STUDY OF THE EFFECT OF MICROSTRUCTURE ON STABLE CRACK GROWTH

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Crack opening displacement (COD) was used to study the resistance to stable crack growth of three powder forged steels. It is shown that the rate of COD per unit of crack growth, $d\delta/dc$, increases with the spacing of the inclusions measured on the fracture surfaces. The values of $d\delta/dc$ also increase with the ratio of inclusion spacing to radius. In this case, the steels show different values of $d\delta/dc$ for any given value of the ratio. This behaviour is analysed as function of the work hardening characteristics of the steels.

INTRODUCTION

Crack opening displacement has been extensively used for assessing the fracture resistance of structural steels (Harrison (1). Several studies have been made on the relation between non-metallic inclusions and COD at initiation and maximum load (Knott (2), Mc Meeking (3) and Baker and Charles (4). Studies have also been made on the influence of the work hardening characteristics of the steels on COD (Clayton and Knott (5). However, much less attention has been given to the influence of inclusion distributions and work hardening characteristics of the steels on the resistance to stable crack growth (Green and Knott (6), Lautridou and Pineau (7) Willoughby et al (8) and Willoughby et al (9).

The objective of the present work has been to investigate the relationship between stable crack growth and both different inclusion distributions, resulting from different oxygen contents, and the work hardening characteristics of the three steels containing these inclusions and produced by the powder forging process. As a result of this process, the density of the steels is practically 100% and they present a non-random distribution of spherical inclusions where the prior powder particle boundaries show higher concentration of inclusions than the rest of the material. Deoxidation treatments during the sintering operation reduce the quantity of oxides on the powder boundaries causing the spacing of the inclusions on those regions to increase. As a consequence, the distribution of inclusions in the regions of the prior powder particle boundaries of the forged material depends strongly on the oxygen content of the steel.

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MATERIALS

Three powder forged steels were studied: a plain carbon steel (M32 – commercially named WP150), a Mn, Mo steel (En16) and a Cr, Mn, Ni, Mo steel (W32). Three or four different oxygen contents in the steels resulted from differing deoxidation conditions during sintering. The chemical composition of the steels is shown in Table 1 and their final oxygen content in Table 2.

TABLE 1 – Chemical analyses of the steels, wt-%

Steel	C	Mn	Si	S	P	Ni	Cr	Mo	Cu
M32	0.400	0.050	0.050	0.090	0.006	0.070	0.040	0.020	0.100
En16	0.230	0.870	<0.020	0.018	0.008	0.060	0.050	0.250	0.000
W32	0.245	0.540	<0.020	0.020	0.013	0.320	0.380	0.340	0.000

TABLE 2 – Oxygen content of the steels, wt-%

M32	0.025	0.080	0.100	-
En16	0.029	0.066	0.145	-
W32	0.027	0.075	0.120	0.180

The steels were oil-quench hardened and tempered at 550°C. The resulting Vickers hardness and tensile properties are shown in Table 3.

TABLE 3 – Vickers hardness and tensile properties of the steels

Steel	Hardness VH	Yield stress MNm^{-2}	True stress at maximum load MNm^{-2}	Work-hardening coefficient
M32	202	445	670	0.17
En16	246	614	729	0.13
W32	267	723	833	0.08

EXPERIMENTAL METHODS

COD Evaluation

The COD testpieces were machined from the fully heat treated material. The testpieces were fatigue pre-cracked and tested in slow, pure (four-point) bending. The testpiece geometry follows the British Standard (10).

The values of $d\delta/dc$ were obtained from the COD (δ) versus crack length (c) curves. Crack length was determined from direct examination of the heat tinted fracture surfaces of the testpieces which were broken in liquid nitrogen temperature, after unloading and heat tinting. The δ versus c plots were always linear and eight testpieces were used for each material. Further details of testpiece geometry and test conditions can be found in earlier publications (Bastian (11), Bastian and Charles (12) and Bastian and Charles (13).

