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The Generation of Internal Stress and its Effects

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Abstract

Internal stresses may be generated continually in many polycrystalline materials. Their existence is manifest by changes in crystal defect concentration and arrangement, by surface observations, by macroscopic shape changes and particularly by alteration of mechanical properties when external stresses are simultaneously imposed.

Continual internal stress generation may arise from thermal cycling of materials with grains having anisotropic thermal expansion coefficients, from irradiation and from cycling through phase transformations. These different origins, however, produce essentially similar effects if an external stress is concurrently applied. A unified theoretical interpretation leads to approximate quantitative analyses in general accord with experimental results. In all cases, a permanent strain is induced proportional to the external stress providing this is less than about half the internal stress level. A “pseudo-creep” process is created, sometimes detrimental in weakening materials at temperatures low in relation to their melting points. Conversely, the linear and near linear relationships offer enhanced ductility and permit mechanical working of some materials that can otherwise be difficult to process. In some instances, ductility can be high enough for the behaviour to be referred to as “internal stress superplasticity” and there is scope for its exploitation.

Crystal anisotropy and internal stress generation

Many examples are available of internal stress generation by temperature changes in some polycrystalline materials. A demonstration of this, more than 60 years ago, was in the experimental studies of Boas and Honeycombe^{1,2}. Their work related to the properties and performance of tin-base and lead-base bearing alloys. Comparative study of these materials revealed substantial roughening with some cracking at the surface of the tin-base alloy after only a few thermal cycles between 30 and 350°C whereas such effects did not occur on the lead-base alloy even after 200 cycles.

These results were achieved consistently to show that that anisotropy of thermal expansion of non-cubic crystals within polycrystalline materials gives rise to internal stress with change of temperature³. The isotropic thermal expansion, implicit in cubic crystals such as lead, precludes these effects.

In early experiments, surface observations by optical microscopy provided the initial indication of internal stress generation by revealing deformation marks, identified as slip lines, mainly parallel within individual grains but changing direction at grain boundaries. Evidence of twinning was also often found. Occasionally, grain boundary migration was noted with boundary positions progressively delineated to mark their movement with each temperature cycle. These effects did not occur to the same extent in different metals and some of them could be absent. X-ray studies provided supporting information on the presence of internal stresses within individual grains. Recrystallisation was rarely observed during cycling treatment but in cadmium it was induced by high temperature annealing after many cycles.

The form of internal stress generated has now become classified as “Type 2 Residual Stress” where intergranular stresses are developed that vary over a grain scale⁴. Calculation of their magnitude⁵ relies first on knowledge of the anisotropic thermal expansion coefficients of single crystals of the material. In an externally stress free environment, a temperature change ΔT induces fractional dimensional increases ϵ_{ij} given by $\epsilon_{ij} = \alpha_{ij} \Delta T$ where the anisotropic thermal expansion coefficients are represented by α_{ij} which is a second rank tensor⁶. In a polycrystalline material, such free expansion is inhibited by the geometrical constraints imposed by the continuing contact of neighbouring grains with differing orientations. Calculations of internal stresses σ_{ij} , that vary on the scale of grain dimensions, depend on these constraints and are compounded by the orientational dependence of elastic moduli represented⁷ by a fourth rank tensor E_{ijkl} such that $\sigma_{ij} = E_{ijkl} \epsilon_{kl}$ where ϵ_{kl} are the constrained fractional grain dimensional changes.

Detailed analytical calculations pose major difficulties but numerical methods have been applied in simplified situations⁸. An estimate can be made of the magnitude σ_I of the average internal stress level⁵ by considering the difference $\Delta\alpha$ of thermal expansion coefficients in different crystallographic directions and multiplying this by an averaged value of Young’s modulus E and by the temperature change ΔT . Providing the material remains elastic, through such an approximate approach, we may write

$$\sigma_I \approx E \Delta\alpha \Delta T \quad (1)$$

For tin in its tetragonal form, along the two equivalent principal crystallographic directions the thermal expansion coefficient is $15.5 \times 10^{-6} \text{ K}^{-1}$ and in the third mutually perpendicular direction it is $30.5 \times 10^{-6} \text{ K}^{-1}$. Thus, $\Delta\alpha$ has a maximum value $15 \times 10^{-6} \text{ K}^{-1}$ and, with $E = 50 \text{ GPa}$, in this calculation based on elastic behaviour, a temperature change $\Delta T = 320 \text{ K}$ could induce a maximum internal stress of 240 MPa. This level is substantially above the value that would be sustained by elastic deformation, so the surface observations of Boas and Honeycombe, indicative of plastic deformation, are readily accounted for.

