Application of Fracture Mechanics for Evaluation and Improvement of Downhole Perforating Tools

Allan Zhong, Jack Clemens and Matthew Mlcak

Halliburton Company

Abstract: At times, oil and gas wells require workover operations to repair or replace corroded downhole equipment. During these maintenance operations, a single hole may be required to allow kill fluids to be circulated to maintain well control. Traditionally, the hole would be made via explosives and mechanical hole-punching methods, which frequently fail to perforate. To improve these operations, slickline-deployed electro-mechanical downhole power unit perforating tools were developed by a major oilfield engineering company and successfully applied in the field for perforating 4½-in. size, J-55 grade steel tubing. To extend the perforating tools to larger size tubing and/or higher grade tubing materials, fracture-mechanics-based finite element analysis is used to evaluate whether or not the perforating tools can perforate the tubing, and if the force required to perforate is within the capacity of the downhole power unit. The fracture mechanics theory used is a two-parameter (fracture toughness and triaxiality) fracture theory, which can model the ductile fracturing perforation process accurately. In this paper, how to use the aforementioned fracture-mechanics-based finite element method to improve the design of the blades of perforating tools is discussed. Since design iterations are primarily conducted via the numerical analysis instead of physical tests, the time and cost for the development of the blades of perforating tools are reduced. The perforating tools for higher grade and/or larger size tubing are successfully developed via the change in perforating the blade geometry and change in blade material.

***Keywords**: Damage, Fracture, Ductile Fracture, Triaxiality, Cutting*

1. Introduction

As oil and gas wells mature, they often require workover operations to repair or replace corroded downhole equipment. During these maintenance operations, a single hole may be required to allow kill fluids to be circulated to maintain well control. Traditionally, the hole would be made via explosives and mechanical hole-punching methods (Bargawi, 2008), which frequently fail to perforate softer grade (e.g. J55 or K-55) tubing. To improve these operations, slickline-deployed electro-mechanical downhole power unit perforating tools were developed and successfully applied in the field for perforating 4½-in. size, J-55 grade steel tubing. To extend the perforating tools to larger size tubing and/or higher grade tubing materials, additional improvements to the developed tool are needed. The main requirements for the perforating tools are 1) force required for perforation is within the capacity of the downhole power unit (DPU® device); 2) the cutting blades in the tool can be used multiple times.

To reduce product development time, minimize physical testing, numerical simulations are used to screen potential design using a fracture-mechanics-based finite element analysis, which can evaluate whether or not the perforating tools can perforate the tubing, and if the force required to perforate is within the capacity of the downhole power unit. The fracture mechanics theory used is a two-parameter (fracture strain and triaxiality) fracture theory (Abaqus, 2010), which can model the ductile fracturing perforation process. In this paper, how to use the aforementioned fracture-mechanics-based finite element method to improve the design of the blades of perforating tools is discussed.

The following sections of the paper are organized as following. First a brief description of a typical DPU tubing blade cutter is presented. Then triaxiality dependent fracture/damage mechanics theory is discussed along with approaches for model parameter identifications. The finite element model is presented in Section 4. Representative numerical examples are given in Section 5 along with relevant conclusions. The paper ends with discussions on possible improvements of the numerical models and a summary.

2. DPU Perforating Tools (Bargawi, 2008)

The Downhole Power Unit (DPU) battery-operated electromechanical device can produce a setting or retrieving force without the use of explosives or atmospheric chamber. In operation, a gear motor operates a linear drive to generate a gradual controlled, axial compressive or tensile force to move the cutting blade or punch to perforate tubing.

When deploying the DPU perforating tool on a slickline, it is conveyed into the well using a standard slickline tool string and wire. The DPU device has an on board timer that is preset on surface prior to running into the well. Once the tool is at the target position where the tubing is to be perforated, the tools are held static. Once a preset time has lapsed, the DPU tool will activate and the perforating blade will be in motion to make the cut.

An illustration of a DPU perforating tool is shown in Figure 1. The DPU tool transmits the required force to the cutting blade in a cam-type action using a hardened blade on a pivot point that cuts a hole in the tubing wall. The DPU tool linear actuation is slow, and actuation is approximately 0.5 inch per minute. Thus during initial movement of the blade, the drive pushes the blade and anchors the blade against the tubing wall. As the drive continues to move, the blade continue to rotate, pushing against the tubing wall, until the wall is damaged and a hole is produced, see Figure 2. Then the blade retracts and the tool can be pulled out

It is noted that perforating process involves no manipulation of the slickline from surface. The retrieving of the tool requires no jarring. Generally standard slickline equipment is onsite during workover jobs, eliminating mobilization and rig-up costs for traditional perforation. With the DPU perforating tool, a safer (i.e. no explosives involved) and more cost-effective approach is provided for tubing perforation in a workover.

