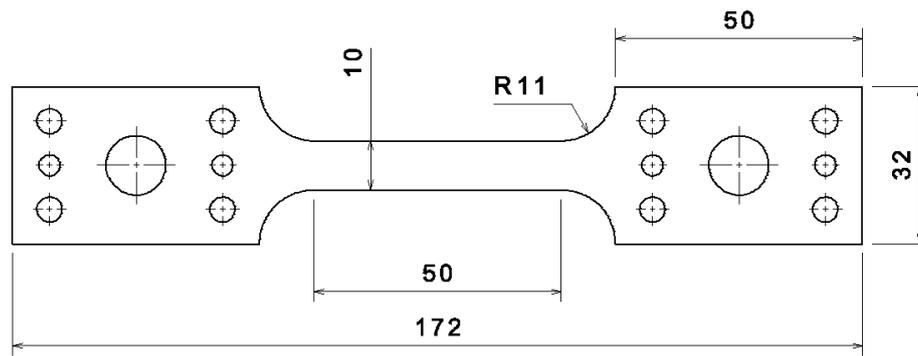


FIGURE 1 – Geometry and dimensions of the uniaxial tensile test specimen.

deformation is filmed through the insulated box door with a high speed camera (Photron FASTCAM APX RS, 250K). The images are then post-processed by GOM CORRELATE software.

2.2 Experimental Results and Discussion

In this section, the results of the experimental investigations are presented and discussed. Stress-Strain plots at different experimental conditions are analyzed, showing the influence of strain rate and temperature on the mechanical behavior of the studied material.

Effect of Strain Rate

Figure 2 shows the stress-strain variation at ambient temperature ($T=20^{\circ}\text{C}$) and for three initial loading rates. The effect of strain rate is obvious on the ultimate tensile strength $\sigma_{ultimate}$. For a reference test

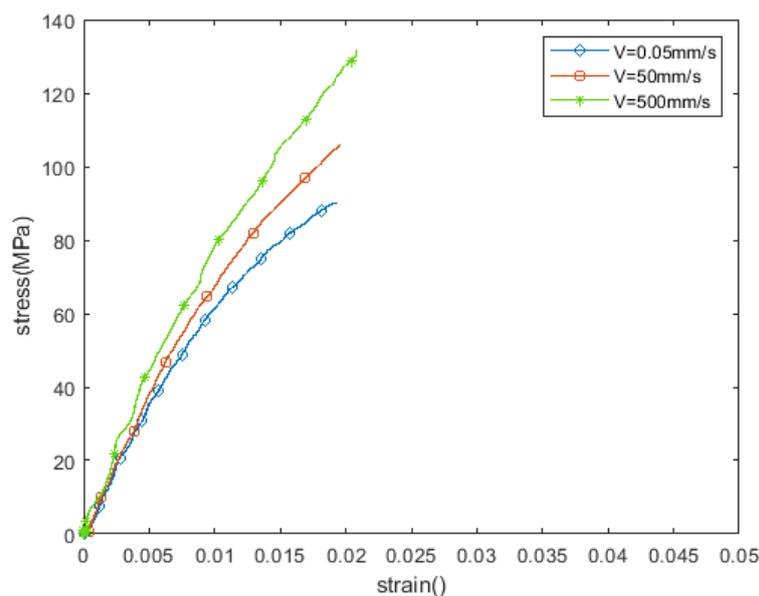


FIGURE 2 – Tensile stress-strain variations at room temperature ($T=20^{\circ}\text{C}$) for three different initial strain rates $\dot{\epsilon}_1 = 0.001 \text{ s}^{-1}$, $\dot{\epsilon}_2 = 1 \text{ s}^{-1}$ and $\dot{\epsilon}_2 = 10 \text{ s}^{-1}$ corresponding to tensile speeds of 0.05mm/s, 50mm/s and 500mm/s, respectively.

velocity of 0.05mm/s, $\sigma_{ultimate}$ increases by 16% and 43% if the value of the reference velocity is

multiplied by a factor of 10^3 and 10^4 , respectively. Compared to the lowest strain rate, a small increase of 7% and 14% is noticed in the elongation at failure $\epsilon_{failure}$ and Young's modulus E , respectively, at the highest strain rate. E along with Poisson's ratio ν are determined according to ISO-527 1A. Table 2 summarizes the values of the tensile properties determined from these uniaxial tensile tests.

Parameter	T=20 °C		
	V=0.05mm/s	V=50mm/s	V=500mm/s
E (MPa)	8101	8621	9251
ν (-)	0.43	0.48	0.46
$\sigma_{ultimate}$ (MPa)	91	106	130
$\epsilon_{failure}$ (%)	1.94	1.96	2.08

TABLE 2 – Tensile properties at room temperature and different loading rates.

