Proceedings of the 10th World Congress on Mechanical, Chemical, and Material Engineering (MCM'24)
Barcelona, Spain - August 22-24, 2024
Paper No. ICMIE 117
DOI: 10.11159/icmie24.117

Development of Johnson Cook Plasticity and Damage Model Parameters for the Time-dependent Behavior of High-Density Polyethylene

Abdulla Alhourani[1,*], Imad Barsoum[1,2], Jamal Sheikh-Ahmad[1,3], Suleyman Deveci[4]
[1]Department of Mechanical and Nuclear Engineering, Khalifa University
Abu Dhabi, United Arab Emirates
100059806@ku.ac.ae; imad.barsoum@ku.ac.ae
[2]Department of Engineering Mechanics, Royal Institute of Technology – KTH
Teknikringen 8, Stockholm, Sweden
[3]Department of Mechanical Engineering, Western New England University
Springfield, Massachusetts, USA
jamal.sheikh-ahmad@wne.edu
[4]Borouge Pte. Ltd.
Abu Dhabi, United Arab Emirates
suleyman.deveci@borouge.com
Corresponding author: Abdulla Alhourani (100059806@ku.ac.ae)

Abstract - The Johnson-Cook (JC) flow stress and failure parameters have been specifically tailored for high-density polyethylene (HDPE) pipe material from mechanical monotonic tensile tests covering various strain rates. The calibrated constitutive model underwent successful validation under a different loading condition resembling drop weight impact tests, including impact speeds of 2, 3 and 4 m/sec. Numerical simulations using Abaqus commercial software demonstrated the accuracy of the JC material model, with validation based on the 2 m/sec speed revealing dishing (indentation damage) in the HDPE plate, and the higher velocities (3 and 4 m/sec) validating the JC damage model with penetration damage. The material model exhibited strong validation, showcasing excellent agreement between experimental impact tests and numerical predictions across all testing conditions.

***Keywords*:** Damage parameters; Finite element analysis; High density polyethylene; Impact testing; Johnson-Cook

1. Introduction

High density polyethylene (HDPE) stands as a cornerstone in many applications of interest, including oil and gas pipelines, packing materials and marine structures. Despite its widespread usage, instances of premature failures necessitate rigorous engineering evaluations [1], underlining the critical need for accurate constitutive models to predict its complex behavior. Generally, polymers are highly sensitive to external influencing factors such as temperature, strain rate, loading condition and humidity; which is attributed to their molecular structure and rheological nature [2]. The semi crystalline structure of HDPE shapes its mechanical properties and plays a role in the non-linear time and temperature dependent material behavior. Therefore, the development of complex robust material models becomes imperative to augment the understanding and ensure the dependability of HDPE material in the desired industries.

Developing a single material model applicable to a broad range of strain rates poses a challenge due to the non-linear deformation behavior of thermoplastics. At lower strain rates, they may exhibit more elastic behavior, while higher strain rates can induce more pronounced viscoelastic and time-dependent responses. Various HDPE constitutive material models are proposed in the literature, which are either temperature dependent or strain rate sensitive due to the lack of thermomechanical testing data at a comprehensive range of conditions [3]. Eyring [4] developed a model based on the thermal activation, which provides an insight about the mechanical response of thermoplastics. Others took it a step further and modified the model to account for different activation states [5] and also developed an elastic-viscoplastic rheological material model [6].

Damage incurred during drop weight impact tests on thermoplastics, such as polycarbonate (PC) and polymethyl methacrylate (PMMA), can manifest in various forms such as dishing and penetration [7]. To accurately capture the induced damage, a developed constitutive model must be employed. Although the JC plasticity model was initially developed for metal deformations, it has proven effective in modeling thermoplastics like PC. The JC plasticity model needs to be complemented by a JC damage model to accurately predict the material's behavior under dynamic impact tests. Notably, researchers like Sarikaya et al. [7] have extended the JC plasticity model by incorporating failure parameters to simulate PC's response to dynamic impact tests. Additionally, Xu et al. [8] applied the JC flow stress empirical model to simulate the same material behavior under Izod impact tests, adjusting parameters based on thermal history variations.

In the present investigation, the JC plasticity model in conjunction with the JC damage model are incorporated and calibrated based on monotonic tensile testes to predict the behaviour of HDPE plates under impact loading conditions. This combined modeling approach is aimed at providing a comprehensive understanding of how HDPE responds to dynamic loading, considering both plastic deformation and the induced damage.

