

Materials with memory

H. Bargmann

hold the electrolyte. However the magnet surfaces are not flat and this makes the problem of positioning the anode difficult and also the probe wears away. Alternatively, it is possible to use a jet of electrolyte but then there is a high probability of corrosion.

The selected technique is to shim the magnets by sticking thin iron foils onto the pole surfaces in the required areas. The poles are there generally slightly concave in appearance and a male replica can be machined so that iron foils coated with araldite can be pressed into precise positions on the magnet and the resin cured by heating with an infrared source.

This is a simple way of modifying the magnet pole pieces and it has the advantage that, once the corrections have been made, new field measurements of the magnetic field can be carried out and further corrections applied, if necessary, without delay. The big problem is to make flat iron foils approximately 10 microns thick, 20 cm long and 2 cm wide.

To deposit this thickness of iron on, for example, a copper substrate is a relatively simple operation. However, when iron is plated it is not ductile like normal iron but very brittle. In addition, there are very high internal stresses between the plate and the substrate and if the copper is chemically dissolved in 1 % nitric acid to release the foil, the strip bends and the foil is cracked.

To overcome this a second layer of metal can be plated on top of the iron so that when the two layers are removed chemically at the same time the iron remains flat and unbroken. If the second layer is copper the rate of solution of the plated layer with respect to the rolled copper substrate is difficult to control. It was found by experiment that if a layer of nickel of controlled thickness is plated on the iron both the nickel and the copper can be dissolved at equivalent rates

in a sodium cyanide/sodium sulphate bath at 60 °C to produce a satisfactory foil. For a 10 µm iron foil, a nickel coating of 12 µm is needed (other thicknesses produce a cracked foil). The foils are still very brittle and have to be stress relieved before use.

The vacuum furnace in which heat treatment is carried out is in the West workshop while the foils are made in the Godet workshop and the first foils broke in transit. The stress relieving operation is carried out at temperatures between 700 and 900 °C and, since the foils must not be contaminated with either copper or nickel, stress relief cannot be carried out before the supporting layers are removed. The diffusion of nickel and copper into iron at low temperatures is very slow and by experiment it was found that heat treatment at 450 °C gives sufficient ductility to the foils that, after stripping, they can be transported safely. A final stage of vacuum heat treatment is carried out to give complete stress relief while the flatness of the foil is maintained.

Rapid heating or cooling results in temperature gradients in the foil which cause local plastic deformation. In addition, there is an allotropic change in iron at approximately 900 °C, and this can also cause plastic deformation. It is therefore necessary to heat and cool the foils slowly — a rate of 100 °C per hour was found to be satisfactory.

Having worked out how to steer between all these obstacles the workshops finally emerged with very thin, flat, stress free foils. Their cost is about one tenth of that asked by outside industry.

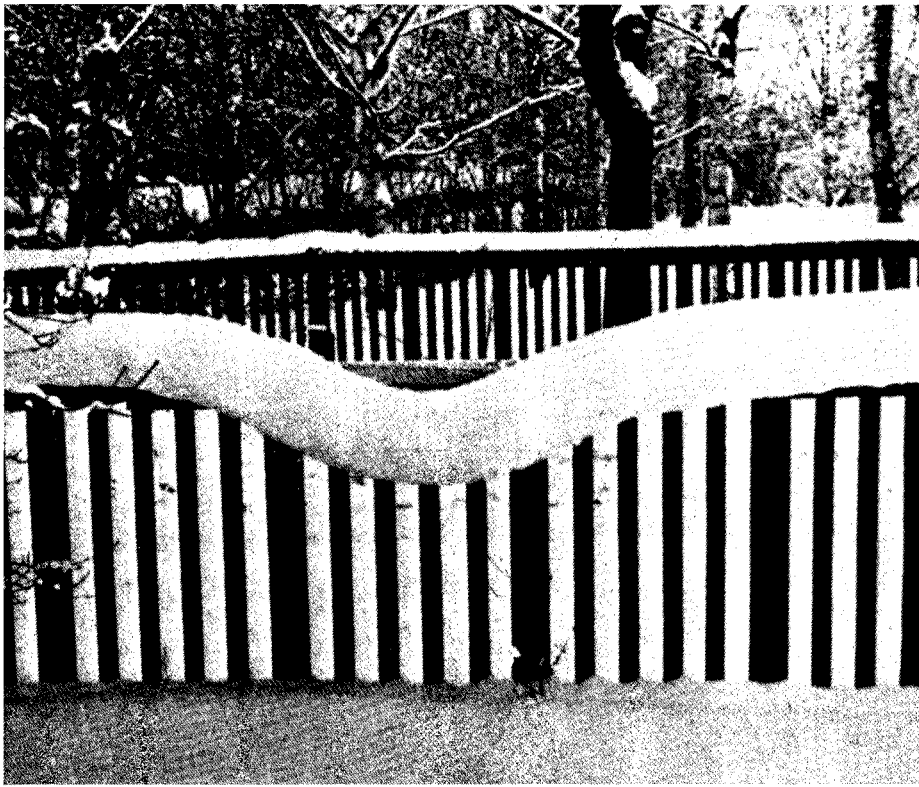
CERN has an obvious interest in the behaviour of materials and structures since it indulges in a great deal of mechanical construction and since it often exposes materials to rather extreme conditions. For the most part the necessary knowledge can be gathered from other fields where applied research has had to be done in order to use materials under still more extreme conditions. For example, a great deal of the necessary knowledge of how materials are going to behave in intense fluxes of radiation has been gathered in the nuclear reactor industry.

