Experimental and Numerical Study of the Penetration of Tungsten Carbide Into Steel Targets During High Rates of Strain

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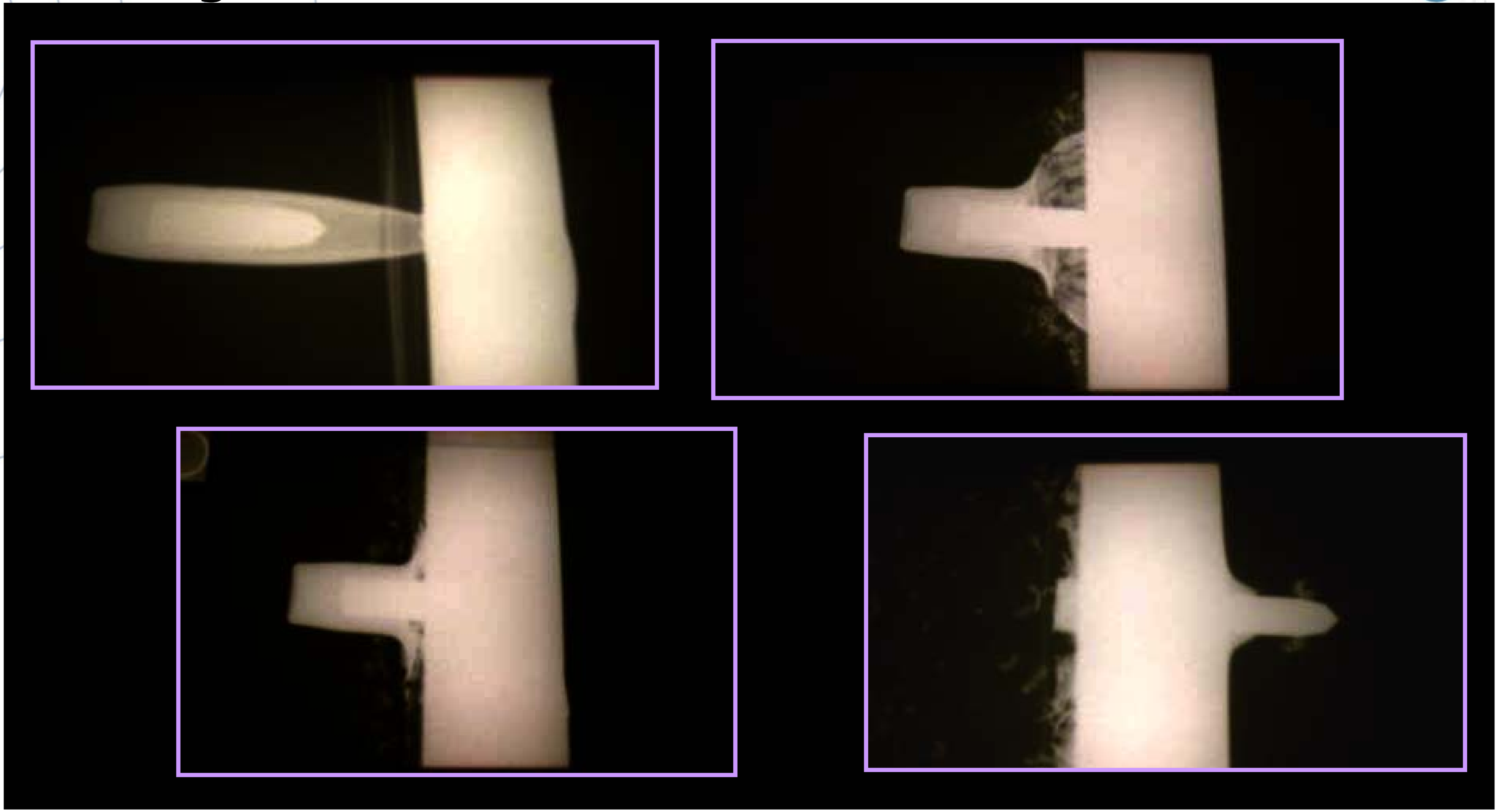
Introduction

- Overall purpose of our research programme: Establishment of a constitutive model with corresponding material data of a given Tungsten Carbide material, containing Cobalt
  - Obtain insight and understanding
  - Enable numerical modeling
- Focus in this work: Strain rate dependency of the plastic yield stress and/or the fracture stress

Flash X-Ray Picture of Nammo Raufoss 12.7 mm MP ammunition with Tungsten Carbide Cobalt Penetrator