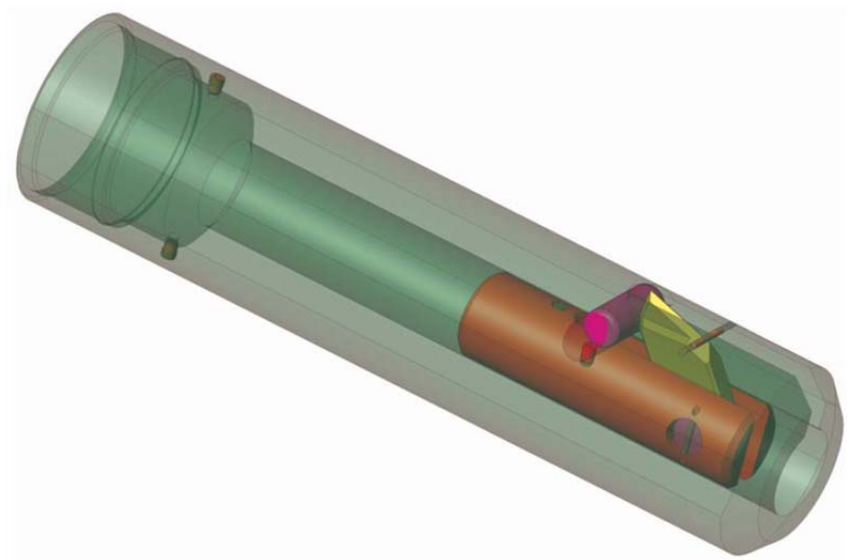
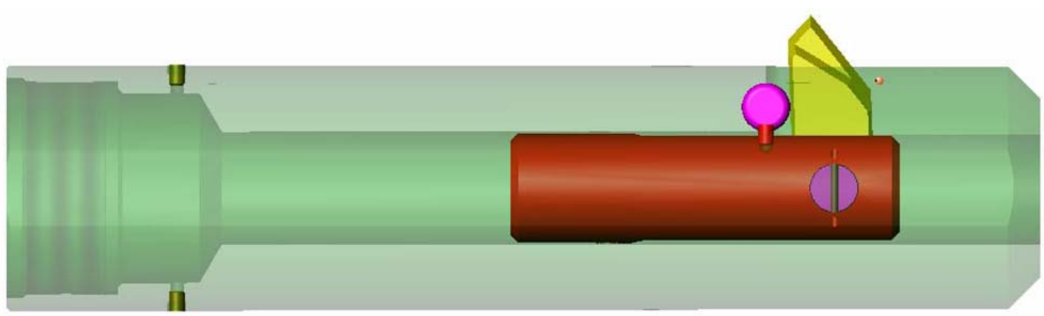
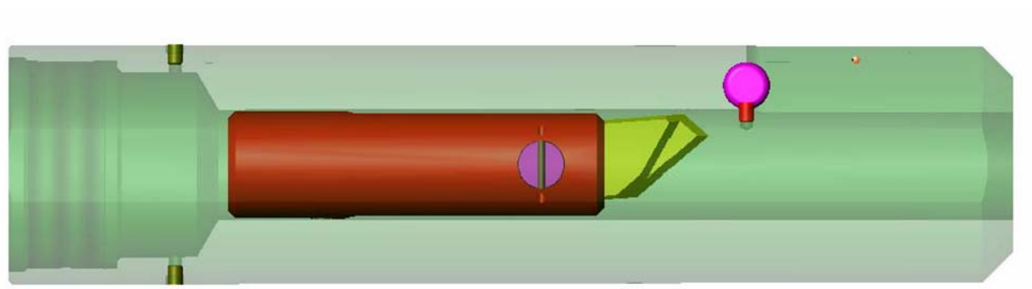


Figure 1: Illustration of a DPU® perforating tool



(a)



(b)

Figure 2: Illustration of a DPU perforating tool in (a) “blade-extended” position, (b) “fully retracted” position

3. Two-Parameter Fracture and Damage Mechanics

From damage mechanics point of view, fracture initiation is determined by maximum principle stress or fracture strain. Considering geometric constraint, one can show that the fracture initiation strain for ductile failure is dependent of stress triaxiality (Rice, 1969). This type of model (two parameter theory) is relevant to ductile fracture, which is the result of voids nucleation, growth and coalescence. Many models have since been developed with various degree of success. More recent ductile fracture models account for the influence from the third invariant of deviatoric stress (three parameter theory). Both approaches are available in Abaqus (Abaqus manuals, 2013).

