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A detailed review and Prediction of Ductile Fracture Behavior of Materials by Using ANN and DOE Techniques

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ABSTRACT

Nowadays sheet metal applications are very wide in the automotive as well as aerospace industries, at the same time failures are also occurs occasionally during the applications which leads in losses in the resources. Earlier researchers were studied the failure analysis through various Failure Mode and Effective Analysis (FMEA) technique and tried to predict the fracture before failure occurs. This work attempts to predict the ductile fracture criterion for the sheet metal to avoid the failure by means of considering various controllable and uncontrollable parameters. With the Design of Experiments and the Artificial Neural Network techniques a ductile fracture initiation criteria modeled and the model will be validated through Finite element simulation for the verification of the quality. If comparison results are within the limit condition, the model can be utilized for the prediction of ductile fracture before it happens in the real application.

Keywords: Ductile Fracture, ANN, Doe.

1. Introduction

Fracture mechanics is the field of mechanics concerned with the study of the propagation of cracks in materials. It uses methods of analytical solid mechanics to calculate the driving force on a crack and those of experimental solid mechanics to characterize the material's resistance to fracture. In modern materials science, fracture mechanics is an important tool in improving the mechanical performance of mechanical components. It applies the physics of stress and strain, in particularly the theories of elasticity and plasticity, to the microscopic crystallographic defects found in real materials in order to predict the macroscopic mechanical failure of bodies. Fractograpy is widely used with fracture mechanics to understand the causes of failures and also verify the theoretical failure predictions with real life failures. The prediction of crack growth is at the heart of the damage tolerance discipline.

1.1 Deformation

Depending on the type of material, size and geometry of the object, and the forces applied, various types of deformation may result. The image to the right shows the engineering stress vs. strain diagram for a typical ductile material such as steel. Different deformation modes may occur under different conditions, as can be depicted using a deformation mechanism map.

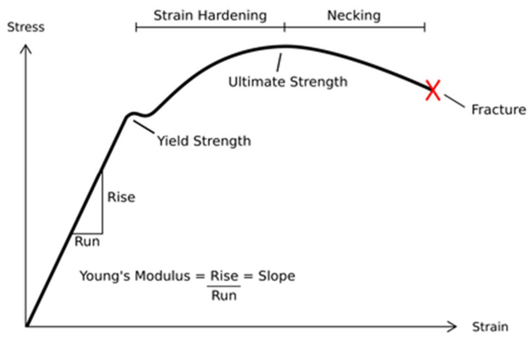

Figure 1: Typical stress vs strain diagram with the various stages of deformation

1.2 Elastic deformation

This type of deformation is reversible. Once the forces are no longer applied, the object returns to its original shape. Elastomers and shape memory metals such as Nitinol exhibit large elastic deformation ranges, as does rubber. However elasticity is nonlinear in these materials. Normal metals, ceramics and most crystals show linear elasticity and a smaller elastic range.

Linear elastic deformation is governed by Hooke's law, which states:

$$\sigma = E\varepsilon$$

Where σ is the applied stress, E is a material constant called Young's modulus, and ε is the resulting strain. This relationship only applies in the elastic range and indicates that the slope of the stress vs. strain curve can be used to find Young's modulus. Engineers often use this calculation in tensile tests. The elastic range ends when the material reaches its yield strength. At this point plastic deformation begins. Note that not all elastic materials undergo linear elastic deformation; some, such as concrete, gray cast iron, and many polymers, respond nonlinearly. For these materials Hooke's law is inapplicable.

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1.3 Ductile Fracture

One of the most important and key concepts in the entire field of Materials Science and Engineering is fracture. In its simplest form, fracture can be described as a single body being separated into pieces by an imposed stress. For engineering materials there are only two possible modes of fracture, ductile and brittle.

