Extensional necking instabilities in Newtonian and non-Newtonian material: modeling the formation of Ganymede's grooved terrain. M.T. Bland and A.P. Showman

Overview: Ganymede's pervasive 5-10 km-wavelength grooves have been suggested to result from a necking instability during an epoch of lithospheric extension, but to date few quantitative studies of groove formation have been performed. We present two-dimensional numerical models of necking instabilities under conditions that are appropriate to Ganymede at the time of groove formation. Preliminary simulations indicate that extensional necking instabilities can occur under a range of conditions, many of which may be relevant to Ganymede. The form of the surface topography produced by these instabilities varies as a function of the strain rate, amount of extension, initial topographic perturbation, and rheological parameters.

The Model: We use the two-dimensional, finite-element code Tekton to simulate the extension of a stiff surface layer overlying a ductile substrate. Newtonian, power-law and plastic flow regimes have been explored. The power-law regime employs recent laboratory data for both dislocation creep and grain-boundary-sliding flow mechanisms while the plastic domain utilizes a Drucker-Prager yield criterion appropriate for rock-like material. The nominal domain size is 100 km long and 24 km deep, which allow us to span several long-wavelength grooves yet still resolve individual short-wavelength grooves. Free parameters in the model include the strain rate, temperature gradient, rheology, and initial perturbation.

Results: Extension of the domain described above results in the formation of a necking instability. Surface morphologies produced by the growth of the instability are consistent with Ganymede's grooved terrain. However the growth of the instability is a strong function of the rheologic regime.

Newtonian Rheology. While the mechanical behavior of an icy lithosphere is not well described by a Newtonian rheology, modeling such a case provides an important baseline for comparison to more complex power-law rheologies. In these cases it has been found that at high strains, the surface morphologies produced are consistent with Ganymede's grooved terrain. After 30% extension of the domain, simulated grooves have amplitudes of 50 m to 450 m and wavelengths of 10 km to 30 km. Examination of the strain rate and temperature gradient parameter space has shown that both the dominant wavelength produced by the instability and the groove amplitudes are highly dependent on the temperature gradient and strain rate. Both the largest groove amplitudes and longest wavelengths are produced at high strain rates and modest temperature gradients. While no combination of strain rate and temperature gradient was found that would match both the amplitude and wavelength of Ganymede's grooves, the conditions that produce a surface with the most consistent morphology have strain rates of 10^{-14} s^{-1} and temperature gradients of 5 K/km (which have too long a wavelength) or 45 K/km (which have too low an amplitude). Notably the formation of the necking instability is independent of the initial perturbation imposed on the system.

Power-law Rheology. The growth of necking instabilities in a power-law flow regime is significantly more complex than in the Newtonian regime. In the power-law regime the growth of the instability is strongly dependent on the initial perturbation assumed. Thus short wavelength perturbations produce short wavelength grooves while long wavelength perturbations produce long wavelength grooves. Furthermore, perturbation growth is generally inhibited relative to growth in the Newtonian regime. Only the longest wavelengths (~100 km) have growth factors large enough to produce amplitudes consistent with the Ganymede's grooves. However, such long wavelengths are inconsistent with the 5-10 km periodicity of the grooved terrain.

Plastic Rheology. The inclusion of plastic flow allows for realistic modeling of brittle behavior in the near surface layers of an icy lithosphere. In general, a plastic layer greatly enhances the amplitude of necking instability but decreases its periodicity. Despite this, modeled profiles of surface morphology are consistent with photoclinometric profiles created from voyager data. In such models groove wavelengths decrease with increasing temperature gradient while groove amplitudes increase with decreasing strain rate. The most consistent models have strain rates of 10^{-14} s^{-1} and temperature gradients of 45 K/km. It should be noted that the plastic flow properties of low temperature ice are poorly constrained. This introduces significant uncertainty into the results of the model. These uncertainties are currently under investigation.

Conclusions and Future Work: We have produced numerical models of the formation of Ganymede's grooved terrain via an extensional necking instability. The most consistent models require a plastic surface layer underlain by a non-Newtonian viscous layer with a temperature gradient of 15 K/km or greater and a strain rate of 10^{-14} s^{-1}. Future work will focus on refining our understanding of the necking instability process in each rheological regime.

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