In this work, the two-parameter theory that fracture is dependent of failure strain and stress triaxiality, is utilized because the perforation of (ductile steel) tubing is a ductile-fracture process. For this particular application, we can neglect the rate effect of ductile-failure initiation process.

In this context, fracture strain is defined as equivalent plastic strain at the onset of crack initiation (damage initiation). Stress triaxiality (η) is defined as the ratio of hydrostatic stress (p) over von Mises stress (σ),

$$\eta = -\frac{p}{\sigma} \qquad (1)$$

It is easy to show that $-\infty < \eta < \infty$.

A typical relation between fracture strain and stress triaxiality is shown in Figure 3: the larger the stress triaxiality, the lower the fracture strain. In special cases such as hydrostatic tension (i.e. $\eta = +\infty$), fracture strain is ~ 0, it takes no plastic strain to have crack initiated, while for hydrostatic compression ((i.e. $\eta = -\infty$), it takes infinitely large plastic strain to initiate a crack, or fracture will not occur.

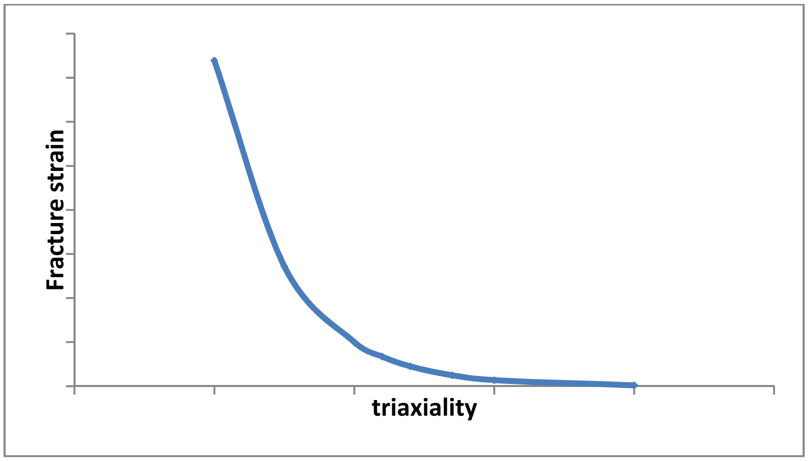


Figure 3: illustration of fracture strain dependence on triaxiality

One simple experimental procedure to determine the fracture strain vs. stress triaxiality curve is described in Abaqus technology brief (SIMULIA, 2012). A more elaborate approach is described in (Prantl, 2013). In either case, the curve is determined via a hybrid approach, the fracture strain is measured via physical tests, and the stress triaxiality at crack initiation is calculated from finite-element analysis.

A major drawback of using damage mechanics in finite-element model is that the numerical prediction is mesh sensitive. Fracture energy-based damage evolution law can minimize mesh dependence. The fracture energy is defined as following:

$$G_f = \int_{\bar{\varepsilon}_0^{pl}}^{\bar{\varepsilon}_f^{pl}} L\sigma_y d\varepsilon^{pl} \quad (2)$$

Where L is the characteristic length of the model; it is a typical length of a line across an element for a first-order element.

4. Finite Element Model for Tubing Perforation

Geometry and Mesh

Considering symmetry, the FEA models account for half the geometry of the tool's CAD models as shown in Figure 4.

(a)

(b)

Figure 4: the geometry and mesh for one of the tools: (a) the assembly; (b) mesh for the tubing

Very fine first-order HEX mesh is used for the tubing, and the mesh for the section, which might be perforated, is finer, and the elements are nearly in cube shape. The characteristic length for the perforated section is purposely kept constant for all models created in this project.

Materials

The tool is constructed of various grades of steel. All materials are characterized as elastic-plastic materials. In addition, the tubing material can have ductile fracture failure. There was no data for ductile failure initiation criterion. The fracture strain vs. triaxiality curve was determined via back fit to existing test results from 4 ½-in. size tools cutting various grade of tubing as described in the following.