2. Materials and Methods

2.1 Experimental Outline

To calibrate the chosen constitutive model, HDPE tensile tests following ISO 527 type 1BA standard were performed at different strain rates (0.0033, 0.033, 0.33, and 2.187/sec) with respect to a set temperature of 23 ºC. Tensile samples, 2 mm thick, were obtained from compression-molded plaques with a gauge length of 25 mm. Impact tests, conducted per ISO 6603 standard with a 60 x 60 mm^2 square samples, from the same HDPE compression-molded sheets. For repeatability purposes, three repetitions were performed for each tensile and impact test condition (2, 3 and 4 m/sec), providing a reliable and comprehensive dataset for calibration and validation.

2.2 Constitutive Model Calibration

The JC flow stress equation without the thermal softening term (tensile tests conducted at room temperature) is represented in Eq. (1) [9]:

$$\sigma_{eq} = \left(A + B\varepsilon_p^n\right)\left(1 + c\ln\left(\frac{\dot{\varepsilon}_{eq}}{\dot{\varepsilon}_0}\right)\right) \tag{1}$$

Where σ_{eq}, A, B, ε_p n, c, $\dot{\varepsilon}_{eq}$ and $\dot{\varepsilon}_0$ are the equivalent flow stress, equivalent plastic strain, initial yield strength, strain hardening coefficient, strain hardening exponent, strengthening coefficient of strain rate, plastic strain rate and reference strain rate, respectively. The $\dot{\varepsilon}_0$ is set as 0.0033/sec. Similarly, the JC damage model (excluding temperature effect) and damage accumulation are expressed in Eqs. (1) - (2), respectively [9]:

$$\varepsilon_f^p = \left(D_1 + D_2 e^{D_3\left(\frac{\sigma_m}{\sigma_{eq}}\right)}\right)\left(1 + D_4\ln\left(\frac{\dot{\varepsilon}_{eq}}{\dot{\varepsilon}_0}\right)\right) \tag{2}$$

$$D = \int \frac{d\varepsilon_p}{\varepsilon_f^p\left(\frac{\sigma_m}{\sigma_{eq}}, \frac{\dot{\varepsilon}_{eq}}{\dot{\varepsilon}_0}\right)} \tag{3}$$

Where ε_f^p, σ_m, σ_{eq}, D_1, D_2, D_3, D_4 and D are the plastic failure strain, mean stress, equivalent Mises stress, initial fracture strain, exponential factor, triaxiality factor, strain rate factor and those four represent the material's damage status. D is the cumulative damage in which failure occurs when such parameter equals to 1.

To simulate the dynamic response of HDPE material during the impact tests, JC plasticity and damage models are to be properly calibrated. The elastic properties and model parameters are found in Table 1 after confidently predicting the engineering stress strain plots in Figure 1. Since challenges exist in terms of the required sample preparation and testing to determine the failure parameters in addition to the displacement damage evolution of linear softening, a sensitivity study was performed where such values were varied.

Table 1: HDPE elastic properties and calibrated JC dynamic model parameters.

Elastic Properties		Plasticity Parameters				Damage Constants				
E (MPa)	ν	A (MPa)	B (MPa)	n	C	D_1	D_2	D_3	D_4	Damage Evolution
1000	0.45	8.859	30.56	0.3838	0.0455	0.3	0.075	0.333	0.0005	0.0013

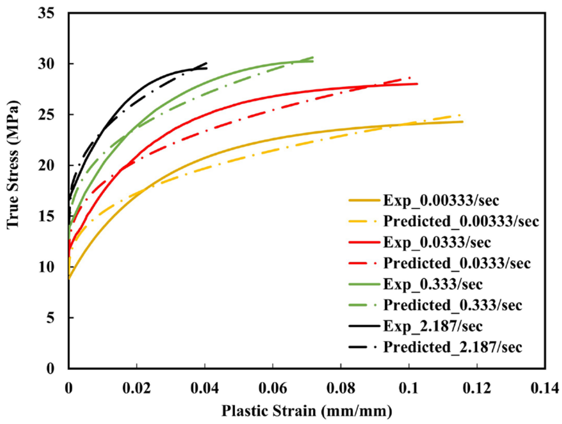

Fig. 1: Comparison between the experimental and predicted stress strain curves of the calibrated JC plasticity material model parameters.

