

THE DEVELOPMENT AND IMPLEMENTATION OF FINITE ELEMENT ANALYSIS TECHNIQUES IN THE DESIGN OF PRESS TOOLING

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ABSTRACT

Rapid and reliable methods for component development and economic manufacturing layout are today crucial factors for the application of press tooling techniques in mass production of automotive industry components. The use of Finite Element Analysis (FEA) based forming simulation can provide a more detailed insight into the real behaviour of a structure. An LS-DYNA finite element model was developed to analyse the material behaviour during the piercing process of a drainage hole for a shock absorber seat. The simulation is intended to simulate tearing that occurs during the manufacturing stage. Once the current punch produces the observed tearing we can modify the punch to eliminate the problem.

Keywords: finite element, tearing, failure criterion, manufacturing

1. INTRODUCTION

1.1 Background

Finite element analysis modelling of sheet metal stamping is an important step in the design of tooling and process parameters. One of the critical measurements to determine the effectiveness of a numerical model is its capability of accurately predicting failure modes. To be able to make accurate predictions of deformation, tool force, blank design, etc., computer simulation is almost indispensable. In the automotive industry the tooling design can now be made by computer and analysed by FEA and the number of prototypes required to qualify a product design before manufacturing is greatly reduced. Also mechanical forces and material loading parameters when forming components can be found. (See Figure 1 below for a typical piercing simulation assembly)

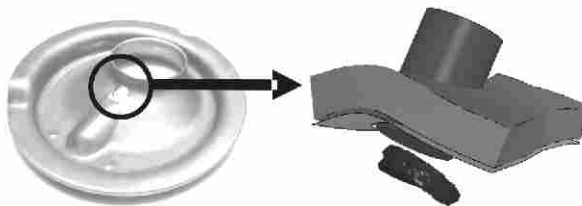


Fig 1: Piercing simulation assembly

The use of FEA-forming simulation provides several key benefits:

- It can provide a more detailed insight into the real behaviour of a structure, by representing accurately the material behaviour, contact and friction, and geometric non-linearity.
- It allows the number of physical prototyping tests to be reduced. Detailed FE-forming analysis can be used in place of prototyping tryouts, provided that the engineer has confidence that the analysis can produce reliable results.
- It provides an accurate estimate of the limit load for limit state design of part and process designs.

In the following sections of this paper the use of FEA, especially LS-DYNA, in several key areas of piercing technology and preceding processes is considered.

1.2 Objective

The aim of the research is to develop techniques that will reduce the amount of time spent during the tool qualifying stage. By accurately setting a finite element simulation that closely matches the experimental or real-life situation we can understand the material behaviour and properties before the tool designing phase commences. In this analysis, during the piercing process of the drainage hole for a shock absorber seat, there is visible material tearing (on the neck) which, as a result, causes the component to be rejected. This results in material waste and prolonged cycle time since the operation now has to be done separately at a different workstation.

The initial phase of the simulation is to emulate the current tearing in the production, and the second phase is to eliminate the tearing by using a different punch design and material data input. Several punch designs have been made and will be simulated. By closely matching the simulation and the actual physical behaviour we can then make further recommendations for the piercing process and further improvements to the finite element simulation of such processes.

2. FUNDAMENTALS OF PIERCING PROCESS

Tool design is a specialised phase of tool engineering. While there are many die-cutting operations, some of which are very complex, they can all be reduced to plain blanking, piercing, lancing, cutting off and parting, notching, shaving and trimming. The design of the die block depends mainly on the workpiece size and thickness. The design of the punch is largely influenced by the area to be pierced and the pressure required to penetrate the work piece. The area to be pierced determines the method of holding the punch.

The cutting action that occurs in the piercing is quite similar to that of the chip formation ahead of a cutting tool. The punch makes contact with the material supported by the die and a pressure build-up occurs. When the elastic limit of the work material is exceeded the material begins to flow plastically (plastic deformation). It is often impractical to pierce holes while forming or before forming because there would be distortion in the forming operation [11]. In such cases piercing in a piercing die is done after forming. During the piercing process the punch penetrates the work material and the blank (often referred to as the slug), and is displaced into the die opening.

