A constitutive model of the compressive mechanical properties of ultra high molecular weight polyethylene (UHMWPE) at different temperatures and different strain rates

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Abstract
The impact resistance of UHMWPE is related to temperature and strain rate. In order to determine the compressive mechanical properties of UHMWPE, quasi-static and dynamic compression tests were conducted on UHMWPE using an MTS universal testing machine and split Hopkinson pressure bar equipment, respectively. Stress–strain curves for UHMWPE over the temperature range of −40 °C~100 °C and strain rate range of 0.001~3300 s⁻¹ was generated. By comparing the stress–strain curves of UHMWPE with molecular weights (MWs) of 3, 6 and 9 million in a quasi-static state, it was found that UHMWPE with a MW of 6 million had better compressive mechanical properties than other UHMWPE samples. Using the stress–strain curves for UHMWPE with a MW of 6 million at different strain rates and temperatures, the yield strength of UHMWPE increased with an increasing strain rate and decreased with increasing temperature were obtained. Based on the quasi-static and dynamic experimental results for UHMWPE with a MW of 6 million, a constitutive model of plasticity at different temperatures and strain rates was established. This model agreed well with the experimental results. This study provides both theoretical and empirical reference for the study of the mechanical properties of UHMWPE materials.

1. Introduction
Ultra high molecular weight polyethylene (UHMWPE) refers to polyethylene with molecular weights (MW) in excess of 1.5 million, and they possess most of the excellent properties of ordinary polyethylene and as well as properties of other plastics. Due of its excellent performance, meaning its impact resistance, wear resistance, hygienic non-toxicity, corrosion resistance, self-lubricity, low temperature resistance, non-absorption, tensile strength, low density, and poor adhesion, UHMWPE is widely used in various applications such as the aerospace industry, medical equipment and power machinery [1–3]. In weapon manufacturing, when UHMWPE is used to make parts such as the rotating band of a projectile, the impact of the working temperature and the high overload of the projectile on the compressive mechanical properties of UHMWPE must be considered. Therefore, it is very important to study the compressive mechanical properties of UHMWPE at different temperatures and different strain rates.

In order to meet the different requirements on UHMWPE performance in different industries and make it more widely useful in engineering, many scholars have studied the mechanical properties and created constitutive models of this material. Kurtz et al [4] studied the effects of irradiation oxidative degradation on the quasi-static tensile mechanical properties of UHMWPE, and used an exponential model to predict the tensile mechanical behavior of UHMWPE under quasi-static conditions. Later studies from this group [5] focused on the yield, plastic flow and fracture behavior of two different implantable UHMWPEs (GUR1120 and 4150HP).
They found that the yield behaviors of the two UHMWPEs were similar, but the plastic flow and the fracture behavior were noticeably different, and ultimately the fracture behavior of UHMWPE can be experimentally determined based on the ultimate true stress and the critical defect size. Bergström et al \cite{5} compared the reproducibility of the J2-plasticity theory, the Arruda-Boyce model, the Hasan–Boyce model and the Bergström-Boyce model for predicting the compressive mechanical behavior of UHMWPE under tensile quasi-static conditions. By combining the previous theories, a new hybrid model was proposed that could effectively predict the quasi-static tensile and compressive mechanical behaviors of UHMWPE. Kurtz et al \cite{7} also studied the effects of heat treatment and γ-irradiation on the mechanical properties of UHMWPE under static conditions. They found that changing the heat treatment method and radiation dose significantly changed the mechanical properties of UHMWPE. In this case, the Arrhenius model was used to accurately predict the thermodynamic behavior of UHMWPE materials between 20 °C and 60 °C. Crowen et al \cite{8} examined the effects of different hydroxyapatite (HAP) content on the mechanical properties of UHMWPE under high strain rates. A numerical SHPB model of an elastic material (which was much lower than aluminum) was developed with the ANSYS commercial software package, and a numerically developed split Hopkinson pressure bar system was verified using the experimental results of the high strain rate on the constitutive behavior of nanocomposites. Hughes et al \cite{9} considered the dynamic compression mechanical properties of low-density polyethylene, high-density polyethylene and UHMWPE using a modified Hopkinson bar system. This group found that the improved Hopkinson bar system could effectively improve the signal-to-noise ratio of the transmitted signal. Under the same conditions, the yield stress of UHMWPE was larger than that of low-density and lower than that of high-density polyethylene. Xu et al \cite{10} compared low-density polyethylene and UHMWPE under static and dynamic conditions using uniaxial compression tests and found that UHMWPE had a stronger energy absorption capacity than low-density polyethylene under the same conditions. The constitutive parameters for the Copper-Symonds model for these two materials at room temperature were also determined in this work. Based on the Souza-Martins method, Wang et al \cite{11}, for the first time, used dissipative particle dynamics (dpd) simulation to study the flow behavior of the shear–tension coupled flow of UHMWPE/PA6 blends. They found that the shear–tension coupling rate had a significant effect on the flow behavior of UHMWPE/PA6 blends. The shear–tension coupled flow-induced orientation behavior was more pronounced than the shear flow. Wang et al \cite{12} studied the mechanical behavior and crystal structure of primary filaments and primary fibers of UHMWPE and HDPE blend fibers. Their results showed that blending UHMWPE with HDPE could improve the fine-grained structure and dense structure of the as-fabricated blended fibers, thereby improving the tensile strength and initial modulus of the composite fibers.

