LIFE PREDICTION OF SOLDERS IN ELECTRONICS
(BENEFITING FROM PREVIOUS EXPERIENCE)

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ABSTRACT

Efficient structural design of soldered joints is becoming increasingly important as miniaturisation continues. The paper explores, from a materials standpoint, how life prediction approaches used for more conventional high temperature structural materials such as steels, nickel and titanium alloys, may be suitable for solders. In general, solders operating at around room temperature are more volatile in their behaviour than the comparator alloys at their usual service temperatures which may be as high as 1000°C. In particular, the reported values of modulus for solders exhibits a marked scatter and all their monotonic properties are sensitive to strain rate. While cooling rate after casting (and initial microstructure) appear to have little effect on high stress creep, pronounced differences arise when ageing or strain occurs prior to creep. Unusually, the fatigue life of solders is reduced by all types of dwell during strain-controlled cycling, and the extent of stress relaxation during dwells is large. The degree of microstructural instability is high and may merit closer attention in life prediction models than is necessary for other structural alloys.

KEYWORDS

Solders, life prediction, creep, fatigue, microstructural instability

INTRODUCTION

With electronics projected to become the largest global industry early in the next millennium and an estimated 10^{13} solder joints being produced per annum (Vincent and Humpston, 1994) the performance of the latter is receiving ever-growing attention. While processability/manufacturability of joints is a predominant consideration, two emerging issues are likely to become critical in the coming decade. These are:

(i) The continuing demand for component miniaturisation had led to a situation, particularly in Surface Mount Technology, in which solder joints have a structural role, in addition to providing electrical conduction paths. To guarantee structural integrity as joint sizes diminish (and service requirements increase) by over-conservative structural design is no longer feasible. An alternative approach is to adopt the design methodologies used for advanced technology applications (aerospace and nuclear power generation) although this has been hindered by the lack of appropriate data regarding mechanical behaviour of solder alloys.

(ii) The major constituent of most common solders is lead, a toxic material under notice from the environmental lobby for its abolition. It is likely that the kinetics of this process will be determined by political and economic pressures rather than purely technical considerations. Several candidate replacement alloys (many based upon tin) have been identified as possessing the necessary metallurgical, physical and processing characteristics. However, the level of knowledge and understanding of mechanical behaviour, which can subsequently be employed for life prediction purposes, for these new alloys is minimal.

The present paper examines, from a materials perspective, the proposition of transferring current life prediction approaches for high technology applications to the solder joint situation. Attention is focused on the generic materials context rather than the joint-specific geometry case, which computational stress and strain analyses can accommodate once the appropriate materials data and understanding are available. Only the eutectic, or near eutectic lead-tin solder will be considered since this system represents our best collection of knowledge of all solders. To establish 'points of contact' with conventional high temperature design, comparisons will be drawn with the behaviour of low alloy and stainless steels, titanium and nickel-base alloys, so providing coverage of the bulk of fossil fuel and nuclear power generation, together with engine interests. One objective will be to explore how the behavioural characteristics of these materials impinge upon life prediction and how this information may facilitate the task for solders.

The cornerstone for the comparability exercise between the behaviour of solder and that of the high temperature alloys mentioned above, is the homologous temperature (T_h = T/T_m in K) each experiences in typical service conditions. Figure 1 summarises these, and demonstrates, rather surprisingly at first sight, that the solder alloy at or around room temperature is as severely 'heated' as a nickel-base superalloy operating at some thousand degrees higher in absolute terms. The repercussions of this are accentuated time dependent mechanical and environmental susceptibility, together with a higher level of microstructural instability than exhibited by the more traditional high temperature alloys above.

