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A thermodynamically consistent peridynamics model for visco-plasticity and damage. (English) Zbl 1440.74035

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Summary: This article presents a unified visco-plastic-damage model in the peridynamics set-up which may be applied across different regime of strain rates and temperatures. In the model, we introduce two internal variables, one describing plastic flow and other the damage in the material. Exploiting the idea of master balance, in addition to the conventional momentum balances, we postulate micro-force balances for both plastic flow and damage evolution in terms of additional peridynamic force states. The equations of motion are in the form of integro-differential equations and do not require continuity of field variables. Using the idea of energy equivalence and entropy equivalence, constitutive relations for the peridynamic force states are determined. The proposed peridynamic visco-plastic-damage model may be thought as a non-trivial extension of the recently developed peridynamic visco-plasticity model [the second author et al., "A dynamic flow rule for viscoplasticity in polycrystalline solids under high strain rates", Int. J. Non-Linear Mech. 95, 10–18 (2017; `doi:10.1016/j.ijnonlinmec.2017.05.010`)]. The current scheme couples the visco-plasticity and damage in a thermo-dynamically consistent manner and provides temperature evolution which reflects contribution from both plasticity and damage. The efficacy of the model is demonstrated through simulations of the adiabatic shear band propagation as observed in Kalthoff-Winkler experiment and the shear plugging failure of Weldox 460 E steel plates along with the determination of the ballistic limit.

MSC:

74A45	Theories of fracture and damage
74C10	Small-strain, rate-dependent theories of plasticity (including theories of viscoplasticity)

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References:

[1] Zukas, J., High velocity impact dynamics (1990), Wiley

[2] Rahaman, M. M.; Dhas, B.; Roy, D.; Reddy, J., A dynamic flow rule for viscoplasticity in polycrystalline solids under high strain rates, Int. J. Non-Linear Mech., 95, 10-18 (2017)

[3] Dieter, G. E.; Bacon, D. J., Mechanical metallurgy (1986), McGraw-hill: McGraw-hill New York

[4] Lemaitre, J.; Chaboche, J. L., Mechanics of solid materials (1994), Cambridge university press

[5] Berdin, C.; Besson, J.; Bugat, S.; Desmorat, R.; Feyel, F.; Forest, S.; Lorentz, E.; Maire, E.; Pardoen, T.; Pineau, A.; Tanguy, B., Local approach to fracture (2004), Presses de l'Ecole des Mines, Paris

[6] Besson, J., Continuum models of ductile fracture: A review, Int. J. Damage Mech., 19, 1, 3-52 (2010)

[7] Pineau, A., Development of the local approach to fracture over the past 25 years: Theory and applications, Int. J. Fract., 138, 1-4, 139-166 (2006) · Zbl 1112.74473

[8] Johnson, G. R.; Cook, W. H., Fracture characteristics of three metals subjected to various strains, strain rates, temperatures and pressures, Eng. Fract. Mech., 21, 1, 31-48 (1985)

[9] Børvik, T.; Langseth, M.; Hopperstad, O.; Malo, K., Ballistic penetration of steel plates, Int. J. Impact Eng., 22, 9-10, 855-886 (1999)

[10] Gurson, A. L., Continuum theory of ductile rupture by void nucleation and growth: Part i—yield criteria and flow rules for porous ductile media, J. Eng. Mater. Technol., 99, 1, 2-15 (1977)

[11] Tvergaard, V.; Needleman, A., Analysis of the cup-cone fracture in a round tensile bar, Acta Metall., 32, 1, 157-169 (1984)

[12] McClintock, F. A., A criterion for ductile fracture by the growth of holes, J. Appl. Mech., 35, 2, 363-371 (1968)

[13] Hancock, J.; Mackenzie, A., On the mechanisms of ductile failure in high-strength steels subjected to multi-axial stress-states, J. Mech. Phys. Solids, 24, 2-3, 147-160 (1976)

[14] Rice, J.; Tracey, D. M., On the ductile enlargement of voids in triaxial stress fields, J. Mech. Phys. Solids, 17, 3, 201-217 (1969)