Fracture strain vs. triaxiality curve

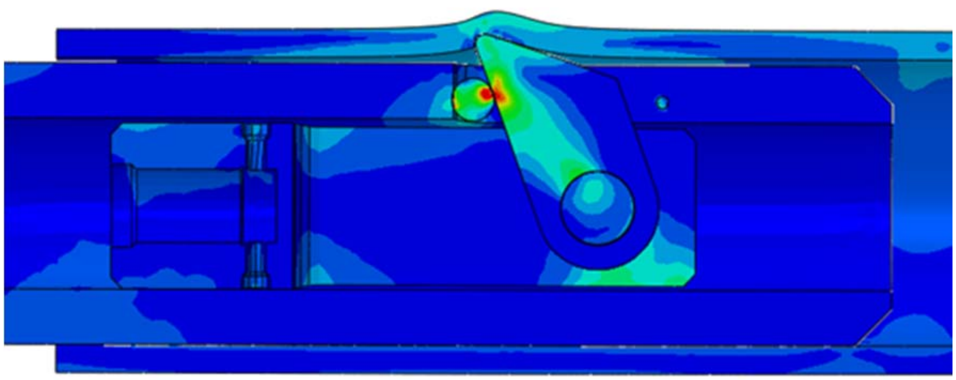
Three points on the curve are "known" if uniaxial stress strain curve is available. For uniaxial stress state, stress triaxiality is 1/3, the fracture strain at crack initiation can be assumed to be the plastic strain corresponding to tensile strength of the material. It is also known that fracture strain is 0 for hydrostatic tension; it is infinite for hydrostatic compression. In the models, it is assumed that for large-stress triaxiality (e.g. 10), the fracture strain is very small; for small-stress triaxiality (e.g. -10), the fracture strain is very large. Two more stress states have known stress triaxiality, equal biaxial tension has stress triaxiality at 2/3, and pure shear has the value 0. Based on general trend illustrated in Figure 3, the fracture strains at $\eta=2/3$ and $\eta=0$ may be roughly estimated. These 5 points on the fracture strain vs. triaxiality curve form the initial estimate of the curve, and the final curve is obtained by adjusting the fracture strains until predicted perforation force matches the tested force.

It is noted that as fracture strain at η=1/3 (uniaxial tension) is adjusted; the corresponding fracture energy needs to be adjusted accordingly per equation 2.

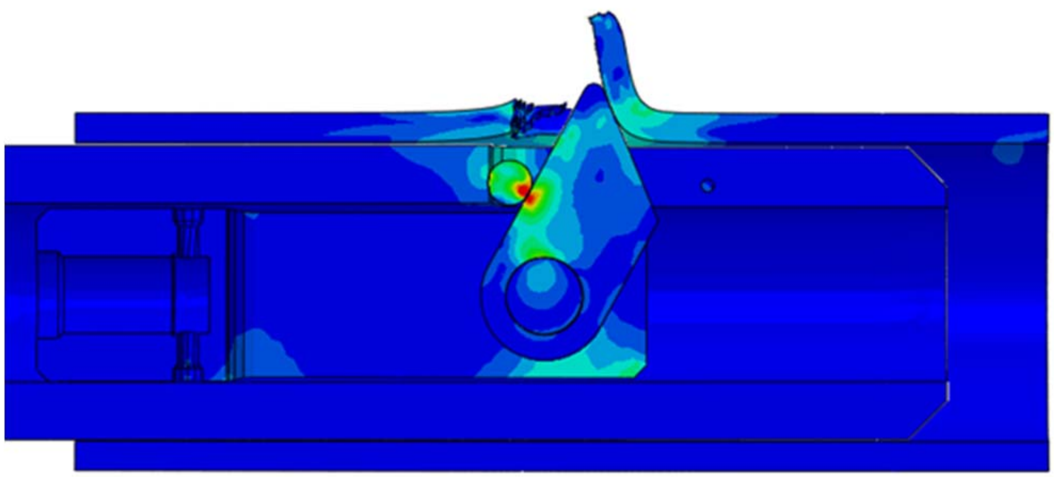
Hindsight, an easier way for estimating the fracture strain vs. stress triaxiality is to use the Rice-Tracey relation (Rice, 1969):

$$\bar{\varepsilon}^{pl}(\eta) = C\, e^{-1.5\eta} \quad (3)$$

In this approach, all that is needed is the fracture strain at uniaxial tension. In fact the set of data given in the Abaqus technology brief (SIMULIA, 2012) can be represented by this equation well.