In recent years there has been particular interest in knowing how materials will stand up to loads. For instance, the ISR vacuum chambers at intersection regions, must withstand atmospheric pressure and yet must be extremely thin so as to allow the particles emerging from the interactions to reach the detectors outside with as little hindrance as possible. Also there have been material failures which were difficult to understand because large safety factors had been used in the design.

This led CERN to delve into some applied research to try to understand more deeply the behaviour of materials under stress. The research involved development of continuum mechanics — the mathematics of material behaviour.

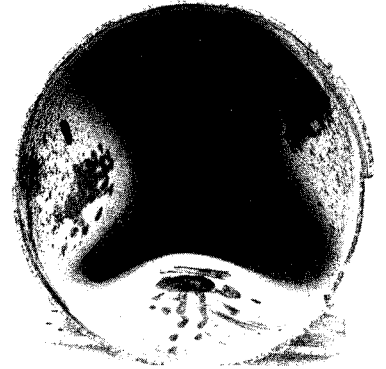
The celebrated theory of elasticity for solid bodies at elevated temperature frequently ceases to hold — the solid becomes viscoelastic. This is well known in modern aero-space engineering in reactor technology, and at CERN (in connection with certain equipment for special heat treatment of vacuum chambers). Viscoelastic solids do not respond only to the prevailing external influences but have a memory of what has happened to them during their entire past.

To some extent all structural ma-



An example of creep in crystalline material. The distortion of the snow cap on a garden fence in Sweden developed over a couple of days while the external influences on the snow remained virtually unchanged.
(Photo from F.K.G. Odquist's book 'Mathematical theory of creep and creep rupture' by courtesy of the Clarendon Press.)

A cylindrical shell 50 cm in diameter (made of niomic 75) which has creep buckled under atmospheric pressure after some time, despite no change in the stresses to which it was subjected and despite having a generous safety factor above the strength needed to resist ordinary elastic buckling.



materials possess the property of elasticity — the deformation of a body disappears when the load to which it has been subjected is removed. This was first announced for the special linear case in 1676 by Robert Hooke in the form of the anagram 'ceiiinosssttuv' which he spelled out two years later as 'Ut tensio sic vis' or 'The power of every springy body is proportional to its extension'. Practically all the great mathematical physicists of the following 300 years spent some time elaborating on the terms 'power', 'springy', and 'extension' and the theory of elasticity has found wide application in the solution of engineering problems during the past century. Many good engineers still believe in Hooke's law as the only law describing the behaviour of solid material. And if there are obvious deviations such as when, under constant load, plastic deformations increase with time (so-called 'creep') and so on... these faithful engineers take care of them by adding generous safety factors into their design.

Hooke's simple law is very often violated since creep effects under mechanical stress are observed in most solids. They are known in glass and bitumen (liquids, more or less, with very high viscosity) in concrete and in organic polymer. Organic polymer at low temperatures is a brittle, glassy solid. At elevated temperatures it is a rubbery material, like tangled

yarn. At still higher temperatures it becomes like a dish of spaghetti — additional viscous flow appears as the temperature increases, mainly due to shorter segments of chains of molecules sliding more easily over one another (viscoelasticity). Finally, the polymer turns into a viscous fluid. In all these cases, creep has a linear viscoelastic nature and hence can be treated by good clean mathematics.

Metal creep at elevated temperatures is mainly due to time-dependent plastic deformation of grains, grain-boundary sliding, or direct diffusion. Here, non-linear behaviour is predominant and it is also in the corresponding mathematics.