[15] Le Roy, G.; Embury, J.; Edwards, G.; Ashby, M., A model of ductile fracture based on the nucleation and growth of voids, Acta Metall., 29, 8, 1509-1522 (1981)

[16] Bridgman, P. W., Studies in large plastic flow and fracture (1952), McGraw-Hill: McGraw-Hill New York · Zbl 0049.25606

[17] Jones, N., Dynamic inelastic failure of structures, Trans. Japan Soc. Mech. Eng. Series A, 63, 616, 2485-2495 (1997)

[18] Zaera, R.; Rodríguez-Martínez, J. A.; Rittel, D., On the taylor – quinney coefficient in dynamically phase transforming materials. application to 304 stainless steel, Int. J. Plast., 40, 185-201 (2013)

[19] Ravichandran, G.; Rosakis, A. J.; Hodowany, J.; Rosakis, P., On the conversion of plastic work into heat during high-strain-rate deformation, (AIP conference proceedings, vol. 620 (2002), AIP), 557-562

[20] Bourdin, B.; Francfort, G. A.; Marigo, J. J., Numerical experiments in revisited brittle fracture, J. Mech. Phys. Solids, 48, 4, 797-826 (2000) · Zbl 0995.74057

[21] Mumford, D.; Shah, J., Optimal approximations by piecewise smooth functions and associated variational problems, Comm. Pure Appl. Math., 42, 5, 577-685 (1989) · Zbl 0691.49036

[22] Kuhn, C.; Müller, R., A phase field model for fracture, (PAMM: Proceedings in Applied Mathematics and Mechanics, vol. 8 (2008), Wiley Online Library), 10223-10224 · Zbl 1394.74176

[23] Kuhn, C.; Müller, R., A continuum phase field model for fracture, Eng. Fract. Mech., 77, 18, 3625-3634 (2010)

[24] Ambrosio, L.; Tortorelli, V. M., Approximation of functional depending on jumps by elliptic functional via t-convergence, Comm. Pure Appl. Math., 43, 8, 999-1036 (1990) · Zbl 0722.49020

[25] Amor, H.; Marigo, J. J.; Maurini, C., Regularized formulation of the variational brittle fracture with unilateral contact: Numerical experiments, J. Mech. Phys. Solids, 57, 8, 1209-1229 (2009) · Zbl 1426.74257

[26] Miehe, C.; Hofacker, M.; Welschinger, F., A phase field model for rate-independent crack propagation: Robust algorithmic implementation based on operator splits, Comput. Methods Appl. Mech. Engrg., 199, 45-48, 2765-2778 (2010) · Zbl 1231.74022

[27] Miehe, C.; Welschinger, F.; Hofacker, M., Thermodynamically consistent phase-field models of fracture: Variational principles and multi-field fe implementations, Internat. J. Numer. Methods Engrg., 83, 10, 1273-1311 (2010) · Zbl 1202.74014

[28] Borden, M. J.; Hughes, T. J.; Landis, C. M.; Verhoosel, C. V., A higher-order phase-field model for brittle fracture: Formulation and analysis within the isogeometric analysis framework, Comput. Methods Appl. Mech. Engrg., 273, 100-118 (2014) · Zbl 1296.74098

[29] Ambati, M.; Gerasimov, T.; De Lorenzis, L., A review on phase-field models of brittle fracture and a new fast hybrid formulation, Comput. Mech., 55, 2, 383-405 (2015) · Zbl 1398.74270

[30] Hofacker, M.; Miehe, C., A phase field model for ductile to brittle failure mode transition, Proc. Appl. Math. Mech., 12, 1, 173-174 (2012)

[31] Ulmer, H.; Hofacker, M.; Miehe, C., Phase field modeling of brittle and ductile fracture, Proc. Appl. Math. Mech., 13, 1, 533-536 (2013)

[32] Duda, F. P.; Ciarbonetti, A.; Sánchez, P. J.; Huespe, A. E., A phase-field/gradient damage model for brittle fracture in elastic – plastic solids, Int. J. Plast., 65, 269-296 (2015)

