IMPROVEMENTS TO THE EPSILON-ALPHA POROSITY MODEL FOR IMPACT SIMULATIONS.
G. S. Collins¹, H. J. Melosh², C. R. Wilson³ and K. Wünnemann², ¹Impacts and Astromaterials Research Centre, Dept. Earth Science and Engineering, Imperial College London, London SW7 2AZ, UK (g.collins@imperial.ac.uk), ²Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, USA, ³Museum für Naturkunde, Leibniz-Institute at the Humboldt University, D-10099 Berlin, Germany.

Introduction: Porosity is an important property of many small solar system objects. Results of the Deep Impact Experiment, for example, suggest that the impacted comet may be as much as 75% pore space [1]. It has long been known that porosity has a strong influence on shock wave attenuation and shock heating in hypervelocity impacts [2]. The compaction of a substantial volume of pore space can dramatically decrease the peak shock pressure and increase the post-shock temperature of impact-processed materials. Hence, pore collapse may play a major role in disruption, melt and vapor production, momentum transfer and crater formation, when solar system bodies collide.

Porosity model: A popular approach for modeling porous compaction in cases where pores are too small to be modeled explicitly is the p-α model [3,4]. In this model, compaction is quantified by distension (α; the ratio of solid density to bulk density), which is equivalent to 1/(1-porosity). If the distension is known, the density of the solid matrix component can be computed from the product of the bulk density and the distension. A conventional nonporous equation of state can then be used to compute the pressure in the solid matrix material from the solid material density and the specific internal energy. The pressure in the bulk porous material is then defined as the pressure in the solid matrix component divided by the distension. The advantage of this formulation is that the same equation of state (table or formulae) can be used to compute the pressure in the solid component of a porous material as it was used for a nonporous material of the same composition. The only additional requirement to compute the thermodynamic state of a porous material is to derive the distension from another state variable; the so-called compaction function.

In the p-α model the compaction function defines the distension in terms of pressure, which conveniently expresses exactly what is measured in laboratory crush experiments. However, due to the interdependence of pressure and distension, implementation of the p-α model in a hydrocode often requires iterative subcycling to find both simultaneously [5]. An alternative approach, called the ε-α model, is to compute the distension from the volume strain [6]. As the volume strain is usually known prior to computing the pressure, this approach avoids the need for expensive subcycling making it attractive from the perspective of hydrocode efficiency. Wünnemann et al. [6] showed that a simple exponential relationship between distension and volume strain provides a good description of static and dynamic crushing of low porosity materials.

Model Improvement: A limitation of the original ε-α model is that it prescribes a form for the compaction function that does not allow for the solid part of the porous material to expand relative to its initial density. In other words, it assumes that the volume strain is entirely mechanical (due to compression and compaction) and that no component of the volume strain is due to thermal expansion. For low (<50%) porosity materials this assumption is perfectly adequate, but for highly porous materials the extreme heating caused by pore-space collapse during compaction can cause significant expansion of the solid component of the porous material. In such cases the original ε-α model does not correctly predict the shape of the Hugoniot curve at high pressure.

To improve the treatment of highly porous materials in planetary-scale impact simulations, we have modified the ε-α model to account for thermal expansion of the matrix. To do this, we compute the volume strain due to thermal expansion of the matrix and subtract this from the total volume strain to give the mechanical volume strain needed by the ε-α model. The thermal volume strain εₜₜ is computed from the change in specific internal energy E using the approximate relationship:

$$\epsilon_t = \Gamma_\alpha/c_0^2 (E-E_0)$$

Where Γ₀ is the Gruneisen parameter and c₀ is the bulk sound speed of the solid matrix material in the reference state. Although approximate, the improved ε-α model provides a satisfactory description of porous compaction for initial porosities up to 80%. Such high porosities are typical of many known asteroids and comets, as well as the planetesimals that accreted to form the terrestrial planets and satellites. Moreover, this simple modification is easily implemented into a hydrocode and preserves the efficiency advantage of a strain-based compaction function.

Validation: Figure 1 shows that the improved ε-α model correctly predicts the shape of the Hugoniot curve for high porosity materials and demonstrates the good agreement between Hugoniot data for porous iron and numerically computed Hugoniot curves using the improved ε-α model (coupled with the Tillotson equation of state for solid iron) for initial porosities up to...
Further validation experiments are ongoing to test the hydrocode implementation of the improved compaction model.

Figure 1 A comparison between Hugoniot data for porous iron and curves calculated using the improved ε-α model. The agreement between the model and experimental data is good for initial porosities up to 80%.

**Dilatancy:** A further improvement of the ε-α porosity model is to relate porosity to shear strain, as well as volume strain. During crater formation, shear deformation of geologic materials with low initial porosity results in an increase in pore space caused by fracturing and the rearrangement of grains as they move over one another—a process known as dilatancy or bulking. For geologic materials with a high initial porosity, on the other hand, the reverse occurs. Such materials have extremely skeletal matrices, with critical support for the pore spaces in very few places. As this material is sheared and fractures, these critical bonds are broken and the unsupported pore space collapses. We are developing a dilatancy model to account for both of these processes. With continued shearing, both high and low porosity materials will tend to a “critically dilatant” distension \( \sigma_{\text{crit}} \). Our model relates distension to plastic shear strain through a dilatational pressure increment that is positive when distension is less than the critical state and negative when it is greater than the critical state.

**Results:** The original ε-α model was used in the iSALE hydrocode to investigate the effect of low-moderate target porosity on cratering efficiency [6], melt production [7] and ejection velocity. Results of those studies show that, for the same impactor properties, craters formed in porous targets are smaller (in volume and diameter) than those formed in nonporous targets. In addition, ejection velocities and the momenta of ejecta thrown from the growing crater are lower when the target is porous. At the same time, the presence of porosity significantly reduces the critical pressure required for shock melting, which enhances melt production in impacts.

Using the improvements to the ε-α model described here, we extended the results of these studies to porosities between 50 and 80%. Figure 2 shows the reduction in cratering efficiency with increasing target porosity, as determined by a suite of iSALE impact simulations and laboratory experiments in a centrifuge [9]. The model results tend to over-estimate crater volume compared to the experiments.

Figure 2 Cratering efficiency (cratered mass/impactor mass) as a function of porosity for suite of iSALE simulations and laboratory experiments [9].

**Acknowledgements** We gratefully acknowledge Boris Ivanov and Dirk Elbeshausen for their help in the development of iSALE and Keith Holsapple for stimulating discussion about porosity algorithms. GSC was funded by NERC Fellowship grant: NE/E013589/1; KW was funded by Helmholtz Alliance grant “Planetary Evolution and Life”. HJM was funded by NASA grant NNX08AM21G.