Modern continuum mechanics is now based on non-linear thermodynamics: from the first and second law (together with certain invariance requirements that the material properties should not depend on the observer) all the thermo-mechanical equations emerge and they severely restrict the possible laws describing material behaviour. What remains is still a wide class of functional relations — relating, for example, the present state of stress of a body with its previous history of deformation. From these relations it emerges that a solid at low temperatures obeying Hooke's law has a memory of one state only (the unstressed initial configuration) while at high temperatures, viscoelastic solids have memory of their



Handling high voltages

a) Voltage holding in vacuum

F. Rohrbach

entire past (frequently a fading memory as with human beings).

These problems and their mathematical treatment have been tackled at CERN since the solutions were not available from elsewhere. The following case will indicate that the solutions are certainly needed.

The cylindrical shell of a vacuum furnace at CERN buckled under external atmospheric pressure, at high temperature, after a finite time. The cylinder was more than adequately designed to resist ordinary (elastic) buckling having a safety factor of 20. The material was good high temperature steel with 80 % nickel, 15 % chromium, and 2 % iron. It should have easily withstood external atmospheric pressure at high temperature, and it did so perfectly for more than a year. But then it collapsed abruptly, as if it were made of paste, though the external conditions were unchanged. Gradual amplification of geometrical imperfections had accumulated and finally led to sudden collapse. The structure had memory and did not respond only to its prevailing load, but also to its loading history and collapsed when its present plus its entire history became too much.

CERN calculations are in excellent agreement with the observed failures and give precise advice on how to ensure safe constructions in the future. Similar problems occur frequently also in aerospace and nuclear reactor engineering and the CERN work will be useful there.

In addition to the specialized systems which are to be found around the large particle accelerators, there are many other devices which have to operate in vacuum and at high voltage. Apart from electrostatic separators, accelerating columns, deflectors and electrostatic septums, there are other applications such as cathode-ray tubes, electron microscopes, high-power cryolinks, generators for use in interstellar or lunar space, electron guns for industry... This range of applications led many university and industrial laboratories to make a great effort during the past decade to overcome the problems of insulation in vacuum, certain aspects of which remain obscure today.

At CERN the need to obtain good performance from the high voltage pre-injector of the PS and to achieve high-quality separated beams of secondary particles led to an intense programme of technological research beginning in 1961 in order to improve voltage holding in vacuum and to increase the reliability of the existing equipment. CERN thus had the opportunity to do pioneer work in this field.

To quote a few figures : in 1961, a maximum electric field of 55 to 60 kV/cm could be obtained using large (about a square metre) electrodes 10 cm apart ; in 1969, 110 to 120 kV/cm was being recorded under the same conditions. Yet this is still surprisingly far from the theoretical limit of 100 000 kV/cm !

An attempt was made to discover the mechanisms which lead to breakdown in vacuum and more especially in ultra-high vacuum (less than about 10^{-8} torr). By measuring the arc formation time accurately as a function of the voltage and the gap between two plane pure titanium discs, information was obtained on the role played in the breakdown mechanisms by field emission and by the impact of charged microparticles. This re-

search has shown that, depending on the gap between the electrodes, one or other of the phenomena predominates.

In the case of short gaps (less than about 10 mm), the electrical discharge is initiated by the explosion of a cathode micropoint (0.1 to 0.5 μm high), caused by too intense a field emission leading to thermal instability of the emitting point. At greater distances, it is the so-called microparticles (from 0.01 to 10 μm in diameter) that cause the breakdown when they are torn from the anode, accelerated (up to velocities of several km/s) and strike the cathode. The impact produces a microscopic flaw which is sufficient to initiate an intense electron emission causing spontaneous breakdown due to the creation of microscopic points.

There is a great difference in the time involved in these two types of mechanism ; in the case of short gaps, the breakdown lasts a few tens of nanoseconds whilst at greater distances, when the microparticle has to be formed as well, it is a matter of microseconds and even milliseconds. The mechanism of formation of microparticles is still under investigation but there can no longer be any doubt as to their existence. It is thought that, apart from the arc itself and the metal fusion that it causes, microparticles may also be created by a mechanism of accelerated surface diffusion at the anode under electron bombardment and the resultant anode heating : the electron bombardment is due to emission from the microscopic cathode points.

We now have a clearer understanding of why it is possible to improve the insulation in vacuum considerably by using cathodes coated in insulating metallic oxide (such as Al_2O_3) or glass ; the use of a cathode coated with an insulating layer prevents electron field emission.