(a)



(b)

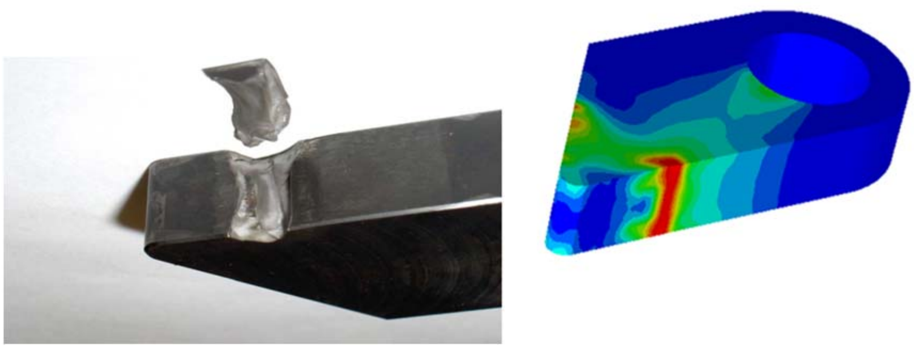
Figure 5: Perforation of a 3 ½-in. 10.2#, J55 tubing (a) right before the cut was made; (b) end of the cut

5. Representative Numerical Results

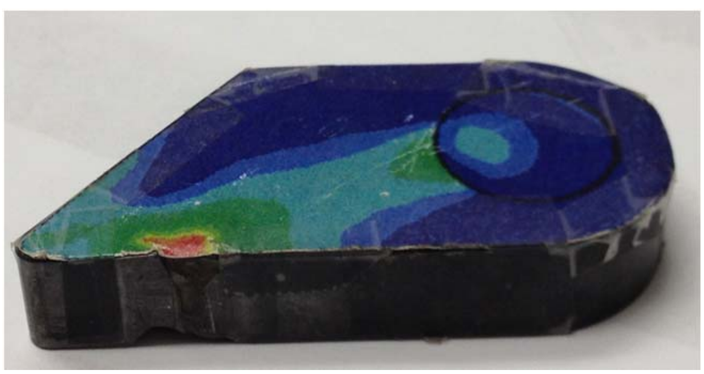
Numerous analyses were conducted to determine the approximated fracture strain vs. stress triaxiality curves for different grades of materials (e.g. J55, P110). The ductile fracture properties are then utilized in simulation of various design changes, as well as different type of perforators, including single blade, double blade and punch.

5.1 Single Blade

This example is for analysis of the perforation of 3.5-in. 10.2# J55 tubing, which was physically tested later. The simulation predicted that stress concentration on the cutting blade reached the tool steel yield strength, indicating a possibility of fracturing, see Figure 5. The predicted fracture location matched test results, Figure 6.



(a)



(b)

Figure 6: Comparison of test measurement and numerical prediction: (a) fractured blade and predicted stress concentration; (b) overlay of the stress contours over the real part

The blade should be cracked during making the cut (Figure 5a). This and other analyses showed that the blade design can be improved by increase the pivot's diameter and increase the fillet radius on backside of the blade, which is in contact with the pivot. Numerical simulation also showed that wider blade requires more force to perforate and thus more likely to crack the blade. An additional design change is to change the blade material from brittle tool steel to more ductile steel. These design changes significantly improve the perforating tools' durability in field applications.

