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On the modelling of compaction in planetesimals

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Abstract

Compaction of planetesimals is an important process that influences the interior structure and the thermal evolution of asteroid belt members. To model this process, however, typically a simplified approach has been assumed which reduces the porosity in some temperature interval, e. g. between 670 K and 700 K[1,2,3] - an assumption that neglects the pressure dependence of the porosity loss. In the present study, we compare a temperature dependent compaction approach with the temperature and pressure dependent one, for which varying material structures and varying methods of the computation of the effective stress are applied.

1. Model

Investigations of the structure of chondritic meteorites reveal significant variation in the average porosity between different samples[4] suggesting that they formed at different depths in a regolith zone of the respective parent body. The average porosities (0-27 % for H chondrites, 0-14 % for L chondrites and 0-18 % for LL chondrites) are small compared to the average porosity of a random loose or a random close packing (the latter being 44 % and 36 %). However, those random packings should be expected for the objects that accreted from dust in the protoplanetary nebula and did not experience compaction due to radiogenic heating. Here we investigate the loss of porosity using the thermal evolution model from [5] which includes compaction due to hot pressing[6] where the effective stress is calculated according to the geometric deformation theory from [7] and [8], adopting four different packings of dust grains (cubic, orthorhombic, rhombohedral and body-centred cubic). As an approximation we assume that the grains are equally sized spheres with some initial radius R_0, arranged in a regular three dimensional array. Four basic systems are defined by the geometric arrangement of the grains and the coordination number (the number Z of the contact points, an average value for equally sized spheres). In the simple cubic packing every grain has four neighbours in a horizontal layer and additional two above and below. Orthorhombic packing corresponds to six neighbours in a layer (plus 2 above and below). The rhombohedral packing has coordination number 12 and the body-centred cubic packing 8. For the present study the code has been supplemented with a module which reduces porosity linearly between 670 and 700 K (temperature-dependent only). Interested in thermal metamorphism without melting, we consider bodies with maximum temperatures of ≤ 1425 K (the solidus temperature of the silicate phase).

One of the most common forms of plastic flow is power law creep which describes the relation between the steady-state strain rate $d\varepsilon/dt$ and the effective stress during hot pressing: $d\varepsilon/dt=C\sigma_1^n$, with the stress σ_1 acting during creep, the material constant n, the function of temperature $C = C(T)$, and the time t. The strain rate during densification of powder can be given in terms of the rate of change of the relative density $D=1-\phi$ (or of the porosity ϕ) as

$$\frac{d\varepsilon}{dt}=-\frac{dl}{ldt}=\frac{1}{D}\frac{dD}{dt} \qquad (1) .$$

This is an approximation on the strain rate during densification of a powder compact of the height l in a die and can be applied in the first approximation to small planetary bodies. By setting

$$\frac{1}{D}\frac{dD}{dt}=C\sigma_1^n \qquad (2)$$

we obtain

$$\frac{\partial \log(1-\phi)}{\partial t}=\frac{1}{D}\frac{dD}{dt}=C\sigma_1^n \qquad (4)$$

where C and n need to be determined experimentally and σ_1 needs to be computed with respect to the infinitesimal/intrinsic geometry of the material. Thereby, σ_1 changes with the relative density during compaction. The effective stress during hot pressing is not equal to the applied stress σ_0 and depends on the porosity ϕ. Frequently, an inversely linear dependence $\sigma_1=\sigma_0(1-\phi)^{-1}$ on the relative density is used, as suggested by [9]. Thereby, any specific intrinsic geometry of the material is neglected. The latter is accounted for in the approach of [8]:

$$\sigma_1 = \sigma_0 \alpha_1^{-1} \left(D^{2/3} \beta_1^{2/3} R^2 - 1 \right)^{-1}, \quad (5)$$

which we adopt in the present study (here R is radius of a deformed grain). The effective stress from Eqn. (5) (see Fig. 1) contains the parameters α_1 and β_1 which reflect the assumptions on the packing of dust grains. Combination of Eqns. (4) and (5) yields

$$\frac{\partial \log(1-\phi)}{\partial t} = C \left[\sigma_0 \alpha_1^{-1} \left(D^{2/3} \beta_1^{2/3} R^2 - 1 \right)^{-1} \right]^n \quad (6)$$

The parameters $C = C(T)$ and n which depend on the temperature and material properties (e.g. activation energy) are derived from the experiments of creep of olivine during hot pressing[6]: $C(T) = Bb^{-3}exp(-E/RT)$, $n \approx 3/2$. Here, B is a constant $\approx 1.6\times10^{-5}$ - 5.4×10^{-5}, E = 85±29 kcal mol^{-1} is the activation energy, R is the gas constant and b is the initial grain radius.

2. Results

From the approach described above, we conclude that the temperature at which compaction takes place depends strongly on the size of the planetesimal.

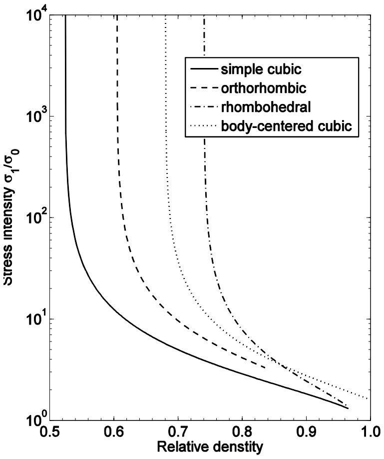

Fig. 1. The stress intensity for the adopted packings plotted against porosity.

Only in a rather narrow parameter space it occurs between 670 and 700 K (considering H-chondritic material). Depending on the pressure, initial grain size, activation energy and initial porosity, the proper temperature interval is rather 600 - 1200 K. Different temperature intervals follow for the four packings utilised in the present study as compared to the temperature dependent approach. Especially for small bodies (radius ≈ O(1) km) the temperature evolution and final porosity profiles deviate considerably (gaps of over 40 % between the maximum temperatures were observed). Also, the material properties play an important role, e.g., for planetesimals containing hydrated silicates or ice, an activation energy, which are smaller by almost one order of magnitude than the value adopted for H-chondrites leads to compaction at temperatures even below 500 K. In our simulations, smaller initial grain size favours compaction, e.g., a body with the radius of 60 km which formed at 5.5 Ma after the formation of the calcium-aluminium-rich inclusions with an initial porosity of 40 %, compacts to an average porosity of 13 % for the initial grain size b of 10^{-7} m, and does not compact at all for $b=10^{-5}$ m (having maximum temperatures ≤ 800 K in both cases). This identifies a further key parameter.

3. Conclusions

The compaction of planetesimals has a strong effect on the evolution, final structure and the cooling history of a planetesimal. The simplified approximation by the loss of porosity between 670 K and 700 K should not be used, as it neglects the effect of pressure and material properties – compaction is overestimated predicting too low final porosities and thus an unrealistic fast cooling.

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