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Assessment of Ductile Fracture of Steel under Monotonic and Cyclic Loading

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Abstract—*The performance of structures is greatly dependent on the material behavior. In order to properly asses its performance, a structure has to be evaluated against a likely range of possible material behavior. A combined experimental study has been carried out to develop procedures, generate and calibrate material model parameters. Also to simulate the behavior and predict fracture of steel under monotonic and cyclic loading.*

1. INTRODUCTION

Constitutive relations for materials at high strain rates are important in many industrial applications, such as crashworthiness, structural impact and plastic forming operations. Since high rate loading conditions may lead to adiabatic temperature rise in the material, it is necessary to allow for high strain rates and elevated temperatures in the constitutive model. Furthermore, constitutive relations for metals under impact loading are normally empirical or semi-empirical, and thus extensive experimental investigations are typically needed to determine the material constants with the required accuracy [4]. High strength ductile steels constitute a wide variety of structural steels that find a wide variety of applications involving impact and dynamic loading. Understanding the failure mechanisms under a wide range of loading conditions in these materials would lead not only to better design methods but could also lead to ways of enhancing the desired properties of these steels [5][6]. Ductility is an important factor for tool steels since high ductility will prevent the material to fail by small cracks formed during service of the component. Ductility is often defined as the materials ability to resist plastic deformation without macroscopic fracture or crack initiation. Ductile materials show considerable elongation until failure caused by necking. The mechanism for initiation of a ductile crack when the material is subjected to an outer load is de-bonding of the matrix at particles, cracking of particles leading to void formation or pre-cracked particles due to prior working operations also leading to void formation [1], [2]. This void formation occurs in normal production materials but for a single crystalline material with high purity, i.e. no grain boundaries or present defects, ductile fracture can still occur by void nucleation. The voids nucleate by high-dislocation density cell walls due to the plastic deformation [3].

2. MICROSTRUCTURE OF FRACTURE IN METALS

Most often ductile fracture occurs in a trans granular manner, which means through the grains rather than only along grain boundaries.In a simple tensile test, ductile fracture begins by the nucleation, growth and coalescence of microvoids at the center of a sample (in the necked region). The stress causes separation of the grain boundaries or the interfaces between the metal and small impurity particles (inclusions or precipitates). As the local stresses increase, the micro-voids grow and coalesce into larger cavities. Eventually the metal-to-metal contact is too small to support the load and fracture occurs.

3. DEFORMATION AND FAILURE

Fracture: Static loading

1) Brittle: rapid run of cracks through a stressed material
2) Ductile
3) Environmental (combination of stress and chemical effects)

High-strength steel may crack in the presence of hydrogen gas, Creep rupture (creep deformation proceeding to the point of separation)

Fatigue/cycling loading

1) High cycle/low cycle
2) Fatigue crack growth
3) Corrosion fatigue

4. CRACK FORMATION MECHANISMS

Metals typically form cracks by the accumulation of dislocations at a crack nucleation site (grain boundaries, precipitate interface, free surface, etc.)

5. FRACTURE OF MATERIALS

Fracture can be classified according to the path of crack propagation:

1. Transgranular–the crack travels directly through the grains of the material (sometimes called cleavage because it occurs along certain crystallographic planes). It can be ductile or brittle.
2. Intergranular–the crack propagates along grain boundaries. This is primarily brittle fracture.

A variety of Loading Conditions that can lead to fracture:

Static Overloading ($\sigma > \sigma_{yield}$) and ($\sigma >$ Tensile Strength)

1) Dynamic Overloading (impacting)

2) Cyclic loading (fatigue)

3) Loaded at elevated temperatures (creep)

4) Loading at cryogenic temperatures (ductile to brittle transition)

5) Loading in a corrosive environment (stress corrosion)