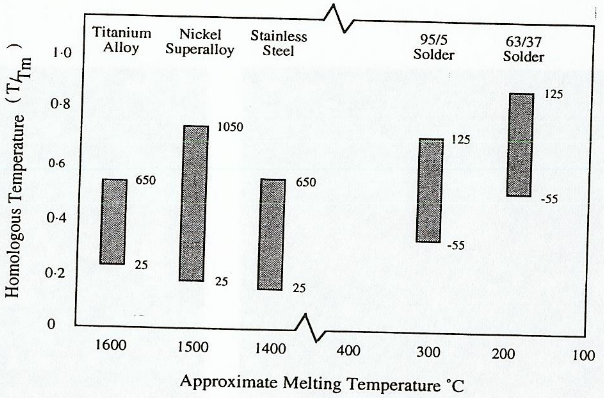

Fig. 1 Homologous temperatures for engineering alloys for their typical applications at high temperatures

In practice, joint failure generally arises as a consequence of thermomechanical fatigue (TMF) which develops when materials, with quite different coefficients of thermal expansion, experience fluctuating temperatures stemming from power switching or changes in external environment. Fully controlled and monitored TMF testing is extremely time-consuming and expensive, and all high temperature materials design approaches have been evolved on the basis of less complex data which additionally, provide a better insight into the metallurgical phenomena producing the observed behaviour (Plumbridge, 1996).

The following paragraphs briefly compare the monotonic, cyclic, creep and fatigue-creep characteristics of the materials and comment on their relevance with regard to utilisation for life prediction purposes.

MONOTONIC STRESS-STRAIN BEHAVIOUR

While many design methods are restricted to elastic behaviour, modern high temperature approaches are able to accommodate plasticity effects. Even here, there is usually an elastic component which is based upon the proportionality between stress and strain, and this modulus generally appears as a constant in stress analysis. Intuitively, we expect the value of a 'constant' to be so within a few percent but closer inspection reveals that a significant degree of variability exists. For 1Cr-Mo-V steel, reported values (Maier, 1987) of modulus show a ± 15 percent variation at room temperature and this increases to ± 30 percent at 550°C (T_h = 0.48). For Type 316 stainless steel (Verrilli, *et al*., 1992) a variation of around ± 15 percent is observed at ambient and 538°C (T_h = 0.48). Some 55 determinations of the modulus of Nimonic 75 at room temperature fell within a ± 13 percent band (Dean, *et al*., 1994). The spread of measured data arises from intrinsic inaccuracies of the measurement systems, specimen and test machine characteristics and test conditions (Dean, *et al*., 1994). A lack of uniformity in procedures and the absence of detailed information in the literature impedes a proper rationalisation of the problem. However, review of the published moduli values for solders indicates a far more serious difficulty since a variation in excess of five is observed (Table 1).

Table 1 - Reported Values of Young's Modulus for Solders

Alloy	Modulus (GPa)
60Sn-40Pb	38.6±4
"	16
"	15
"	30
"	35
"	43.4
63Sn-37Pb	32
"	30.34
"	5.7
"	20.5
"	11.1
	18.5

A factor which contributes to the above, and which has particular relevance to solders, is the effect of strain rate. The measured modulus of stainless steels at 816°C (T_h = 0.65) is unaffected by a change in strain rate of two orders of magnitude (Berling and Slot, 1969) whereas increasing the strain rate by this amount produces a 12 percent increase in a modulus of a 12Cr-Mo-V steel at 550°C (T_h = 0.55) (Hartnagel *et al.*, 1992). In contrast, the measured modulus of a near-eutectic solder at room temperature increases by almost 50 percent as a result of the same change in strain rate (Jen and

Majerus, 1991). It is clear from this that the selection of a value for modulus in expressions for life prediction and stress analysis is of considerable importance.