However, the above research was mainly aimed at understanding the static or dynamic mechanical properties of UHMWPE at room temperature. There have been few studies on the mechanical properties proposing constitutive models of UHMWPE considering a range of strain rates or at different temperatures. In order to study the effect of MW, temperature and strain rate on the compressive mechanical properties of UHMWPE, an MTS universal testing machine and SHPB device were used to compare the compressive mechanical properties of UHMWPE with MWs of 3, 6 and 9 million under quasi-static conditions. The deformation behavior and strain rate effects on UHMWPE with a MW of 6 million over the temperature range from −40 °C to 100 °C were studied. In this paper, a constitutive model of the yield stress and plasticity of UHMWPE with a MW of 6 million from −40 °C to 100 °C and 0.001 to 3300 s⁻¹ was created using the improved J-C model \cite{13}. This structural model agrees well with the experimental results.

2. Experimental procedures

2.1. Materials and sample preparation

The UHMWPE studied in this paper was produced by compression molding. The manufacturing process was certified by ISO9001 standards. German Tekona and UHMWPE raw materials were put into a high-speed mixer for mixing. After stirring for a period of time, the raw materials were then put into a hot press. After 2–8 h of hot pressing, cold pressing was conducted. After cold pressing for 2–8 h, the resulting billet was then placed in a pressure keeping machine to ensure cooling and setting yielding a 1000 × 1000 × 15 mm UHMWPE sheet. The different UHMWPE raw materials have different MWs, and each correspond to a specific molding temperature and mold time. The prepared plates were then turned into quasi-static compression test pieces having a diameter of 10 mm and a height of 10 mm and dynamic compression test pieces having a diameter of 10 mm and a height of 5 mm. The quasi-static compression specimen size was determined according to the GBT 1041–2008 Plastic Compression Performance Measurement design \cite{14}. The length-to-diameter ratio L/D for dynamic compression tests was determined based on Tang's research \cite{15}, in which an L/D = 0.5 reduced the influence of inertia effects and the friction effect on the end face of the test piece. Although Xu et al \cite{10} experimentally demonstrated that UHMWPE samples had almost no difference in mechanical properties in
different directions under compression or tension due to UHMWPE’s isotropic properties, in order to avoid experimental errors, the axial direction of the compressed cylindrical test pieces used in these experiments was perpendicular to the UHMWPE plate surface. The prepared compressed test pieces were allowed to stand at room temperature for 48 h so that any residual stress was removed prior to experimentation.

2.2. Quasi-static testing
Quasi-static compression testing of UHMWPE was performed on an MTS testing machine. The test machine performed a compression test on UHMWPE specimens having MWs of 3, 6 and 9 million, respectively, at a constant compression rate of 0.6 mm min\(^{-1}\), 6 mm min\(^{-1}\), and 60 mm min\(^{-1}\). In order to ensure the accuracy of the experimental data, the deformation of the test piece during compression experiments was recorded using an extensometer. The friction in the experiment was reduced by applying grease to the end face of the test piece and the end face of the indenter. To reduce the experimental error, three experiments were performed on different test pieces of the same MW and loading rate, and three sets of experimental data for the loading force \(F\) (kN) and displacement \(S\) (mm) were obtained. Their average values were taken for data processing.