Moreover, when the yield stress is reached, the plastic strains arising during the upward and downward temperature changes during a thermal cycle are not fully reversible. Where there are no overall external stresses and the material has no preferred crystal orientation there is little macroscopic change of shape but internal stresses are manifest by lattice parameter variations and by microscopic surface changes.

In a material with preferred crystal orientation, however, macroscopic changes can occur on a larger scale. Particular attention has been given⁹ to the behaviour of the α (orthorhombic) phase of uranium because of its early importance in nuclear technology and its high crystallographic anisotropy. It has a large coefficients of thermal expansion in the [100] and [001] directions but a small negative coefficient along [010]. Since plastic deformation under the stresses induced by the upward and downward temperature changes are not reversible, depending on crystallographic texture, large permanent strains can be induced by ratchetting, with each thermal cycle adding an increment of deformation. As illustrated in Fig 1, in an as cast uranium bar with nearly random grain orientation, the overall length change is negligible. This is in contrast with the behaviour of a hot rolled bar with marked crystallographic texture, where similar temperature cycling results in substantial change in length. The most random crystallographic texture in such bars, coupled with the production of relatively fine grains, is obtained by quenching from the β -phase and this procedure is adopted to minimise this growth effect. Since the surface grains are less constrained, there is differential strain between each grain at the surface, creating a wrinkled appearance on a scale that increases linearly with grain size.

The effects of thermal cycling of material without preferred crystallographic orientation under external stress.

An important question arises of the effect of internal stresses when they are generated in a material to which an external stress is concurrently applied. An answer is facilitated by analogy with the case¹⁰ where internal stresses are created by neutron bombardment of randomly textured polycrystalline uranium causing this material to deform under very small external stress. After a time the internal stress reaches the yield stress σ_Y because of the orientational dependence of irradiation growth of individual grains. A somewhat similar situation occurs during temperature change ΔT sufficient to create an internal stress up to the level σ_Y . When a small external stress σ (sufficient only to cause elastic strain $\epsilon_e = \sigma / E$ in an otherwise stress free material) is applied, the elastic strain ϵ_e it creates is then converted to a plastic strain ϵ . This is initiated when $E\Delta\alpha \Delta T \approx \sigma_Y$. It follows that, after internal elastic strain σ_Y / E has been overcome,

$$\epsilon / \sigma \approx \Delta\alpha \Delta T / \sigma_Y. \quad (1)$$

If an internal stress exceeds σ_Y for every positive or negative change of temperature over a range ΔT , progressively large external strains can be built up in externally stressed thermally cycled polycrystalline materials with grains that have anisotropic thermal expansion coefficients. It is noted from equation (1) that

the strain is linearly dependent upon stress. This has proved to be an important feature, frequently relevant to commercial processing, and such aspects are considered later. It is noted that the strain produced is not directly related to time but to the rate of build up of the internal stress. Hence, it is inappropriate to describe this phenomenon as a creep process. It has been more suitably termed “pseudo-creep”.