Solders exhibit a marked sensitivity to strain rate in their overall monotonic stress-strain response. Strength increases with more rapid straining and this effect is enhanced at higher temperatures (Fig. 2). Typically, an increase in strain rate by two orders of magnitude produces a fifty percent enhancement in tensile strength at room temperature whereas a fourfold strengthening may be may be observed at 170°C (Kawashima *et al.*, 1992). A similar trend exists with ductility although its magnitude does not appear as temperature-sensitive. Typical variations in strain to failure for two orders of magnitude change in strain rate are between fifty and a hundred percent. Ductility is often regarded as an indicator of resistance to high strain fatigue i.e. when the plastic component of total strain exceeds its elastic counterpart. For solders, where it is almost impossible to detect conventional elasticity on the stress-strain curve except at very high strain rates, typically above $10^2 s^{-1}$, this will be relevant in most circumstances. Across a wide spectrum of strain rates the yield strength of a lead-tin eutectic alloy has been shown to be less sensitive to strain rates above $10^{-2} s^{-1}$, and the domain of high sensitivity is highly dependent upon grain size (Clyens and Campbell, 1972). The magnitude of these effects is generally greater than those reported for the comparator alloys for which a change in strain rate of two orders of magnitude produces differences of a few percent in strength at room temperature (Loveday, 1992). Many stainless steels at around 600°C exhibit a substantial fall (2-3x) in strain to failure at strain rates below $10^{-5} s^{-1}$ (Marshall, 1984).

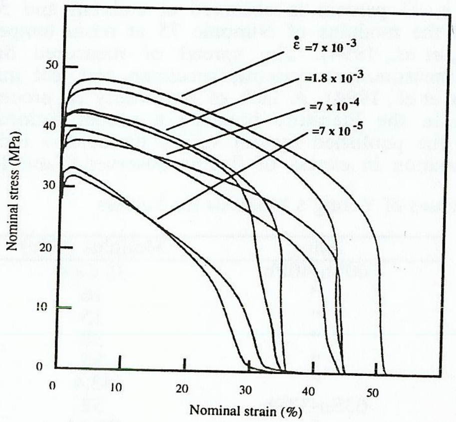

Fig. 2 Effect of strain rate on the stress-strain response of a eutectic solder at room temperature. (Kawashima et al, 1992).

To reduce interfacial energy levels and the supersaturation of tin, the as-cast structure of solder is unstable and, even at room temperature, the shear strengths of the eutectic and a 60Sn-40Pb alloy may fall by around 10 and 30 per cent respectively (Lampe, 1976; Whitmore *et al.*, 1990). Thereafter, changes are considerably slower. It has been proposed that variations in initial microstructure may be neutralised by such ambient temperature ageing since both rapid and slow cooled conditions attain a similar strength after 30 days at room temperature (Whitmore *et al.*, 1990). Severe ageing (200 days at 170°C) may halve the room temperature strength of eutectic soldered, plug in ring, joints (Anon A, 1987) at high crosshead rates (50 mm min^{-1}) but when the deformation is slow (0.05 mm min^{-1}) it is difficult to observe any influence of ageing.

Extended ageing produces only slight (<10%) strengthening in stainless steels in the temperature range 5-700°C, together with a reduction in ductility of up to 50 percent. Cold work produces effects of a similar magnitude, but in combination with prior ageing these are reduced (Plumbridge, 1996). While deformation effects are identical in lCr-Mo-V, the influence of ageing is insignificant in this, and the other heat treated comparator alloys, unless the exposure temperature is greater than that of the ageing temperature. For example, the strength of lCr-Mo-V was unaffected by ageing for 10^4h at 600°C since its heat treatment included an anneal at 700°C (Plumbridge and Bartlett, 1981).

CREEP BEHAVIOUR

Operating at such high homologous temperatures, it is inevitable that the creep behaviour of solder alloys will be a significant factor in determining joint performance. Since joints are formed in-situ, then it is probable that their initial condition, or microstructure, will vary both from component to component (according to the sizes and thermal conductivities of the joint elements) and more locally, within a single joint as determined by local cooling rates. The obvious question is 'how does this variability in starting point affect creep behaviour?' It is pertinent to note that it is likely to be creep, rather than monotonic or high strain cyclic properties, that might be expected to be most sensitive to microstructural effects.

To answer the question above, bulk samples of eutectic lead-tin solder were subjected to different cooling rates on solidification and subsequently crept (Plumbridge and Gagg, 1996). Figure 3 clearly indicates that a cooling rate change from 4 °C s^{-1} to $7x10^{-3}$ °C s^{-1} has a marked influence on microstructure, when the dendritic and lamella eutectic configuration produced by slow cooling is replaced by a more uniform arrangement of the spheroidal lead-rich phase, after quenching. Constant stress creep testing at 75°C shows little effect of initial microstructure (Plumbridge and Gagg, 1996) and the majority of data fall within a range of three on life. (Fig.4).