Metallography

The inclusion distributions, characterized by their mean centre-to-centre spacings, s, mean free-paths, λ, and mean radii, r, were estimated from measurements made on the fracture surfaces of the COD testpieces, at very high magnifications. Details of the methods and the expressions used in the calculations can be found in other references (12, 13).

RESULTS AND DISCUSSION

The values of $d\delta/dc$ obtained are plotted as function of the oxygen content of the three steels, Figure 1. This shows that $d\delta/dc$ decreases with increasing oxygen content and, consequently, decreasing inclusion spacings. A plot of $d\delta/dc$ versus s is shown in Figure 2, where this trend is clearly demonstrated. This means that the ammount of crack opening displacement per unit crack growth is influenced by the spacing of the inclusions in the region of the prior powder particle boundaries, which is the preferential ductile crack path for the steels of the study (11).

It is also clear from other studies of the influence of microstructural factors on $d\delta/dc$ and on δ_i, where plots of δ versus c are shown, that there should be an effect of inclusion spacing on the resistance to cracking. Reference (6), for instance, shows a $d\delta/dc$ about 0,125 for a 0.032% S steel with inclusion spacing of 104 μm, whereas a 0,24% S steel with inclusion spacing of 46 μm and same orientation as the previous one showed $d\delta/dc$ equal to 0,074. Okumura et al (14), working with an AC potential drop apparatus, obtained plots of δ versus c where $d\delta/dc$ is dependent on the sulfur content of the steel and, consequently, on the spacing of the inclusions. In the same way, reference (8) also showed an influence of the spacing of the inclusions on $d\delta/dc$.

It is important to note that Figure 2 shows no difference between the graphs $d\delta/dc$ versus s of the steels, although the steels show some appreciable differences of tensile properties, Table 3. This lack of distinction between the steels can also be observed in Figure 3 where the plot is as function of λ, which measures the amount of matrix between the inclusions. Here also, $d\delta/dc$ increases with λ although no difference between the values of $d\delta/dc$ of each steel is noticiable at any given λ value. In fact, differences in $d\delta/dc$ arising from the different flow properties of the steels at any given s or λ value should only become noticeable if the sizes of the inclusions were similar, otherwise the differences could be masked by inclusion size effects. It is easy to visualize that different behaviour should be expected from a steel with inclusion distributions with the same centre-to-centre spacing but different sizes. The same could be said in relation to the effect of the mean free-path.

The size ranges of the inclusion populations studied in the present work were different. This may explain the difficulties found for separating the specific influence of the flow properties of each steel on the $d\delta/dc$ values. A possible way of overcoming these problems could be by plotting $d\delta/dc$ as function of the spacing of the inclusions normalized for their sizes, s/r. This seems to be possible since it appears that the spacing of the inclusions and their sizes have opposite effects on fracture thoughness and therefore on stable-crack growth. It is already shown that $d\delta/dc$ increases with the spacing of the inclusions. On the other hand, from the deleterious influence of increasing inclusion size on toughness at constant spacing, it is reasonable to suppose that increasing size will also affect negatively the cracking resistance, also an indication of toughness. Thus $d\delta/dc$ should be proportional to s/r.

Figure 4 clearly shows $d\delta/dc$ to increase with s/r for these powder forged steels. It is interesting to note that, for any value of s/r, the steels show different $d\delta/dc$ values, although the difference is not very large for the alloyed steels. The differences between the steels largely persist in Figure 5, where the confidence intervals of the values of s/r are shown (95% confidence level). This must be an indication that the specific influence of the matrix characteristics on $d\delta/dc$ come into evidence only when all the important inclusion distribution parameters are taken into consideration. The figure shows that steel M32, with lowest yield limit and highest work hardening coefficient has the highest $d\delta/dc$ values. On the other hand, steel W32, with highest mechanical strength and lowest work hardening capacity, shows the lowest $d\delta/dc$. It is apparent from the graphs that $d\delta/dc$ also depends on the work hardening capacity of the steels.

Studies of the influence of the work hardening characteristics of steels on stable crack growth have been carried out (8). These studies showed that $d\delta/dc$ is affected by the amount of cold prestain given to the material, which reduces its capacity to work harden.

