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Temperature and strain rate dependent tensile strength model for short fiber reinforced polymer composites

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Abstract. Understanding and characterizing the tensile behavior of short fiber reinforced polymer composites (SFRPCs) under high temperature environments and dynamic loadings is of great significance for their wide application. In this work, a temperature and strain rate dependent tensile strength model is developed, based on the modified rule of mixture and the Force-Heat Equivalence Energy Density Principle. The combined effects of component properties, fiber length, fiber orientation, residual thermal stress, temperature and strain rate are taken into account. The proposed model is proved to be efficient in predicting the tensile strength of SFRPCs under a wide range of temperatures and strain rates, through the comparison between the experimental data and model predictions. Furthermore, based on the present model, the influencing factors analysis of tensile strength of SFRPCs and its evolution with temperature and strain rate is investigated and discussed. This work provides a solid theoretical basis for the design, optimization and tensile property prediction of SFRPCs under extreme conditions.

Keywords: analytical modeling; short fiber reinforced polymer composites; strain rate; temperature; tensile strength

1. Introduction

Short fiber reinforced polymer composites (SFRPCs) have recently attracted considerable interest due to their outstanding mechanical properties, good corrosion resistance and acceptable manufacturing costs (Heim *et al*. 2013, Luo *et al*. 2021, Shokrieh *et al*. 2020). They are one of the most promising structural materials applied in extreme-environment-related fields, such as aerospace, automotive industries and energy industry (Bensaid, *et al*. 2020, Kang *et al*. 2021, Li *et al*. 2018, Mortazavian and Fatemi 2017). As is known to all, tensile strength is one of the important properties of structure materials for practical applications, which have attracted a special interest. (Deng *et al*. 2018, Zhu *et al*. 2008). Meanwhile, SFRPCs are often exposed to high temperature environments and dynamic loads during service. And both temperature and strain rate have

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significant effects on the mechanical properties of SFRPCs, which have always been the subject of the scientific research (Asli *et al*. 2021, El-Qoubaa and Othman 2017, Jia *et al*. 2018). Thus, deeply understanding and reasonably characterizing the quantitative effects of strain rate and temperature on the tensile strength of SFRPCs is of significance to the design and wide applications of these composites used under such extreme conditions.

In the past few decades, many scholars have conducted experimental research on the mechanical properties of SFRPCs, and mainly focused on their tensile strength. The effects of fiber distribution, length, content as well as loading condition such as temperature and strain effect on tensile properties of SFRPCs was the subject of numerous works (Chen *et al*. 2018, Liu *et al*. 2020, Lim *et al.* 2021, Thomason 2002). For instance, through three-point bending tests under dynamic and static load, Jia *et al*. (2018) studied the effects of temperature and strain rate on the mechanical behaviors of carbon fiber reinforced polymer composites. The results indicated that the flexural strength increased with the increase of strain rate, and decreased with the rise of temperature. Shi *et al.* (2002) researched the tensile properties of underfill epoxy composite at different temperatures (-40°C~240°C) and different strain rates (10^{-5} s^{-1} to 10^{-1} s^{-1}). It showed that the elastic modulus and tensile strength nonlinearly decreased with the increase of temperature, and increased with strain rate. Moreover, Wang *et al*. (2002) tested the tensile strength of polyamide-6 composites reinforced by short glass fiber at different strain rates (0.05 min^{-1}~5.0 min^{-1}) with the temperature ranges from 21.5°C to 100°C, and developed an empirical constitutive model related to temperature and strain rate. Hashemi (2011) studied the influence of strain rate, temperature and fiber content on the tensile strength of polybutylene terephthalate composites. It showed that their tensile strength decreased linearly with the increase of temperature, increased nonlinearly with increasing fiber content, but increased linearly with the natural logarithm of strain rate.

In addition, Miwa and Horiba (1993) conducted an experimental study on the tensile properties of short fibers/epoxy composites at different strain rates and temperatures, and it is pointed out that the tensile strength can be estimated by the additive rule of hybrid mixtures. The mechanical response of styrene-maleic anhydride reinforced by short glass fiber was evaluated by Peterson *et al.* (1991), and similar experimental results as Hashemi (2011) were found. Recently, a comparison study on the temperature and strain rate dependent tensile strength was conducted between short carbon and glass fiber reinforced PEEK composites by Chen (2019). The results showed that their tensile strength increased with the increasement of strain rate, and decreased with increasing temperature.

From the above experimental research, it can be concluded that there are many factors affecting the tensile strength of SFRPCs, including the component strength, fiber content, fiber length, fiber orientation and load condition such as strain rate and temperature. As a result, physical-based theoretical model of tensile strength needs to include the effects of all these factors, which makes modelling the tensile strength of SFRPCs a complex task. Although the experimental research can reveal the failure mechanisms of SFRPCs and deepen our understanding on the evolution of tensile strength with strain rate and temperature, the quantitative relationship between the tensile strength of SFRPCs and its related influencing factors is difficult to be characterized by experiments (Li *et al*. 2018). To accurately characterize the tensile strength of SFRPCs at different strain rates and temperatures and accelerate their performance improvement and wide application, it is essential and urgent to develop a physical-based temperature and strain rate dependent tensile strength model.

In the past, researchers have done a lot of work in the mathematical modeling of the mechanical properties of SFRPCs. Micromechanical theories such as the rule of mixture, bridging model, shear lag model, Mori-Tanaka method and Halpin-Tsai model, have been widely adopted to characterize the mechanical properties of polymer composites at normal temperatures (Chen 1971, Eshelby 1957, Fu and Lauke 1996, Huang *et al*. 2019, Kelly and Tyson 1965, Mori and Tanaka 1973). And notable among them is the tensile strength model for SFRPCs based on the rule of mixture and its modified forms. For instance, Liang (2011) assumed that all short fiber were aligned in the load direction and established a tensile strength model based on the force balance relationship. According to the modified linear rule of mixture (Kelly and Tyson 1965), Mortazavian and Fatemi (2015) developed a tensile strength model for SFRPCs, which can consider the effects of fiber orientation and fiber length. It is of great significance to consider the influence of temperature in the modeling process with the increasing service temperature of SFRPCs. However, the previous micro-mechanical models rarely consider the effect of temperature on tensile strength. Fortunately, Li *et al*. (2018) recently considered the effect of temperature and proposed a physic-based theoretical model of temperature-dependent tensile strength of SFRPCs, which provides a good prediction method for the tensile strength at elevated temperatures. However, the effect of strain rate is not involved in the model, and thus, cannot predict the high temperature tensile strength under dynamic loads. Although there are many research works (Seyedalikhani *et al*. 2019, Khademi *et al*. 2020, Shokrieh *et al*. 2013, 2016) on the strain rate behavior of unidirectional composites and nanoparticle filled polymers under dynamic loads. Currently, there is still a lack of analytical models that can easily and accurately predict the tensile strength of SFRPCs under a wide range of temperatures and strain rates.