The true stress–strain characterizes the physical properties of a material [16]. In this paper, the mechanical properties of UHMWPE were studied using true stress–strain curves. In order to obtain the true stress–strain curve from the quasi-static compression experiments, the acquired \(F-S\) curve was first converted into an engineering stress \(\sigma_E\) and engineering strain \(\varepsilon_E\) as follows:

\[
\sigma_E = \frac{F}{A_i},
\]  
\[
\varepsilon_E = \frac{L_4 - L_i}{L_i},
\]  
\[
S = L_3 - L_4,
\]

where \(F\) is the loading force; \(S\) is the head displacement; \(A_3\) and \(L_3\) are the initial cross-sectional area and length of a test piece, respectively; and \(L_i\) is the instantaneous length of the test piece.

2.3. Dynamic testing
In this paper, the dynamic compressive mechanical properties of UHMWPE with a MW of 6 million were tested at \(-40^\circ\text{C}, -10^\circ\text{C}, 25^\circ\text{C}, 50^\circ\text{C}, 70^\circ\text{C},\) and \(100^\circ\text{C}\) using a split Hopkinson pressure bar (SHPB) as an experimental setup. Figure 1 shows a schematic diagram of the principle of the SHPB experimental apparatus used in this work. The low temperature tests at \(-40^\circ\text{C}\) and \(-10^\circ\text{C}\) was carried out in a liquid nitrogen cooled furnace, and the high temperature tests at temperatures higher than \(25^\circ\text{C}\) were carried out in a high temperature furnace. The test piece was placed between the incident bar and the transmission bar. The center of the cylindrical test piece should coincide with the center of the end faces of the incident and transmission bars as much as possible. When using the temperature device, the part of the aluminum bars in contact with the test
piece and the test piece were heated or cooled in the furnace at the same time. During each experiment, the
temperature change in the furnace was monitored in real time by a thermocouple. In order to ensure that the
temperature of the test piece was the same as the temperature inside the furnace, each test piece was kept at the
concomitant temperature for 5 min before starting each dynamic compression test. At the same impact
velocity, two empty bar experiments with temperature were carried out. It was found that the amplitudes of
incident and transmitted waves at $-40^\circ C$ and $100^\circ C$ were the same as those at room temperature. Therefore,
the influence of temperature on aluminum bar was ignored in this work. Each experiment was repeated 3 times
at the same temperature and the same strain rate, and the average value was taken to ensure the accuracy of the
experimental data.

UHMWPE is a low-impedance material. In order to obtain a high signal-to-noise ratio [9], the bar materials
in the experiment were all made of 7A04 aluminum alloy. This bar material had an elastic modulus ($E_0$) of 70
GPa, a density ($\rho$) of 2.81 g cm$^{-3}$, and a wave velocity ($C_0$) of 4991 m s$^{-1}$. The impact bar, the incident bar and
the transmission bar had a diameter ($d$) of 14.5 mm and lengths of 400 mm, 1500 mm and 2000 mm,
respectively. Based on the strain signals $\varepsilon_r(t)$ and $\varepsilon_t(t)$ obtained from the strain gauges on the incident bar and the
transmission bar, the $\sigma_E$, $\varepsilon_E$ and the nominal strain rate ($\dot{\varepsilon}$) of the material during the deformation process were
calculated as follows [16]:

$$\dot{\varepsilon} = -\frac{2C_0}{L_S} \varepsilon_r(t),$$

(6)

$$\varepsilon_E = \int_0^t \dot{\varepsilon} dt,$$

(7)

$$\sigma_E = \frac{A_0E_0}{A_S} \varepsilon_r(t),$$

(8)

where $A_S$ and $L_S$ are the initial cross-sectional area and length of the test piece, respectively; and $C_0, A_0$ and $E_0$
represent the elastic wave velocity, cross-sectional area and elastic modulus of the bar, respectively. The true
stress ($\sigma_T$) and the true strain ($\varepsilon_T$) corresponding to the test piece were calculated using equations (4)–(5).