[33] Libersky, L. D.; Petschek, A., Smooth particle hydrodynamics with strength of materials, (Advances in the free-Lagrange method including contributions on adaptive gridding and the smooth particle hydrodynamics method (1991), Springer), 248-257

[34] Shaw, A.; Roy, D.; Reid, S., Optimised form of acceleration correction algorithm within sph-based simulations of impact mechanics, Int. J. Solids Struct., 48, 25-26, 3484-3498 (2011)

[35] Swegle, J.; Hicks, D.; Attaway, S., Smoothed particle hydrodynamics stability analysis, J. Comput. Phys., 116, 1, 123-134 (1995) · Zbl 0818.76071

[36] Meleán, Y.; Sigalotti, L. D.G.; Hasmy, A., On the sph tensile instability in forming viscous liquid drops, Comput. Phys. Comm., 157, 3, 191-200 (2004)

[37] Silling, S. A., Reformulation of elasticity theory for discontinuities and long-range forces, J. Mech. Phys. Solids, 48, 1, 175-209 (2000) · Zbl 0970.74030

[38] Silling, S. A.; Epton, M.; Weckner, O.; Xu, J.; Askari, E., Peridynamic states and constitutive modeling, J. Elasticity, 88, 2, 151-184 (2007) · Zbl 1120.74003

[39] Silling, S. A., Linearized theory of peridynamic states, J. Elasticity, 99, 1, 85-111 (2010) · Zbl 1188.74008

[40] Foster, J. T.; Silling, S. A.; Chen, W. W., Viscoplasticity using peridynamics, Internat. J. Numer. Methods Engrg., 81, 10, 1242-1258 (2010) · Zbl 1183.74035

[41] Amani, J.; Oterkus, E.; Areias, P.; Zi, G.; Nguyen-Thoi, T.; Rabczuk, T., A non-ordinary state-based peridynamics formulation for thermoplastic fracture, Int. J. Impact Eng., 87, 83-94 (2016)

[42] Rahaman, M. M.; Roy, P.; Roy, D.; Reddy, J., A peridynamic model for plasticity: Micro-inertia based flow rule, entropy equivalence and localization residuals, Comput. Methods Appl. Mech. Engrg., 327, 369-391 (2017)

[43] Ambati, M.; Gerasimov, T.; De Lorenzis, L., Phase-field modeling of ductile fracture, Comput. Mech., 55, 5, 1017-1040 (2015) · Zbl 1329.74018

[44] Francfort, G. A.; Marigo, J. J., Revisiting brittle fracture as an energy minimization problem, J. Mech. Phys. Solids, 46, 8, 1319-1342 (1998) · Zbl 0966.74060

[45] Reddy, J. N., An introduction to continuum mechanics (2013), Cambridge university press

[46] Wang, Z.; Beyerlein, I.; LeSar, R., Dislocation motion in high strain-rate deformation, Phil. Mag., 87, 16, 2263-2279 (2007)

[47] Kosevich, A., Dynamical theory of dislocations, Phys.-Usp., 7, 6, 837-854 (1965)

[48] Czarnota, C.; Jacques, N.; Mercier, S.; Molinari, A., Modelling of dynamic ductile fracture and application to the simulation of plate impact tests on tantalum, J. Mech. Phys. Solids, 56, 4, 1624-1650 (2008)

[49] Jacques, N.; Mercier, S.; Molinari, A., Effects of microscale inertia on dynamic ductile crack growth, J. Mech. Phys. Solids, 60, 4, 665-690 (2012)

[50] Coleman, B. D.; Noll, W., The thermodynamics of elastic materials with heat conduction and viscosity, Arch. Ration. Mech. Anal., 13, 1, 167-178 (1963) · Zbl 0113.17802

[51] Gurtin, M. E., On the plasticity of single crystals: Free energy, microforces, plastic-strain gradients, J. Mech. Phys. Solids, 48, 5, 989-1036 (2000) · Zbl 0988.74021