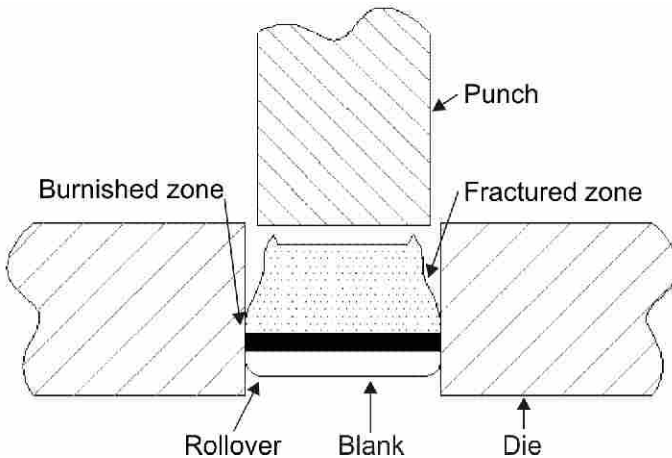


Fig 2: Characteristic appearance of the cutting edges

Upon observation of the cutting surface (see Figure 2 above for a characteristic appearance of the cutting edges), a radius is formed on the top edge of the hole and the bottom edge of the blank. This radius is often referred to as the rollover and its magnitude is dependant on the ductility of the material. Compression of the blank against the walls of the die opening burnishes a portion of the edge [10]. Further continuation of the punching pressure then starts the fracture at the cutting edge of the punch and die. For good quality piercing, a clearance between the die and punch should always be assigned. Angular clearance is also assigned to prevent the back pressure caused by the blank build-up especially when the punch or die block is fragile. Recommended angular clearance varies from 0.25° to 2° per side.

3. MATERIAL THEORY

The FEA focuses on the behaviour of the blank material as a result of the punching load to produce the drainage holes. Different factors such as work hardening and strain hardening play an influential role since the piercing forms part of a progressive operation. The punch and die are made of hardened die steel (e.g. H13 or P20 pre-hardened steel).

The die and punch behaviour does not form part of this analysis.

The blank material is a hot-rolled, high-strength, low-alloy structural steel SUPRAFOAM TM-380. This is steel that is used in the manufacturing of automotive components because of its improved formability, which is achieved by reduced pearlite, which also imparts excellent weldability and toughness to the steel. The high strength is derived from precipitation hardening by micro alloying elements and carefully controlling the parameters during the hot-rolling process. Severe forming can readily be carried out on TM 380 due to its superior formability, thus further increasing the steel's versatility. With the need for higher yet stronger structures, effective mass savings can be achieved without the penalty of reduced overall strength by selecting a steel which has a combination of higher tensile and yield strengths and reduced thickness.

Chemical properties:

Grade	C	Mn	Si	P	S	Al	Nb	Ti	Mo
TM 340	0,05	0,50	0,03	0,015	0,005	0,04	0,015	-	
TM 380	0,06	0,65	0,03	0,015	0,005	0,04	0,025	-	
TM 420	0,08	0,85	0,03	0,015	0,005	0,04	0,030	-	
TM 460	0,10	1,25	0,04	0,015	0,005	0,04	0,030	-	
TM 500	0,06	1,50	0,25	0,015	0,005	0,04	0,040	0,015	
TM 600	0,06	1,80	0,25	0,015	0,005	0,04	0,030	0,015	0,25

Table 1: Chemical composition

Mechanical properties:

Grade	Yield strength (MPa)	Minimum tensile strength ¹ (MPa)	Minimum elongation ² (%) for thickness t		Mandrel diameter for 180° bend test ³ for strip thickness t
			$t \leq 3,0$ mm	$t > 3,0$ mm	
TM 340	340 - 420	400	22	24	0,5 t
TM 380	380 - 460	450	20	22	0,5 t
TM 420	420 - 500	490	19	21	0,5 t
TM 460	460 - 560	530	18	20	1,0 t
TM 600	600	650	12	12	1,0 t

Table 2: Mechanical properties

Some typical applications for this steel are body chassis components for the automotive and truck industry, bumper brackets, engine mounting brackets and wheel centres, crane jibs and booms and a wide variety of mining equipment and cold-formed sections. See Table 1 and Table 2 for chemical composition and mechanical properties as stated in the data sheet.

