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Dynamic Fracture of Ductile Materials

Modeling of ductile failure in high strength steel

N. Herzig[a]*, S. Abdel-Malek[a], L.W. Meyer[a], S.J. Cimpoeru[b]

[a]*Nordmetall Material and Impact Engineering, Adorfer Hauptstrasse 16, 09221 Neukirchen, Germany*
[b]*Defence Science and Technology Group, 506 Lorimer St, Fishermans Bend 3207, Victoria, Australia*

Abstract

Ductile fracture is an important field in dynamic materials research. The simulation of ductile failure by means of numerical codes requires accurate material models that are validated with data obtained from precise high-rate mechanical testing. In this work, a high strength quenched and tempered steel is studied over a wide range of strain rates using different test methods to achieve a range of stress states with numerical computations being used to determine the precise stress and strain rate states for the multiaxial GISSMO model. The consideration of stress state, not only in tensile triaxiality 0.33 and above but also in shear, tension/shear and compression/shear, will lead to greater accuracy in failure predictions for a wide range of applications involving complex multiaxial stress states, particularly for thick and high strength materials.

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1. Introduction

Failure of metallic materials exposed to impact loading or underlying penetration processes is affected by high strain rates, temperature, loading history, and stress state. In general, there are two mechanisms for crack formation which lead to ductile failure. The first mechanism is known as void growth and linkage. Thereby, voids grow under high levels of stress triaxiality and join up to initiate micro cracks. The second mechanism is shear dominated. Thereby,

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* Corresponding author. Tel.: +49-371-50349022; fax: +49-371-50349011.
E-mail address: norman.herzig@nordmetall.net

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the voids or imperfections are distorted under shear stress and elongated so that a crack is initiated. Shear dominant failure occurs in the region of low and negative stress triaxiality.

Abdel-Malek et al. [1] investigated the ductile failure behaviour of HY80. They found the fracture surface appearance of voids depends on the state of stress. For the modelling of ductile failure, many models were developed (e.g. [2], [3] and [4]). Johnson-Cook [3] and similar models that use notched tensile specimens are used to estimate failure strain as a function of stress triaxiality. However, these models cover only the range of void growth and linkage failure. Hence, in the region of shear dominant failure, the failure strains are often overestimated.

Hooputra et al. [5] developed a failure model with two equations: one equation for the void growth and linkage failure and the second for shear dominant failure. It is very complex to describe failure strain over the whole range of stress triaxiality using a single equation. For the LS-Dyna GISSMO model [6,7] the failure curve (failure strain) is therefore defined as a function of stress triaxiality in tabular form.

For the characterisation of the adiabatic shear and ductile shear failure at high strain rates, Meyer et al. [8,9] used inclined compression specimens. Different compressive/shear stress states can be achieved by changing the specimen inclination angle. Hat-shaped specimens can also be used for tensile/shear investigations at high strain rates [10].

In this work, the ductile failure of a high strength quenched and tempered steel was investigated for a wide range of strain rates and temperature at a number of different stress states. For void growth at high stress triaxiality, both cylindrical and notched specimens were tested under tensile loading. In the range of loading dominated by shear stress, both compression/shear and hat (tension/shear) test specimens were employed. These stress states are described by the stress triaxiality σ_m/σ_v, which is the ratio of hydrostatic stress σ_m to the equivalent stress σ_v

$$\sigma_m = -P = \frac{\sigma_1+\sigma_2+\sigma_3}{3} \tag{1}$$

$$\sigma_v = \sqrt{\frac{1}{2}\left[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2\right]} \tag{2}$$

where P is pressure and σ_1, σ_2 and σ_3 are the principal stresses. Negative values of triaxiality involve compression and compression/shear whereas positive triaxiality involves tension and tension/shear. Zero triaxiality is a pure shear stress state.

2. Experimental methods

2.1. Tensile loading

Tensile testing was performed using cylindrical specimens and two different notched specimen geometries to cover a wide range of tensile stress triaxiality conditions. Tests at room temperature were performed at four different strain rates 10^{-3}, 1, 10^2 and 10^3 s^{-1}. Tests at high temperatures up to 600°C were carried out at high strain rates of 10^2 s^{-1}.

Quasi-static tests were performed using a universal mechanical testing machine. Tensile testing at a moderate high strain rate of 1 s^{-1} was performed on a servo-hydraulic testing machine. Tensile tests at high strain rates of ~10^2 s^{-1} and 10^3 s^{-1} were performed using a rotating wheel machine. The working principle of a rotating wheel machine (or flywheel device) is shown in Fig. 1. It consists of a flywheel (at Nordmetall flywheel masses of 220 kg or 10,000 kg are available) with a claw, which is released at the required test velocity and impacts a yoke. The yoke pulls the test specimen, which is attached in a specimen holder. Due to the high amount of stored energy in the flywheel, the testing velocity and thus strain rate is virtually constant up to failure even for high strength and high ductility materials.