IMPLEMENTATION OF ADVANCED PLASTICITY MODELS IN OPENFOAM

MICHAEL CLANCY[1], PHILIP CARDIFF[1], PETER DE JAEGER[1,2], ALOJZ IVANKOVIĆ[1]
[1]*University College Dublin, School of Mechanical and Materials Engineering, Ireland, michael.clancy@ucdconnect.ie*
[2] *N.V. Bekaert S.A., Belgium*

Keywords: *solid mechanics, plasticity, distortional hardening*

The use of the finite-volume method, in particular the segregated approach advocated in [1], has been proven to be a viable approach in the solution of solid mechanics problems. The implementation of a large-strain Lagrangian solution methodology and its application to metal forming has now been carried out by [2]. The extension of this suite of tools to handle advanced plasticity models has been carried out by the present authors. The overall aim of the work is to more accurately describe the deformation behaviour of steel wire products during forming processes.

Need for advanced material models

The availability of robust and fast numerical methods, such as radial-return map for the Von-Mises yield criterion, has led to widespread use of computational plasticity models in mechanical forming applications for the prediction of geometry and mechanical properties. All major finite-element codes now contain one of the standard implementations of this plasticity model.

The need for models with the ability to describe anisotropic yield strengths was found for forming simulations in [3][4]. During processing the reorientation of material leads to the formation of a crystalline texture. In the case of pearlitic steel, a large portion of which finds its use in ultra-high strength wire, this texture takes the form of regularly spaced cementite lamellae in a ferrite matrix. The cementite lamellae are hard and brittle, compared to the relatively softer ferrite. With geometric inhomogenity comes expected anisotropic behaviour. Confirmation of the yield-anisotropy of pearlitic microstructures is found in [5]. A failure of basic material models in the prediction of wire geometry is seen, which creates difficulty in the production of novel wire products. An example of such a geometry is seen in Figure 1. The use of anisotropic material models, which can accurately capture the initial and evolved yield-strength in all directions is required.

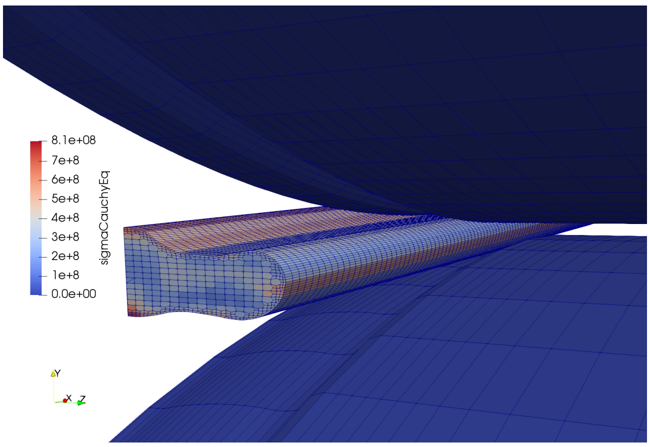
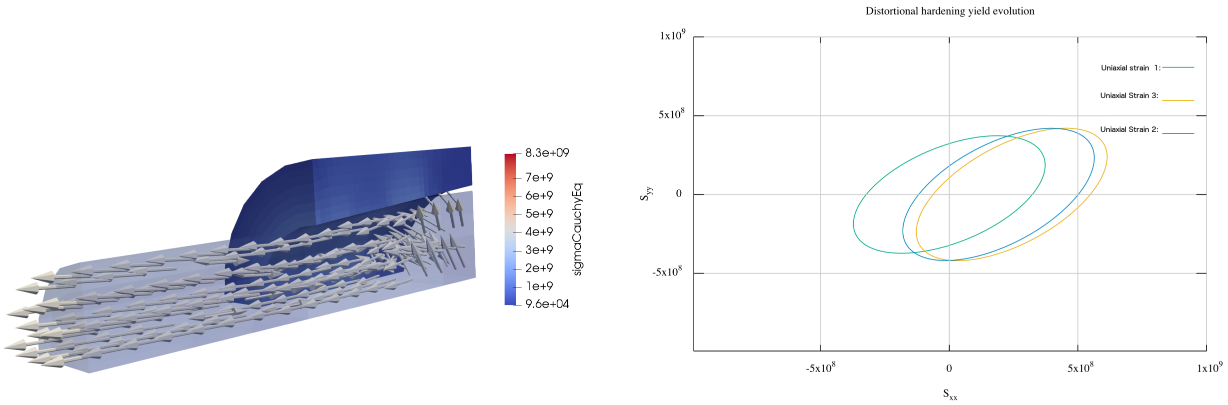


Figure 1: An example of special wire geometry where advanced material models find application.

