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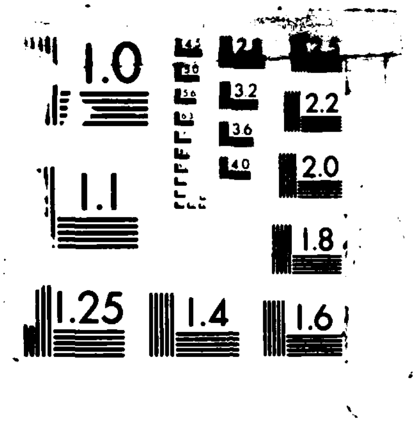

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DYNAMIC FRACTURE OF HIGH STRENGTH STEEL

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FINAL REPORT

I.M. FYFE

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COLLEGE OF ENGINEERING
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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Dynamic Fracture	Ductile Failure
Fracture Mechanics	Impact
Void Nucleation	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Ductile failure under a variety of loading conditions is examined in order to assess the importance of inertia, precompression and mean tensile stress on the failure process. A number of plastic instability concepts are also examined with regard to their ability to provide generality to failure criteria based on void nucleation and growth concepts. It was determined that inertia plays an important role in localization and can dramatically inhibit the

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necking process. Precompression appears to be relatively unimportant, unless the material is very highly strain-rate sensitive. It was determined that a viable void volume fraction failure criteria can be established which is applicable over a wide range of impact conditions if the nucleation strains dependence on the mean tensile stress is incorporated in the theory.

Keywords: Dynamic fracture; Fracture mechanics;
Metal fatigue, Physical metallurgy.

Problem Statement

The ability to predict the ductile failure of materials subjected to high strain rate deformation is limited at present by the lack of well-defined theory which is compatible with the different deformation conditions where failure occurs. Existing theories have been developed around the void nucleation and growth concept, but the generality of these models has still to be established. As plastic instability is an integral part of ductile failure, whether the loading is dynamic or static, this aspect of failure formed the central core of the project. However, two problems in particular were examined from this broad description. One was to determine where in the failure process strain rate effects are important, and the other was concerned with the role played by the mean stress on the nucleation process.

Approach

To examine the generality of a constitutive model, data in as many configurations as possible is desirable. The basic approach was to use experimental data from two configurations (Kolsky torsional bar, plate impact) to determine the material constants, and then failure analysis was carried out on a third independent configuration. The third experimental configuration was unique to, and so its development was part of, this project. The configuration in this case was the radial expansion of a thin ring, which could be loaded to failure either statically or dynamically; in the latter case the loading mechanism was an exploding wire system.

The essential elements of the experimental techniques used in the loading of the thin rings were developed earlier[1]. Changes introduced during this

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[1] Rajendran, A.M. and Fyfe, I.M., "Inertia Effects on the Ductile Failure of Thin Rings", J. Appl. Mech. 49, 31-36 (1982).

program were mainly those required to allow high strength steels to be tested, and the need to be able to determine strain rates, and failure strains. The final experimental configuration is shown in Fig. 1. The dimensions of the ring were controlled by the requirement that stress waves through the thickness of the ring had to have 'rung out' before failure strains were reached, and that no twisting occurred in the ring due to the loading technique. Although, this project had the experimental component outlined above the main thrust was to examine the theoretical models used to calculate failure. In consequence the bulk of the effort was directed to developing the analysis techniques appropriate to predict failure in the three configurations chosen. The theory was based on the Gurson hole growth concept, in which material rate sensitivity was incorporated through the description of the matrix material. A variety of plastic instability theories were examined, and a number of computer codes were adapted to handle these concepts. Initially the analysis was based on rather complex analysis techniques, and a number of codes were used to calculate the void nucleation and growth levels. However, once it was established which parameters were important it was possible to develop one fairly simple computer program to calculate the void volume fraction levels if the stress invariant time histories of the deformation were known.

With the material constants independently established from the torsion and plate impact test data, a series of experiments were carried out with the thin ring configuration to determine the radial velocity, and acceleration of the ring. From this data it was then possible to determine the loading history required to produce the deformations observed. By changing the inner diameter of the steel die it was possible to control the ring expansion. The ring was at first allowed to expand dynamically to the point where localization or shear bands could just be observed, and from the inner diameter of the steel die it was then possible to calculate the hoop strain where this occurred. A further series of tests were conducted where the rings were allowed to expand until failure occurred. The rings were then examined optically and a measure of the radial and hoop strains at failure was obtained.

