VOID NUCLEATION AND GROWTH DURING TENSILE DEFORMATION IN STEEL

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ABSTRACT

Void nucleation and growth in steels with low sulphur content was investigated. A series of smooth tensile bars were pulled to increasing plastic strains. Based on the results of these tests, a procedure was established to estimate the critical strain for void nucleation and the relative void volume at the nucleation event. The relationship of these two parameters to inclusion volume and distribution was examined. The same procedure was used to measure the relationship between void growth, plastic strain and stress triaxiality. The Rice-Tracey model for void growth underestimates the void growth rate when compared to measured void growth rate in a tensile bar.

KEYWORDS

Void initiation, Void growth, Plastic strain, Stress triaxiality, Relative void volume.

INTRODUCTION

The failure of many metallic materials occurs by a phenomenon known as ductile fracture. This is a three stage process: void nucleation, void growth and void coalescence - leading to final rupture. A large improvement in material toughness could be achieved if any of these three stages could be controlled and retarded. It is, therefore, necessary to identify and study the various factors affecting these stages. The present study investigates only the first two stages.

Various theoretical and experimental studies of the initiation of voids in ductile metals have been made (Barnby, 1967; Barnby, 1969; Beremin, 1981; Fisher, 1981; Goods, 1979; Hancock, 1976; Rogers, 1960; Shi, 1982; Shockey, 1980; Smith, 1967). It has been shown that the primary sites for void initiation are around non-metallic inclusions and hard second phase particles. Initiation of voids occurs under the combined influence of plastic deformation and stress state (Goods, 1979). The extent of plastic deformation required to initiate a void around an inclusion depends on the cohesion of the inclusion to the matrix. Inclusions with negligible bonding will initiate voids at a small plastic deformation, i.e. low stress, by separation at the interface, e.g. MnS in steel (Hancock, 1976). More cohesive particles such as carbides in steel or oxides in copper require considerably more plastic deformation for void initiation, i.e. higher stress, than inclusions (Fisher, 1981; Rogers, 1960). The size of the inclusions and their orientation to the direction of loading also influences the nucleation strain (Beremin, 1981).

The criterion for nucleation of voids is based upon a critical stress model which states that in order for a particle to separate from the matrix, a critical stress must be developed within the material at the particle-matrix interface (Goods, 1979; Hancock, 1976; Shockey, 1980). As the materials being examined have a particular stress-strain behaviour, a measurement of the macroscopic strain developed in a smooth tensile bar provides a suitable parameter to indicate nucleation though the nucleation mechanism will be controlled by high internal stress.

Void growth occurs under the combined influence of plastic strain and stress triaxiality. Several models have been proposed to describe void growth under the influence of these factors (Berg, 1962; McClintock, 1968; Melander, 1980; Rice, 1969; Wilkinson, 1982). Experimental work on void growth has also been reported (Beremin, 1981; Hancock, 1976; Melander, 1980; Shi, 1982; Shockey, 1980). These experiments show that the models which predict void growth generally underestimate the void growth observed in real materials. The tests in many of these experiments were conducted on notched round tensile bars, strains and the triaxiality being estimated using the Bridgeman (1944) analysis. Estimation of strains and triaxiality using this analysis are subject to some errors.

THEORETICAL CONSIDERATIONS

Previous models for void nucleation from second phase particles deal with individual particles and predict that a critical local stress or strain is required to separate the interface. The experimental support for these models is based on carefully controlled experiments conducted using a metal matrix containing only one type of second phase particle from which voids can nucleate. In practice, however, engineering materials contain more than one type of second phase particle of more than one size. This leads to the continuous nucleation and growth of voids with increasing macroscopic strain until a certain critical strain is reached. After this critical level a further increase in strain produces growth. We have estimated the end of significant nucleation of voids by direct observation. As nucleation and growth occur simultaneously it is necessary to describe this experimental work by means of model which can deal with both of these features. Previous experiments (Beremin, 1981; Hancock, 1976; Melander, 1980; Shi, 1982; Shockey, 1980) reported the strain required to cause nucleation by observing voids in the necked portion of a tensile bar. The specimen was examined from the fracture surface of the specimen along the tensile axis until a region where no voids were thought to occur. The strain at this point was then estimated and described as the nucleation strain. In the present study, un-notched tensile bars subjected to various levels of strain have been examined to estimate void numbers, void size distribution and total relative void volume. All work has been carried out at strains between the yield stress and the ultimate tensile stress in order to eliminate the effects of varying triaxiality during neck formation.