4. FINITE ELEMENT ANALYSIS SETUP

4.1 Failure Criterion

The first phase of this research is to replicate the tearing that takes place during the piercing process. For this reason a failure criterion observing the mechanical properties was set. The blank material was set to observe the stress strain curve behaviour as in tensile testing machines where a specimen is stretched in the direction of its long axis. The applied force and subsequent deflection of the gauge length are recorded (see Figure 3 below a typical specimen).

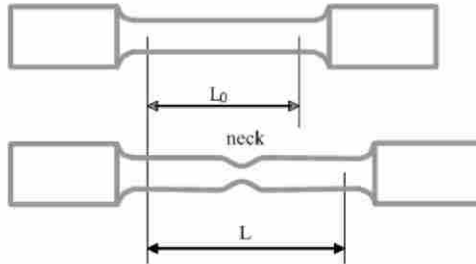


Fig 3: A typical specimen

The general shape and magnitude of the stress-strain curve of any metal will however depends on its composition, heat treatment, prior history of plastic deformation, strain rate, temperature, and state of stress imposed during the testing. The parameters which are used to describe the stress-strain curve of a metal are the tensile strength, yield strength or yield point, percent elongation, and reduction of area. The first two are strength parameters; the last two indicate ductility. See Figure 4 below showing a typical stress strain curve.

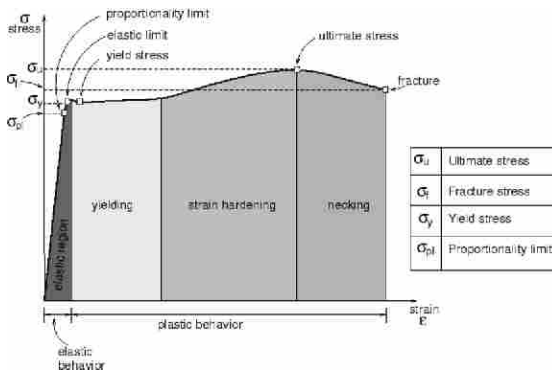


Fig 4: Typical stress strain curve

<http://www.shodor.org/~jingersoll/weave/tutorial/node4.html>

The engineering stress-strain curve however does not give a true indication of the deformation characteristics of a metal because it is based entirely on the original dimensions of the specimen, and these dimensions change continuously during the test. The cross-sectional area of the specimen also decreases rapidly at the necking stage, and the load required for continuing deformation falls off.

This makes the conversion from engineering to true stress prior to necking vital in obtaining realistic results. The derivation of the above equation assumes both constancy of volume and a homogenous distribution of strain along the gauge length of the tension specimen (see below for true and engineering stress conversion).

$$\sigma = S(1 + e), \quad \epsilon = \ln(1 + e)$$

σ : True Stress

S: Engineering Stress

ϵ : True Strain

e: Engineering Strain

4.2 Forming limit diagram

For any sheet metal-forming process, a Forming Limit Diagram (FLD) is used to predict the formability of the material. The FLD is a plot of the maximum strains that can be sustained by sheet materials prior to the onset of localised necking. This is a useful concept for characterising the formability of sheet metal. Both experimental and numerical results in the literature have shown that the level of the FLD is strongly strain-path-dependent and the prediction of the FLD depends on the shape of the initial yield function and its evolution [7].