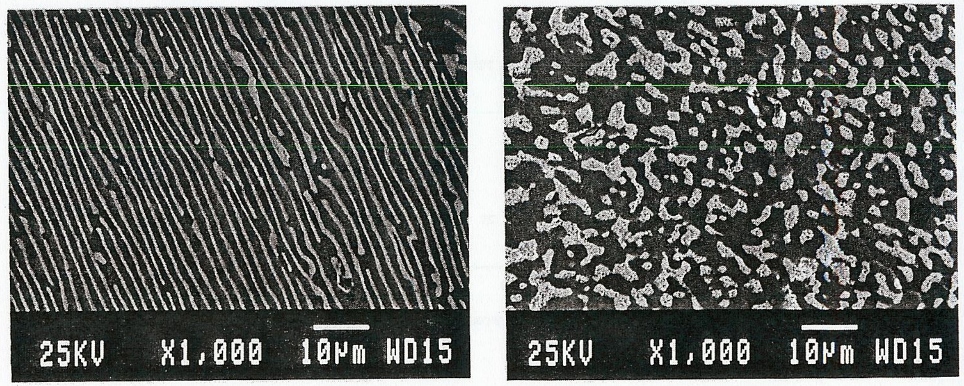

Fig. 3 Effect of cooling rate on microstructure of a eutectic lead-tin solder

a) furnace cooled; b) water quenched

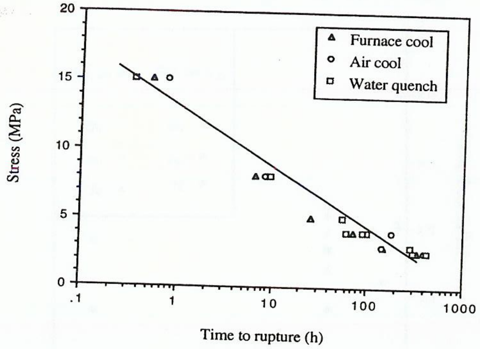

Fig. 4 Influence of cooling rate on creep of a eutectic solder at 75°C.

In addition to, but intimately connected with, the variability in initial microstructure that exists in solder, the subsequent instability of the microstructure merits serious consideration. The influence of ageing for 100h at 75, 100 and 130°C on subsequent creep was examined for an applied stress of 4.07 MPa. Little effect is apparent for the furnace cooled microstructure with all respective lives falling within a range of two. A reduction in creep life is generally observed for the air cooled alloy with a maximum change of about a factor of four on life. Creep in the water quenched condition is more sensitive to ageing and reductions up to an order of magnitude are observed. (Fig. 5) In contrast, the application of a prior strain (5%) has an insignificant effect upon the creep life of the alloy in this condition. Both the furnace, and air-cooled structures exhibit a reduction in rupture time by up to 2-3 times. Combining prior strain with ageing before creep again produces diverse outcomes according to the initial cooling rate. As compared with the cold worked only condition, the rupture time for the furnace cooled material is increased to a level similar to that of the alloy without any intermediate treatment; the air cooled material shows very little change whereas a reduction in creep life of an order of magnitude occurs for the water-quenched alloy.

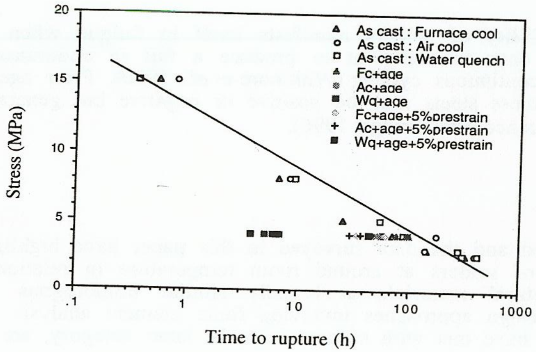

Fig. 5 Effect of prior ageing and prior strain plus ageing on creep of a eutectic solder at 75°C.