Effect of Temperature

The remarkable temperature sensitivity of the mechanical behavior of glass fiber reinforced polypropylene is illustrated in Figure 3 showing stress-strain variations at quasi-static loading rate of 0.05mm/s for three different temperatures T=20°C (ambient), T=70°C, and T=120°C measured in the oven. Both

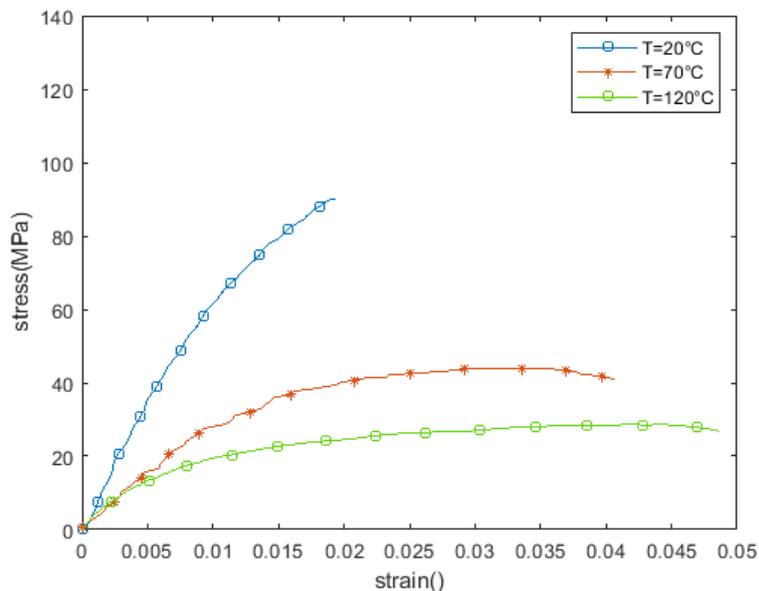


FIGURE 3 – Quasi-static ($\dot{\epsilon}_1 = 0.001 \text{ s}^{-1}$) tensile stress-strain variations at three different temperatures (T=20°C, T=70°C and T=120°C).

Young's modulus E and the ultimate tensile strength $\sigma_{ultimate}$ decrease with increasing temperature. By referring to T=20°C, the value of E decreases by 56% and 62% at T=70°C and T=120 °C, respectively, and the value of $\sigma_{ultimate}$ decreases by 51% and 67% at T=70°C and T=120 °C, respectively. Whereas, the elongation at failure $\epsilon_{failure}$ increases as the temperature increases i.e. the value of $\epsilon_{failure}$ measured at T=20°C increases by 109% and 150% at T=70°C and T=120 °C, respectively. The temperature dependent tensile properties are listed in Table 3.

Parameter	V=0.05mm/s		
	T=20°C	T=70°C	T=120°C
E (MPa)	8101	3546	3059
ν (-)	0.43	0.45	0.48
$\sigma_{ultimate}$ (MPa)	91	44.5	30.2
$\epsilon_{failure}$ (%)	1.94	4.07	4.86

TABLE 3 – Tensile properties at quasi-static loading rate and different temperatures.

3 Phenomenological Constitutive Modeling

The experimental investigations performed in this work underlined the noticeable effect of strain rate and temperature on the mechanical behaviour of discontinuous glass fiber reinforced polypropylene. In this section, the isotropic phenomenological constitutive model of G'Sell and Jonas [15, 17] is selected to describe the behavior of the studied material. Isotropy is considered since the fibers are supposed to have an isotropic distribution in the plate.

The constitutive equation of the model is stated in (1).

$$\sigma(\epsilon, \dot{\epsilon}) = K \cdot \exp(h\epsilon^2) (1 - \exp(-W\epsilon)) \cdot \dot{\epsilon}^m \quad (1)$$

Where σ is the equivalent stress, ϵ represents the equivalent strain, and $\dot{\epsilon}$ the equivalent strain rate. m (strain rate sensitivity), K (scaling factor), h , and W are material parameters. Low strain levels are represented by the term $(1 - \exp(-W\epsilon))$. The term $\exp(h\epsilon^2)$ represents the plastic strain hardening which takes place at high strain levels as in the case of glassy unreinforced polymers [7].

In this work, the plastic strain hardening term is neglected ($h=0$) due to the low level of deformation at rupture. Additionally, the effect of the temperature can be incorporated in the model equation by performing a temperature sensitivity analysis for the material parameters and expressing them as a function of temperature. Therefore, the constitutive equation considered in this work becomes as stated in (2) and the model parameters are calibrated based on the obtained experimental results.

$$\sigma(\epsilon, \dot{\epsilon}, T) = K(T) \cdot (1 - \exp(-W(T) \cdot \epsilon)) \cdot \dot{\epsilon}^{m(T)} \quad (2)$$