[52] Borden, M. J.; Hughes, T. J.; Landis, C. M.; Anvari, A.; Lee, I. J., A phase-field formulation for fracture in ductile materials: Finite deformation balance law derivation, plastic degradation, and stress triaxiality effects, Comput. Methods Appl. Mech. Engrg., 312, 130-166 (2016)

[53] Miehe, C.; Aldakheel, F.; Raina, A., Phase field modeling of ductile fracture at finite strains: A variational gradient-extended plasticity-damage theory, Int. J. Plast., 84, 1-32 (2016)

[54] Miehe, C.; Welschinger, F.; Aldakheel, F., Variational gradient plasticity at finite strains. part ii: Local – global updates and mixed finite elements for additive plasticity in the logarithmic strain space, Comput. Methods Appl. Mech. Engrg., 268, 704-734 (2014) · Zbl 1295.74014

[55] Miehe, C.; Hofacker, M.; Schänzel, L. M.; Aldakheel, F., Phase field modeling of fracture in multi-physics problems. part ii. coupled brittle-to-ductile failure criteria and crack propagation in thermo-elastic – plastic solids, Comput. Methods Appl. Mech. Engrg., 294, 486-522 (2015) · Zbl 1423.74837

[56] Ambati, M.; Kruse, R.; De Lorenzis, L., A phase-field model for ductile fracture at finite strains and its experimental verification, Comput. Mech., 57, 1, 149-167 (2016) · Zbl 1381.74181

[57] Bourdin, B.; Francfort, G. A.; Marigo, J. J., The variational approach to fracture, J. Elast., 91, 1-3, 5-148 (2008) · Zbl 1176.74018

[58] Larsen, C. J.; Ortner, C.; Süli, E., Existence of solutions to a regularized model of dynamic fracture, Math. Models Methods Appl. Sci., 20, 07, 1021-1048 (2010) · Zbl 1425.74418

[59] Bourdin, B.; Larsen, C. J.; Richardson, C. L., A time-discrete model for dynamic fracture based on crack regularization, Int. J. Fract., 168, 2, 133-143 (2011) · Zbl 1283.74055

[60] Borden, M. J.; Verhoosel, C. V.; Scott, M. A.; Hughes, T. J.; Landis, C. M., A phase-field description of dynamic brittle fracture, Comput. Methods Appl. Mech. Engrg., 217, 77-95 (2012) · Zbl 1253.74089

[61] Hofacker, M.; Miehe, C., Continuum phase field modeling of dynamic fracture: Variational principles and staggered fe implementation, Int. J. Fract., 178, 1-2, 113-129 (2012)

[62] Hofacker, M.; Miehe, C., A phase field model of dynamic fracture: Robust field updates for the analysis of complex crack patterns, Internat. J. Numer. Methods Engrg., 93, 3, 276-301 (2013) · Zbl 1352.74022

[63] Schlüter, A.; Willenbücher, A.; Kuhn, C.; Müller, R., Phase field approximation of dynamic brittle fracture, Comput. Mech., 54, 5, 1141-1161 (2014) · Zbl 1311.74106

[64] Roy, P.; Pathrikar, A.; Deepu, S.; Roy, D., Peridynamics damage model through phase field theory, Int. J. Mech. Sci., 128, 181-193 (2017)

[65] Kalthoff, J. F., Modes of dynamic shear failure in solids, Int. J. Fract., 101, 1-2, 1-31 (2000)

[66] Børvik, T.; Hopperstad, O.; Berstad, T.; Langseth, M., Numerical simulation of plugging failure in ballistic penetration, Int. J. Solids Struct., 38, 34-35, 6241-6264 (2001) · Zbl 1057.74035

[67] Clayton, J., Modeling and simulation of ballistic penetration of ceramic-polymer-metal layered systems, Math. Probl. Eng., 2015 (2015)

[68] Breitenfeld, M.; Geubelle, P.; Weckner, O.; Silling, S., Non-ordinary state-based peridynamic analysis of stationary crack problems, Comput. Methods Appl. Mech. Engrg., 272, 233-250 (2014) · Zbl 1296.74099