Initial cooling rates have no consistent effect upon creep strains to failure. However, in the air-cooled and water quenched conditions both ageing and strain plus ageing enhance subsequent creep ductility, sometimes quite significantly (up to 5-6x). This effect is not apparent in the furnace-cooled condition, except for ageing at 130°C. Otherwise, the strains to failure are similar or slightly reduced with respect to the slow cooled alloy. Variations in creep ductility may have a direct influence upon fatigue-creep performance when creep processes dominate. Endurance may be extended with increasing ductility and the possibility of a transition to fatigue domination or a mechanistic interaction between creep and fatigue processes is enhanced.

The results reported above, obtained within one laboratory using a single batch of material, are in general agreement with other published work (Kashyap and Murty, 1983). For joints also, findings are apparently conflicting. For example, severe ageing (200 days at 170°C) impairs the room temperature creep strength at high stress levels but enhances it at lower values (Anon B, 1987). It is difficult to determine clearcut trends in this behaviour, and a complete understanding is some way off. From the designers viewpoint, however, the salient feature is that for the relatively short lifetimes examined (<1000h), all data fit reasonably well onto the Monkman-Grant expression ($\dot{\varepsilon}t_r$ = Constant). (Fig. 6).

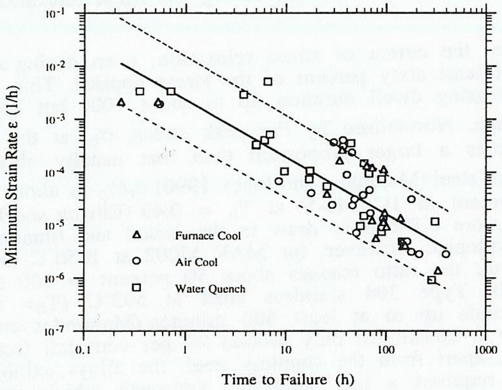

Fig. 6 Minimum strain rate versus time to rupture for creep for all conditions and prior treatments. (The solid line is the best fit for the unaged alloys).

Of the comparator alloys, the effects of prior strain and ageing have been most extensively examined in stainless steels. In the absence of recovery and recrystallisation, cold work considerably enhances subsequent creep resistance, albeit at the expense of ductility (Donati *et al*., 1974; Bernard *et al*., 1981). Ageing (10^4h at 625 and 675°C) increases minimum creep rate by some 5x and rupture time is reduced by 75 per cent (Dean and Plumbridge, 1981; Sikka *et al*., 1977). These effects appear more pronounced at high applied creep stresses above yield. Similarly, in service ageing (1.25×10^5h at 618°C) produces an order of magnitude reduction in time to rupture, together with a fall in ductility which was associated with the formation of brittle intergranular phases (Ellis and Byum, 1983).

FATIGUE BEHAVIOUR

As the softest component in the joint, the solder experiences the majority of deformation constrained within it. Load changes during strain controlled fatigue indicate that eutectic solder cyclically softens continuously throughout life. These strength changes arise due to microstructural deterioration and crack initiation and growth. Since there is no clear plateau in the load range v cycles plot, it is difficult to identify precisely when the onset of significant cracking occurs. (Sandström, *et al.*, 1993 and Jiang *et al.*, 1996) propose that the majority of the load fall may be attributed to cracking. The extent of the softening at half life is about 20 percent with respect to the first cycle. This is similar to that measured in a 1Cr-Mo-V steel at both room temperature and 565°C (Plumbridge and Bartlett, 1982) Annealed stainless steels cyclically harden considerably and a doubling in strength can be achieved (Plumbridge *et al.*, 1980). Titanium and nickel alloys are usually very stable at temperatures around 600°C and 900°C respectively, although the latter does exhibit hardening and softening, according to strain range, above 1000°C (Plumbridge and Stanley, 1986; Plumbridge and Ellison, 1991). Unlike titanium and nickel alloys but similar to low alloy and stainless steel (Plumbridge and Bartlett, 1982; Plumbridge *et al.*, 1980) there are only very small mean stresses (<1MPa) developed during fully reversed strain cycling. These are most apparent in the case of the unbalanced tensile dwell cycle profile and reach about 3 MPa in compression. Although these are still small, in this sense they would probably be beneficial, acting against the tendency for grain boundary cavitation during the stress relaxation phase of the dwell in tension.

