

a much slower variation of viscosity with depth than that derived from diffusion creep. Specifically, lower mantle viscosity was no higher than about 10^{23} poise, or several orders of magnitude lower than that given by Macdonald. This was not too significant in itself, for Dicke (*J. geophys. Res.*, **74**, 5895; 1969) had recently obtained a lower mantle viscosity of 10^{22} poise from an analysis of the equatorial bulge and Goldreich and Toomre (*J. geophys. Res.*, **74**, 2555; 1969) had suggested a value of 10^{22} – 10^{24} poise to explain polar wandering.

But as Brennen (*J. geophys. Res.*, **79**, 3993; 1974) now points out, the more important problem is that the Weertman curve is apparently inconsistent with the original isostatic recovery data upon which McConnell's model was based. To discover whether the theoretical model of Weertman may be reconciled with the observational isostatic data, Brennen has thus carried out a hydrodynamic analysis of isostatic recovery flow in the mantle. He concludes, first, that the rapid increase in viscosity with depth demonstrated by McConnell and others is simply a spurious effect resulting from the incorrect assumption of Newtonian flow. The real increase of viscosity is much slower and in general agreement with that predicted by Weertman; certainly the strain rates are higher than Weertman's critical value for the onset of dislocation motion. The best fit between the data and the model is then given by a mantle viscosity which increases with depth as $\exp(5 \times 10^{-4}z)$, where z is the depth in kilometres. In short, not only may observation and theory be reconciled, the reconciliation may be taken as evidence that the theory is substantially correct—that is, that mantle flow is non-Newtonian and arises largely from dislocation motion.

Glassy alloys

from Robert W. Cahn

SINCE times prehistoric, metallurgists have quenched iron or steel in water to harden them. Nowadays they know that the hardness is linked to the presence of a metastable crystal form, containing more carbon in solution than iron should at ambient temperature. This crystal form, martensite, has attracted immense research attention, because the genesis, hardness and breakdown of martensite are all absorbingly interesting scientific problems.

It is surprising, then, that it was not until 1960 that anyone reflected seriously upon the possibility of improving on the fastest rate of quenching then available: dropping a sliver of steel into a bucket of water might cool it at a measly rate of perhaps $1,000^\circ\text{C}$

per second. It was always a fair guess that the faster one can quench an alloy, the less chance it has to convert to the equilibrium structure and the more likely it is to be fixed in some abnormal and potentially intriguing crystal structure. Yet no one seriously went into the matter until Pol Duwez at California Institute of Technology, in 1960, recognised that the only effective way to speed up cooling rates substantially was to start from the liquid state. He conceived the idea of blasting a small molten drop of alloy by means of a gaseous shock wave against a sloping piece of copper: the technique soon acquired, over the opposition of its fastidious inventor, the onomatopoeic designation 'splat-cooling'. The drop is atomised and then 'splatted' out into a thin liquid layer, which gives up its latent heat to the copper in a very short space of time.

We now know that splat-cooling and related techniques can generate cooling rates from 10^6 to as much as 10^9 degrees C per second. A complete new metallurgy has been created: highly supersaturated solid solutions, a whole zoo of new metastable crystal structures, and glassy alloys have all been developed. Several hundred research papers have recently been reviewed by Jones (*Rep. Prog. Phys.*, **36**, 1425; 1973): the work covers not only structures but also anomalous mechanical, electrical and magnetic properties.

Of late, there has been a sudden burst of research on the least understood of the new metallurgical species, glassy alloys. The interest stemmed primarily from the work of David Turnbull at Harvard. Turnbull is renowned for his studies on crystallisation of molten metals, in particular his classic studies on the freezing of molten microspheres. It was a natural transition for him to examine the conditions for the congealing of liquid alloys into a glassy state, uncrystallised. He adopted one of Duwez's early alloys, Pd-Si, which could readily be liquid-quenched to a glassy state, and studied its crystallisation on reheating (for example, Chen and Turnbull, *Acta Met.*, **17**, 1021; 1969). Turnbull's ideas then inspired a metallurgist, John Gilman, to more systematic studies. It had already been recognised that alloys of transition metals with metalloids were the most sluggish to crystallise and therefore aptest to form glasses. Gilman became research manager at Allied Chemical Corporation at Princeton and instituted a systematic programme of study. His colleagues, including several of Turnbull's former collaborators, examined a range of alloys based on nickel or iron or mixtures of both, with substantial additions of carbon, boron, phosphorus, silicon and aluminium. They standardised on the 'roller-

quenching' technique: a fine stream of molten alloy impinges on a pair of rollers, very rapidly rotating in contact, and a narrow continuous glassy ribbon emerges. These glasses typically have a glass transition temperature, T_g , in the range of 650–720 K, and a crystallisation temperature, T_c , some tens of degrees higher. Polk and Chen (*J. Non-Cryst. Solids*, **15**, 165; 1974) have recently reported on the characteristics of some of these alloys. One generalisation which emerges is that the stablest glasses—that is, those with the largest value of $(T_c - T_g)$ —are those which contain the lowest metalloid content consistent with glass formation. The metalloid solute seems to exert its crystallisation-inhibiting effect by a combination of simple jamming of metal atoms (because the small metalloids fill up the voids between the metal atoms) and strong bonding between solvent and solute, which inhibits displacive rearrangements. Typical compositions include $\text{Fe}_{75}\text{P}_{15}\text{C}_6\text{Al}_4$ and $\text{Fe}_{38.5}\text{Ni}_{38.5}\text{P}_{18}\text{B}_2\text{Al}_3$.

The glassy ribbons are extremely strong, with ultimate tensile strengths typically exceeding 200,000 pounds per square inch (Americans are incurably addicted to these venerable units). Several of these alloys, notably nickel-based alloys such as Ni-P-B-C-Al, when the roller-quenching rate was high enough, combined very high strength with measurable ductility (Chen and Polk, *J. Non-Cryst. Solids*, **15**, 174; 1974). This is a unique combination: normally very high strength goes with extreme brittleness, as with fine silicon or carbon fibres. The manufacturers expect to apply their ribbons to reinforcing functions, for instance in car tyres.

The physical mechanism underlying the limited ductility of the alloy glasses is also strikingly novel. Pampillo and Reimschuessel (*J. Mater. Sci.*, **9**, 718; 1974) have recently shown that the ribbons deform by a process akin to glide in a metallic crystal. Thin layers of alloy, inclined at 45° to the tensile axis, behave as if they were liquid and the two halves of the ribbon slide over each other. This is probably due to the incipient destruction of short-range (glassy) order and the consequential weakening of resistance to glide. Fracture initiates at several points and the cracks spread along an already defined glide plane, and eventually the cracks collide and the crystal tears apart, showing on the fracture surfaces a pattern of veins which mark the loci along which the cracks collided.

A great deal of work is now in progress on the properties, especially the mechanical behaviour, of these alloy glasses and a number of papers is expected soon in several journals, including the three cited in this survey.