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The grain-boundary sliding component in high-temperature fatigue

Recent measurements of grain-boundary sliding (GBS) during high-temperature fatigue of Magnox Al80 [1], α-iron [2], copper and α-zirconium [3] have shown that the rates of GBS can be up to three orders of magnitude greater than those rates reported for monotonic (creep) stress. The rates of GBS in fatigue are consistent with observations which indicate the importance of GBS in high-temperature fatigue failure [1–5, 7]. However, although the rate of GBS has been measured in high-temperature fatigue, there have been no attempts to assess the contribution of GBS strain to the total strain as has been done so extensively for high-temperature creep [6].

For creep conditions, the strain contribution of GBS (ϵ_{gb}) is generally observed to be proportional to the total strain (ϵ_t), i.e. $\epsilon_t = \epsilon_{gb}/\lambda$, where the value of λ tends to increase with increasing temperature and decreasing stress [6]. Values of λ (conventionally expressed as percentages) up to ~ 90% which have been reported show that the GBS strain can make a major contribution to the total creep strain under low-stress high-temperature conditions. If a similar expression for λ applies to fatigue as that in creep, substantial values of λ might be expected because of the low stresses and high temperatures used in many tests. The present communication reports estimates of λ derived from measurements of GBS in Magnox Al80 [1], α-zirconium and copper [3] which were subjected to low-strain high-temperature fatigue.

For fatigue conditions, the estimates of λ are based on the ratio of the average measured GBS strain per cycle ($\bar{\epsilon}_{gb}$) to the total strain per cycle ($\bar{\epsilon}_t$) i.e. $\bar{\lambda} = \bar{\epsilon}_{gb}/\bar{\epsilon}_t$. The expression $\bar{\epsilon}_{gb} = K\bar{s}/d$ was used to calculate $\bar{\epsilon}_{gb}$, where $\bar{s}$ is the average GBS per cycle (μm cycle^{-1}), d is the average grain size

TABLE I Estimates of $\bar{\lambda}$ for cyclic stress conditions

Material	Frequency (Hz)	T (° C)	$\bar{\epsilon}_t$ (σ, MPa)	d (μm)	$\bar{s}$ (μm cycle^{-1})	$\bar{\epsilon}_{gb}$ (μm cycle^{-1})	$\bar{\lambda}$ (%)
Magnox Al80 [1]	60	430	4.4×10^{-5} (2.4)	3048	1.4×10^{-7}	4.5×10^{-11}	0.0001
			1.4×10^{-4} (4.1)	3048	7.5×10^{-7}	2.5×10^{-10}	0.0002
			2.4×10^{-4} (4.4)	3048	1.1×10^{-6}	3.7×10^{-10}	0.002
			3.2×10^{-4} (5.8)	3048	2.0×10^{-5}	6.5×10^{-9}	0.002
			1.6×10^{-4} (5.8)	864	7.2×10^{-7}	8.3×10^{-10}	0.005
α-zirconium [3]	15.6	700	8×10^{-3}	102	2.9×10^{-4}	2.9×10^{-6}	0.04
Copper [3]	15.6	400	8×10^{-3}	113	2.3×10^{-4}	2.0×10^{-6}	0.03
		500	8×10^{-3}	113	5.0×10^{-4}	4.4×10^{-6}	0.06
		550	8×10^{-3}	113	6.1×10^{-4}	5.4×10^{-6}	0.07
α-iron [2]	0.125	700	2×10^{-2}	75	7.8×10^{-3}	1.0×10^{-4}	0.50

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(μm), and K is a geometrical term taken as being equal to unity. The total strain per cycle was taken as $\bar{\epsilon}_t = 4\epsilon_p$ where $\pm\,\epsilon_p$ is the plastic strain amplitude. The values of ϵ_p used to estimate $\bar{\lambda}$ were $\pm\,1.1, 3.5, 4, 6, 8 \times 10^{-3}\,\%$ for Magnox Al80 [1] and $\pm\,2 \times 10^{-1}\,\%$ for α-zirconium and copper [3]. The estimated values of $\bar{\lambda}$ are given in Table I, together with a value of $\bar{\lambda}$ for high-strain fatigue test on α-iron [2] for comparison. For α-iron, $\epsilon_p = \pm\,5 \times 10^{-1}\,\%$ [2].

The table shows that, contrary to what might be expected, the estimates of $\bar{\lambda}$ for low-strain fatigue range from 0.0001% for Magnox Al80 to 0.07% for copper. These values of $\bar{\lambda}$ are very small compared with the values of λ for creep (reported as high as ~ 90% [6]) and are small even compared with $\bar{\lambda} = 0.5\%$ for the high-strain fatigue test on α-iron. The very small values of $\bar{\lambda}$ appear to conflict with the known importance of the influence of GBS on high-temperature fatigue failure. For example, Evans and Skelton [1] have shown that in Magnox Al80 (which has $\bar{\lambda} = 0.0001\%$) GBS controls cavity growth and the attainment of a critical value of GBS results in failure.

These apparently anomalous values of $\bar{\lambda}$ for low-strain high-temperature fatigue may be rationalized if $\bar{s}$ is equated to the average irreversible GBS per cycle rather than summing the forward and reverse GBS per cycle without regard to sign, i.e. $\bar{s} = |\bar{s}_F - \bar{s}_R|$ rather than $\bar{s} = |\bar{s}_F| + |\bar{s}_R|$, where $\bar{s}_F$ and $\bar{s}_R$ are respectively the average forward and reverse GBS per cycle. The former method of treating GBS is consistent with the observations of Harper [7] who found that fully reversing the applied creep stress produced partial recovery of prior GBS in copper at 500° C. The latter method of handling GBS may be more appropriate to describe the development of damage in high-strain high-temperature fatigue with hold times [8] where the conditions for the nucleation and growth of cavities may correspond more closely with those for high-temperature creep.

Examination of Table I indicates that, for copper, the value of $\bar{\lambda}$ increases with temperature which is similar to the temperature dependence of λ in creep [6]. Further, the data for Magnox Al80 show that $\bar{\lambda}$ increases with stress (or strain) amplitude which is opposite to the usual stress dependence of λ in high temperature creep [6]. This suggests that reversed GBS in fatigue may be increasingly inhibited by such processes as increased grain-boundary dislocation/dislocation interactions and grain boundary/matrix dislocation interactions. This inhibited reversed GBS would tend to prevent cavities sintering-up and thereby affect cavity growth.

In summary, the estimated contribution of grain-boundary sliding strain to the total strain in low-strain high-temperature fatigue is several orders of magnitude smaller than that reported for high-temperature creep. This difference is attributed to the measured GBS in fatigue which results from the accumulated, irreversible GBS rather than the sum of the forward and reversed GBS taken without regard to sign. The data also suggest that $\bar{\lambda}$ tends to increase with increasing temperature and stress.

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