In all dwell tests, the extent of stress relaxation, even during a 10s hold, is substantial and constitutes at least sixty percent of the stress applied. This increases to over eighty percent with increasing dwell duration up to about 100s but appears unaffected by the precise cycle shape. Normalised by the peak stress, σ_p, at the start of relaxation, this 'damage' constitutes a larger proportion than that usually observed. For example, in Type 316 stainless steel (Majumdar and Jones, 1990) σ_r/σ_p is about 18 percent ($T_h = 0.53$) and about 55 percent in 1Cr-Mo-V at $T_h = 0.49$ (Ellison and Patterson, 1976). Similar comparisons are more difficult to draw in the nickel and titanium alloy because of the mean stresses developed. However, for MAR M002 at 1050°C ($T_h = 0.80$), where these are relatively small, the ratio reaches about 50 percent in 100 seconds (Plumbridge and Ellison, 1991). In Type 304 stainless steel at 593°C ($T_h= 0.52$), stress relaxation continues for periods up to at least 600 minutes (Majumdar and Jones, 1990) but even after this duration it constitutes only around 20 per cent fall from its original value. It is significant that, apart from the stainless steel, the alloys exhibited a creep dominated failure and thus required a life prediction approach which could accommodate this. However, the assumption that all the strain produced by stress relaxation contributes to damage in a single location is erroneous, since it is partitioned between matrix and grain boundaries according to the operating strain rates. Assuming a value for Young's modulus of 30GPa, the variation is tensile strain rate during the dwell for the solder is between $1.7\text{x}10^{-3}\text{s}^{-1}$ and $1.7 \text{ x } 10^{-6}\text{s}^{-1}$.

In terms of endurance, the insertion of a hold period into the strain cycle produces a significant life debit, which is more pronounced at the lower strain range examined. Somewhat unusually, all types of dwells are deleterious with the tensile-only dwell cycle slightly more damaging than the other profiles. There is also evidence of a saturation effect for dwell periods in excess of 100s. (Fig.7)

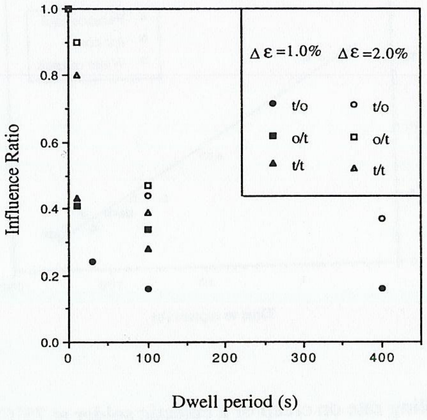

Fig. 7 The influence of dwells during strain controlled cycling at room temperature. (Influence ratio is N_f (dwell): N_f (No dwell)

The comparator structural alloys used in this study fall into two categories with respect to their behaviour under fatigue-creep testing. Stainless and low alloy steels are tensile-dwell sensitive, in that the maximum life debit results after applying strain cycles which contain a dwell only at the point of maximum tensile strain. In contrast, the nickel and titanium alloys are compression-dwell sensitive and for these an unbalanced tensile-dwell cycle may even produce an increase in life over that observed in continuous cycling. It is important to appreciate that these observations apply only to the available data which is very much related to operating conditions in service. The balance between fatigue and creep damage processes is sensitive to temperature, strain range and strain rate, and so outside the relatively narrow spectrum of available data dominant mechanisms may change. The onset of such a process has been observed in a nickel-based superalloy, which becomes susceptible to tensile dwells when testing above a 1000°C (Plumbridge and Ellison, 1991). The susceptibility to all dwell types exhibited by solders is thus unusual.