We have used a modified form of the Rice-Tracey equation (1969) as suggested by Shockey (1980).

$$V_v = V_o \exp\left(-T_1 * \frac{\sigma m}{\sigma} * (\bar{\varepsilon}p - \bar{\varepsilon}p_o)\right) \tag{1}$$

V_v = relative void volume at $\bar{\varepsilon}p$

V_o = relative void volume at $\bar{\varepsilon}p_o$

σm = hydrostatic stress

σ = equivalent stress (flow stress at $\bar{\varepsilon}p$ in uniaxial tension)

$\bar{\varepsilon}p$ = equivalent plastic strain ($\bar{\varepsilon}p = 2\ln\left({}^{Do}/Df\right)$ for a tensile test)

$\bar{\varepsilon}p_o$ = equivalent plastic strain at nucleation

T_1 = material constant describing void growth

Rearranging Equation 1:

$$\mathrm{In}\ {}^{V}v/V_o = -T_1 * \frac{\sigma m}{\sigma} * (\bar{\varepsilon}p - \bar{\varepsilon}p_o)$$

EXPERIMENTAL PROCEDURE

Materials:

Two types of steels, A508 CL3 and Ni-Cr rotor steel were examined. The compositions, mechanical properties and manufacturing methods can be seen in Tables 1a and 1b. The microstructures of both the Ni-Cr rotor steel and the A508 CL3 were bainitic with an ASTM grain size number between 7 and 8.

Tensile Tests

The tensile tests were carried out at 100°C on Hounsfield No. 12 specimens for the A508 CL3 and at ambient temperature on Hounsfield No. 14 specimens for the Ni-Cr rotor steel. The tests were carried out using a 50 kN Instron universal testing machine at a cross-head displacement rate of 0.2 mm/min. Tensile strain was calculated by measuring the change of diameter in the gauge length of the specimen.

Metallography

The inclusion size, distribution and relative void volumes were calculated using photographs of polished specimen at 700X magnification. The inclusions were measured using a Tektronics 4052a computer and digitising tablet.

In order to observe voids, two techniques were used. The tensile test pieces were sectioned in the longitudinal direction at -196°C at the mid-diameter of the specimen. One half of the specimen was examined using a scanning electron microscope (SEM) at 700X and 2800X magnification.

Relative void volumes were estimated using a point counting technique (Hilliard, 1961) with a grid of 100 lattice points on 100 fields at each magnification. Relative void volumes and void size distributions were estimated from photographs taken on both the SEM and an optical microscope using a digitising tablet coupled to a computer. The results of both of these methods gave good agreement.

RESULTS AND DISCUSSION

From the tensile tests carried out the equivalent stress - equivalent strain relationships (Ramberg-Osgood) for the two materials under consideration is:

Ni-Cr Rotor Steel:

$$\frac{\varepsilon}{\varepsilon_o} = \frac{\sigma}{\sigma_o} + 2.863\left[\frac{\sigma}{\sigma_o}\right]^{7.496} \quad \text{or} \quad \frac{\sigma}{\sigma_o} = 0.869\left[\frac{\varepsilon}{\varepsilon_o}\right]^{0.129}$$

A508 CL3

$$\frac{\varepsilon}{\varepsilon_o} = \frac{\sigma}{\sigma_o} + 6.09\left[\frac{\sigma}{\sigma_o}\right]^{4.485} \quad \text{or} \quad \frac{\sigma}{\sigma_o} = 0.810\left[\frac{\varepsilon}{\varepsilon_o}\right]^{0.140}$$

Examination of unstrained A508 CL3 revealed the presence of two types of inclusions, MnS which were irregular in shape but elongated and Ti (C,N) which were regular. Very small total volumes of inclusions were present. Similar observations were made on the Ni-Cr rotor steel. Examination of fracture surfaces using the SEM showed that at low strains void initiation occurred by decohesion of MnS inclusions, from the matrix. As the materials were subjected to higher strains a large increase in the number of voids present was observed. The source of these voids could not be attribute to specific particles, some however, were found to be associated with Ti (C,N) inclusions and a number of cracked carbides were observed in the Ni-Cr rotor steels.