3. Results and discussion

3.1. Quasi-static experiments

The purpose of quasi-static compression testing was to compare the compressive mechanical properties of
UHMWPE with different MWs. As shown in figure 2, the stress–strain curves of UHMWPE with MWs of 3, 6
and 9 million were obtained by aligning the static compression experimental data at strain rates of 0.001 s$^{-1}$, 0.01
s$^{-1}$, 0.1 s$^{-1}$ at 25°C. It can be seen that the three different molecular weight UHMWPE samples exhibited
similar stress–strain characteristics, namely, there was only a small linear elastic section, followed by a
distribution yield with no significant yield point, and then a strain hardening stage.

![Figure 2. True stress–strain curves of UHMWPE with molecular weights of 3, 6 and 9 million at strain rates of 0.001 s$^{-1}$, 0.01 s$^{-1}$ and
0.1 s$^{-1}$.
]
The elastic modulus and yield stress were extracted using the inverse method \cite{17} and are summarized in Table 1. The result shows that the three MWs UHMWPE have obvious strain rate effect between 0.001–0.1 s\(^{-1}\), and with the increase of strain rate, the yield stress and elastic modulus of UHMWPE increase. At the same strain rate, the UHMWPE samples with a MW of 6 million had a greater yield stress and elastic modulus than that either of the UHMWPE samples. The 3 and 9 million MW UHMWPE samples had a similar yield stress and elastic modulus. This was because UHMWPE with a large MW should exhibit more excellent mechanical properties under compressive stress. However, as the MW increases, the molecular segments are more likely to entangle, reducing the compression resistance of UHMWPE \cite{18}.

### 3.2. Dynamic experiments

The quasi-static experiment shows that UHMWPE with MW of 6 million has more excellent compression mechanical properties. And in engineering applications, the UHMWPE with MW of 6 million is mainly used. Therefore, in this work, the 6 million MW UHMWPE samples were chosen for further examination and then the dynamic compressive mechanical properties over the range from −40 °C to 100 °C were studied. Figure 3 is a comparison of the test pieces before and after this test. The result shows that with the increase of strain rate, the diameter and thickness of the specimen become larger and smaller after compression. Since grease was applied to both ends of the test piece before the test, the two ends of the test piece were less impacted by the friction force and the deformation was uniform.

#### 3.2.1. Strain rate effects

In order to study the effects of strain rate on the compressive mechanical properties of UHMWPE, dynamic compression tests of UHMWPE with a MW of 6 million was carried out using an SHPB device. The dynamic compressive mechanical behavior of UHMWPE with a MW of 6 million at over the range from 1300 to 3300 s\(^{-1}\) was determined by controlling the pressure parameters of this device. Combined with the quasi-static experimental data, a true stress–strain curve from 0.001 s\(^{-1}\) to 3300 s\(^{-1}\) was generated and is shown in figure 4. The strain rate error in the figure did not exceed 100 s\(^{-1}\).

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| Molecular weight (million) | Strain rate (s\(^{-1}\)) | Yield stress (MPa) | Elastic modulus (MPa) |
|---------------------------|--------------------------|-------------------|-----------------------|
| 3                         | 0.001                    | 12.96 ± 0.11      | 442.37 ± 10.11        |
| 6                         | 0.001                    | 14.99 ± 0.10      | 597.28 ± 22.31        |
| 9                         | 0.001                    | 13.11 ± 0.10      | 471.41 ± 15.79        |
| 3                         | 0.01                     | 15.11 ± 0.12      | 507.75 ± 16.92        |
| 6                         | 0.01                     | 16.20 ± 0.10      | 672.92 ± 13.76        |
| 9                         | 0.01                     | 15.23 ± 0.15      | 540.27 ± 25.12        |
| 3                         | 0.1                      | 15.83 ± 0.15      | 535.23 ± 9.53         |
| 6                         | 0.1                      | 18.12 ± 0.20      | 699.35 ± 17.35        |
| 9                         | 0.1                      | 16.43 ± 0.21      | 567.56 ± 14.55        |

Figure 3. Comparison of test pieces before and after experimentation.
The result shows that, similar to the quasi-static experiments, the elastic modulus and yield stress of UHMWPE increased with increasing strain rate at high strain rates. Many researchers believe that this phenomenon is related to the secondary molecular processes often occurring in polymers [19–21]. An increase in the strain rate causes the UHMWPE chain to harden, thereby reducing the molecular mobility of the segment and increasing the yield stress.