In view of the above literature survey, this study aims to establish a theoretical prediction model of temperature and strain rate dependent tensile strength for SFRPCs. To accomplish this, based on the modified rule of mixture and the Force-Heat Equivalence Energy Density Principle, a theoretical model is developed for the prediction of tensile strength of SFRPCs over a wide range of temperatures and strain rates. The proposed model includes the influence of component properties, fiber length, fiber orientation, residual thermal stress as well as strain rate and temperature. To validate the developed theoretical model, case studies are conducted over a wide range of temperatures and strain rates. The predicted results of the proposed model are compared with the available experiments, and excellent agreement is obtained. Further, using the proposed model, the influencing factors analysis of tensile strength is also studied and discussed, and some suggestions for improving the tensile strength of SFRPCs under extreme environment are proposed. This work can provide a straightforward approach for the prediction of tensile strength of SFRPCs under a wide range of strain rates and temperatures, and then provide theoretical guidance on such new materials preparation and application.

2. Theoretical framework

In this section, the modified rule of mixture (Kelly and Tyson 1965, Bowyer and Bader 1972) is applied to characterize the tensile strength of SFRPCs. First, we consider the influence of orientation and length of short fiber on tensile strength of SFRPCs on the basic of the rule of mixture. Then, the effects of temperature and residual thermal stress are further considered based on the Force-Heat Equivalence Energy Density Principle. Finally, the effect of strain rate is considered by adding a strain rate term to the temperature dependent tensile strength formula of composites. The following part is the detailed modeling process.

2.1 The effect of length distribution and orientation of fiber

Based on the rule of mixture, the tensile strength of fiber reinforced composites can be expressed as

$$\sigma_c = \sigma_f^c V_f + \sigma_m^c V_m \tag{1}$$

where σ_c is the tensile strength of composites, σ_f^c and σ_m^c respectively denote the effective strength contribution of short fibers and polymer matrix, V_f and V_m respectively denote the volume fraction of fiber and matrix.

It is known that the length distribution and orientation of short fiber will significantly affect the strength of SFRPCs (Jayaraman and Kortschot 1996, Templeton 1990). In order to consider the influence of the above two factors on tensile strength, under the assumption of relative strong interface, Eq. (1) can be modified as follow (Mortazavian and Fatemi 2015)

$$\sigma_c = \chi_1 \chi_2 \sigma_f V_f + \sigma_m V_m \tag{2}$$

where χ_1 denotes fiber orientation factor, which is used to characterize the influence of fiber orientation on tensile strength; χ_2 denotes fiber length factor, which characterizes the influence of fiber length distribution on tensile strength; σ_m and σ_f denote the tensile strength of polymer matrix and fiber, respectively.

The fiber orientation factor χ_1 can be expressed as (Jayaraman and Kortschot 1996)

$$\chi_1 = \int_0^{\frac{\pi}{2}} h(\theta)\,(cos\,\theta) d\theta \times \int_0^{\frac{\pi}{2}} h(\theta)(cos^3\,\theta - \nu\, sin^2\,\theta\, cos\,\theta)\, d\theta \tag{3}$$

where $h(\theta)$ denotes the fiber orientation density function, and the following relationship shall be satisfied

$$\int_0^{\pi/2} h(\theta) d\theta = 1 \tag{4}$$

In particular, for the SFRPCs in injection molding process (Chin *et al*. 1988)

$$h(\theta) = \frac{\lambda e^{-\lambda\theta}}{(1 - e^{-\frac{\pi\lambda}{2}})} \tag{5}$$

where λ denotes the fiber shape parameter, and its value is usually taken as 0.06 for injection-molded material (Mortazavian and Fatemi 2015).

Moreover, according to our previous work (Li *et al*. 2018), the simplified fiber length factor, χ_2, can be determined by using the following equation

$$\chi_2 = \frac{\bar{l}}{2} l_{cr} \tag{6}$$

where $\bar{l}$ denotes the mean length of short fibers, l_{cr} is the critical fiber length, which can be given by the shear-lag theory (Ohsawa *et al*. 1978)

$$l_{cr} = \frac{\sigma_f d_f}{2\tau_y} \tag{7}$$

where τ_y is the interfacial shear strength, d_f denotes the fiber diameter.

Accordingly, substituting Eqs. (3) and (6) into Eq. (2), the tensile strength of SFRPCs at normal temperature can be expressed as

$$\sigma_c = \left[\int_0^{\frac{\pi}{2}} h(\theta)\,(\cos\theta)d\theta \times \int_0^{\frac{\pi}{2}} h(\theta)(\cos^3\theta - \nu\sin^2\theta\cos\theta)\,d\theta\right]\frac{\bar{l}}{2l_{cr}}V_f\sigma_f + V_m\sigma_m \tag{8}$$

2.2 Temperature effect

As mentioned above, SFRPCs are inevitably subjected to high temperature environment in service, and their mechanical properties have strong temperature sensitivity. Thus, to characterize the quantitative influence of temperature on tensile strength, Eq. (8) is extended to different temperatures

$$\sigma_c(T) = \left[\int_0^{\frac{\pi}{2}} h(\theta)\,(\cos\theta)d\theta \times \int_0^{\frac{\pi}{2}} h(\theta)(\cos^3\theta - \nu\sin^2\theta\cos\theta)\,d\theta\right]\frac{\bar{l}}{2l_{cr}(T)}V_f\sigma_f(T) + \sigma_m(T)V_m \tag{9}$$

where T denotes the current temperature, $\sigma_c(T)$, $\sigma_m(T)$ and $\sigma_f(T)$ respectively represent the tensile strength of composites, matrix and fiber at T temperature; Here, the weak influence of temperature on χ_1 is ignored. $l_{cr}(T)$ is the critical fiber length at T temperature, which can be expressed as

$$l_{cr}(T) = \frac{\sigma_f(T)d_f}{2\tau_y(T)} \tag{10}$$

where $\tau_y(T)$ is the interfacial shear strength at T temperature.