3.1 Parameters Identification at T=20 °C

In this section, the three unknown parameters of (2), are determined calibrated based on tests performed at room temperature ($T= 20^\circ\text{C}$). The first term to be identified is the strain rate sensitivity parameter m . By considering the logarithmic form of (2), m is found to be the slope of the plot $\ln(\sigma)$ vs. $\ln(\dot{\epsilon})$ at a given temperature T and strain level ϵ as shown in (3),

$$m = \left(\frac{\partial \ln \sigma}{\partial \ln \dot{\epsilon}} \right)_{T, \epsilon} \quad (3)$$

The value of the strain rate sensitivity parameter m is assumed constant for all strain levels (taking an average of m values at five different strain levels : $\epsilon= 0.005$, $\epsilon= 0.008$, $\epsilon=0.01$, $\epsilon=0.015$, and $\epsilon=0.018$ as suggested in [15]). K and W are determined using the nonlinear optimization function in MATLAB,

fmincon. The cost function to be minimized is defined by the error δ as follows,

$$\delta = \min \sum_{i=1}^n (\sigma_{\text{model}} - \sigma_{\text{experimental}})^2 \quad (4)$$

Where n is the total number of data points, σ_{model} is the predicted stress, and $\sigma_{\text{experimental}}$ is the stress measured experimentally. The identified parameters of the model are listed in Table 4. Two additional sets of the calibrated parameters should be obtained at $T=70^\circ\text{C}$ and $T=120^\circ\text{C}$ in order to integrate the temperature sensitivity in the model. This is not reported in this article.

$m[/math>$	$K[\text{MPa}]$	$W[/math>$
0.02618	146.65	66.81

TABLE 4 – Identified parameters of G'Sell & Jonas model at the room temperature $T=20^\circ\text{C}$.

3.2 Comparison With Experimental Data

For the purpose of comparison, Figure 4 shows stress-strain plots generated from experimental results and the predictions of the constitutive model. It can be stated that the model is able to give good approximation of the material's response. However, there is a small discrepancy between the experimental observations and the model's predictions at higher strain rates. This can be attributed to many factors affecting the accuracy of the model one of which is considering m as constant at all strain level whilst it obviously varied at each strain. Therefore, defining m in equation 1 as a function of ε can improve the accuracy of the results[18]. This will be accomplished in future works.

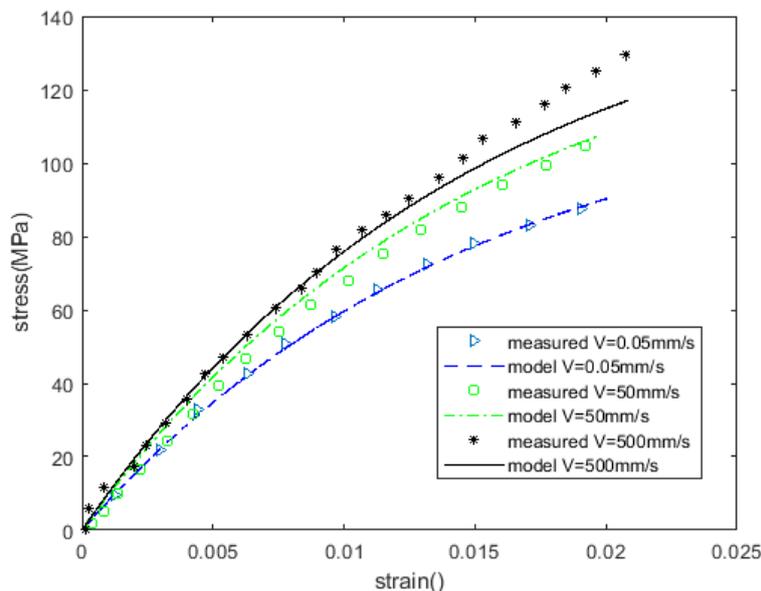


FIGURE 4 – Comparison between experimental and predicted stress-strain curves at $T=20^\circ\text{C}$.

4 Conclusion and Future Perspective

In this paper, experimental investigations are involved in order to determine the influence of temperature and strain rate on the tensile properties of glass fiber reinforced polypropylene, as an attempt to understand the behavior of this material during thermoforming applications. According to the results obtained from uniaxial tensile tests at different operating conditions, the mechanical response is strongly affected by both strain rate and temperature. In a first step, the constitutive model of G'Sell and Jonas is chosen to model the strain rate dependency of the material at room temperature. After model calibration, it is shown that experimental and predicted results agree well.

For a better prediction of the behavior, the original equation can be modified to consider the strain rate sensitivity m as a function of strain level ε which will be done in future works. Moreover, the material parameters of G'Sell and Jonas model will be calibrated at 70°C, and 120 °C in order to generalise the model and describe the combined effect of temperature and strain rate on the mechanical behavior of glass fiber reinforced polypropylene. Furthermore, a complex mechanical characterization closer to the real conditions of a thermoforming process will take place by considering biaxial tensile tests on cruciform shaped specimens while integrating the effect of strain path in addition to temperature and viscous effects. A comprehensive material model will finally be identified based on the biaxial characterization and numerically validated by performing finite element simulations of the forming process.

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