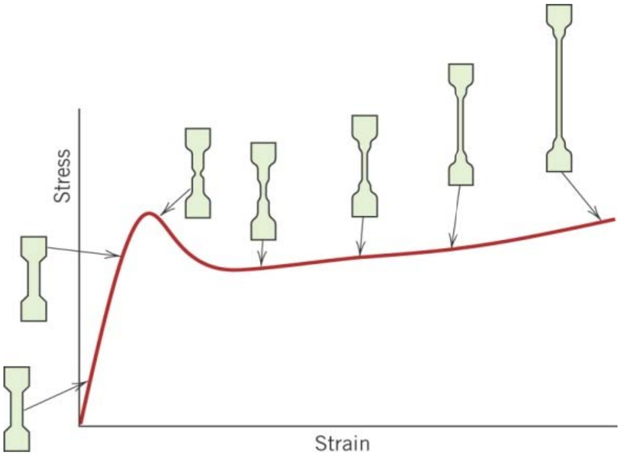


Fig. 1: Necking formation

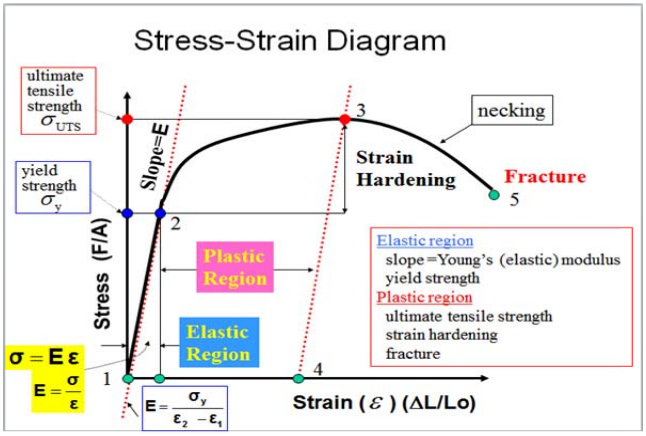
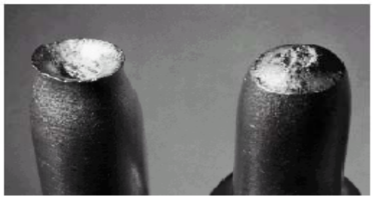
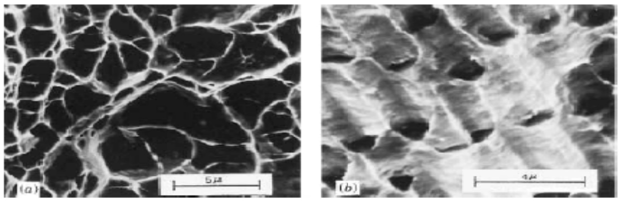


Fig. 2: Stress-Strain Diagram



(Cap-and-cone fracture in Al)



Scanning Electron Microscopy: *Fractographic* studies at high resolution. Spherical "dimples" correspond to micro-cavities that initiate crack formation.

Fig. 3: Microscopic fracture graphic

6. PREVENTING FAILURE

In service, under loading (mechanical, thermal) you should;

a) Avoid excess deformation that may deteriorate the functionality

b) Avoid cracking that may propagate to complete fracture

7. LITRATURE REVIEW

Many researchers have considered various aspects of ductile fracture of steel under monotonic loading and several detailed studies have already been undertaken. According to journal of structural Engineering, Vol. 140 No 5 may 2014, The paper predicted ductile fracture of steel under monotonic loading only from the test results of notchless tensile coupons. A simple fracture model based on the concept of a damage index with only one model parameter is proposed to predict ductile fracture of structural steels. The model is based on an idea of a combination of the void growth model and Miner's rule in incremental form. Moreover, a new method to modify the true stress-true strain data after necking initiates is proposed, and it is found that the hardening modulus of several structural steels after necking initiates is approximately the same. Finally, ductile fracture of smooth and notched steel specimens is numerically simulated for three types of structural steels, which proves simplicity and acceptable accuracy of the fracture model and the modification method of the true stress-true strain.

According to J.Tong, B. Lin, and Lu, K. MadiInternational Journal of *Fatigue*, 2015, **71**, 45. Experiments have been performed on specimens subjected to strain cycles similar to those experienced by sub-surface elements of material in rolling/sliding contact.And the Coffin-Manson relationship may be used to predict the number of cycles to failure. If however, the strain cycle is open, so that the material accumulates unidirectional plastic strain (the situation known as “ratchetting”) a different type of failure, which is termed ratchetting failure may occur. It occurs when the total accumulated plastic strain reaches a critical value which is comparable with the strain to failure in a monotonic tension test. The number of cycles to failure under these circumstances may be estimated by dividing this critical strain by the ratchetting strain per cycle. It is suggested that low cycle fatigue and ratchetting are independent and competitive mechanisms so that failure occurs by whichever of them corresponds to a shorter life. The results of both uniaxial and biaxial tests reported in the literature have been re-evaluated and these, together with new data on biaxial tests on copper, found to be consistent with this hypothesis.

According to S. Deyand M. LangsethInternational Journal of Fatigue, 2014, 66,138.Notched specimens of the structural steel Weldox 460 E have been tested at high strain rates in a Split Hopkinson Tension Bar. The aim was to study the combined effects of strain rate and stress triaxiality on the strength and ductility of the material. It is further considered important to obtain experimental data that may be used in validation of constitutive relations and fracture criteria. The force and elongation of the specimens were measured continuously by strain gauges on the half-bars, while the true fracture strain was calculated based on measurements of the fracture area. Optical recordings of the notch deformation were obtained using a digital high-speed camera system. Using image processing of the digital images, it was possible to estimatethe true strain versus time at the minimum cross-section in the specimen. The ductility of the material was found to depend considerably on the stress triaxiality. Non-linear finite element analyses of the notched tensile specimens at high strain rates have been carried out using LS-DYNA. A computational material model including viscoplasticity and ductile damage has been implemented in LS-DYNA and determined for Weldox460 E steel. The aim of the numerical simulations was to assess the validity of the material model bycomparison with the available experimental results.

8. CONCLUSION

High strength ductile steels constitute a wide variety of structural steels that find a wide variety of applications based on the experimental investigation carried out from different paper involving impact and dynamic loading. Understanding the failure mechanisms under a wide range of loading conditions in these materials would lead not only to better design methods but could also lead to ways of enhancing the desired properties of the steel.

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