2.3 Constitutive Model Validation

2.3.1 Drop weight impact testing

To verify the predictive capability of the calibrated model under a different loading condition, a validation test involving drop weight impact tests on HDPE was conducted. The force-time data obtained from these tests will be compared with the simulated conditions for impact speeds of 2, 3 and 4 m/sec. It's noteworthy that the impact at uniform speed of 2 m/sec resulted in dishing damage, providing validation for the JC flow stress model. The other velocities exhibited penetration damage in HDPE sheets, which will involve testing the failure constants to assess its effectiveness in capturing and predicting the induced damage.

2.3.2 Drop weight impact simulation

The numerical simulation of the impact test model took place in Abaqus/Explicit, utilizing an axisymmetric condition to optimize computational efficiency. In this setup, the steel puncher was designated as a discrete rigid solid (RAX2), while the HDPE plate adopted an element type of CAX4R—specifically, a 4-node bilinear axisymmetric quadrilateral with reduced integration and hourglass control. To enhance mesh sensitivity analysis in relation to the peak force value, a plate element size of 0.2 mm was determined for the contact region, resulting in 1200 elements (i.e. 1331 nodes) across the axisymmetric 2 mm HDPE plate. This analysis was conducted with an automatic time incrementation. The reference point, highlighted in red, is constrained to the striker, with velocity boundary control set according to the depiction in Figure 2. The orange-labeled sides, comprising the outer edge, top, and bottom surfaces, are pinned due to their location within the clamped area and outside the contact region between the striker and plate. A general contact interaction was established, incorporating a friction coefficient of 0.06, which was determined iteratively. This choice accounts for the application of a lubricant at the center of the plate (where the striker impacts) before testing, aimed at minimizing frictional effects.

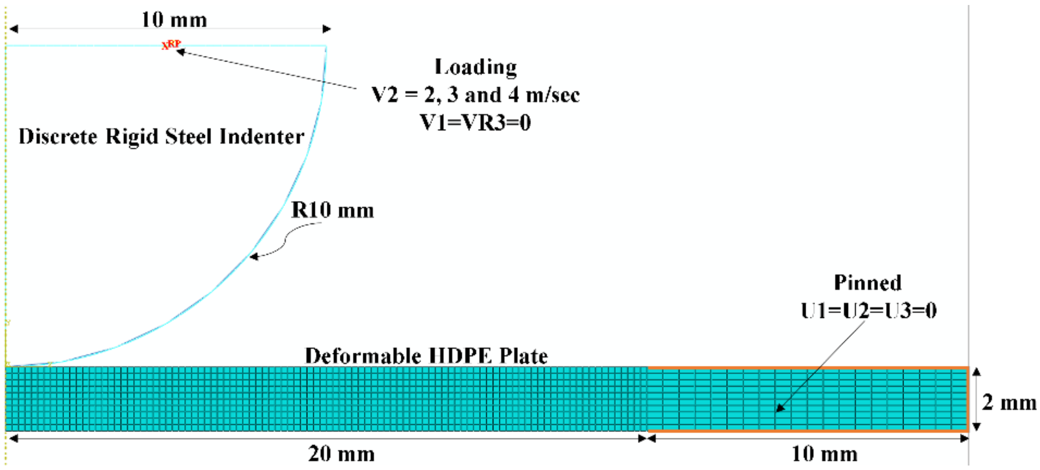

Fig. 2: Schematic diagram of the impact structural model with the dimensions and applied boundary conditions.

3. Experimental and FEA Results

Figure 3 illustrates a comparison between the impact tests and FEA results employing the JC dynamic model, focusing on force-time diagrams. Notably, the experimental peak force values closely align with the simulated values, and a good similarity exists in the force distribution between the simulated and experimental plots. The correlation is particularly evident. The logical inference from the observations is that an increase in impact speed correlates with higher peak force values. This correlation arises from the fact that a greater drop height occurs within a shorter time duration, contributing to the amplification of peak forces.