Introduction

- Tungsten Carbide is in general a superb penetrator material
- The penetration capability will be reduced if the penetrator fractures in an early stage of the penetration or if the penetrator undergoes large plastic deformation
  - for harder targets the penetrator could fracture
  - for higher impact velocity the penetrator could fracture

- Increased fracture stress and reduced plastic flow due to strain rate dependency of intact material could potentially increase the strength of the penetrator

Topics

- Material data established by quasi-static experiments
- Comments on the feasibility of the Johnson-Holmquist constitutive model for Tungsten Carbide containing Cobalt
- Experimental results of firing experiments
- Numerical modeling of the firing experiments

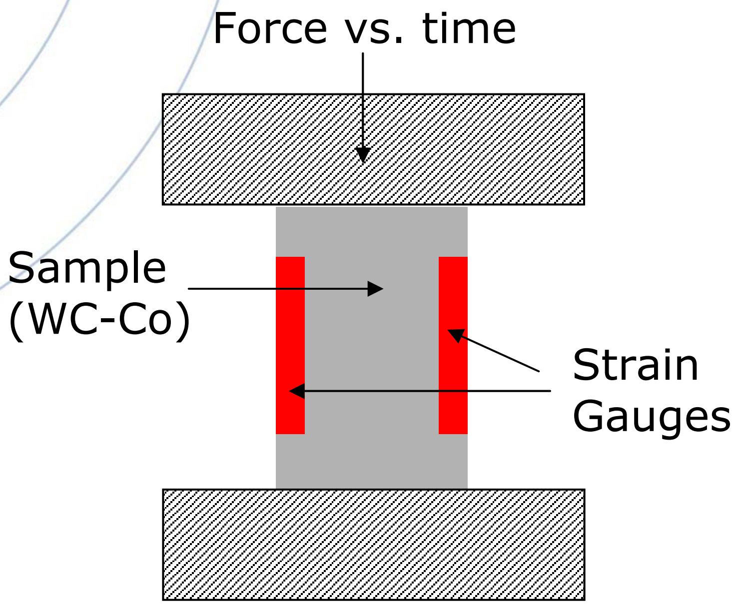
Constitutive Model for WC-Co Penetrator

- The elastic moduli of the intact material
- Plastic yield stress as a function of strain for the intact material
- Fracture stress as a function of pressure for the intact material

- Constitutive relations not presented in this work
  - The fracture development from intact to completely damaged material
  - The constitutive model for the partly of fully damaged material