If the build up of cyclic internal stresses is sustained at a uniform rate, the resultant strain can then be divided by an appropriate time interval and thus readily converted to a strain rate. This consideration is especially useful for materials under conditions for which the yield stress σ_Y cannot be clearly defined. In this case, it is convenient to determine a stress level σ_I to represent the multiaxial stress conditions pertaining to the internal stress. This can be determined from the Levy-von Mises equation ⁷ from which

$$(2/3) \sigma_I^2 = (\sigma'_{xx})^2 + (\sigma'_{yy})^2 + (\sigma'_{zz})^2 + 2(\sigma_{yz})^2 + 2(\sigma_{zx})^2 + 2(\sigma_{xy})^2 \quad (2)$$

Where σ_{yz} etc. are the shear components of the internal stress and σ'_{xx} etc. are tensile deviatoric components (the tensile stresses minus the hydrostatic component) given by

$$\sigma'_{xx} = \sigma_{xx} - (\sigma_{xx} + \sigma_{yy} + \sigma_{zz}) / 3 = (2/3) [\sigma_{xx} - (\sigma_{yy} + \sigma_{zz}) / 2] \quad (3)$$

Linking with the formula for power law creep ¹¹, we note that

$$\dot{\epsilon}_{xx} / \sigma'_{xx} = \dot{\epsilon}_{yy} / \sigma'_{yy} = \dot{\epsilon}_{zz} / \sigma'_{zz} = \dot{\epsilon}_{xx} / \sigma_{yz} = \dot{\epsilon}_{zx} / \sigma_{zx} = \dot{\epsilon}_{xx} / \sigma_{xy} = (3/2) A \sigma_I^{n-1} \quad (4)$$

where $\dot{\epsilon}_{yz}$ etc. are the shear components of the creep rate. A and n are constants in the power law creep equation.

It follows that, providing the internal stress σ_I can be sustained, a creep rate $\dot{\epsilon}$ is established in the direction of a small applied external stress σ , given by

$$\dot{\epsilon} = A \sigma_I^{n-1} \sigma \quad (5)$$

The linearity between $\dot{\epsilon}$ and σ breaks down if the magnitude of σ approaches σ_I and this aspect will be returned to later.

The effect of external stress on materials undergoing phase transformations.

Internal stresses may be created in materials whilst they are undergoing a phase transition ¹². There is a resultant change in volume and frequently in the shape of the material as it transforms from one phase into another.

If an external stress is applied, an additional increment of strain is produced in the direction of the stress. To account for this, an interpretation can be given ¹³ along lines previously discussed for the effect of internal stresses created by crystalline anisotropy whereby a critical feature lies in the conversion of elastic strain,

produced by the applied external stress, to a plastic strain when the internal stress reaches the yield stress.

Detailed analysis¹³ has shown that, in passing through each phase transformation, the permanent strain ε in the material caused by a small external stress σ is given by $\varepsilon = 5 \sigma (\Delta V / V) / 6 \sigma_y$ where $(\Delta V / V)$ is the fractional difference in volume between the two phases and σ_y is the yield strength of the weaker phase. The strain component caused by this volumetric difference is effectively eliminated by cycling both ways through the transformation. Hence, for each two-way cycle, the observed strain only arises from the external stress and the equation now becomes

$$\varepsilon = 5 \sigma (\Delta V / V) / 3 \sigma_y . \quad (6)$$

In the transformation regime it is not always possible to assign a value for the yield strength of the weaker phase as previously discussed in the section dealing with the effects of anisotropic thermal expansion coefficients. The situation with regard to phase transformation has been addressed¹³ with the conclusion that the modification of equation (6) to meet these circumstances takes the form

$$\varepsilon = 4 \sigma (\Delta V / V) [5n / (4n + 1)] / 3 \sigma_y \quad (7)$$

where the deviatoric component σ'_{ij} of an applied stress σ in a material under sustained internal stress σ_y would be sufficient to cause a creep rate $\dot{\varepsilon}_{ij} = (3/2) \sigma'_{ij} A \sigma_y^{n-1}$. This takes into account the multiaxial state of the internal stresses and is a generalised form of equation (5) that relates to the effect of a uniaxial external stress σ . It is noted that, macroscopically, the strain due to the external stress is produced only whilst the internal stress is maintained. This provides the connection between strain and strain rate. In practice, the mode of deformation of the weaker phase often lies between the two extremes of yield and creep but this problem is ameliorated by noting, in comparing equations (6) and (7), that they become identical when $\sigma \rightarrow \sigma_y$ and $n \rightarrow \infty$. The relationship between these parameters, noting their connection through the time duration of the internal stress, is illustrated in Fig 2

From the above equations, repeated cycling both ways through a phase transformation leads to the accumulation of increments of deformation that are each linearly dependent on the applied stress. This remains valid so long as this stress is substantially below the level of the internal stress sufficient for yield. The case where the applied stress approaches this stress has been examined¹⁴ to determine the value of σ / σ_y for which the deviation from linearity becomes significant. Theory is capable of estimating such deviation and is supported by a range of experimental results.(Fig.3). Determination of the conditions for the breakdown of the linear relationship is an important factor in utilising phase transformations in materials' processing.