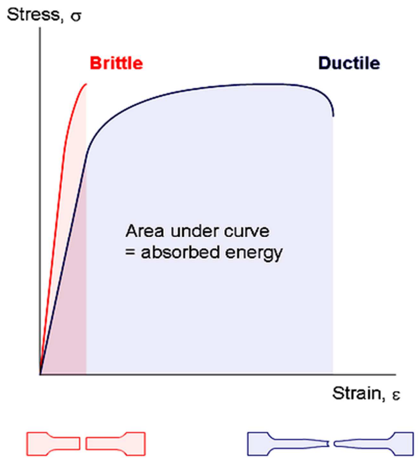

Figure 2: Brittle vs Ductile Stress Strain Behavior

In general, the main difference between brittle and ductile fracture can be attributed to the amount of plastic deformation that the material undergoes before fracture occurs. Ductile materials demonstrate large amounts of plastic deformation while brittle materials show little or no plastic deformation before fracture. Crack initiation and propagation are essential to fracture. The manner through which the crack propagates through the material gives great insight into the mode of fracture. In ductile materials (ductile fracture), the crack moves slowly and is accompanied by a large amount of plastic deformation. The crack will usually not extend unless an increased stress is applied. On the other hand, in dealing with brittle fracture, cracks spread very rapidly with little or no plastic deformation. The cracks that propagate in a brittle material will continue to grow and increase in magnitude once they are initiated. Another important mannerism of crack propagation is the way in which the advancing crack travels through the material.

1.4 Crack Growth

Ductile fracture occurs mainly due to the enlargement of voids due to the external loading conditions which are named as a crack growth. The Fig.- shows the steps incurred in the ductile fracture specimen at the tensile loading condition. Crack will have the enlargement with 900 to the stress formed in the material and the maximum shear stress will be at450 inclined positions.

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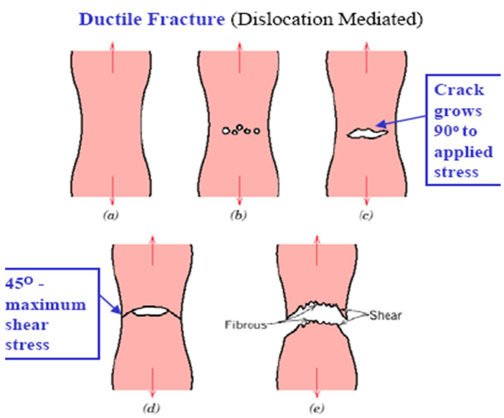

(a) Necking, (b) Cavity Formation,
(c) Cavity coalescence to form a crack,
(d) Crack propagation, (e) Fracture

1.5 Sheet Metal Blanking

Two common forms of sheetmetal fracture are brittle and ductile. Fractures in glass, rocks and ice have the characteristics of brittle fracture. However, brittle fracture in sheetmetal forming is uncommon. A rare example would be a stamping that cracks when dropped on the floor because the chemistry, processing, microstructure and amount of cold work all interact just right to produce a brittle condition.Instead, the more common brittle fractures in sheetmetal happen for specific metal chemistries when subjected to high impact loading at very low (-40 deg.) in-service temperatures. Unfortunately, too many statements are heard in press shops that deformation work hardens the steel so much that it becomes brittle and fails. Others will explain that high-strength grades or full hard tempers of sheet must be formed only once because the material already is so hard after the first hit that any added deformation makes it brittle and unable to withstand a second hit. The usual mode of stamping fracture is ductile fracture. The cross-sections through the sheet thickness in Fig. 1.8 illustrate the difference between brittle and ductile fracture. The brittle fracture (A) has no or very little localized plastic deformation surrounding the fracture. The fracture surface often occurs at a 45-deg. angle through the thickness of the sheet. In contrast, the ductile fracture (B) has significant deformation and thickness reduction prior to the onset of fracture. One can visualize the ductile flow of material before the sheet actually tears. The resulting fracture surface has a cup and cone topography.