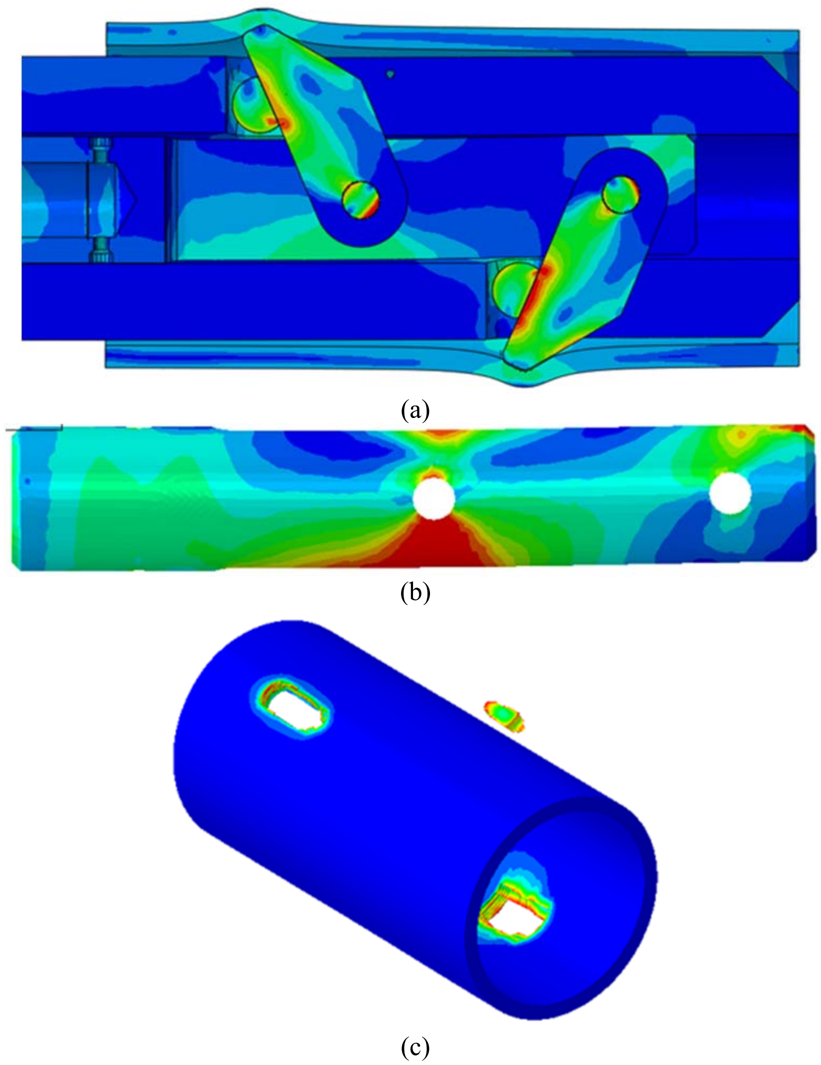


Figure 7: Double blade perforation: a) right before holes are made (stress), b) shaft deformation at peak load (stress), c) perforated casing (plastic strain)

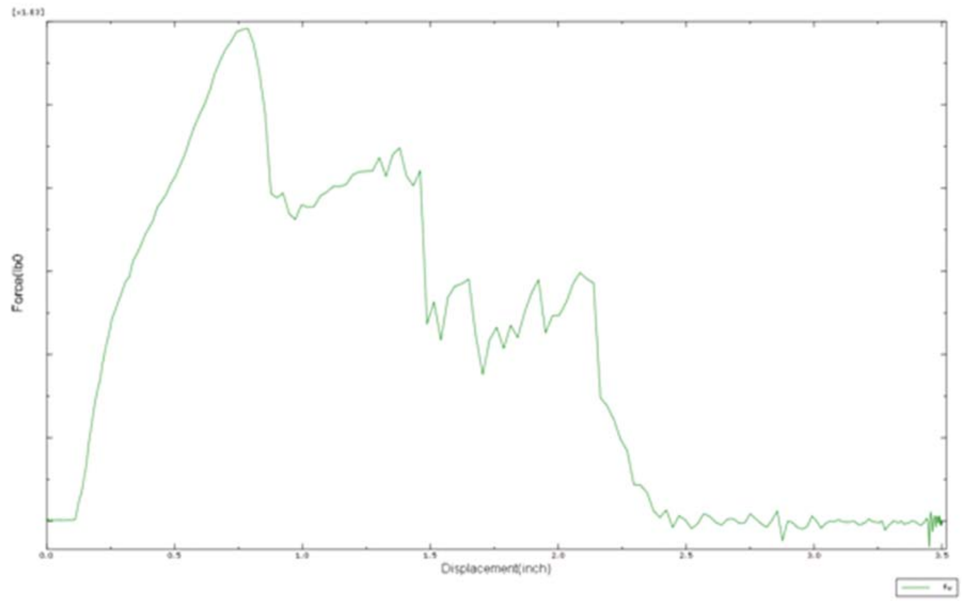


Figure 8: Force vs. stroke curve 4 ½-in. J55 tubing

5.2 Double Blades

Double blade perforating tools are for perforating two holes at the same time. The blade design is the same as the single-blade design. However the force needed to perforate two holes is about double that for perforation of a single hole. In addition to potential blade cracking, there might be issues with the shaft, which the FEA simulation easily identified before any physical tests are performed, and appropriate design changes are made. Shown in Figure 7 are predictions for refined design of double blade perforating tool for 4 ½-in. (3.9-in. ID) J55 tubing.

It is noted that the double-blade perforating tool takes a little bit over two times force to perforate two holes compared to what it takes for a single-blade tool to perforate a single hole. This is partially due to the fact that the shaft is in contact with housing (Figure 7a). This contact could be reduced or eliminated by extending the length of shaft to the right hand side (down side). To minimize the stress concentration on the blades, the pivots have a flat surface in contact with the blades.

5.3 Punch

An alternate design to the blade cutting is to use a punch to punch a hole. The punch is pushed radially via a wedge that rides on the shaft being pulled upward by the DPU tool (see Figure 9.). The goal of this study is to evaluate the efficiency of cutting between using a punch and a blade.