Internal stress generation through chemical effects.

It has been demonstrated¹⁵ that internal stresses can be generated by chemical changes with the effects produced through chemical composition gradients having broadly similar features to those previously described when such stresses arise from anisotropy of thermal expansion or from phase changes. In the chemical case the internal stress is created in a direction perpendicular to the direction of movement of the diffusional interface.

Where the progressive chemical alteration of composition causes a phase change, notably large effects can arise. Such an instance¹⁶ occurs in the cyclic charging and discharging of hydrogen into materials under small loads at constant temperature. Each strain increment is proportional to the applied stress, providing this stress is small.

An example lies in the hydrogen charging of titanium at 860°C that causes transformation of the hexagonal closed packed α phase to the mechanically weaker body centred cubic β phase (Fig. 4). In this material it has also been shown¹⁷ that, without external loading, repeated charge and discharge results in the build up of some permanent strain by ratchetting whereby a strain increment that is not entirely reversible is induced with each cycle. When a small external stress is applied, it produces substantial and reproducible strain increments when the additional strain from the ratchetting is taken into account.

Some consequences of the above effects are considered next.

Practical implications of the influences of internal stress generation

There are some consequences of internal stress generation that present difficulties and require amelioration and others that can beneficially be exploited.

Amongst those that may be detrimental are the effects that can arise in materials with anisotropic crystal structure under irradiation when subjected to small loads. The most significant case, but one that provided a key¹⁰ to the interpretation of the influence of internal stress whatever its origins, lies in the effect of thermal neutron irradiation on the orthorhombic α – phase of uranium. Here, at modest temperatures, the deformation rate is substantially greater than anticipated from testing in a radiation-free environment. In making comparison between these deformation rates, under similar applied stresses, however, clear and important distinctions are necessary. Without irradiation, deformation is directly dependent on time and strongly dependent on temperature; with irradiation, deformation is dependent mainly on the duration and intensity of exposure to the irradiation. To make this distinction more widely recognised, the latter case is specifically termed “pseudo-creep” because the rate of deformation is not sustained when the uranium is removed from the irradiation environment. In the context of the present paper, the distinction can be made in more general terms by the statement that pseudo-creep is not directly dependent upon time but on the maintenance and duration of an internal stress.

Detrimental effects are generally less dramatic than those revealed by irradiation of uranium where the intense local heating through nuclear fission events and the consequent directed movement of interstitials and vacancies play a unique role. Nevertheless, problems can occur on a smaller scale in a wider range of circumstances. It is now clear that internal stress generation, whatever its origin can cause substantial weakening when a material is subjected to external loading.

There are many instances of such weakening leading to limitation of service life through the stresses induced by thermal cycling. A recent case¹⁸ arises in the operation of solid oxide fuel cells (SOFCs), especially when they are used intermittently. To overcome this problem, allowance must be made in their design to accommodate the resulting distortions.

In marked contrast to the detrimental effects mentioned, changes in mechanical properties brought about by internal stress generation can be used to good effect and there is increasing exploitation of the changes that can be induced.

The ability to generate internal stresses in materials by various means has been widely employed. This has been mainly through the facility it creates to permit large tensile strains to be produced by external stresses on materials for which ductility would otherwise be seriously limited. The underlying basis of this rests on the opportunity to alter mechanical properties to a form in which the rate of deformation varies linearly with the applied stress. This situation only applies when this stress is relatively small. Hence the importance, illustrated in Fig. 3, of the extent of deviation from linearity at higher stress levels.