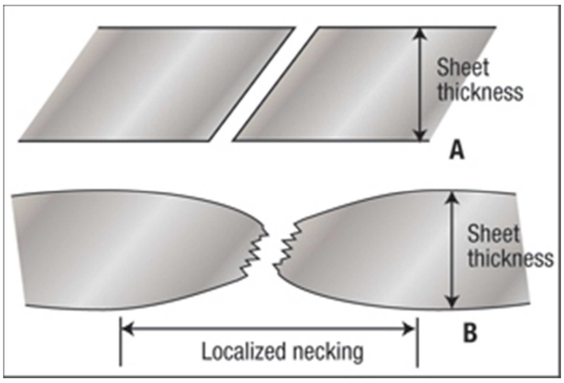

Figure4: Fracture profiles of brittle fracture (A) without any through-thickness thinning, and ductile fracture (B) showing extensive localized thinning.

The amount of deformation or strain that a material can withstand before ductile fracture is very difficult, if not impossible, to predict. Microstructure, grain size, inclusions, stress state, constraints, forming speed and many other factors control the onset of a ductile fracture.

In the press shops, the termination of useful deformation in most stampings is not the unpredictable ductile fracture. A local neck is the failure mechanism that terminates global stamping deformation. Local necking is defined as a narrow line of highly localized thinning with deformation across the neck but no deformation along the line of the thinning.

The forming mode changes to a rigid sheet above and below the neck that move apart as the local neck thins and widens as total deformation force decreases. In a normal tensile-test sample, the local neck is angled about 55 deg. from the major loading axis. This is the angle along which the resultant strain is zero. As specimen width increases, the angle increases until the local neck eventually occurs perpendicular to the major strain direction. As the local neck develops, a high rate of straining occurs within the neck that eventually leads to ductile fracture.

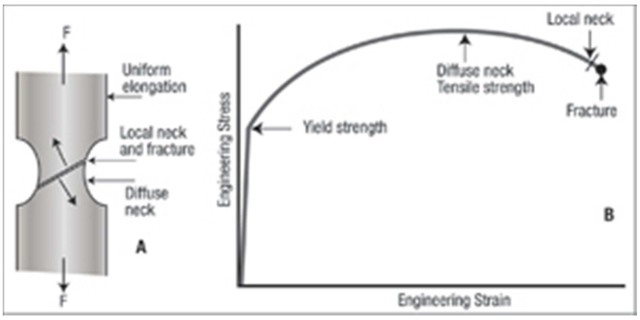

Figure 5: Schematic of a tensile-test sample (A) showing an angular local neck at the onset of fracture, and a stress-strain curve (B) with the local neck occurring just prior to the onset of specimen fracture

The criteria for a local neck defined above for a tensile test remains the same when forming stampings in the press shop. However, the direction of the maximum strain, as well as widely varying gradients of strain that change throughout the stamping with the stroke of the punch, make the theoretical prediction of the onset of local necking almost impossible. However, metal forming studies over the last three decades have collected sufficient data to generate experimental curves that predict the maximum allowable stretchability called forming-limit curves or forming-limit diagrams, these important curves and their application will be the topic of the December column.

So far the discussion has focused on excessive stretching of sheetmetal. Other types of failures occur when sheetmetal is formed compressively. For small amounts of compressive deformation of thick sheets, the compressive direction becomes smaller as sheet thickness (and sometimes sheet width) becomes larger, according to the constancy of volume rule. When the amount of compression becomes too large for a given sheet thickness, the sheetmetal simply forms buckles as the least-energy mode of deformation.

1.7 Applications of Fracture Mechanics

The design process for a component consists of choosing the appropriate geometry, the necessary material strength as per the loading conditions (either cyclic or constant loading), the temperature of usage and structural analysis (Testing and FEM analysis), so that it does not fail under load. The methodologies followed in design criteria traditionally pick up the conventional materials based on standard data and as per the loading conditions proportioning the geometry of the components on basis of analysis. The material strength is chosen keeping in mind the factor of safety, i.e. the ultimate stress (where it fails) is much higher than maximum stress in the component.