With the experimental data from three configurations available, calculations were made to determine plastic instability conditions and void volume faction levels with the objective of determining if failure could be predicted for all three by a single criterion.

The material used throughout this project was 4340 steel, chosen because it was being extensively used in other ARO sponsored projects.

Results

Localization-Necking

The thin ring geometry is in many ways the dynamic equivalent of the quasi-static thin strip test, so it was to be expected that the first indication of failure was the formation of the localized neck. In the dynamically expanded rings a number of necks occurred almost simultaneously, these being fairly uniformly distributed around the circumfrerence. The hoop strains when these occurred could be determined quite accurately. The experimental values were compared with theoretical values as predicted by Hill's quasi-static thin strip theory, and the results were in almost exact agreement, not only with respect to the strain, but also the orientation of the neck. Considering the high strain rates (1.5×10^4/sec), this strongly suggests that the triggering mechanism for plastic instability is not strain rate sensitive. The subsequent necking was examined using a number of sophisticated models which have been developed to predict quasi-static instability, but they proved to either require knowledge of parameters that could not be obtained experimentally, or the value of the parameters was inconsistent with experimental observations. An example of the former is the use of the critical hardening rate of the matrix material in an aggregate, and of the latter the unrealistically large local imperfections required to trigger necking. These results reinforce the idea that ductile failure is a combination of various mechanisms, and that void nucleation and growth must be incorporated in the analysis.

Inertia Effects

The radial expansion at high strain rate was found to inhibit the growth of the necking process. This could be readily explained by noting that all the particles in the ring were expanding radially outward, so that symmetry and inertia combined to ensure that the circumferential motion required to allow necking was severely limited. That the localized neck was inhibited also delayed failure until the ring could be expanded much more than is possible statically, falsely indicating that the failure process was strain rate dependent. However, it was determined that strains close to the failure surface had values which were approximately the same as in quasi-static ring tests. Thus, although average hoop strain of the ring at failure were considerably larger in the dynamic case than the static, the local strains in the area of the failure surface showed very little difference between the two. This also suggests that the failure process is not strain rate sensitive, a result that can be confirmed from the data of other studies[2].

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[2] Shockey, D.A. et al. "Development of Improved Dynamic Failure Models", SRI report, February 1985.

Precompression

In nearly all impact induced failure situations the tensile stresses that cause failure are usually preceded by compressive loading, and therefore any failure analysis has to allow for this stress history effect. A previous study[3] had examined the effects of both precompression and having the deformations arrested by impact. It was determined that the effect of impact loading was slight if the material was not too strain-rate sensitive. Although in principal those tests could have been repeated for the 4340 material used in this project it was decided to rely on micro-hardness tests to confirm changes in the flow stress. In all tests carried out the hardness value between undeformed and deformed specimens showed a very slight increase that was almost within the experimental error.

Void Nucleation

In the thin ring tests there was very little evidence of significant void nucleation until after necking had occurred. This observation was confirmed by making density comparisons between undeformed and deformed rings, where it was observed that the density decreased just prior to fracture. Essentially the same result had been observed in spallation failure, the main difference being that the in spallation the strains at failure were very small compared to those on the ring. This difference in the nucleation strain between the two configurations greatly increased the difficulty in modeling the nucleation behavior. Comparing the strain nucleation model and the stress nucleation model with these results indicated that neither model adequately described the nucleation process. Dislocation theory has shown that nucleation strains would decrease with the increase in mean tensile stress. This idea was

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[3] Fyfe, A.M. and Rajendran, A.M. "Dynamic Pre-strain and Inertia Effects on the Fracture of Metals", J. of Mech. & Physics of Solids, 28, (1980).

incorporated into the analysis conducted for this study and the results are shown in Fig. 2, where it can be seen that it is possible to model failure with results compatible between the three different configurations. The low mean stress dynamic results appear to show that strain rate effects are important. However, in analyzing the data for those two cases the calculations used to obtain the critical void volume fraction assumed that failure occurred at the average strain levels in the failure region. However, it has been shown[2] that the average strains are considerably lower than the nucleation or failure strains when shear bands exist. When techniques are perfected to measure the nucleation strains more precisely, closer agreement with the theory can be expected.

