High strain rate mechanical and fracto-mechanical steel characterization for perforating gun simulation model

SLAP-16-22
Is steel characterization the *key factor* for reliable swelling predictions and/or potential gun carrier failure?
Survivability test conditions: Events

1. Swelling
2. Dynamic Stress Waves (eventually causing the Spalling Failure)
3. Exceeds Plastic Deformation (eventually causing cracking)

Phenomena under investigation: Cracking / Failure

Detonation
Perforating Needle
Gas Pressure Wave & Impact of Casing on inside carrier wall
Tool for gun carrier swelling prediction
IPS-16-32 - Numerical and experimental study on the high strain rate deformation of tubes for perforating gun applications

3D model of a gun carrier with 3 shaped charges

Tests methodology: Split Hopkinson bar test (SHBT)

Johnson-Cook (J-C) constitutive model

\[ \text{Stress} = (\text{Plasticity}) (\text{Log. of strain rate}) (\text{Temperature}) \]

- A, B, n
- C, \( \varepsilon_0 \)
- m

Stress vs. Strain graph

Conventional tests
- \( 10^3 \, \text{s}^{-1} \)
- \( 10^4 \, \text{s}^{-1} \)
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Material behavior: Deformation – Damage - Fracture

**Deformation**
Irreversible shift of atoms, dislocation movement. Nucleation at low plastic strain.

**Damage**
Laminar or volumetric discontinuities on the micro scale (micro-cracks, microvoids, micro-cavities).

**Fracture**
Laminar discontinuities/cracks on the macro scale leading to global failure.

Dealing with material or components containing cracks

Material fracture toughness

**Damage** ("l'endommagement, comme le diable, invisible mais redoutable") describe evolution of degradation phenomena on the microscale from initial (undamaged or pre-damaged) state up to creation of a crack on the mesoscale (material element).
Experimental $J_{D_{\text{INITIATION}}}$

Initiation dynamic fracture toughness

Dynamic fracture toughness $J_{D_{\text{init}}}$ is function of the load applied during the test and the fracture time $t_f$.

The fracture time can be measured by means of fracture gage or by means of DIC (Digital Image Correlation).

The dynamic loads (stress waves) are measured using instrumented bar using high strain gages.
Experimental $J_{ID}^{INITIATION}$

Load vs. time

By means of strain gages positioned on the incident and transmission bars, specimen geometry, cross section, sound propagation rate and Young’s modulus of the equipment bars is it possible to obtain forces and stress vs. time.
Signals Synchronization: input-reflected waves. Using the signal vs. time diagrams of the actual input and first reflected wave signals.

The time-points $t_1$ and $t_2$ corresponding to the wave front of the input and reflected signals can be measured. The time shift from the zero of the time acquisition is given by the formula:

$$ t_{\text{start}} = t_1 + \left( \frac{t_2 - t_1}{2} \right) $$
Experimental $J_{D}^{\text{INITIATION}}$

Fracture time: $t_{\text{init}}$

For each crack gauge, the time at which the crack is considered to start is the point in time corresponding to the first “macro” step of the gauge signal. The very first tiny ones correspond to the pre-crack opening.

Comparison with direct measurement of the initiation time using the high speed images of the test:

$35 \mu s$ (DIC) vs. $36 \mu s$ (Crack gauge)
Numerical model for $J_{D_{\text{INITIATION}}}$

3D model: due to two planes of symmetry only a $\frac{1}{4}$ of the specimen was considered

INPUT: Experimental load vs. time obtained from strain gauge instrumented HOP

The toughness (J integral) as a function of time is calculated by the finite element model of the specimen subjected to the actual loading.

Knowing the initiation time measured with the procedure explained before the toughness at crack initiation is obtained.
Failure predictive model

Development of the predictive model
✓ Local and overall deformation after full scale test - implemented
✓ Addition of damage & fracture toughness - on going
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