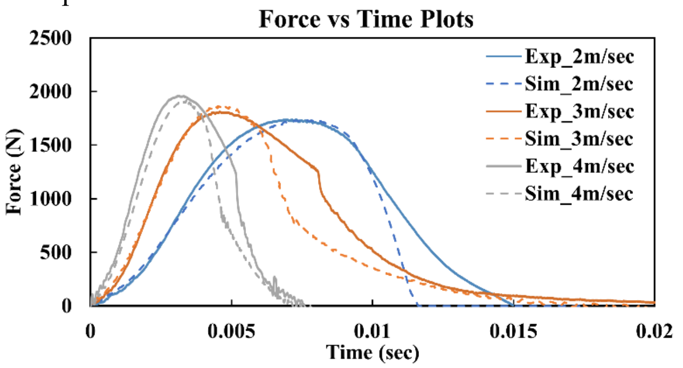

Fig. 3: Comparison of force vs time plots between the drop weight impact validation tests and JC dynamic model predictions.

4. Conclusion

This investigation delves into the non-linear complex behavior of high-density polyethylene under tensile monotonic loading conditions, and this behavior is examined and calibrated using the Johnson-Cook flow stress and damage models. To validate the model, experimental and numerical assessments were conducted through drop weight impact tests. The results demonstrate a commendable agreement with respect to the peak force values and force-time distribution curves across the impact velocities of 2, 3 and 4 m/sec.

References

[1] M. Mouwakeh, S. Masri, M. H. Meliani, R. K. Suleiman, G. Pluvinage, and M. Nait-Abdelaziz, "Analytical and numerical investigation using limit analysis on the ductile failure of pipes containing surface cracks," *Engineering Failure Analysis,* vol. 104, pp. 480-489, 2019/10/01/ 2019, doi: https://doi.org/10.1016/j.engfailanal.2019.06.007.

[2] G. Ayoub, F. Zaïri, M. Naït-Abdelaziz, and J. M. Gloaguen, "Modelling large deformation behaviour under loading–unloading of semicrystalline polymers: Application to a high density polyethylene," *International Journal of Plasticity,* vol. 26, no. 3, pp. 329-347, 2010/03/01/ 2010, doi: https://doi.org/10.1016/j.ijplas.2009.07.005.

[3] B. Ahmad, F. Almaskari, J. Sheikh-Ahmad, S. Deveci, and K. Khan, "Thermomechanical Modeling of Material Flow and Weld Quality in the Friction Stir Welding of High-Density Polyethylene," *Polymers*, vol. 15, no. 15*,* doi: 10.3390/polym15153230.

[4] H. Eyring, "Viscosity, Plasticity, and Diffusion as Examples of Absolute Reaction Rates," *The Journal of Chemical Physics,* vol. 4, no. 4, pp. 283-291, 2004, doi: 10.1063/1.1749836.

[5] T. Ree and H. Eyring, "Theory of Non-Newtonian Flow. I. Solid Plastic System," *Journal of Applied Physics,* vol. 26, no. 7, pp. 793-800, 2004, doi: 10.1063/1.1722098.

[6] A. D. Mulliken and M. C. Boyce, "Mechanics of the rate-dependent elastic–plastic deformation of glassy polymers from low to high strain rates," *International Journal of Solids and Structures,* vol. 43, no. 5, pp. 1331-1356, 2006/03/01/ 2006, doi: https://doi.org/10.1016/j.ijsolstr.2005.04.016.

[7] M. Sarıkaya, M. Güden, Ç. Kambur, S. Ç. Özbek, and A. Taşdemirci, "Development of the Johnson-Cook flow stress and damage parameters for the impact response of polycarbonate: Experimental and numerical approach," *International Journal of Impact Engineering,* vol. 179, p. 104674, 2023/09/01/ 2023, doi: https://doi.org/10.1016/j.ijimpeng.2023.104674.

[8] Y. Xu, H. Lu, T. Gao, and W. Zhang, "Predicting the low-velocity impact behavior of polycarbonate: Influence of thermal history during injection molding," *International Journal of Impact Engineering,* Article vol. 86, pp. 265-273, 2015, doi: 10.1016/j.ijimpeng.2015.08.013.

[9] G. R. Johnson and W. H. Cook, "Fracture characteristics of three metals subjected to various strains, strain rates, temperatures and pressures," *Engineering Fracture Mechanics,* vol. 21, no. 1, pp. 31-48, 1985/01/01/ 1985, doi: https://doi.org/10.1016/0013-7944(85)90052-9.