3.2.2. Temperature effect

As a polymer, the effect of temperature on UHMWPE is of great interest. Figure 5 shows the true stress–strain curves for UHMWPE with a MW of 6 million at a strain rate of 2500 s⁻¹ at −40 °C, −10 °C, 25 °C, 50 °C, 70 °C, and 100 °C, respectively. Comparing the stress–strain curves of UHMWPE at different temperatures, it can be seen that the yield stress of UHMWPE decreased with increasing temperature. This was because the UHMWPE chain becomes
softer as the temperature increases, and the molecular chain mobility increases, resulting in a decreased yield stress [21].

It can also be seen from figure 5 that the slope of the UHMWPE flow curve changes very little between 25 °C and 100 °C. The slope of the flow curve shows a characteristic decreasing trend with decreasing temperature between −40 °C and 25 °C. However, this overall change was small, indicating that temperature had little effect on the strain hardening rate of UHMWPE.

3.3. Constitutive model

Due to the dynamic experimental conditions, the elastic phase of UHMWPE is difficult to reach at a constant strain rate, and the measured elastic modulus is not accurate, making it difficult to study the elastic modulus. Therefore, the elastic phase of the material is ignored. It was found that the uniaxial compressive mechanical behavior of the plastic phase of UHMWPE was very similar to that described by the J-C constitutive model. Therefore, the uniaxial compressive mechanical behavior of the plastic phase of UHMWPE was described with reference to the J-C constitutive model.

As a summary, based on the experimental data on UHMWPE with a MW of 6 million, a constitutive model of the yield and plastic phases of this material was established. The mechanical behavior of UHMWPE at different strain rates and different temperatures under uniaxial pressure was described and then applied to various numerical simulations.

3.3.1. Yielding behavior

(1) Strain rate effect

Equation (9) is the J-C constitutive model [13]:

$$
\sigma = (A + B\varepsilon^p)(1 + C \ln \dot{\varepsilon}^*) (1 - T^*m),
$$

(9)

where $A$ is reference strain rate and initial yield stress at a reference temperature; $B$ and $n$ are the strain hardening modulus and hardening index of the material, respectively; $\varepsilon_p$ is the plastic strain; $C$ is the material strain rate strengthening parameter; $\dot{\varepsilon}^* = \dot{\varepsilon}/\dot{\varepsilon}_0$ is a dimensionless strain rate; $\dot{\varepsilon}_0$ is the reference strain rate; $T^* = (T - T_r)/(T_m - T_r)$ is a homogeneous temperature, $T_r$ is the reference temperature, $T_m$ is the melting temperature, and $m$ is the temperature softening index.

25 °C was selected as the reference temperature. The yield stress of UHMWPE was studied at reference temperature, i.e. $T^* = 0$, $\varepsilon_p = 0$, equation (9) becomes:

$$
\sigma_y = A(1 + C \ln \dot{\varepsilon}^*).
$$

(10)

The yield stress of UHMWPE and ln $\dot{\varepsilon}^*$ showed a nonlinear relationship. Therefore, based on the strain rate correlation term at high-orders proposed by Huh & Kang [22], a strain rate correlation term in a cubic equation was introduced to obtain the following equation (11):

$$
\sigma_y = A(1 + C \ln \dot{\varepsilon}^* + D \ln \dot{\varepsilon}^{2*} + E \ln \dot{\varepsilon}^3),
$$

(11)

where $C$, $D$, and $E$ are material strain rate strengthening parameters. Different values can be obtained by selecting different reference strain rates. The strain rate of 2500 s$^{-1}$ was selected as the reference strain rate $\dot{\varepsilon}_0$ to calculate other conditions. The yield stress of UHMWPE at different strain rates at 25 °C was fitted using equation (11). The results are shown in figure 6.

(1) Temperature effect

Since the J-C constitutive model is a description of the mechanical properties of materials at high temperatures, it cannot be used to describe the mechanical properties of UHMWPE at low temperatures. The experimental results show that the increase of strain rate and the decrease of temperature have similar effect on the yield stress of UHMWPE. Therefore, based on the strain rate enhancement effect, the temperature softening constitutive equation of yield stress was derived at reference strain rate, i.e. $\dot{\varepsilon} = \dot{\varepsilon}_0$, $\varepsilon_p = 0$, as shown in equation (12).

$$
\sigma_y = A(1 + F \ln T_a + G \ln T_a^2),
$$

(12)