Figure 1 shows the inclusion distribution in an unstrained material and the void size distribution at different strains. At low strains the void distribution was undistinguishable from the inclusion distribution in an unstrained material. A further significant distribution of voids with the retention of the main peak in the region of small voids.

Figure 2 shows the number of voids per unit area at various strains. This clearly shows that a large increase in the number of voids per unit area is observed at a strain of 0.014. Further, strain increments do not produce significant change in void numbers. This suggests that void nucleation has ceased when this level of strain has been reached. The limited data available at present suggests that nucleation is a bi-linear process as proposed by Shockey (1980). Reference to Figs. 3 and 4, however, indicate that void growth is still taking place after a strain of 0.014 has been reached since the relative void volumes observed are still increasing although the number of voids per unit area shows no significant change. In order to estimate the value of the initiation strain in the growth model (Equation 2) we have chosen the strain at which significant initiation ceases, i.e. the intersection of the two lines shown in Figs. 3 and 4. That is an equivalent strain of 0.019 for the Ni-Cr rotor steel and 0.035 for the A508 CL3. V_o has been selected as the relative void volume at this level of strain, i.e. 0.00185 for the Ni-Cr rotor steel and 0.00415 for the A508 CL3.

The growth rate equation obtained from experimental results is:

$$\ln {}^{V}v/V_o = 0.037 - 3.1\,(\bar{\varepsilon}p - \bar{\varepsilon}p_o)$$

for the Ni-Cr rotor steel and

$$\ln {}^{V}v/V_o = 0.0203 - 3.71\,(\bar{\varepsilon}p - \bar{\varepsilon}p_o)$$

for the A508 CL3.

The growth constant T_1 is therefore equal to 9.3 and 11.12 respectively. Comparison of these values to that obtained from the Rice-Tracey model, which is 1.88, shows that void growth rates are under-estimated by this theory.

Side-grooved, fatigue cracked bend bars have been tested as part of a parallel research programme and show not only that higher relative void volumes occur at a critical distance ahead of the crack tip but also that a different size distribution occurs. This work will be reported in further publications.

CONCLUSIONS

1. Theoretical models under-estimate void growth in tensile bars.
2. Void initiation occurs at relatively low values of tensile strain.
3. Void volume at initiation is higher than inclusion volume suggesting that other types of particles contribute significantly to the failure mechanism.

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TABLE 1a

	C	Mn	Si	Ni	Cr	Mo	P	S
Ni-Cr Rotor Steel Cast	0.30	0.55	0.14	0.5	1.1	0.73	0.01	0.006
A508 CL3	0.20	1.48	0.36	0.89	0.08	0.3	0.006	0.06

TABLE 1b

	U.S. MPa	U.T.S. MPa	El%	R.A.%
Ni-Cr Rotor Steel	624	774.6	31	74
A508 CL3	443.4	563.0	27	71

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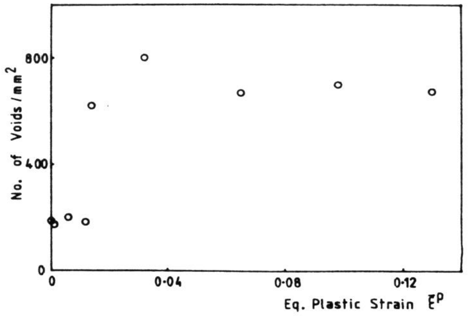

Fig. 1. The effect of equivalent plastic strain on the number of voids per unit area