The results obtained in the present work on the influence of the flow properties of the steels on $d\delta/dc$ can probably be attributed to the fact that steels with small work hardening capacity loose their ability to continue work hardening at lower strains. Thus strain becomes localized earlier and propagation of a unit crack length takes place with smaller crack opening displacements. On the other hand, high work hardening capacities prevent earlier strain localization during crack growth causing therefore larger crack opening displacements per unit of crack growth. It is considered that whilst these results were obtained with powder forged systems they are more generally applicable to the behaviour of second phase particles in a metallic matrix.

CONCLUSIONS

The rate of crack opening displacement per unit of crack growth is influenced by the oxygen content of powder forged steels with higher values of the rate associated with lower oxygen contents.

The rate of crack opening displacement per unit of crack growth is directly related to the spacing of the inclusions, as measured on the fracture surfaces of COD testpieces.

The work hardening capacity of steels influences their resis tance to stable crack growth, but is only clearly evident from results where all the inclusion parameters are taken into consideration.

SYMBOLS USED

COD = crack opening displacement (mm)

c = crack length (mm)

$d\delta/dc$ = rate of crack opening displacement per unit crack growth

δ = crack opening displacement (mm)

δ_i = crack opening displacement at initiation (mm)

λ = mean free-path of inclusions (μm)

r = mean inclusion radius (μm)

s = mean centre-to-centre spacing of inclusions (μm)

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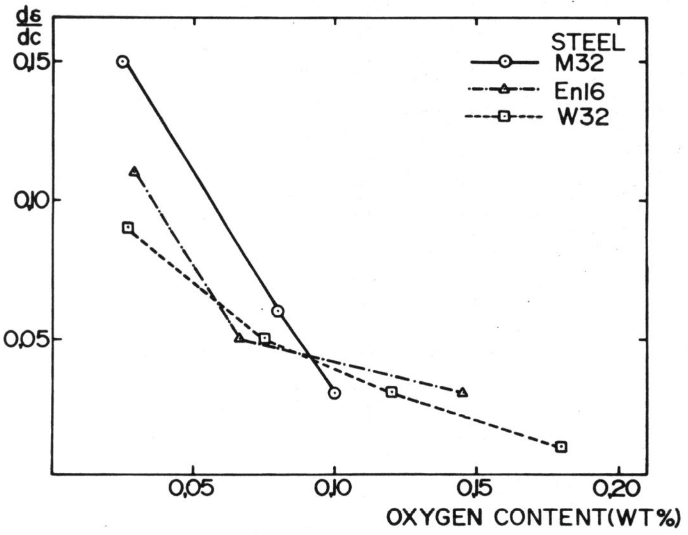