$T_a = T/T_r$, $F$, and $G$ are material temperature softening parameters. The temperature is the thermodynamic temperature in K. The yield stress data at different temperatures were then fitted using equation (12) at a reference strain rate of 2500 s$^{-1}$. The results are shown in figure 7.
3.3.2. Plastic stage

It was found that UHMWPE showed obvious strain hardening after entering the plastic stage, and the slope of flow curve changes little under different temperature and strain rate. Based on the J-C constitutive model and the strain hardening characteristics of the UHMWPE plastic stage, the constitutive model of the UHMWPE in the plastic stage can be represented as

\[
\sigma_p = \sigma_r + B \varepsilon_p^n
\]

(13)

where \(\sigma_p\) represents the plastic stress. Equation (13) was fitted using the stress–strain curves of the plastic phase at 25°C and 2500 s\(^{-1}\), and these results are shown in figure 8. The plastic strain \(\varepsilon_p\) range from 0 to 0.2, and the following results are also in this range.

A constitutive model of the plastic phase of UHMWPE can be obtained by combining equations (11), (12) and (13).

\[
\sigma_p = A(1 + C \ln \dot{\varepsilon} + D \ln \dot{\varepsilon}^2 + E \ln \dot{\varepsilon}^3)(1 + F \ln T_e + G \ln T_e^2) + B \varepsilon_p^n
\]

(14)

The values of parameters \(A, B, n, C, D, E, F, G\) in equation (14) were obtained by fitting equations (11), (12) and (13) with experimental data, which are summarized in table 2.

3.3.3. Verification and analysis of constitutive model

From the above analysis, it can be seen that the modified constitutive model fits well with the theoretical value at the reference temperature and strain rate. In order to verify the accuracy of the UHMWPE constitutive model,
the experimental curves at strain rates of 1300 s\(^{-1}\), 2500 s\(^{-1}\) and 3300 s\(^{-1}\) at different temperatures were compared with the theoretical values obtained using this constitutive model. The results are shown in figure 9.

It can be seen from figure 9 that the theoretical results of the yield stress at temperatures from \(-40^\circ\)C to 100 \(^\circ\)C and strain rates from 1300 s\(^{-1}\) to 3300 s\(^{-1}\) were in good agreement with experimental results. The theoretical values of the plastic phase stress in the range from 1300 s\(^{-1}\) to 3300 s\(^{-1}\) and 25 \(^\circ\)C to 100 \(^\circ\)C were close to the experimental measurements. The experimental values of the plastic stress at \(-40^\circ\)C and \(-10^\circ\)C were relatively small compared to calculated values, and the error was within 10%.

4. Conclusions

By comparing the stress–strain curves of UHMWPE with MWs of 3, 6 and 9 million in a quasi-static state, it was found that the yield stress of UHMWPE with a MW of 6 million was greater than that of UHMWPE with a MW of 3 or 9 million at the same strain rate. In applications requiring high compression resistance, UHMWPE with a MW of 6 million had superior performance.

Comparing the stress–strain curves of UHMWPE with a MW of 6 million at different strain rates and different temperatures, the results showed that the yield strength of UHMWPE increased with increasing strain rate, and plots of the yield stress versus \(\ln(\dot{\varepsilon})\) showed a nonlinear relationship at strain rates from 0.001 s\(^{-1}\) to 3300 s\(^{-1}\). The yield strength of UHMWPE decreased with increasing temperature, and this trend was more prominent in the temperature range from \(-40^\circ\)C to 25 \(^\circ\)C than that from 25 \(^\circ\)C to 100 \(^\circ\)C. However, the temperature and strain rate had little effect on the strain hardening of UHMWPE.

The uniaxial compressive mechanical behavior of the plastic phase of UHMWPE was very similar to that described by the J-C constitutive model. Therefore, the uniaxial compressive mechanical behavior of the plastic phase of UHMWPE was described with reference to the J-C constitutive model. By modifying the J-C constitutive equation, a constitutive equation for UHMWPE with a MW of 6 million at plasticity stage from \(-40^\circ\)C to 100 \(^\circ\)C and 0.001 s\(^{-1}\) to 3300 s\(^{-1}\) was obtained. Theoretical calculations using this model agreed well with the measured experimental results. The proposed constitutive model and research method could also be applied to other MWs UHMWPE. However, it is necessary to obtain its experimental constant by experiments and fitting.