Moreover, according to the Force-Heat Equivalence Energy Density Principle proposed by Li *et al*. (2010, 2021), the tensile strength related to temperature of polymer matrix can be predicted by the following theoretical model (Deng *et al*. 2017, Li *et al*. 2019)

$$\sigma_m(T) = \sigma_m(T_0)\left[\frac{E_m(T)}{E_m(T_0)}\left(1 - \frac{T - T_0}{T_m - T_0}\right)\right]^{1/2} \tag{11}$$

where E_m denotes the Young's modulus of polymer matrix; T and T_0 respectively are current temperature and arbitrary reference temperature. T_m is the viscous flow temperature and melting temperature for amorphous and crystalline polymers, respectively.

Similarly, the temperature-dependent tensile strength of reinforcing fiber can be calculated through our theoretical model without fitting parameters (Zhang *et al*. 2019)

$$\sigma_f(T) = \sigma_f(T_0)\left[\frac{E_f(T)}{E_f(T_0)}\left(1 - \frac{T - T_0}{T_m^f - T_0}\right)\right]^{1/2} \tag{12}$$

where σ_f and E_f denote the tensile strength and Young's modulus of fiber, respectively; T_m^f denotes the melting point of fiber.

Accordingly, substituting Eqs. (11) and (12) into Eq. (9), the temperature-dependent tensile strength analysis model for SFRPCs is obtained

$$\sigma_c(T) = \chi_1\frac{\bar{l}}{2l_{cr}(T)}V_f\sigma_f(T_0)\left[\frac{E_f(T)}{E_f(T_0)}\left(\frac{T_m^f - T}{T_m^f - T_0}\right)\right]^{1/2} + V_m\sigma_m(T_0)\left[\frac{E_m(T)}{E_m(T_0)}\left(1 - \frac{T - T_0}{T_m - T_0}\right)\right]^{1/2} \tag{13}$$

where $\chi_1 = \int_0^{\frac{\pi}{2}} h(\theta)\,(cos\,\theta)d\theta \times \int_0^{\frac{\pi}{2}} h(\theta)(cos^3\,\theta - \nu\, sin^2\,\theta\, cos\,\theta)\,d\theta$.

In addition, residual thermal stress will be generated in SFRPCs during moulding owing to the thermal expansion mismatch, which will influence their strength (Jabbari-Farouji *et al*. 2015). The residual thermal stress of SFRPCs can be expressed as (Miwa *et al*. 1980)

$$\sigma_{\text{Res}} = \frac{2(\alpha_f - \alpha_m)E_m(T_{mold} - T)}{(1+\nu_m) + (1+\nu_f)(E_m/E_f)} \tag{14}$$

where α denotes the coefficient of thermal expansion, ν denotes the Poisson's ratio, subscript *f* and *m* respectively denote fiber and matrix, T_{mold} denotes the mold temperature.

After further considering the temperature effect and relaxation of residual thermal stress caused by material microstructure, Eq. (14) is modified as follow

$$\sigma_{\text{Res}}(T) = A\frac{2[\alpha_f(T) - \alpha_m(T)]E_m(T)(T_{mold} - T)}{(1+\nu_m) + (1+\nu_f)[E_m(T)/E_f(T)]} \tag{15}$$

where *A* denotes the release coefficient of residual thermal stress for characterizing its relaxation (Li *et al.* 2018), *T* denotes the current environment temperature. The influence of temperature on Poisson's ratio can be ignored since its weak temperature dependence.

After combining Eqs. (13) and (15), the temperature-dependent tensile strength model considering residual thermal stress for SFRPCs is established

$$\sigma_c(T) = \chi_1 \frac{\bar{l}}{2l_{cr}(T)} V_f \sigma_f(T_0)\left[\frac{E_f(T)}{E_f(T_0)}\left(\frac{T_m^f - T}{T_m^f - T_0}\right)\right]^{1/2} + V_m\sigma_m(T_0)\left[\frac{E_m(T)}{E_m(T_0)}\left(\frac{T_m - T}{T_m - T_0}\right)\right]^{1/2} + \sigma_{\text{Res}}(T) \tag{16}$$

The above temperature-dependent tensile strength model provides a practical method for predicting the tensile strength of SFRPCs under a wide range of temperatures.

2.3 Strain rate effect

Strain rate is also a vital factor affecting the tensile strength of polymers. To further take into account of the influence of strain rate, the strain rate effect is considered based on the above temperature dependent tensile strength model (Eq. (16)). Shokrieh *et al.* (Seyedalikhani, *et al*. 2019, Shokrieh *et al*. 2013, 2016, Khademi *et al*. 2020) have developed some strain rate dependent micromechanical models on the strength of unidirectional composites and nanoparticle filled polymers, which provide practical approach to characterize the mechanical behavior of polymer composites under dynamic loads. However, their models contain at least two fitting parameters, which are not convenient for engineering application. The strain rate term in the classical Johnson-Cook model (Johnson and Cook 1983) is a simple and general approach to characterize the strain rate effect. Therefore, this term is applied to characterize the strain rate effect of tensile strength of SFRPCs, namely

$$\sigma(\dot{\varepsilon}) = \sigma(\dot{\varepsilon}_0)\left[1 + Cln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right] \tag{17}$$

where $\sigma(\dot{\varepsilon})$ is the tensile strength at strain rates $\dot{\varepsilon}$, $\sigma(\dot{\varepsilon}_0)$ is the tensile strength at reference strain rates $\dot{\varepsilon}_0$, which can be replaced by $\sigma_c(T)$ in Eq. (16). *C* is a fitting parameter, which can be easily obtained by two experimental data at different strain rates at the reference temperature. Compared with Shokrieh *et al.*'s models, Eq. (17) only includes one fitting parameter, which is more convenient for engineering application.