Fracture mechanics follows one of two design principles, either fail-safe or safe-life. In fail safe mode, even if a component fails, the entire structure is not at risk (failure of redundant members). According to the safe life principle throughout the life, no component of the structure may fail. Fracture mechanics estimated the maximum crack that a material can withstand before it fails through analysis taking into consideration the overall dimensions of the structure, the stress value where crack initiation takes place, notch toughness value (ability of a material to absorb energy in the presence of a crack for crack propagation), the behavior of materials under the action of stresses by finding out the stress intensity factor (K), fatigue crack growth and stress corrosion crack growth.

Major applications of fracture mechanics design are material selection, effect of defects, failure analysis and control/monitoring of components. Fracture analysis includes the usage of mathematical models such as linear elastic fracture mechanics (LEFM), crack opening displacement (COD) and J-integral approaches by using finite element analysis (FEM). The relationship used for estimating stress intensity factor is

$$K = c\sigma\sqrt{a}$$

where K is the critical fracture toughness value, c a constant that depends on crack and specimen dimensions, σ the applied stress, and a the flaw size. The above relation is very general and as per the shape of the crack, relations available in standard data books or course books are to be used, any general crack can be approximated to standard shapes used in writing the relations.

For a given material the value of K is dependent on stresses acting and flaw size. Flaw size decreases as the stress increases. Thus a design engineer can dictate the life of a component by choosing appropriate values of K, a and σ. Even there are other parameters that estimate the life of a component like working temperature, loading rate (fatigue), residual stress and stress concentration. The higher the K value, the higher is the resistance to crack growth, and the material can resist higher stresses.

Designers try to decrease the defects in the component arising in casting or manufacturing processes by following good fabrication processes and inspection, and estimate notch-toughness values of materials using methods like charpy V-notch impact test, or drop weight tests. In many investigations it was proved that the material failed at a very much lower than the critical stress intensity factor because of defects in the material or micro cracks. Analysis proved that for any component there are two phases for crack development, i.e. crack initiation and second phase crack growth until failure. Of the two, the first phase covers a larger percentage of fatigue life, and under very large high cycle loading conditions second phase is instantaneous.

The factor $(K/\sigma)^2$ is used for estimating design of component because it estimates crack size, more the value better the resistance to the forces(Stress). But how large this factor has to be is decided by considering type of the structure, frequency of inspection, access to inspection, design life of the structure, consequences of failure, probability of over load, methods of fabrication, required quality, material cost in addition to the results obtained by fracture mechanics analysis.

2. Literature Survey

A.M. Goijaerts, et al. (1) described that in critical applications, the development of a blanking process becomes trial-and-error due to the empirical blanking knowledge. A validated FEM-model of the process is present but a proper ductile fracture model is missing. For that development of ductile fracture model was carried out. From the experimental blanking process they determined the critical value and the characterized the process. The main goal of the research was to predict the product shape of a blanked product. An FEM-model, validated on the deformations in the blanking process, existed but the problem of ductile fracture initiation had not been solved yet. The category of local ductile fracture criteria was chosen for this application. For the characterization of such a model two approaches are discussed. To verify these approaches an experimental setup was built and results are presented for the punch displacement at ductile fracture initiation for five different clearances in the blanking process. David Hunt, (2), Finite Element Assisted Prediction of Ductile Fracture in Sheet Bulging of Magnesium Alloys, M.Eng Thesis.