Figure 1 dδ/dc as function of oxygen content of steels studied

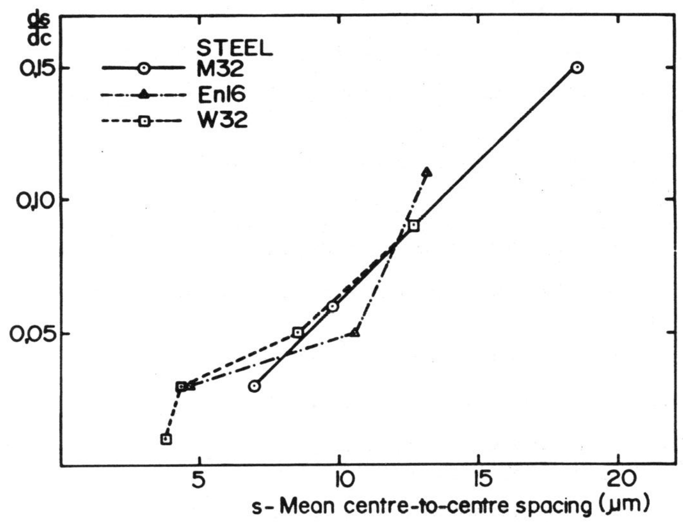

Figure 2 dδ/dc as function of mean centre-to-centre spacing of inclusions

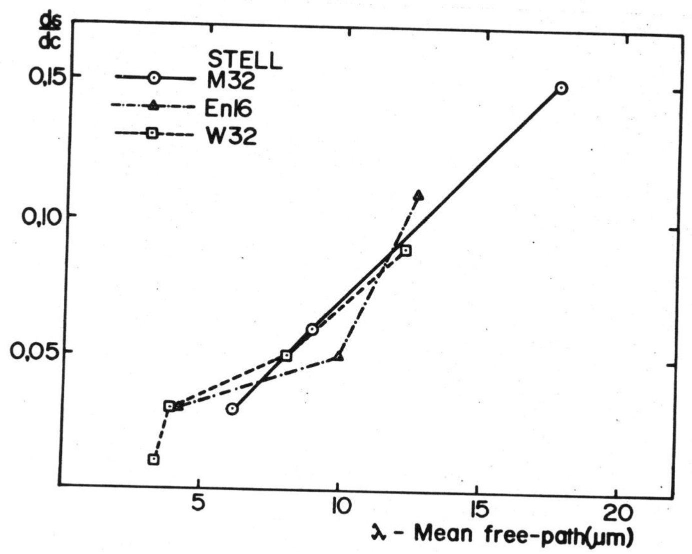

Figure 3 dδ/dc as function of mean free-path of inclusions

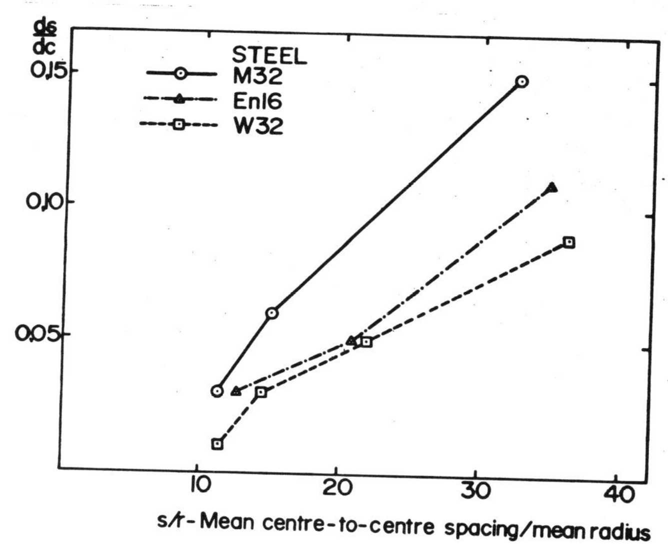

Figure 4 dδ/dc as function of ratio mean centre-to-centre/mean radius of inclusions

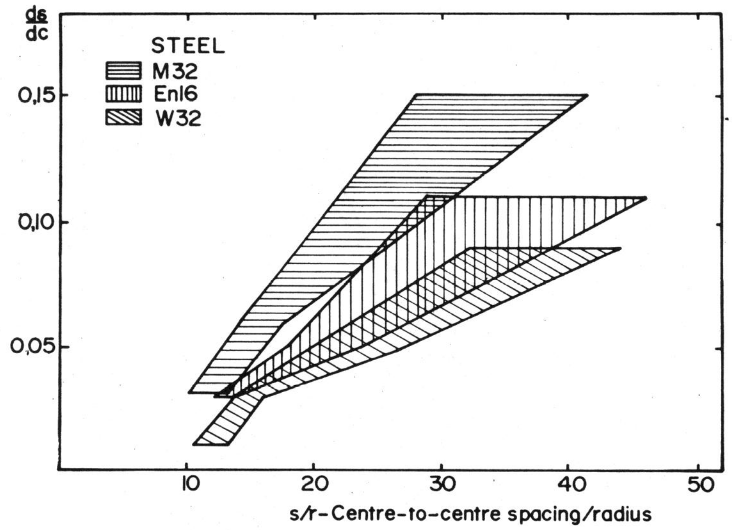

Figure 5 dδ/dc as function of ratio centre-to-centre spacing/radius of inclusions