2.4 Temperature and strain rate dependent tensile strength model

To characterize the comprehensive influence of temperature and strain rate on tensile strength, we combine Eqs. (16) and (17), and the temperature and strain rate dependent tensile strength prediction model of SFRPCs is obtained

$$\sigma_c(T,\dot{\varepsilon}) = \left\{\chi_1 \frac{\bar{l}}{2l_{cr}(T)} V_f \sigma_f(T_0) \left[\frac{E_f(T)}{E_f(T_0)}\left(\frac{T_m^f - T}{T_m^f - T_0}\right)\right]^{1/2} + V_m \sigma_m(T_0) \left[\frac{E_m(T)}{E_m(T_0)}\left(\frac{T_m - T}{T_m - T_0}\right)\right]^{1/2} + \sigma_{\mathrm{Res}}(T)\right\}\left[1 + Cln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right] \tag{18}$$

where $\sigma_m(T_0)$ and $\sigma_f(T_0)$ respectively represent the tensile strength of polymer matrix and short fiber at the reference temperature T_0 and quasi-static load. The formula of temperature-dependent residual thermal stress $\sigma_{\mathrm{Res}}(T)$ is given by Eq. (15).

As can be seen from Eq. (18), the proposed analysis model of tensile strength only needs some easily accessible and fundamental material parameters, such as temperature-dependent Young's modulus of polymer matrix, melting point and tensile strength at the reference temperature, which can be easily obtained from the existing literature, experiments or material handbooks. It is worth mentioning that the proposed model only includes one fitting parameter *C*, which also can be easily determined. Therefore, the proposed model provides simple and practical theoretical means for the prediction of tensile strength of SFRPCs over a wide range of temperatures and strain rates, avoiding large numbers of time-consuming and laborious strength experiments under high temperatures and dynamic loads.

3. Results and discussion

In this section, in order to validate the accuracy of the established theoretical model, we predicted the tensile strength of some typical short carbon and glass fiber reinforced polymer composites under a wide range of temperatures and strain rates, and compared with corresponding experimental results. Moreover, the influencing factors analysis of tensile strength was conducted using the proposed model, and we investigated the effects of fiber content, average fiber length, fiber diameter, matrix Young's modulus and interfacial shear strength on tensile strength of SFRPCs and their evolution with temperature and strain rate, and some suggestions for improving the tensile strength of SFRPCs are obtained.

3.1 Validation of the proposed model

The tensile strength of carbon fiber/PEEK, glass fiber/PEEK, glass fiber/PA6 and glass fiber/PBT composites under a wide range of temperatures and strain rates and at different fiber

Table 1 Material parameters for short fiber reinforced PEEK composites

Material parameters	Carbon fiber/PEEK	Glass fiber/PEEK
Fiber volume fraction, V_f	0.3 (Chen 2019)	0.3 (Chen 2019)
Fiber diameter, d_f/μm	8 (Chen 2019)	8 (Chen 2019)
Fiber mean length, $\bar{l}$/μm	125	60
Fiber thermal expansion coefficient, $\alpha_f(T)$/×10^{-6}°C^{-1}	1 (Suo *et al.* 2010)	5 (Chu *et al.* 2010)
Matrix thermal expansion coefficient, $\alpha_m(T)$/×10^{-6}°C^{-1}	40 (Chu *et al.* 2010)	40 (Chu *et al.* 2010)
Reference temperature, T_0/°C	20	20
Reference strain rate, $\dot{\varepsilon}_0$/s^{-1}	0.001	0.001
Fiber strength at T_0, $\sigma_f(T_0)$/MPa	3500 (Chen 2019)	1553 (Jenkins *et al.* 2015)
Matrix Poisson's ratio, ν_m	0.4 (Kang *et al.* 2021)	0.4 (Kang *et al.* 2021)
Fiber Poisson's ratio, ν_f	0.2 (Kang *et al.* 2021)	0.22 (Gupta and Wang 1993)
Matrix strength at T_0, $\sigma_m(T_0)$/MPa	98	98
Matrix melting temperature, T_m/°C	343 (Chen 2019)	343 (Chen 2019)
Matrix Young's modulus at T, $E_m(T)$/GPa	7×10^(-6)×T^2-0.0035T+4.076 (Rae *et al.* 2007)	7×10^(-6)×T^2-0.0035T+4.076 (Rae *et al.* 2007)
Fitting parameter, C	0.029	0.0262

volume fractions are predicted by Eq. (18). In the calculations, the room temperature is set as the reference temperature T_0, since the tensile strength at room temperature is easier to be achieved. Because the tensile strength of carbon fiber is less dependent on temperature in our research range, we thus ignore its temperature dependence here, namely, its value at room temperature is used to calculate the high temperature tensile strength of composites. Moreover, the interfacial shear strength of fiber reinforced polymer composites can be regarded as the shear strength of matrix under the assumption of strong interface (Ohsawa *et al*. 1978). The existing research (Lees 1968, Mortazavian and Fatemi 2015) also indicated that the matrix shear strength is approximately equal to half of its tensile strength. Thus, the temperature-dependent interfacial shear strength, $\tau_y(T)$, is set as half of the tensile strength of matrix, $\frac{\sigma_m(T)}{2}$, namely, $\tau_y(T)=\frac{\sigma_m(T_0)}{2}\left[\frac{E_m(T)}{E_m(T_0)}\left(1-\frac{T-T_0}{T_m-T_0}\right)\right]^{1/2}$. Meanwhile, the fitting parameter C for considering strain rate effect is obtained by the experimental data of tensile strength at reference strain rate and maximum strain rate at room temperature. The value of release coefficient of residual thermal stress A is 0.01 according to our previous work (Li *et al*. 2018). In addition, in view of the difficulty of directly obtaining the average length of short fiber $\bar{l}$ through experiment, its value is deduced by the experimental data at reference strain rate and room temperature $\sigma_c(T_0,\dot{\varepsilon}_0)$.

3.1.1 Short fiber reinforced PEEK composites

First, the tensile strengths of short carbon and glass fiber reinforced PEEK composites at -30~100°C and various strain rates (10^{-3} s^{-1}~10^3 s^{-1}) are predicted by our model. The corresponding experimental results are from our previous work (Chen 2019). The material parameters in the model are displayed in Table 1 (Chu *et al*. 2010, Chen 2019, Gupta and Wang 1993, Jenkins *et al*. 2015, Kang *et al*. 2021, Rae *et al*. 2007, Suo *et al*. 2010). The value of C is obtained by the two experimental data of tensile strength with strain rates of 0.001 s^{-1} and 10^3 s^{-1} at room temperature.