[69] Littlewood, D. J., A nonlocal approach to modeling crack nucleation in aa 7075-t651, (ASME 2011 International Mechanical Engineering Congress and Exposition (2011), American Society of Mechanical Engineers), 567-576

[70] Wu, C.; Ren, B., A stabilized non-ordinary state-based peridynamics for the nonlocal ductile material failure analysis in metal machining process, Comput. Methods Appl. Mech. Engrg., 291, 197-215 (2015) · Zbl 1423.74067

[71] Yaghoobi, A.; Chorzepa, M. G., Higher-order approximation to suppress the zero-energy mode in non-ordinary state-based peridynamics, Comput. Struct., 188, 63-79 (2017)

[72] Bobaru, F.; Yang, M.; Alves, L. F.; Silling, S. A.; Askari, E.; Xu, J., Convergence, adaptive refinement, and scaling in 1D peridynamics, Internat. J. Numer. Methods Engrg., 77, 6, 852-877 (2009) · Zbl 1156.74399

[73] Mura, T., Micromechanics of defects in solids (2013), Springer Science \& Business Media

[74] Miehe, C.; Teichtmeister, S.; Aldakheel, F., Phase-field modelling of ductile fracture: A variational gradient-extended plasticity-damage theory and its micromorphic regularization, Phil. Trans. R. Soc. A, 374, 2066, 20150170 (2016) · Zbl 1353.74065

[75] Rabczuk, T.; Areias, P.; Belytschko, T., A simplified mesh-free method for shear bands with cohesive surfaces, Internat. J. Numer. Methods Engrg., 69, 5, 993-1021 (2007) · Zbl 1194.74536

[76] Chang, R.; Graham, L., Edge dislocation core structure and the peierls barrier in body-centered cubic iron, Phys. Status Solidi b, 18, 1, 99-103 (1966)

[77] Voyiadjis, G. Z.; Abed, F. H., Effect of dislocation density evolution on the thermomechanical response of metals with different crystal structures at low and high strain rates and temperatures, Arch. Mech., 57, 4, 299-343 (2005) · Zbl 1126.74011

[78] Davey, W. P., Precision measurements of the lattice constants of twelve common metals, Phys. Rev., 25, 6, 753 (1925)

[79] Madenci, E.; Oterkus, E., Peridynamic theory and its applications (2016), Springer · Zbl 1295.74001

[80] Silling, S. A.; Askari, E., A meshfree method based on the peridynamic model of solid mechanics, Comput. Struct., 83, 17-18, 1526-1535 (2005)

[81] Courant, R.; Friedrichs, K.; Lewy, H., On the partial difference equations of mathematical physics, IBM J. Res. Dev., 11, 2, 215-234 (1967) · Zbl 0145.40402

[82] Børvik, T.; Hopperstad, O.; Berstad, T.; Langseth, M., A computational model of viscoplasticity and ductile damage for impact and penetration, Eur. J. Mech. A Solids, 20, 5, 685-712 (2001) · Zbl 1028.74043

[83] Parks, M. L.; Lehoucq, R. B.; Plimpton, S. J.; Silling, S. A., Implementing peridynamics within a molecular dynamics code, Comput. Phys. Comm., 179, 11, 777-783 (2008) · Zbl 1197.82014

[84] Huang, D.; Lu, G.; Liu, Y., Nonlocal peridynamic modeling and simulation on crack propagation in concrete structures, Math. Probl. Eng., 2015 (2015)

[85] Madenci, E.; Oterkus, E., Peridynamic theory and its applications (2014), Springer · Zbl 1295.74001

[86] Børvik, T.; Hopperstad, O. S.; Langseth, M.; Malo, K. A., Effect of target thickness in blunt projectile penetration of weldox 460 e steel plates, Int. J. Impact Eng., 28, 4, 413-464 (2003)

[87] Robinson, P.; Besant, T.; Hitchings, D., Delamination growth prediction using a finite element approach, (European Structural Integrity Society, 27 (2000), Elsevier), 135-147