Implemented material models

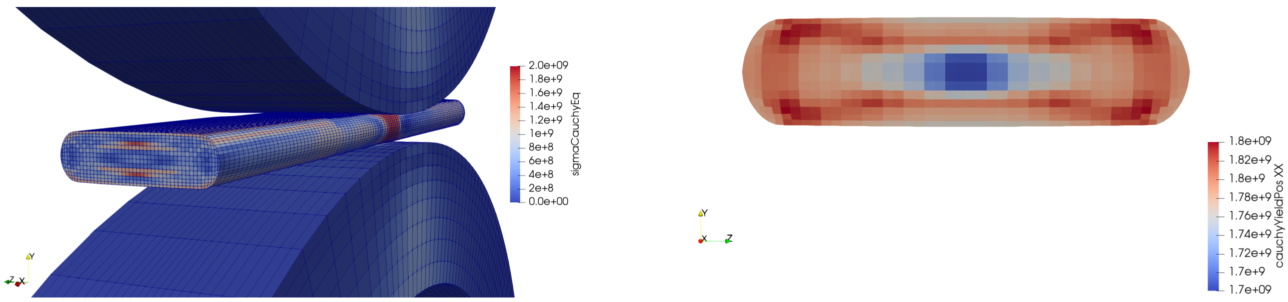
From the vast array of advanced material models that exist, three were selected and implemented within OpenFOAM. The choice of these models were made due to the original authors appreciation for numerical efficiency, which is often secondary to model development. The models selected for implementation are given in the works of [6][7][8]. The most advanced model studied being that of distortional hardening, with the ability to predict evolving anisotropy of the yield-locus as seen in Figure 2b. This model was used to predict the geometry of flat-rolled wire in Figure 3b.

Additionally, a material model with some basis in the physical characteristics of pearlitic steel was developed and implemented by the current authors. This plasticity model was inspired from existing works such as [9][10][11], which



(a) Formation of a material texture during drawing **(b) Evolution of the yield-locus during drawing**

Figure 2: Advanced material models



(a) Flat rolled wire **(b) Distribution of the axial yield-strength**

Figure 3: Simulation of flat-rolling with an advanced material model

aim to capture the material reorientation of the crystal microstructure. A simulation of this material reorientation for wire drawing can be seen in Figure 2a.

The numerical implementation of plasticity models almost always requires the solution of a differential-algebraic system. The differential equations describing the material history parameter evolution must be integrated whilst maintaining the condition that the stress-state either lies upon the yield-surface (indicating plastic flow) or within its boundary (indicating elastic deformation). The use of a backwards Euler integration scheme for the history variable evolution results in the solution of a system of non-linear equations.

Automatic differentiation (AD) was found to be a useful tool that enabled the quick calculation of the Jacobian for each material model implemented. The AD library Fadbad [12] was used for this purpose. The use of templated tensor types in OpenFOAM allowed easy integration with this package.

Acknowledgments

The authors thank the support of NV Bekaert for funding this project, and the Irish Centre for High-end Computing for use of their facilities [13].

References

[1] K. Maneeratana, "Development of the finite volume method for non-linear structural applications," Ph.D. dissertation, Imperial College London, 2000.

[2] P. Cardiff, Ž. Tuković, P. D. Jaeger, M. Clancy, and A. Ivanković, "A lagrangian cell-centred finite volume method for metal forming simulation," *International journal for numerical methods in engineering*, vol. 109, no. 13, pp. 1777–1803, 2017.

[3] T. Massé, Y. Chastel, P. Montmitonnet, C. Bobadilla, N. Persem, and S. Foissey, “Impact of mechanical anisotropy on the geometry of flat-rolled fully pearlitic steel wires,” *Journal of Materials Processing Technology*, vol. 211, no. 1, pp. 103–112, 2011.

[4] B. Plunkett, O. Cazacu, and F. Barlat, “Orthotropic yield criteria for description of the anisotropy in tension and compression of sheet metals,” *International Journal of Plasticity*, vol. 24, no. 5, pp. 847–866, 2008.

[5] M. Kapp, A. Hohenwarter, S. Wurster, B. Yang, and R. Pippan, “Anisotropic deformation characteristics of an ultrafine-and nanolamellar pearlitic steel,” *Acta Materialia*, vol. 106, pp. 239–248, 2016.

[6] A. Bartels and J. Mosler, “On the numerical implementation of thermomechanically coupled distortional hardening,” *International Journal of Plasticity*, vol. 96, pp. 182–209, 2017.

[7] P. Papadopoulos and J. Lu, “On the formulation and numerical solution of problems in anisotropic finite plasticity,” *Computer Methods in Applied Mechanics and Engineering*, vol. 190, no. 37, pp. 4889–4910, 2001.

[8] M. Á. Caminero, F. J. Montáns, and K.-J. Bathe, “Modeling large strain anisotropic elasto-plasticity with logarithmic strain and stress measures,” *Computers & Structures*, vol. 89, no. 11, pp. 826–843, 2011.

[9] J. G. Sevillano, “On the yield and flow stress of lamellar pearlite,” *Pergamon Press Ltd,*, pp. 819–824, 1980.

[10] G. Johansson, A. Menzel, and K. Runesson, “Modeling of anisotropic inelasticity in pearlitic steel at large strains due to deformation induced substructure evolution,” *European Journal of Mechanics-A/Solids*, vol. 24, no. 6, pp. 899–918, 2005.

[11] J. Alkorta, J. Martínez-Esnaola, P. de Jaeger, and J. G. Sevillano, “New mesoscopic constitutive model for deformation of pearlitic steels up to moderate strains,” in *IOP Conference Series: Materials Science and Engineering*, vol. 219, no. 1. IOP Publishing, 2017, p. 012010.

[12] C. Bendtsen and O. Stauning, “Fadbad, a flexible c++ package for automatic differentiation,” Tech. Rep., 1996.

[13] Irish Centre for High End Computing (ICHEC), “Fionn supercomputer,” http://www.ichec.ie, 2012.