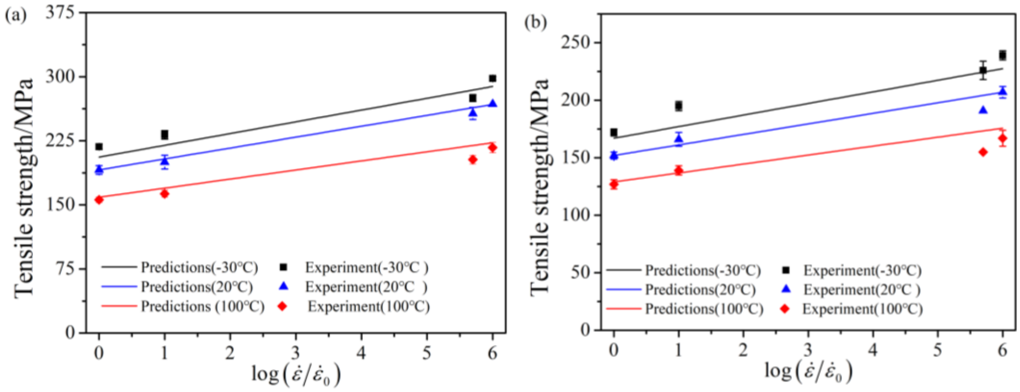

Fig. 1 Temperature and strain rate dependent tensile strength of short (a) carbon fiber and (b) glass fiber reinforced PEEK composites (The experimental data are quoted from Chen (2019))

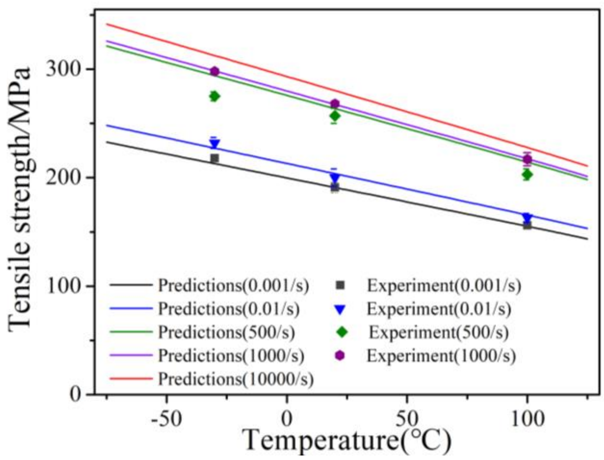

Fig. 2 The change of tensile strength with temperature at different strain rates

Figs. 1(a) and (b) shows the comparison between our previous experimental results (Chen 2019) and model predictions of tensile strength. It can be seen that the theoretical predictions achieve good consistency with the experiments. Meanwhile, it is easy to find that the tensile strength of both the two kinds of PEEK composites decreases with increasing temperature, and increases with strain rates.

Fig. 2 shows the evolution of tensile strength with temperature under different loading rates of short carbon fiber/PEEK composites. Moreover, the tensile strength at -75°C and 125°C with the strain rate ranges from 0.001 s^{-1} to 10^4 s^{-1} are further predicted using the proposed model (Fig. 2), which indicates that both the temperature and strain rate have a significant influence on the tensile strength of SFRPCs.

3.1.2 Short fiber reinforced PA6 composites

Then, the established model (Eq. (18)) is used to predict the tensile strength of E-glass fiber /Polyamide-6 (PA6) composites at 20-125°C and various strain rates. The material parameters required for calculation are given in Table 2 (Buccella *et al*. 2012, Guo *et al*. 2015, Gupta and Wang

Table 2 Material parameters for short glass fiber reinforced PA6 composites

Material parameters	E-glass fiber/PA6	E-glass fiber/PA6
Fiber volume fraction, V_f	0.33 (Wang *et al*. 2002)	0.35
Fiber diameter, d_f/μm	10 (Wang *et al*. 2002)	9.8 (Mortazavian and Fatemi 2017)
Fiber mean length, $\bar{l}/\mu$m	94	103
Fiber thermal expansion coefficient, $\alpha_f(T)/\times10^{-6}$°C^{-1}	5.6 (Gupta and Wang 1993)	5.6 (Gupta and Wang 1993)
Matrix thermal expansion coefficient, $\alpha_m(T)/\times10^{-6}$°C^{-1}	6.6 (Mark 2007)	6.6 (Mark 2007)
Reference temperature, T_0/°C	20	21
Reference strain rate, $\dot{\varepsilon}_0$/s^{-1}	8.33×10^{-4}	5×10^{-5}
Fiber strength at T_0, $\sigma_f(T_0)$/MPa	1725 (Mallick 2000)	1725 (Mallick 2000)
Matrix Poisson's ratio, ν_m	0.4 (MatWeb 2021)	0.4 (MatWeb 2021)
Fiber Poisson's ratio, ν_f	0.2 (MatWeb 2021)	0.2 (MatWeb 2021)
Matrix strength at T_0, $\sigma_m(T_0)$/MPa	60 (Mortazavian and Fatemi 2015)	60 (Mortazavian and Fatemi 2015)
Matrix melting temperature, T_m/°C	215 (Buccella *et al*. 2012)	215 (Buccella *et al*. 2012)
Matrix Young's modulus at T, $E_m(T)$/GPa	$0.017T^2$-$3.7371T$ +326.8 (Guo *et al*. 2015)	$0.017T^2$-$3.7371T$+326.8 (Guo *et al*. 2015)
Fitting parameter, C	4.391	0.017