The Finite Element Model of a sheet bulging process was built and validated with results obtained from physical testing. The FEA model uses Oyane’s ductile fracture criterion to predict whether fracture has occurred in the material and also to predict the location of fracture if it occurs. This validated FEA model implements a failure range where the failure is predicted over a range of draw depths, and sensitivity analysis provides a confidence level in this range by varying some of the material properties and examining the effects on the prediction of fracture. Emad Al-Momani, et al. (3) metal blanking is a widely used process in high volume production of sheet metal components. The main objective was to present the development of a model to predict the shape of the cut side. The model investigates the effect of potential parameters influencing the blanking process and their interactions. This helped in choosing the process leading parameters for two identical products manufactured from two different materials blanked with a reasonable quality on the same mold. Finite Element Method (FEM) and Design of Experiments (DOE) approaches were used in order to achieve the intended model objectives. The combination of both techniques was proposed to result in a reduction of the experimental cost and effort in addition to getting a higher level of verification. It can be stated that the Finite Element Method coupled with Design of Experiments approach was provided a good contribution towards the optimization of sheet metal blanking process. A.M. Goijaerts, et al. (4) studied and focused on the evaluation of ductile fracture methodologies, which are needed to predict product shapes in the blanking process. Earlier two approaches were elaborated using local ductile fracture models. The First strategy incorporates the characterisation of a ductile fracture model in a blanking experiment. The second methodology was more favorable for industry. In that approach, instead of a complex and elaborate blanking experiment, a tensile test is used to characterize a newly proposed criterion, which was shown to predict accurately the ductile fracture for different loading conditions. Ahmad Rafsanjani, et al.(5) proposed a methodology to predict the ductile damage in the sheet metal blanking process using a coupled thermo mechanical finite-element method. A constitutive material model combined with the ductile fracture criteria was used. The effect of material softening due to the heat generated during plastic work in a specimen was considered in blanking simulations. The sheet metal blanking process was simulated using DEFORM2D, a commercial finite-element code. The effect of material softening due to heat generation because of plastic deformation was introduced to the simulation using a coupled thermo mechanical finite element method. The effect of punch speed and punch–die clearance on blanking quality was carefully examined. To verify the validity of the proposed model, several blanking simulations performed and the results compared with those obtained from an experimental study. I.M. Gunter, et al.(6) added some spinal additions>2.5 vol.%, the additional crack initiation sites associated with the brittle particles embrittle the molybdenum and hinder the ductilizing grain size effect, resulting in a decrease in ductility beyond 2.5 vol.% spinel. Thus, it would appear that controlling the molybdenum grain size, rather than adding spinel particles, is a more effective means of controlling ductility of molybdenum when fracture occurs inter granularly. Molybdenum-base materials exhibit excellent potential for such applications due to the high strength and high melting point of molybdenum; however, the oxidation resistance of molybdenum metal is extremely poor. Although several molybdenum silicides exhibit excellent oxidation resistance, these intermetallics are too brittle for practical use as structural materials. D. Brokken, et al (7) exhibited the large, localized deformations were handled by a combination of an Operator Split Arbitrary Lagrang Euler (OS-ALE) method and full remeshing was done. Transport of the state variables between subsequent meshes for the OS-ALE and remeshing methods was achieved by the Discontinuous Galerkin (DG) method and an interpolation procedure, respectively.Ductile fracture is incorporated using a discrete cracking approach. The calculated product shapes are compared to experimental observations, showing an overall good agreement. The element elimination procedure is capable of modelling separation, it is inherently mesh dependent. Furthermore, the adoption of rigid plastic material behaviour obstructs the modelling of spring back effects. It is concluded that a mesh independent finite element procedure to predict the shape of blanked products is not yet available. Yanshan Lou, et al.(8) implements a ductile fracture criterion was proposed to model fracture behavior of sheet metals for nucleation, growth and shear coalescence of voids during plastic deformation. In the new ductile fracture criterion, void nucleation is described as a function of the equivalent plastic strain, void growth is a function of the stress triaxiality and void coalescence is controlled by the normalized maximal shear stress. The paper presents nucleation; growth and coalescence of voids are analyzed comprehensively to develop reasonable models to describe these processes. These models are combined to construct a new ductile fracture criterion. Parametric study is carried out to investigate the effect of the normalized maximum shear stress and the stress triaxialility on the shape of FFLDs. The new criterion is applied to construct the FFLD of DP780 as well as the fracture locus of Al 2024-T351 to validate their performance on prediction of the equivalent plastic strain to fracture in a wide range of stress states from the uniaxial compression to the balanced biaxial tension of sheet metals.A ductile fracture criterion is newly proposed for prediction of FFLDs with efficient procedure to obtain the material constants in the criterion. The criterion is constructed with consideration of damage accumulation induced by nucleation, growth and shear coalescence of voids. These three processes are described as functions of the equivalent plastic strain,