The inherent instability of solders manifests itself in fatigue when room temperature exposure for 120 days is sufficient to produce a fall in endurance by an order of magnitude during continuous cycling (Whitmore *et al.*, 1990). Prior ageing effects on the fatigue life of stainless steels may be positive or negative but generally fall within the ±2x band on endurance (Plumbridge, 1996).

DISCUSSION

The results reported and the data surveyed in this paper have highlighted the volatility of the behaviour of solders at around room temperature in relation to that of more conventional structural materials at broadly similar homologous temperatures. The consequence for design approaches involving finite element analysis and life prediction expressions, which have met with success with the latter category, are now considered.

The wide range of measured values for Young's modulus and the sensitivity of this and other monotonic properties to strain rate introduces a significant degree of uncertainty about features, which for most structural alloys, secure assumptions can usually be made. The selection of appropriate values for analysis is axiomatic, but possibly may need to be application-specific. For example, partitioning total strain into its elemental components may involve use of a strain-rate modified modulus.

While the majority of structural materials are produced to fairly tight specifications in terms of microstructure and strength, the original starting condition of solders falls within a much broader band determined by the local cooling rate. Compounding this variability, the intrinsic instability of solders, even at room temperature, probably means that the precision of current design methods achieved for the comparator alloys is unlikely to be achieved. An implicit assumption of most life prediction models and the Monkman-Grant relationship is that the microstructure will remain constant.

The creep data described have been relatively short term, with lives below 1000h. Intuitively, it seems reasonable to expect that microstructural effects may exert their greatest influence at low stresses which would be associated with longer creep lives. The present results indicate that microstructure does not have a significant effect on high stress creep, although there are marked differences in the creep response after prior ageing and cold work, with the water quenched condition being particularly sensitive.

The absence of consistent trends is probably associated with the occurrence of more than one dominant failure mechanism each of which may exhibit a different dependence upon strength and ductility. Transitions in the observed effects of ageing, either prior to or during creep, for example, could result when strength peaks and ductility continues to increase. In all cases, it is the balance between processes which is influential. Similar findings have been made in stainless steels and nickel alloys (Neailey and Plumbridge, 1988); Jianting *et al.*, 1984). More work is required in this area to furnish the understanding necessary to underpin phenomenlogically-based design approaches.

During high strain fatigue, solders display a higher proportion of stress relaxation in hold periods than do the comparator alloys. This suggests a failure dominated by creep and the requirement for a creep-based expression for life prediction. However, the observed susceptibility to all types of dwell-containing cycles indicates a more complex situation. Saturation effects, in terms of dwell duration, have been observed in stainless steels which is the least stable of the comparator alloys. The previous argument regarding the balance of strength and ductility as ageing proceeds may apply to solders but in this, and the cycle shape sensitivity above, further work and more understanding is required.

CONCLUSIONS

This paper has drawn attention to several features in the mechanical behaviour of solders which merit consideration in the context of life prediction.

1. The uncertainty regarding the value of modulus, its apparent strain rate sensitivity and the accommodation of this into analysis
2. The influence of both strain rate and prior strain and ageing on monotonic properties.
3. The relative independence of creep at high stress levels to initial microstructure which contrasts with the high sensitivity of creep in the water quenched condition to prior ageing or strain.
4. The enhancement of creep ductility caused by prior ageing and prior strain plus ageing of the air cooled and water quenched alloy.
5. The extensive stress relaxation which occurs during dwells in high strain fatigue, and the vulnerability, in terms of endurance, to all types of dwell-containing cycle.

In the majority of these aspects solder behaviour, as determined by the magnitude of the changes, is more pronounced than that of the comparator alloys. It is contended that this merits serious consideration when attempting to apply trends in the established structural alloys to solders. Overall, our current knowledge-base and level of understanding are limited. Considerably more work is required to develop a thorough mechanistic appreciation of the processes likely to cause failure in service.

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