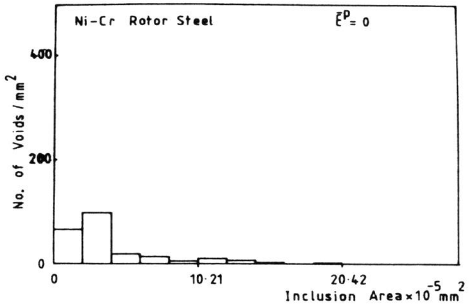

Fig. 2a. The effect of equivalent plastic strain on the void size distribution

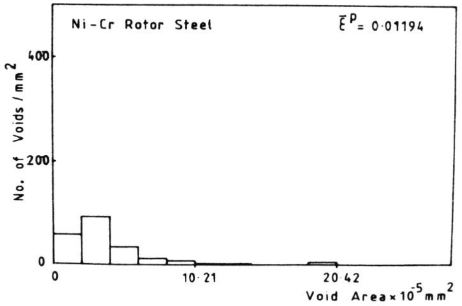

Fig. 2b. The effect of equivalent plastic strain on the void size distribution

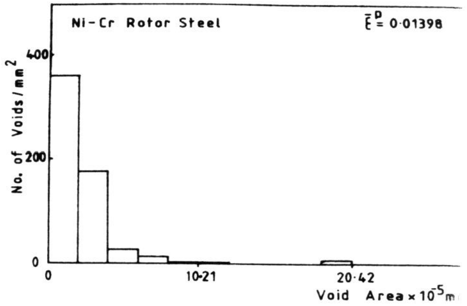

Fig. 2c. The effect of equivalent plastic strain on the void size distribution

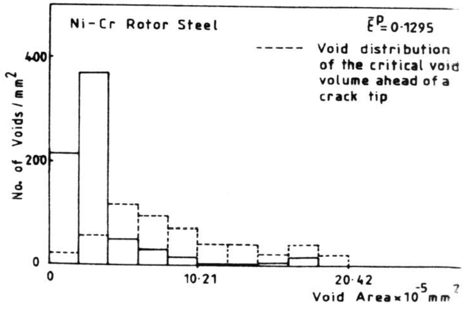

Fig. 2d. The effect of equivalent plastic strain on the void size distribution

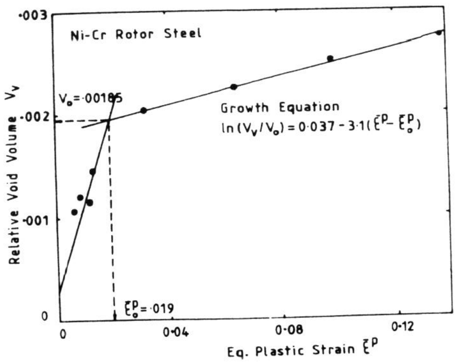

Fig. 3. Variation of relative void volume with equivalent plastic strain for Ni-Cr Rotor steel

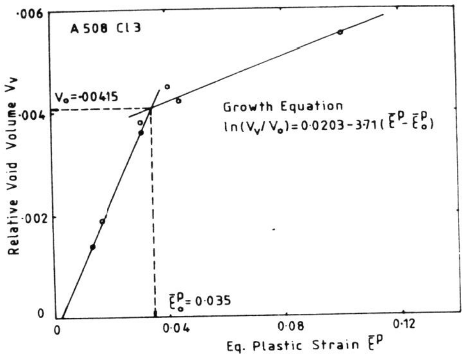

Fig. 4. Variation of relative void volume with equivalent plastic strain for A508 CL3

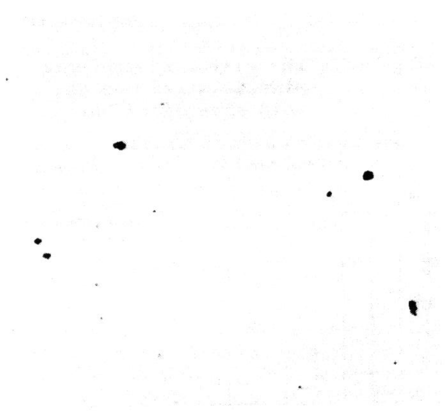

Plate 1a. Micrograph of specimen strained to $\varepsilon^{-P} = 0.0119$, Mag. x700

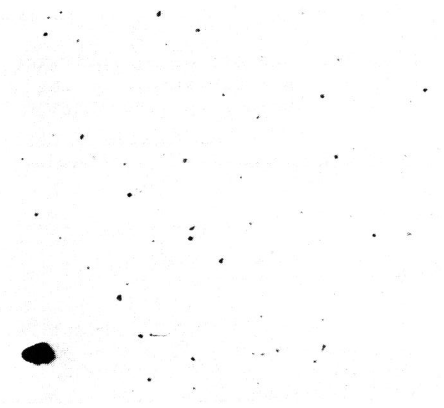

Plate 1b. Micrograph of specimen strained to $\varepsilon^{-P} = 0.1295$, Mag. x700