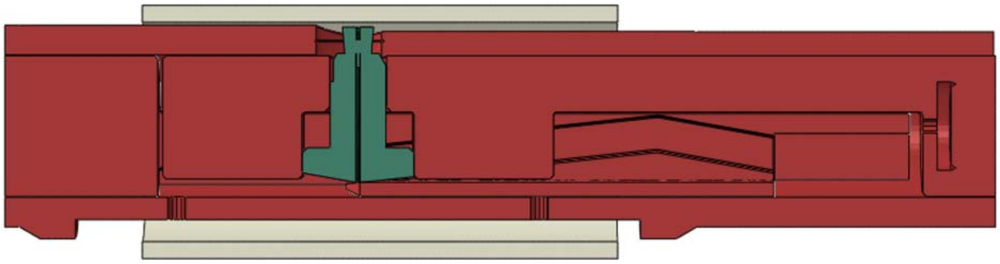
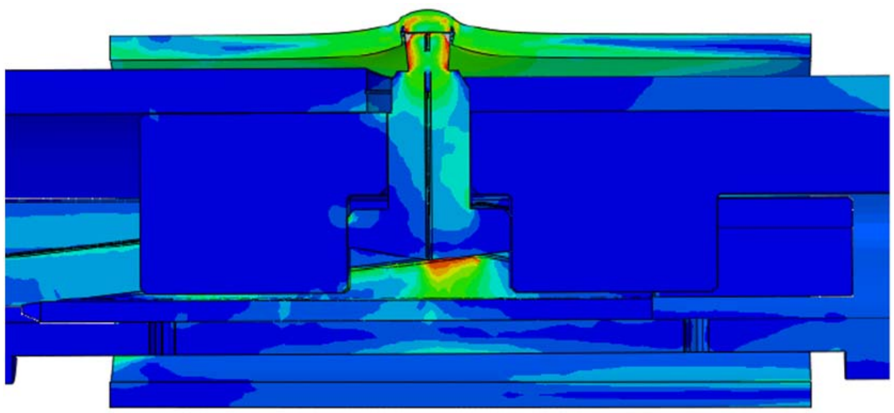
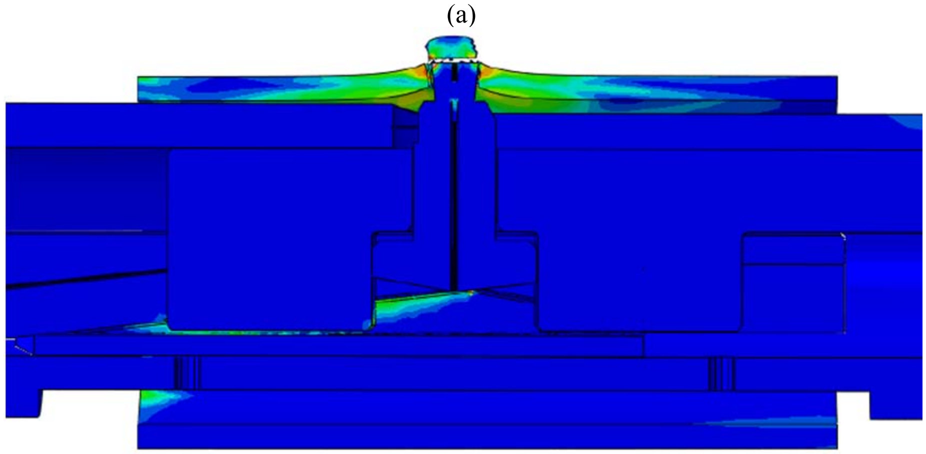


Figure 9: Perforating tool with a punch.



(a)



(b)

Figure 10: Punch a hole of 0.56-in. diameter hole in a 5.5-in. 20# tubing (a) right before the cut, (b) hole punched