Hole Growth

Two hole growth models were used in the study, one the classic case as derived by Rice and Tracey, and the other as proposed by Gurson. It was determined that, if a perfectly plastic material was assumed, the difference in these two models was not very great at low void volume fraction levels. In the analysis of plate impact experiments it was found that the hole growth, as predicted by either of these two models, seemed to be lower than what might have been expected considering the high mean tensile stress and strain rates. As far as could be determined the lack of growth was due to the shortness of the loading pulse. However, other investigators examining tensile test data have also expressed some concern about the theory's inability to predict void growth levels which are compatible with experimental evidence. Failure prediction for a dynamically loaded thin ring using the void volume fraction concept is shown in Fig. 3.

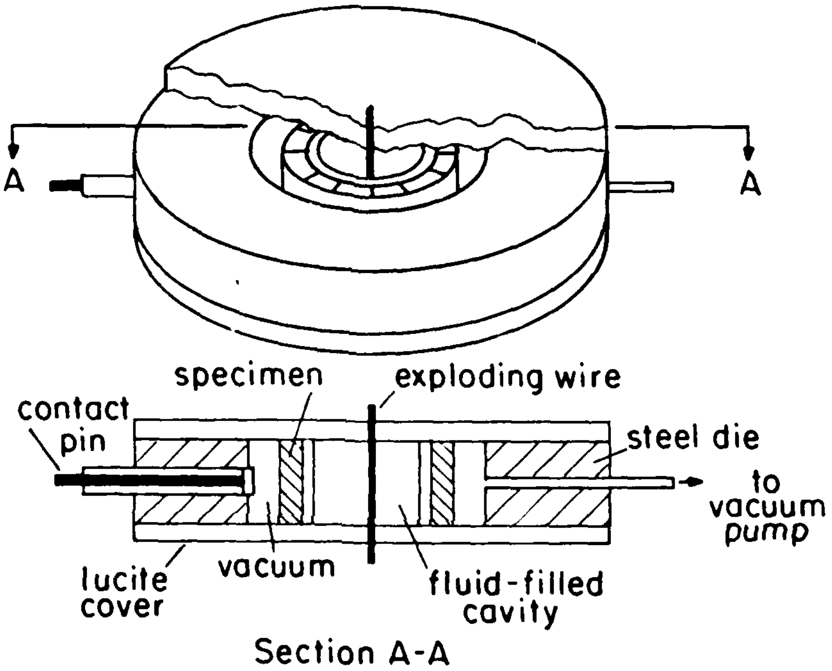

Fig. 1 Exploding-wire Experimental Configuration for High strain-rate Tests on Thin Rings