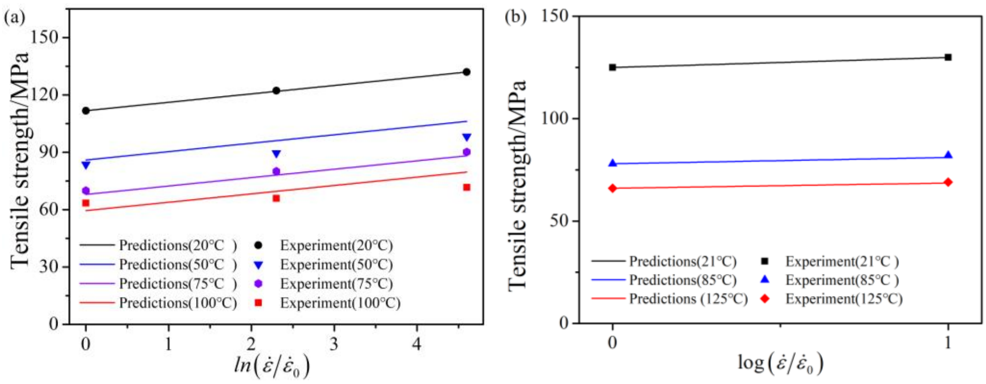

Fig. 3 Temperature and strain rate dependent tensile strength of short glass fiber/PA6 composites: (a) 33% vol fiber (The experimental data are quoted from Wang *et al*. (2002)) (b) 35% vol fiber (The experimental data are quoted from Mortazavian and Fatemi (2017))

1993, Mallick 2000, Mark 2007, MatWeb 2021, Mortazavian and Fatemi 2015, Mortazavian and Fatemi 2017, Wang *et al*. 2002). For the PA6 composites with 33% vol fiber, the value of C is obtained by the two experimental data of tensile strength at room temperature with strain rates of 5/min and 0.05/min; For the PA6 composites with 35% vol fiber, the value of C is obtained by the two experimental data of tensile strength at room temperature with strain rates of 5×10^{-5} s^{-1} and 5×10^{-1} s^{-1}. The evolution of tensile strength of composite (33% vol fiber) with strain rates (0.05/min, 0.5/min, 5/min) at different temperatures (20, 50, 75 and 100°C) is illustrated in Fig. 3(a). Moreover,

Table 3 Material parameters for short glass fiber reinforced PBT composites

Material parameters	glass fiber/PBT
Fiber volume fraction, V_f	0.3 (Mortazavian and Fatemi 2017)
Fiber diameter, d_f/μm	9.81 (Mortazavian and Fatemi 2017)
Fiber mean length, $\bar{l}/\mu$m	85
Fiber thermal expansion coefficient, $\alpha_f(T)$/X10^{-6}°C^{-1}	5.6 (Gupta and Wang 1993)
Matrix thermal expansion coefficient, $\alpha_m(T)/\times10^{-6}$°C^{-1}	6.7 (Mark 2007)
Reference temperature, T_0/°C	23
Reference strain rate, $\dot{\varepsilon}_0/s^{-1}$	4×10^{-4}
Fiber strength at T_0, $\sigma_f(T_0)$/MPa	1725 (Mallick 2000)
Matrix Poisson's ratio, ν_m	0.3 (Chin *et al*. 1988)
Fiber Poisson's ratio, ν_f	0.2 (MatWeb 2021)
Matrix strength at T_0, $\sigma_m(T_0)$/MPa	64 (Mortazavian and Fatemi 2015)
Matrix melting temperature, T_m/°C	245 (Pyda *et al*. 2006)
Matrix Young's modulus at T, $E_m(T)$/MPa	$0.1819T^2$-$40.7T$+3141(Hashemi 2000)
Fitting parameter, C	0.09

Fig. 3(b) shows the comparison between the experiments (Mortazavian and Fatemi 2017) and theoretical predictions of tensile strength of PA6 composite (35% vol fiber) at different temperatures (21°C-125°C) and different strain rates (5×10^{-5} s^{-1}~5×10^{-1} s^{-1}). As can be seen from Fig. 3, it can be concluded that the theoretical predictions of our model are in good agreement with the experimental results.

3.1.3 Short fiber reinforced PBT composites

Based on the present model, the tensile strength of polybutylene terephthalate (PBT) composites reinforced by short glass fiber at different strain rates from room temperature to 125°C was predicted. The main material parameters for calculations are given in Table 3 (Chin *et al*. 1988, Gupta and Wang 1993, Hashemi 2000, Mallick 2000, Mark 2007, MatWeb 2021, Mortazavian and Fatemi 2017, Mortazavian and Fatemi 2015, Pyda *et al*. 2006). The value of C is obtained by the two experimental data of tensile strength with strain rates of 4×10^{-4} s^{-1} and 4×10^{-3} s^{-1} at room temperature. Fig. 4(a) shows the comparison between our model predictions and experimental data (Mortazavian and Fatemi, 2017) at a range of strain rates between 4×10^{-4} s^{-1} and 4×10^{-3} s^{-1} and different temperatures (23°C-125°C), and an excellent consistency is obtained between them.

Moreover, Hashemi (2011) studied the effects of fiber content and strain rate (7.58×10^{-6}~7.58×10^{-2} s^{-1}) on the tensile strength of PBT composites. The evolution of tensile strength at room temperature with strain rate under different fiber volume content (5.8% vol, 12.15% vol, 19.52% vol) is displayed in Fig. 4(b). In the predictions, the value of average fiber length $\bar{l}$ respectively are 210μm, 228 μm and 180 μm for the fiber volume content of 5.8%,12.15% and 19.52%. The reference strain rate $\dot{\varepsilon}_0$ is 7.58×10^{-6} s^{-1}, the fitting parameter C equals to 0.0142, which is obtained by the two experimental data (V_f=5.8% vol) with strain rates of 7.58×10^{-6} and 7.58×10^{-2}. Good consistency is achieved between the experiments and model predictions under different fiber content. Fig. 4(b) indicates that our established model has a good prediction ability for the tensile strength of SFRPCs under different fiber content over a wide range of strain rates.