Conflicts of interest

The authors declare no conflict of interest.
Figure 9. Plastic stress–strain curves at different strain rates and temperatures.

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References

[1] Ying L 2005 Characteristics and application progress of UHMWPE Foreign plastics 11 36–40
[2] Jimin H and Yadong H 1996 Properties and applications of UHMWPE Engineering Plastics Applications 05 53–59
[3] Zhan C and Datong Q 2001 Properties and application of UHMWPE in machinery Mech. Eng. Mater 8 1–3
[4] Kurtz S M, Rinnac C M, Santner T J and Bartel D L 1996 Exponential model for the tensile true stress-strain behavior of as-irradiated and oxidatively degraded ultra high molecular weight polyethylene Journal of Orthopaedic Research Official Publication of the Orthopaedic Research Society 14 755
[5] Kurtz S M, Pruitt L, Crawford R P, Crane D J and Edidin A A 1998 The yielding, plastic flow, and fracture behavior of ultra-high molecular weight polyethylene used in total joint replacements Biomaterials 19 1989
[6] Bergström J S, Kurtz S M, Rinnac C M and Edidin A A 2002 Constitutive modeling of ultra-high molecular weight polyethylene under large-deformation and cyclic loading conditions Biomaterials 23 2329–43
[7] Kurtz S M, Villarraga M L, Herr M P, Bergström J S, Rinnac C M and Edidin A A 2002 Thermomechanical behavior of virgin and highly crosslinked ultra-high molecular weight polyethylene used in total joint replacements Biomaterials 23 3681–97
[8] Crowley J and Vijaya B 2008 Dynamic Constitute behavior of UHMWPE-HAP Nanocomposites Proc. of the Xth Int. Congress and Exposition (Florida USA: Orlando)
[9] Hughes F, Prudom A and Swallowe G 2013 The high strain-rate behaviour of three molecular weights of polyethylene examined with a magnesium alloy split-Hopkinson pressure bar Polym. Test. 32 827–34
[10] Ming-Ming X, Guang-Yan H, Shun-Shan F, McShane Graham J and Stronge William J 2016 Static and Dynamic Properties of Semi-Crystalline Polyethylene Polymers 8 4
[11] Junxia W, Ping L, Changlin C, Dingshan Y and Dissipative A 2019 Particle dynamics study of flow behaviors in ultra high molecular weight polyethylene/ polyamide 6 blends based on souza-martins method Polymers 11 8
[12] Fei W, Lichao L, Ping X and Mingyin J 2017 Crystal structure evolution of UHMWPE/HDPB blend fibers prepared by melt spinning Polymers 9 3
[13] Johnson G R 1983 A constitutive model and data for materials subjected to large strains, high strain rates, and high temperatures Proc. 7th Inf. Sympo. Ballistics 541–7
[14] 2008 GBT 1041-2008 Plastic Compression Performance https://max.book118.com/html/2014/0219/5997395.shtm
[15] Zhiping T 1985 Optimum size of specimens in dynamic mechanical properties test of transversely isotropic materials Explosion & Impact 21–10
[16] Lizhi X, Guangfa G, Zhen Z, Jiangbo W, Chun C and Zhonghua D U 2019 Compressive mechanical properties of polyethylene at different strain rates Explosion & Impact 39 56–65
[17] Tao J 2016 Yield Behavior and Macroscopic Phenomenological Constitutive of Semi-crystalline polymer PhD diss Taiyuan University of Technology
[18] Xiangpei Q 2017 Compressibility experiments of UHMWPE with different molecular weights Chem. Eng. Equi 12 16–8
[19] Xiao C J, Hoo Y J and Yee A F 1994 Correlation between the shear yielding behavior and secondary relaxations of bisphenol a polycarbonate and related copolymers Macromolecules 27 2761–8
[20] Bauwens-Crowet C 1973 The compression yield behaviour of polymethyl methacrylate over a wide range of temperatures and strain-rates J. Mater. Sci. 8 968–79
[21] Bauwens-Crowet C, Bauwens I and Home’s G 1972 The temperature dependence of yield of polycarbonate in uniaxial compression and tensile tests J. Mater. Sci. 176–83
[22] Huh H, Kang W J and Han S S 2002 A tension split hopkinson bar for investigating the dynamic behavior of sheet metals Exp Mechanics 42 8–17