4.3 Blank material definition

The blank material properties were assigned such that, during the piercing process when the nodal element experiences a strain level beyond the elastic region, it is automatically deleted from the simulation. To facilitate this, a special material was assigned. MAT_020 (MAT_PIECEWISE_LINEAR ELASTICITY) was assigned to the blank material. This is a common material that is used in a majority of LS-dyna analyses which require a failure criterion. This material is an elasto-plastic material which has an arbitrary stress versus strain curve and arbitrary strain rate dependency. Failure based on plastic strain or minimum time step size can be defined [9].

Many of the constitutive models in LS-dyna do not allow failure and erosion. The MAT_ADD_EROSION option provides a way of including failure in these models although the option can be added to other constitutive models with other failure/erosion criteria. Each of the criteria is applied independently, and once any of them is satisfied, the element is deleted from the calculation.

Since the piercing required involves material removal over a thickness, a tetrahedron mesh was used. The tetrahedron is one kind of pyramid that has a flat base and a triangular face above it. The base can also be of any polygon shape. For volume mesh generation, tetrahedral meshes are widely used for number of viscous flows, structural/fracture analyses etc. due to their simplicity in terms of mesh generation. See Figure 5 for a typical tetrahedron mesh.

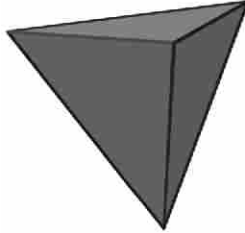


Fig 5: A typical tetrahedron mesh.

Since volume mesh can imply a considerably time consumption task, mass scaling and adaptive meshing were also assigned. Mass scaling refers to a technique according to which non-physical mass is added to a structure in order to achieve a larger explicit timestep. Mass scaling therefore reduces the CPU cost (time) and improves the performance. Mass scaling is also recommended to be used when performing explicit analysis.

Adaptive meshing (otherwise known as “look-ahead meshing”) helps to improve a mesh by moving nodes, splitting elements, or remeshing the model. This is done by the software to reduce elemental distortion or refine a mesh in areas where error estimates are highest. The software derives the new mesh by analysing the data variation along the boundaries and within the interior regions of the faces.

During adaptive meshing, the software may encounter singularities in the model. A singularity represents infinite stresses that theoretically occur at singular points, sharp corners, or geometric discontinuities. To account for singularities, adaptive meshing slows down the refinement of the meshing in these areas. The software averages the mesh weight of the points surrounding a singularity, instead of deriving the weight at the site of the singularity. The software attempts to refine the mesh adequately near the singularities and to satisfy the specified energy error norm. At the site of a singularity, infinite mesh refinement is required for convergence. Here the software attempts to avoid the extremely fine levels of mesh refinement occurring at a singularity. Although you can run adaptive meshing as many times as you need to smooth a mesh and/or generate more elements, you must also consider factors such as computer run times, resources, and input time. With some models, you could run adaptive meshing many times to find an infinite solution at an artificial, singular point.

Though each run may yield a finer mesh, it is rarely practical to go beyond two or three runs.

4.4 Contact

In this LS-dyna analysis contact is established when an imaginary surface projects one-half thickness normal to each segment. This contact for this tearing analysis uses a CONTACT AUTOMATIC SINGLE SURFACE keyword. This is a single surface contact, that is, the contact is defined wholly by the slave side [9]. By convention, slave and master terminology is used where one body is designated as master, the other is designated as slave. Slave nodes are checked for penetration through master segments. The failure nodes have been assigned a specific strain level such that when a certain limit is reached, the node must be deleted. The characteristics of this type of contact are that only the slave side is defined and no segment orientation is required. The effects of friction will have a major impact on the wearing of the punch and die. For the purpose of the analysis a standard coefficient of friction between two metals is assigned.

4.5 Motion of punch

Tool motion is imposed using the BOUNDARY PRESCRIBED MOTION RIGID keyword. This keyword uses a load curve (user defined) to define its movement; when the punch proceeds towards its final position, the work piece experiences a complex sequence of stresses and strains as it is formed into its final shape. See Figure 6 below for a typical displacement curve used in the analysis.