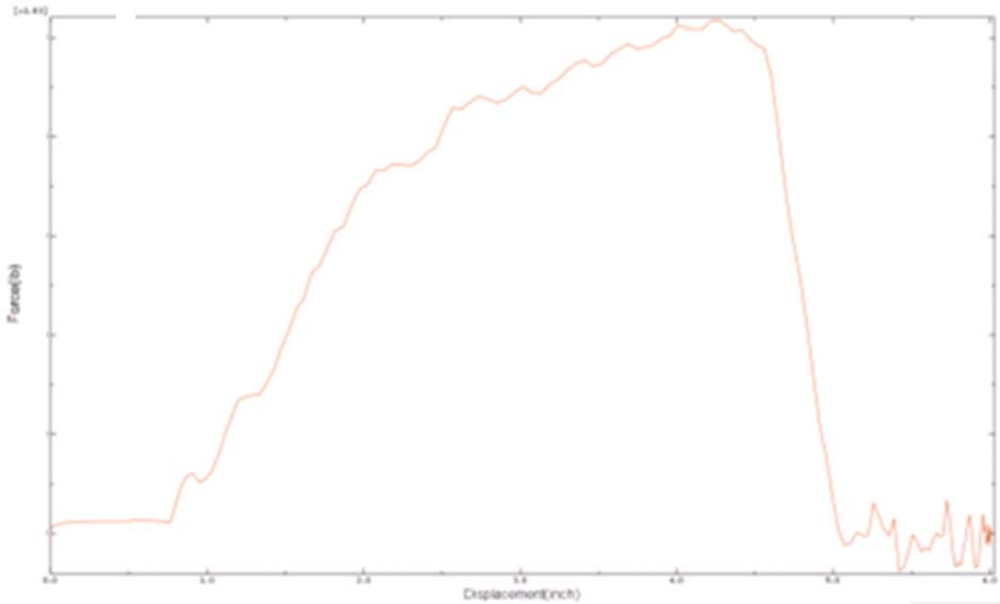


Figure 11: Force needed to punch a 0.56-in. hole in a 5.5-in. 20# J55 tubing

The model predicted a perforation force for a 0.56-in. diameter (or 0.246- in.^2) hole. This compares with a perforation force for a corresponding blade that cuts a 0.7425- in.^2 rectangular hole. When force per unit square inch hole is compared, the blade is more efficient (using less force per square inch) among these two designs. This could be explained as following: for punch – the cut is simultaneous at the hole perimeter; for blade, the cut is not simultaneous around the perimeter –it cuts only a small portion of the hole perimeter –thus more efficient.

6. Discussions and Summary

The main deficiency of the models used here is the lack of measured fracture strain vs. stress triaxiality curve. Back fit the curve at five stress triaxiality level might contribute to some quantitative discrepancy between numerical predictions and physical measurement. For business-critical applications it is a must that material specific failure properties are measured instead of estimated. The failure model most likely should account for triaxiality and lode angle, as well as rate effect (Dunand and Morh, 2011).

There is also a need to evaluate shear failure criterion for this application to see if it is more suitable for this application than ductile failure criterion.

Numerically the biggest issue is the mesh dependence of the numerical prediction.

Nevertheless ductile failure criterion is successfully applied to the evaluation and improvement of DPU downhole perforating tools. Due to space limitation, not all relevant cases are presented. In summary, what have been done in this work include:

a) Determine ductile failure properties via back fit known test results by matching predicted perforating force to measured one. The properties for three ductile steels were obtained.

b) The FEA simulations correlate with test results reasonably well when proper ductile failure property is identified both qualitatively and quantitatively

c) For same tubing material, determined perforating force for different tubing sizes, 3 ½, 5 ½ and 7-in. to ensure that the force is within DPU's capacity

d) For same tubing size, evaluated effect of different grade of materials on perforating force, again to ensure perforating force is within DPU's capacity

e) Evaluated new concept design of double blade perforating tools, identified deficiency in initial new concept designs without physical tests.

f) Compared efficiency of punching a hole with punch vs. cutting a hole with blade.

g) Most importantly, the perforating tools for higher grade and/or larger size tubing are successfully developed via the change in perforating blades' geometry and change in blade material.

7. Acknowledgements

The authors are grateful to Halliburton Management for permission to the publication of this work.

8. References

1. Abaqus User's Manual, Version 6.10-1, Dassault Systèmes Simulia Corp., Providence, RI.
2. Bargawi, R. A., Dean, D., Clemens, J, Whitmire, C. (2008), New Electro-Mechanical Perforating Technology Reduces Cost and Increases Safety in Workover Operations, SPE113805, 2008 SPE/ICoTA Coil Tubing and Well Intervention Conference and Exhibition, The Woodland, Texas, USA, 1-2 April 2008.
3. Rice, J. R., Tracey, D.M. (1969), On the Ductile Enlargement of Voids in Triaxial Stress Fields, Journal of Mechanics and Physics of Solids, Vol17 pp201-217.
4. Dassault Systèmes Simulia Corporation (2012), Pipeline Rupture in Abaqus/Standard with Ductile Failure Initiation, Abaqus Technology Brief
5. Prantl, A., Spaniel, M, Moravec, M., Dzugan, J. Konopik, P. (2013), Identification of Ductile Damage Parameters, 2013 SIMULIA Community Conference Proceedings.