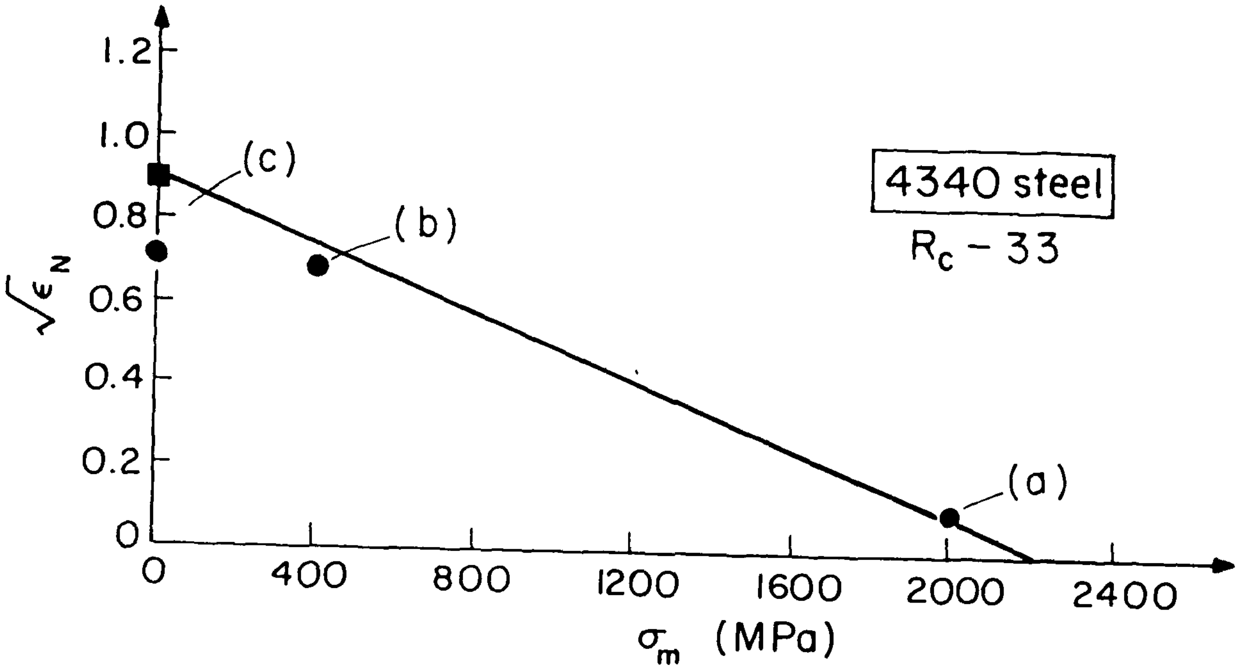

Fig. 2 Nucleation Strain as a Function of the Mean Tensile Stress. (a) spallation , (b) dynamic thin ring (c) Kolsky torsional bar ●--dynamic, ■--static

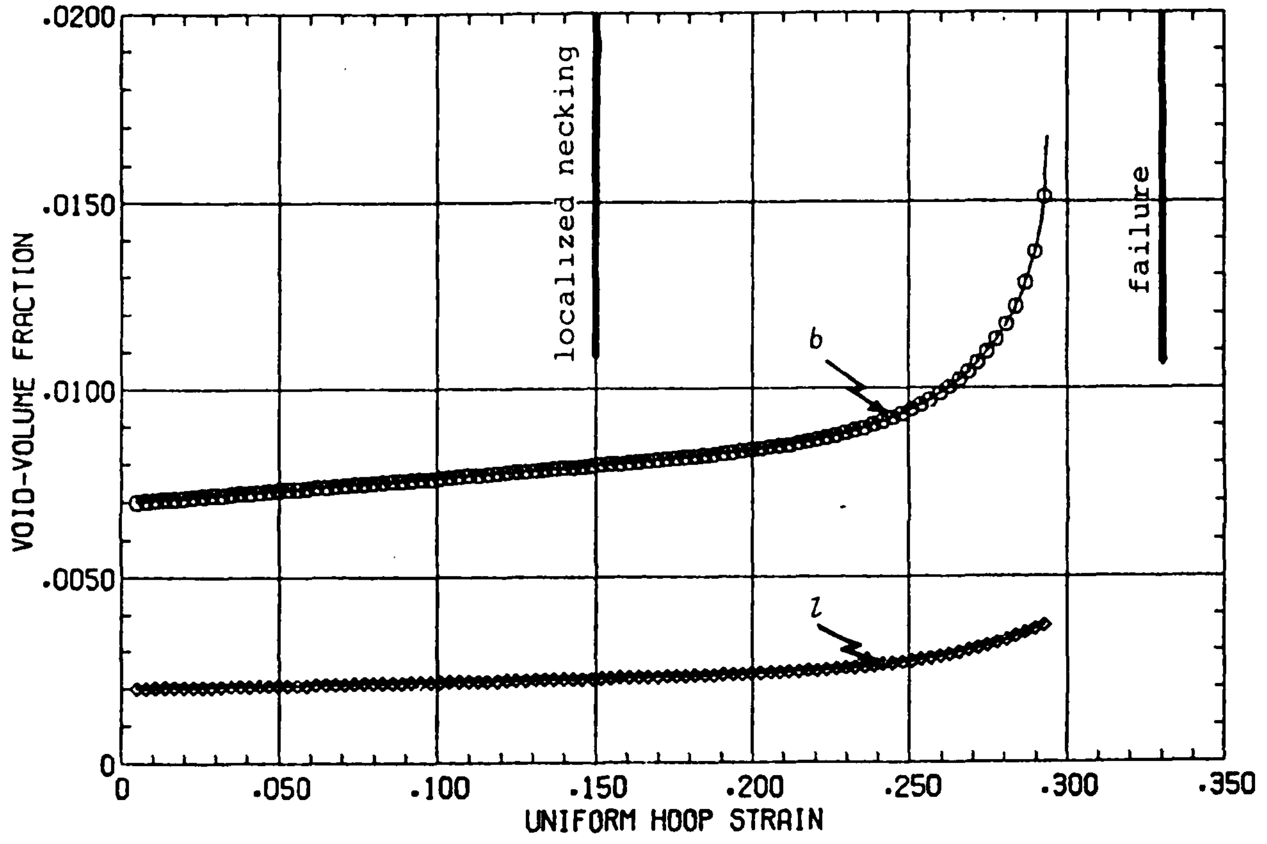

Fig. 3 Void Volume Fraction as a Function of the Average Hoop Strain; (l) outside necked region (b) inside necked region

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