In many instances, the increase in ductility, where the linear relationship holds, leads effectively to superplastic behaviour with many demonstrations available, as in Fig 5. This has become a wide field of investigation with increasing practical application. The particular form discussed in the present paper has been termed "Internal stress superplasticity" (ISS)^{19,20}. Notably, interest in this field has extended to composite materials^{21,22,23}, allowing shape changes in component fabrication processes that would be difficult or impossible by other means.

ISS continues to find niche applications. It has been shown, for example (Fig. 6), to be beneficial in allowing densification to be accelerated by thermal cycling during the hot pressing of powders²⁴ and accomplished with a reduction in overall energy consumption. In contrast with this application, its potential for the production of materials in different geometrical form has also been demonstrated, particularly to obtain light weight porous metallic structures. The production of titanium foam through the expansion of high-pressure argon bubbles has been enhanced by alternating changes of gas atmosphere from pure argon to an argon-hydrogen mixture creating internal stress by α/β phase change cycling²⁵.

Conclusions

Internal stresses may be continually created by a variety of methods. Where a material has grains of anisotropic crystallographic structure and thermal expansion coefficients, internal stresses inevitably arise on subjection to temperature

changes. When these changes are sufficiently large and grains are randomly oriented, the consequence of such stresses is mainly manifest by surface changes representative of the crystallographic modes of deformation. When there is preferred grain orientation, distortion can arise on a much larger scale, producing substantial overall strain through ratchetting on account of the lack of full reversibility of the deformation modes.

The presence of internal stresses markedly influences a material's response to external stress. A special case arises in neutron irradiation of α -uranium, with random crystallographic texture, through the intense effects of the fission process. Somewhat similar effects, however, occur when the internal stresses are produced by thermal cycling in many materials and composites with grain or component anisotropy. Comparable effects are noted in externally stressed materials when internal stresses are created by temperature cycling through phase changes.

There is experimental support for broadly similar theoretical analysis to all the above situations. In such analysis, a value for an effective yield stress was first sought to make quantitative comparisons and predictions. Whilst this remains an important parameter when it can be appropriately defined and measured, the theory has been extended to incorporate the situation where power law creep parameters have greater relevance. The value of this approach is further magnified by the realisation of a continuum of behaviour between the extremes of yield and creep that is amenable to analysis throughout the range.

A most significant feature of the consistency of experimental results and the unification of their interpretation, covering all situations where the ratio of external to internal stress is below some specific value, is that the strain rate is linearly related to the external stress in the creation of a pseudo-creep process. This feature can lead to difficulties. It implies that distortion can occur under external stresses lower than those where effects would be expected. In marked contrast, however, this linear relationship implies that, in any deformation processing, ductility is greatly enhanced. Material behaviour with such enhancement has been termed "internal stress superplasticity". This has proved to be an important property that can be exploited.

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Captions

Fig. 1 The effect of 850 cycles between 50 and 600°C on uranium bars 25 mm diameter. The left bar was cast and has negligible preferred crystal orientation. The right bar was hot rolled and has strong preferred orientation resulting in large growth on thermal cycling⁹.

Fig. 2 Noting that the strain rate induced by the external stress is operative only over the time period during which the internal stress is sustained, strain and strain rate are related through this specific time. Hence, an analogy can be drawn between the effect of increasing stress exponent n in power law creep, shown in Fig 2 (a) and the limiting value exemplified by the yield stress indicated in Fig 2 (b).

Fig. 3 Limit to the linear relation between normalised strain and applied stress for materials after a complete thermal cycle¹⁴ through a phase transition.

Fig. 4 Titanium-hydrogen phase diagram showing concentration range of hydrogen injection and removal cycles causing reversible α/β phase transitions¹⁶.

Fig. 5 Tensile ductility of 12% in a SiC whisker reinforced 6061 aluminium alloy at 450 C (middle picture) in contrast with 1400% elongation achieved in the same composite material (lower picture) with 36 cycles per hour between 100 and 450 C superimposed²⁰.
(Courtesy of Cambridge University Press).

Fig. 6 Enhancement of the densification of zinc by thermal cycling compared with isothermal compaction at the same pressure²⁴.