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the stress triaxiality, and the normalized maximal shear stress to be multiplied to represent a fracture model. The model endows a cut-off value of _1/3 for the stress triaxiality for appropriate application to ductile materials. Jun Zhou a, Xiaosheng et al (9) focused the plasticity and ductile fracture behaviors of an aluminum alloy 5083-H116 are studied through a series of experiments and finite element analyses. A recently developed stress state dependent plasticity model, the I1–J2–J3 plasticity model, is implemented to describe the plastic response of this material. Furthermore, a ductile failure criterion based on a damage parameter defined in terms of the accumulative plastic strain as a function of the stress triaxiality and the Lode angle is established. The calibrated I1–J2–J3 plasticity model and ductile failure model are utilized to study the residual stress effect on ductile fracture resistance. A local out-of-plane compression approach is employed to generate residual stress fields in the compact tension specimens. Fracture tests of C(T) specimens having zero, positive and negative residual stresses are conducted. The numerical results, such as load–displacement curves and crack front profiles, are compared with experimental measurements and good agreements are observed. Both experimental and finite element results show significant effect of residual stress on ductile fracture resistance.

3. Problem Definition

From the literature survey various researchers identified blanking process is the major manufacturing process of various automotive as well as aerospace components in the very large quantity. In those stated industries, application of sheet metal functions has major impact to meet the requirements. Focusing on the prediction of failure, the enlargement of the crack in the sheet metal is characterized by the researchers concentrated only on the critical parameters. The exact fracture points due to the crack propagation during the application were not presented. If the exact nucleation of the void, void-coalescence and crack propagation is available, the fracture can be predicted before the failure happens. This project work aims to predict the fracture condition of the material in which crack propagates at its critical value by means of introducing ductile fracture criteria for a specific application. This criterion is also applicable to various other working conditions. The behaviour of materials is mainly based on the ductile properties of the sheet metal and so the ductile fracture has been chosen for prediction.

4. Proposed Work

The objective function of the work deals with the predictions of ductile fracture in the sheet metal blanking process by modelling ductile fracture initiation criteria which is suitable for various working conditions of the materials. Proposed work plan will be as follows,

- Study of blanking process
- Identifying the controllable and non-controllable factors of blanking process.
- Proposing the process conditions through literature review
- Choosing the assumptions and measuring devices
- Material selection
- Punch and die specifications
- Design of Experiments
- Results from DOE

- Applications of ANN
- Finding Optimized parameters for numerical simulation- Result-I
- Finite Element Analysis
- FEA Simulation planned to identify the crack propagation and fracture conditions – Result-II
- Comparison of Results I and II
- Validation of the model

5. Conclusion:

From the literature survey identified that blanking process is the major manufacturing process of various automotive as well as aerospace components in the very large quantity. Focusing on the prediction of failure, the enlargement of the crack in the sheet metal is characterized by the researchers concentrated only on the critical parameters. The exact fracture points due to the crack propagation during the application were not presented. If the exact nucleation of the void, void-coalescence and crack propagation is available, the fracture can be predicted before the failure happens. On the completion of implementation of the proposed work, the fracture behavior can be predicted by ANN as with the help of DOE techniques.

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