As can be seen from the above results, the tensile strength of SFRPCs increases with the increase

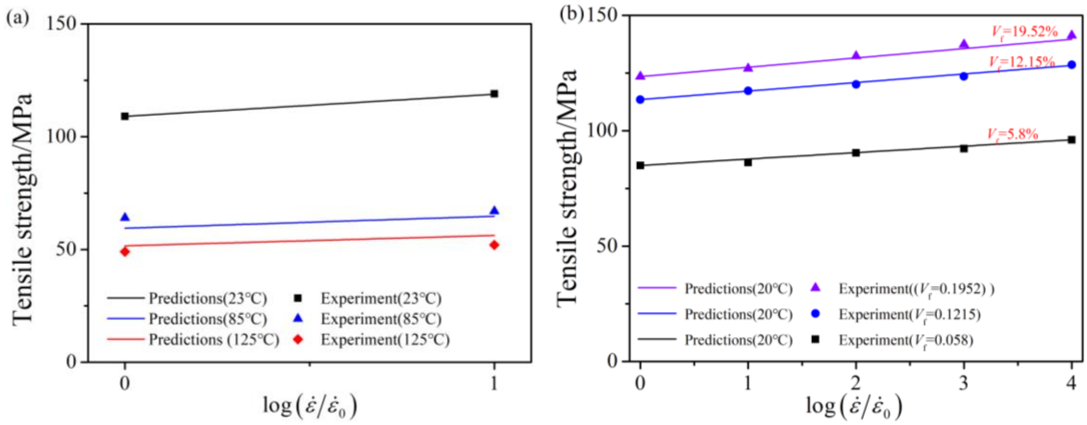

Fig. 4 Tensile strength of PBT composites (a) At different temperatures and strain rates (The experimental data are quoted from Mortazavian and Fatemi (2017)) (b) Under different fiber content (The experimental data are quoted from Hashemi (2011))

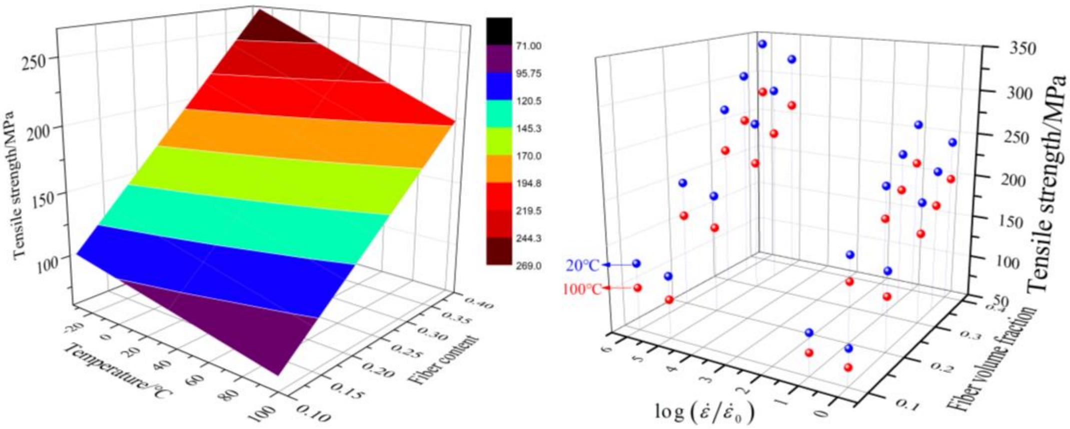

Fig. 5 The effect of fiber content on tensile strength

of strain rate and the decrease of temperature. Meanwhile, through the comparison between the theoretical predictions and experimental results of tensile strength, the proposed theoretical model (Eq. (18)) is capable of accurately predicting the tensile strength of SFRPCs for different temperatures, strain rates and fiber content. As the basic material parameters in the model are easy to obtain, the established model here provides a simple and practical means for the prediction of tensile strength of SFRPCs under a wide range of temperatures and strain rates.

3.2 Influencing factors analysis

As can be seen from Eq. (18), the tensile strength of SFRPCs is significantly affected by the properties of components as well as their evolution with temperature and strain rate. To further investigate the quantitative effect of important material parameters on tensile strength of SFRPCs, the sensitivity of tensile strength to fiber content, average fiber length, fiber diameter, matrix Young's modulus and interfacial shear strength under a wide range of strain rates and temperatures

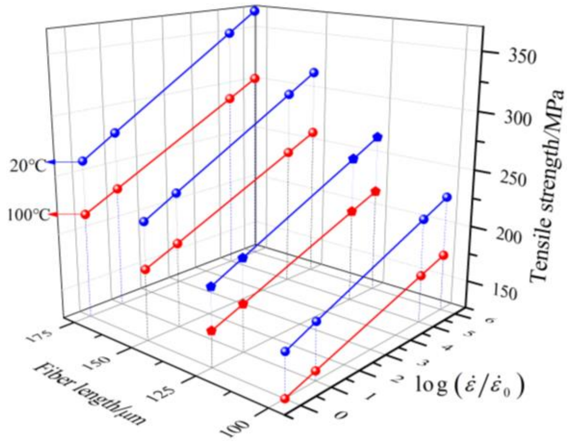

Fig. 6 The effect of average fiber length on tensile strength

have been investigated in detail.

Fig. 5 displays the variation of tensile strength with fiber volume fraction of short carbon fiber/PEEK composites with a range of strain rates between 0.001 s^{-1} and 1000 s^{-1} at different temperatures, while the initial fiber volume fraction is 30%. As can be seen from Fig. 5, increasing the fiber content to some extent is helpful to increase the tensile strength of composites, which is consistent with the experimental results of Karsli and Aytac (2013). However, the fiber content cannot exceed the critical value, otherwise fiber agglomeration will occur and weaken the mechanical properties of SFRPCs. On the other hand, increasing the fiber content can lead to the decrease of average fiber length because of fiber breakage during the process, which also have influence on the tensile strength of composites. Moreover, it is worth noting that as shown in Fig. 5, the sensitivity of tensile strength to fiber content decreases with the increase of temperature and increases with the increase of strain rate.

Moreover, the average length of short fiber also plays a vital role in determining the tensile property of SFRPCs. We take short carbon fiber/PEEK composite as an example, and analyzed the quantitative influence of average fiber length ($\bar{l}$) on the tensile strength of composites, where the initial effective length is 125 μm. As can be seen from Fig. 6, improving the average fiber length is conducive to improving the tensile strength of composites when the length is lower than the critical fiber length ($l_{cr}(T)$), since the fiber carries more loads. Meanwhile, a similar conclusion is found in the experimental results of Miwa *et al*. (1994), and they also indicated that the reinforcing effect of the short fiber is greatly weakened when the fiber length reaches a certain level. In addition, Fig. 6 also indicates that the sensitivity of tensile strength to average fiber length varies little with the change of temperature, and it is more effective to increase the tensile strength of SFRPCs by increasing the fiber length at a high strain rate.