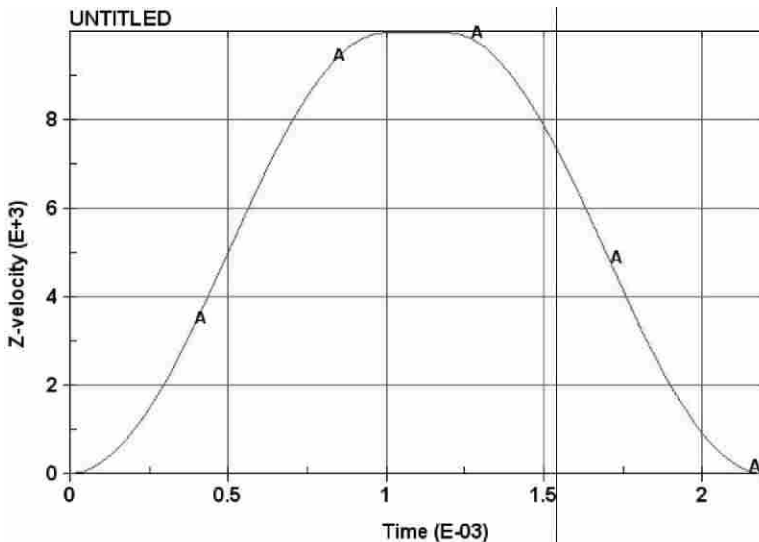


Fig 6: A typical displacement curve

5. RESULTS

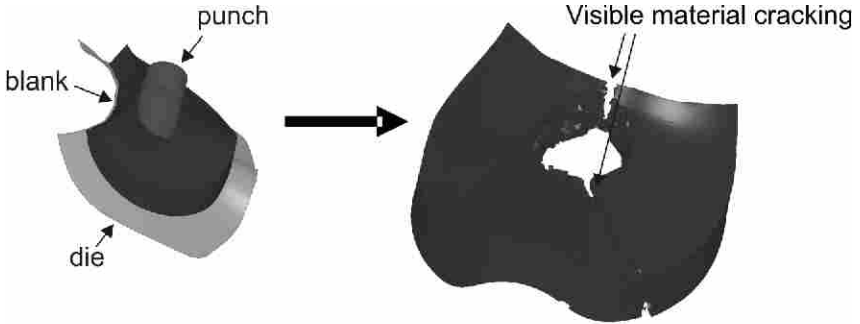


Fig 7: Piercing process assembly

The study of the piercing process with LS-dyna led to several conclusions and recommendations. The piercing process was assembled with the punch and die as solid elements and the blank material to the TMs 380 specification with a tetrahedron mesh. The punch was given an arbitrary travel distance (see Figure 7 for the piercing process assembly). The simulation of the piercing was performed successfully.

When simulating the material with a yield strength of 154 Mpa there is visible cracking on the material neck and around the drainage hole, and no cracking when using the actual material yield stress (380 Mpa). The difference in the material behaviour indicates the necessity to develop an accurate material failure model. This significant difference in material behaviour, energy levels and crack propagation was observed with the different material data inputs. For this analysis a single stress-strain curve was defined. This posed a limitation since the material behaviour will always follow that strain path irrespective of the piercing speed.

The failure criterion has been set such that when an element node reaches a certain limit it is deleted. This means that to a certain level energy is lost and hence the mass is reduced. This is in conflict with the basic energy laws and hence close attention should be paid to the material laws and failure criteria set.

This engineering approach assumes that the die-face deformations during the piercing process are negligible and industrial practice has proved the validity of this assumption. This notion of an ideally rigid die construction may nevertheless be questionable when it comes to the punching/forming of high strength steel due to higher forming loads.

Finally testing and simulation of the piercing process is recommended as it would greatly provide insight into the material behaviour, mechanical properties, and press machine setting parameters. An accurate representation would greatly reduce the amount of time spent during the tool try-out phase and the number of prototypes required.

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