DEFORM™ Application #252

Chevron Crack Analysis

Background:

During metal forming, the workpiece is subject to plastic deformation and the strain required to produce the final component varies. At some point, the materials reach a limit of ductility and further deformation can result in ductile fracture.

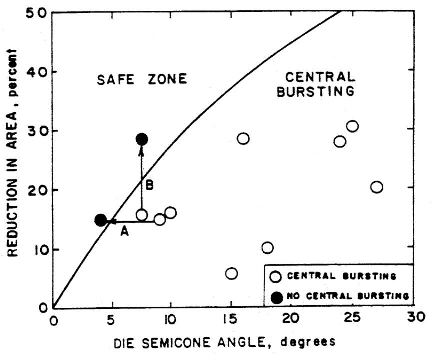
In some processes, ductile fracture is designed into an operation. For instance, blanking and piercing rely on the generation of a controlled crack through a deformation zone. Machining and shearing are also examples where material is pushed beyond its ductility limit intentionally.

By contrast, surface and internal fractures in forged or headed parts result in a product that is rarely suitable for it's intended purpose. Surface cracks and internal fractures such as chevron cracks are examples of defects that have been observed in industry. These conditions are commonly considered detrimental and generally unacceptable for the final application.

Problem:

Chevron cracks are a form of ductile fracture observed in extrusions. The occurrence of chevron cracking in automotive axle shafts and steering components has led to 100% inspection procedures. This is time consuming, costly, and does not prevent defect formation.

Traditionally, the problem has been addressed by criteria that define combinations of die semicone angles and reductions in area to prevent central bursting. The strain hardening capacity of the deforming material and friction in the operation were also accounted for by the criteria. These characteristics are summarized in a forming limit diagram, where a safe zone and a central bursting zone are defined.



the proposed relationship between die geometry and risk of central bursting

Ductile Fracture:

Using simulation, a damage model can be used to indicate the likelihood of ductile fracture. The various ductile fracture criteria available [1] can generally be represented by the following expression:

$$\int F(deformation)\,d\bar{\varepsilon} = C$$

A variety of damage models have been proposed, taking into account normal stress, shear stress, strain and other criteria [2]. When the maximum damage value (MDV) of the material exceeds the critical damage value (CDV), crack formation is probable.

Cockcroft and Latham's criterion [3] states that fracture will occur when the cumulative energy due to the maximum tensile stress exceeds a certain value. This criterion has provided good agreement at predicting the location of a tensile failure based on a maximum damage value. The model is based on the equation:

$$\int^{\bar{\varepsilon}_f} \sigma^* d\bar{\varepsilon} = C_a$$

A non-dimensional form of the above equation has also been developed:

$$\int^{\bar{\varepsilon}} \frac{\sigma^*}{\sigma} d\bar{\varepsilon} = C_b$$

Further developments have since been made to the equation, but the Cockcroft and Latham criterion appears to be valid at predicting both surface and chevron type cracks.

Design Environment for FORMing

Experimental:

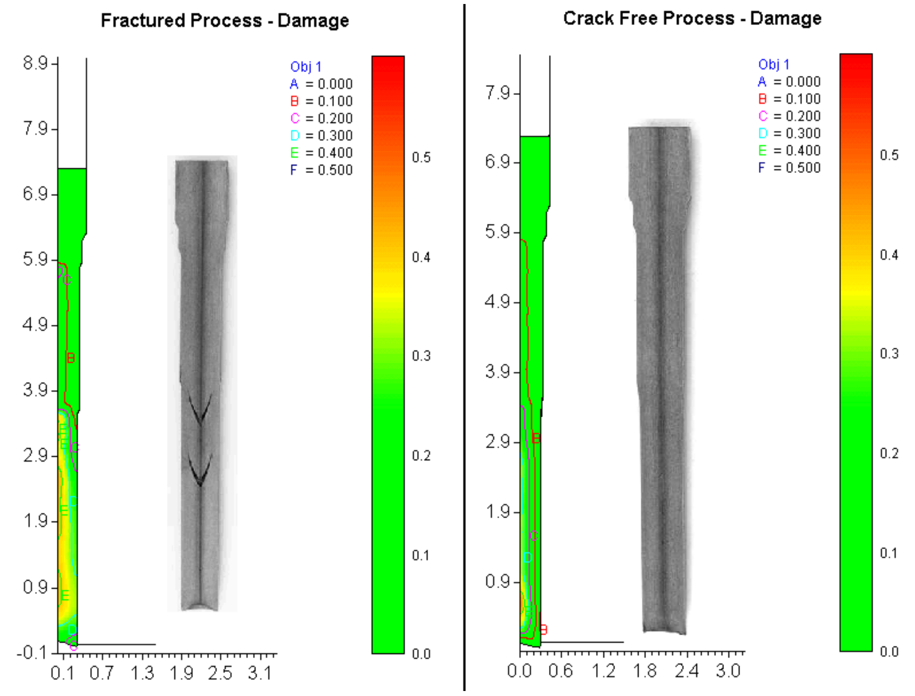
One method to determine a material's CDV is to perform compression and notched tensile tests until cracking is detected. After testing, DEFORM™ simulations are performed to calculate damage values, based on matching the geometry and process conditions of the tests. The predicted MDV at the instant of fracture is a good representation of the CDV of the material. Since the crack is not visible until after it has formed in the tensile test, a higher estimation of the CDV is likely. Averaging the CDV's from the two types of tests is a reasonable approach.

Results:

A comparison was made between two automotive shaft designs manufactured using a double extrusion. The only parameter changed was die semicone angle for the minor diameter. 500 steel shafts (AISI-1024) were produced with a nominal 22.5° extrusion die angle. An additional 500 with a 5° die angle. Chevron cracks (central bursting) were observed on 1.2% of the shafts made from the 22.5° die, but none were observed in the product produced using the 5° angle.

Process simulation using DEFORM™ was used to analyze both processes. The simulation indicated a higher damage value for the product extruded with the 22.5° die angle than for the parts produced with the 5° angle. The high damage value corrolated well with the location of the chevron cracks.

When damage levels are very high, such as in a shearing operation, fracture will occur consistantly. When processes are well below the ductility limit, fractures are not expected to occur. A narrow range exists in between these two regions where the chance of cracking is probabilistic and a higher damage prediction can be interpreted as a greater chance of fracture.


Fractured Process - Damage

Crack Free Process - Damage

The simulation shows contours of damage for both processes. The extrusion on left exhibits higher damage due to 22.5° die angle. The photograph (left) shows corresponding extruded shaft with chevron cracks. The 5° die angle (right) has lower damage and no central bursting was observed.

Wrap Up:

The analysis of ductile fracture is a relatively advanced use of the finite element method (FEM). The required material data is not commonly available and the material laws are less well established. Consequently, a higher level of understanding is necessary.

On the other hand, DEFORM™ has been used successfully to assist designers in eliminating existing cracks in components by providing damage levels for alternative designs. Reducing predicted damage generally reduces the probability of fracture.

The most successful damage based fracture predictions have been cases where the stress state is primarily tensile. In cases with a predominately compressive stress, damage models still require development to be effective in a wide range of processes.

References:

1. Kim, Yamanaka & Altan, Prediction and elimination of ductile fracture in cold forgings using FEM simulations, SFTC reference paper #103.
2. Cockcroft & Latham, Ductility and the workability of metals, SFTC reference paper #100.
3. Hoffmann, Santiago-Vega & Vazquez, Prevention of ductile fracture in forward extrusion, SFTC reference paper #110.

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