To fully understand the quantitative effect of short fiber size on the tensile properties of SFRPCs at different temperatures and different strain rates, we also analyzed the effect of fiber diameter on the tensile strength. As shown in Fig. 7, when the fiber volume fraction and average length are constant, the tensile strength of the composite decreases with the increase of fiber diameter within a certain range, which is likely due to the increase of critical fiber length caused by the increase of fiber diameter. In addition, with the increase of temperature and the decrease of strain rate, the change of tensile strength caused by changing the same fiber diameter decreases. The above results

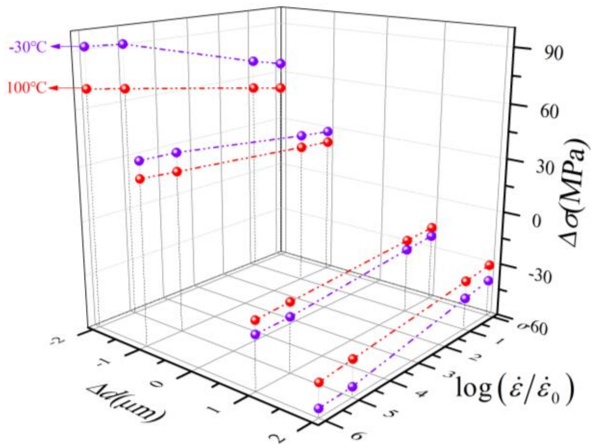

Fig. 7 The effect of fiber diameter on tensile strength

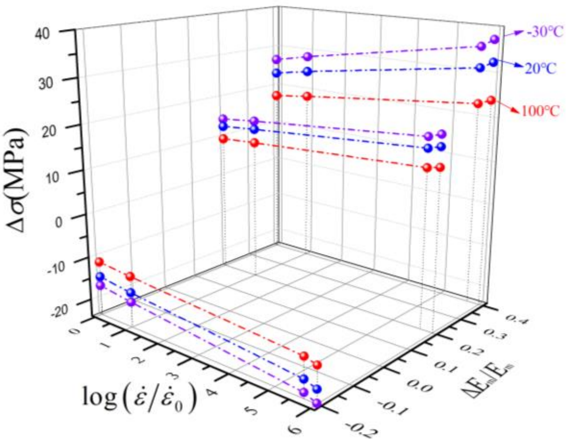

Fig. 8 The effect of Young's modulus of matrix on tensile strength

show that the strengthening effect of SFRPCs caused by decreasing fiber diameter is more significant at low temperatures and high strain rates.

The variation of tensile strength with the change of matrix Young's modulus at different temperatures and strain rates is displayed in Fig. 8, to investigate the quantitative influence of matrix property on tensile strength of SFRPCs. It is easy to find that increasing the Young's modulus of matrix is also beneficial to increase the tensile strength of SFRPCs, especially at lower temperatures. During material preparation, adding inorganic filler can improve Young's modulus of the matrix, and further enhance the tensile strength of composites. Moreover, Fig. 8 also indicates that the sensitivity of tensile strength to matrix Young's modulus increases with the increasement of strain rate. Thus, increasing Young's modulus of the matrix to improve the tensile strength is more effective at dynamic load.

Besides, interfacial property plays a crucial role in controlling the tensile properties of SFRPCs. To characterize the quantitative influence of interfacial shear strength on tensile strength of SFRPCs, we plot the $\frac{\Delta\sigma}{\sigma}$ VS. $\frac{\Delta\tau_y}{\tau_y}$ curves of short carbon fiber/PEEK composites at 20℃ and 100℃ and

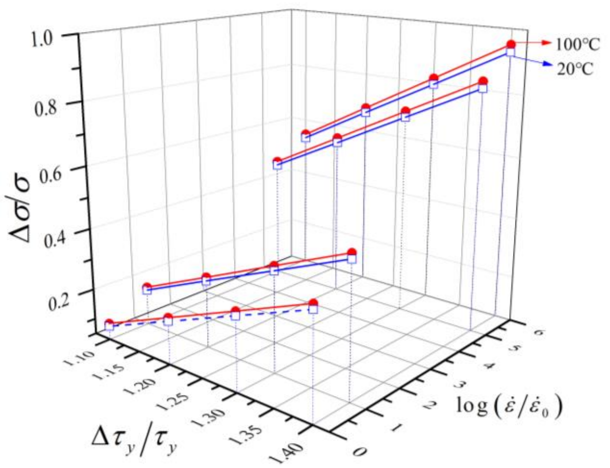

Fig. 9 The effect of interfacial shear strength on tensile strength

different strain rates (Fig. 9), where $\frac{\Delta\sigma}{\sigma}$ denotes the ratio of the change in tensile strength to the initial value, and $\frac{\Delta\tau_y}{\tau_y}$ denotes the ratio of the change in interfacial shear strength to the initial value. It is easy to find that the higher the interfacial shear strength, the greater the tensile strength. In the process of material preparation, oxidation treatment or sizing of short fiber is beneficial for the improvement of interfacial properties, which further give rise to the increased tensile strength of composites (Sun *et al*. 2021). Moreover, the enhancement effect increases with the increase of strain rate, however, it does not change significantly with temperature (Fig. 9). Thus, improving the interfacial shear strength is an effective approach for increasing the tensile strength of composites, especially under dynamic loads.

4.Conclusions

As a promising structure material used in extreme-environment-related fields, no consensus has been reached on the temperature and strain rate-dependent tensile strength of SFRPCs. The quantitative relationship between the tensile strength of SFRPCs, temperature and strain rate is still unclear. This paper presented a theoretical model for the prediction of tensile strength of SFRPCs over a wide range of temperatures and strain rates. The combined effects of component strength, fiber length and orientation, residual thermal stress, temperature and strain rate are included in the proposed model.

The established model is validated through the comparison between the theoretical predictions of tensile strength and our previous experimental results of short carbon and glass fiber-reinforced PEEK composites, as well as available experimental data from literature including E-glass fiber/ PA6 and E-glass fiber/ PBT composites. Furthermore, based on the proposed model, the sensitivity of tensile strength of SFRPCs to fiber content, average fiber length, fiber diameter, matrix Young's modulus and interfacial shear strength as well as their evolution with temperature and strain rate have been conducted and discussed. Some methods to improve the tensile strength of SFRPC are also proposed. This study provides a simple and feasible prediction method for the tensile strength of SFRPCs under a wide range of temperatures and strain rates, and also contributes to the development and application of SFRPCs under extreme conditions.

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