Quasi-Static Experiments

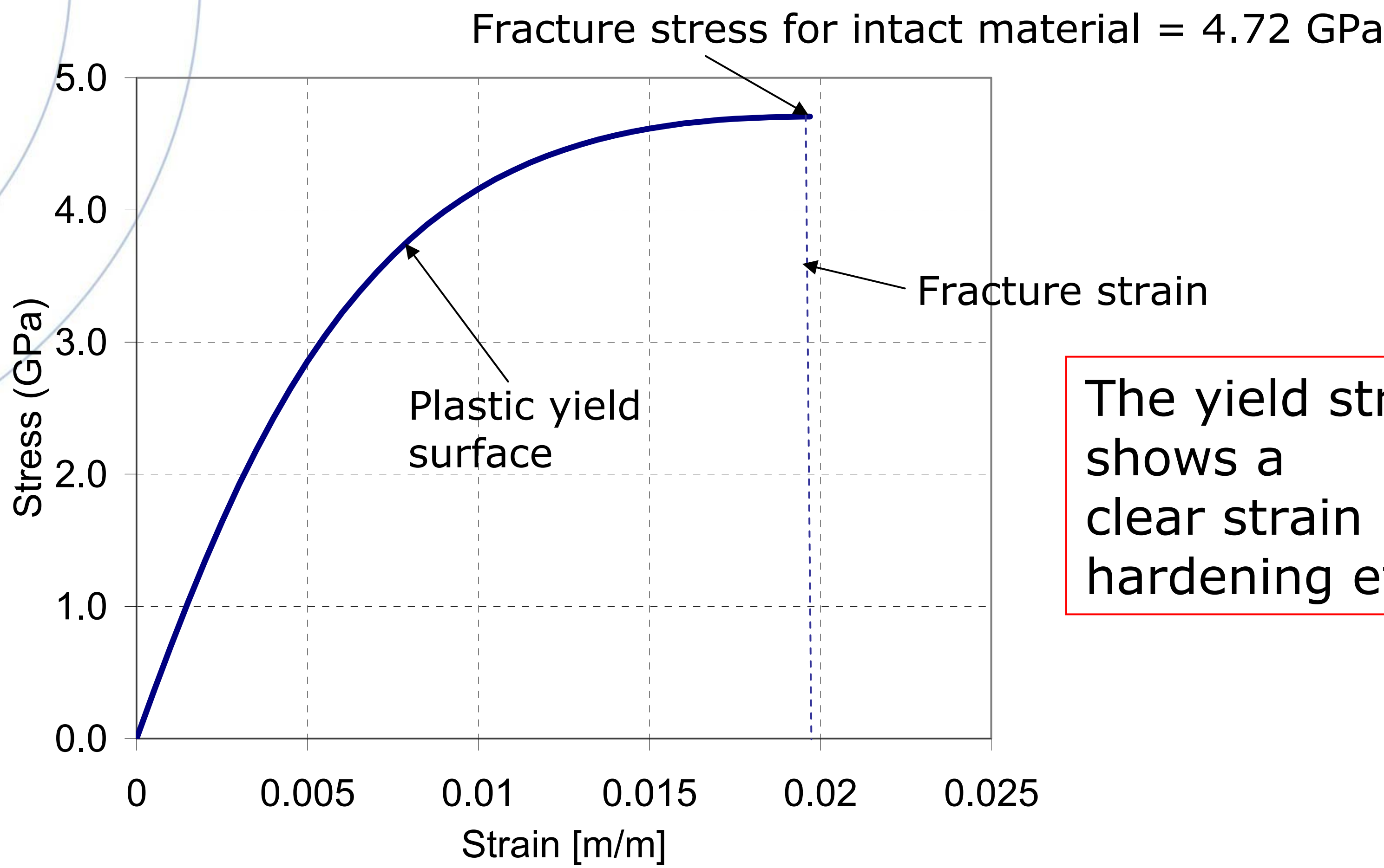
Simple compression



⇒ Elastic moduli (K, E)
⇒ Yield stress (stress vs. strain)
⇒ A fracture point on the intact fracture surface

Quasi-Static material data

From simple compression experiment:

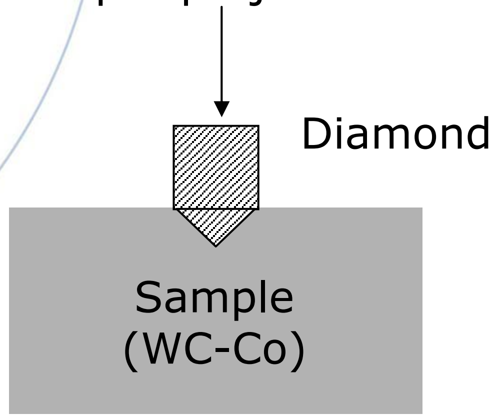


The yield stress shows a clear strain hardening effect

Quasi-Static Experiments

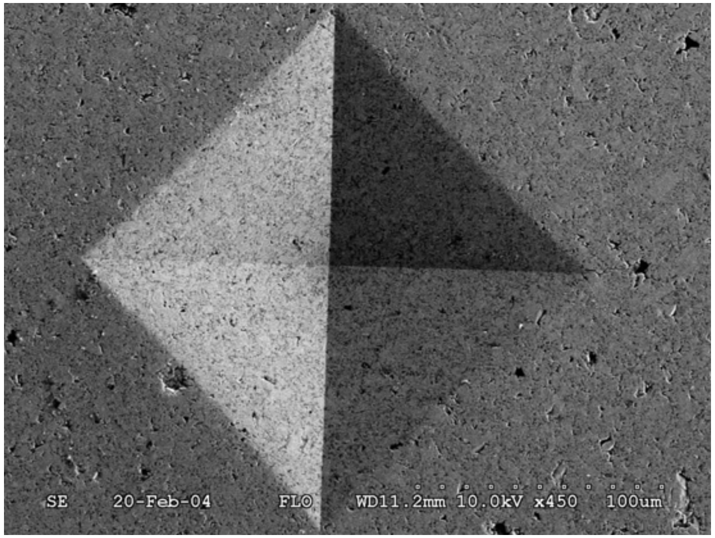
Hardness Measurement

Force per projected area



Loads of 10, 100 and 300 N

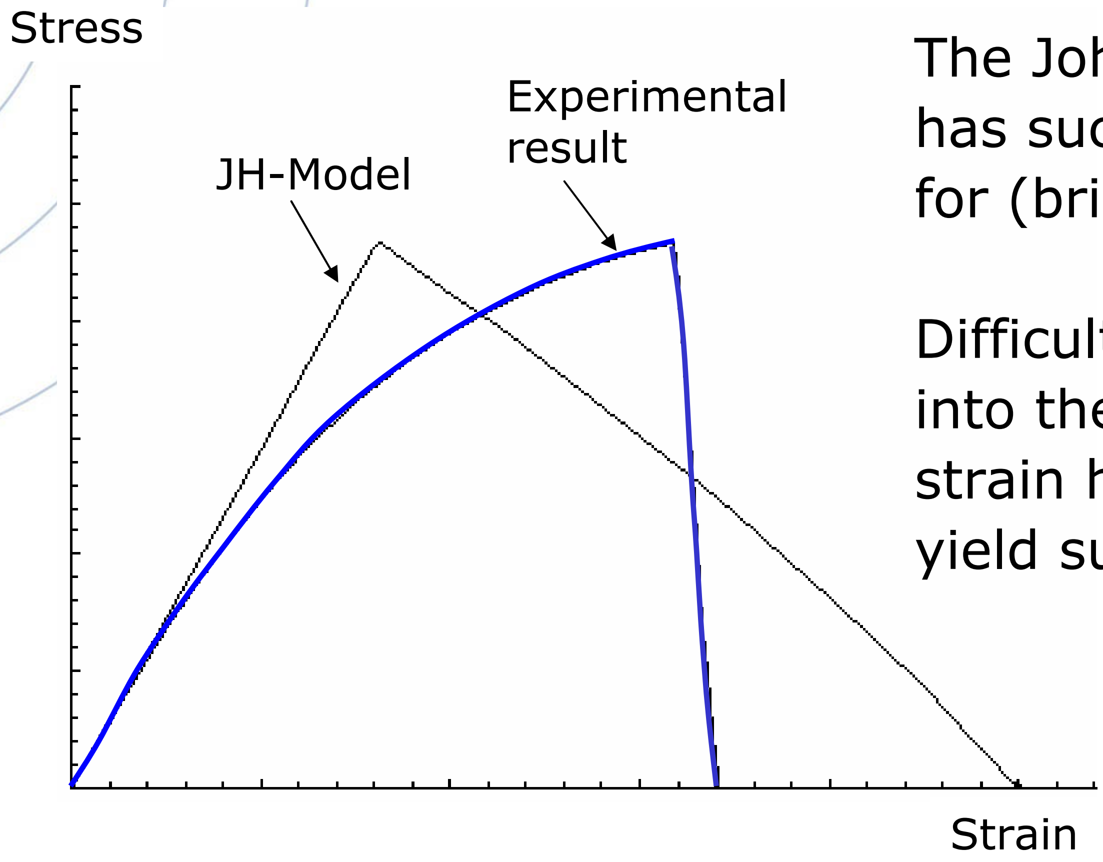
Picture of sample after indentation



⇒ The hardness of intact and damaged material after penetration is measured

Material Model for WC-Co Penetrator

The curves apply in the case of simple compression



The Johnson-Holmquist model has successfully been used for (brittle) ceramic material

Difficult to fit the WC-Co results into the JH models due to the strain hardening of the plastic yield surface

Firing Experiments

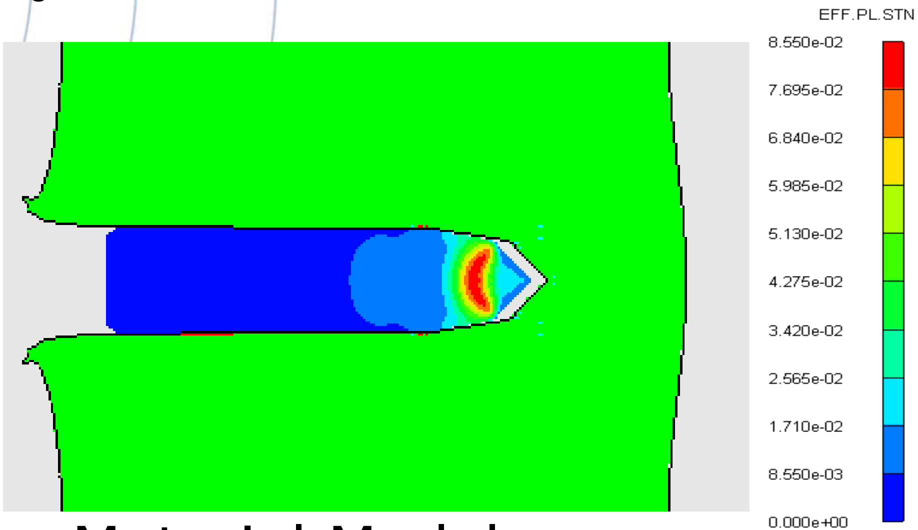
v_0=890 m/s (strain rate of 10^4 -10^5 /s), 40 mm armor steel

Penetration depth
= 30 – 31 mm

- No sign of plastic flow or fracturing
- Hardness after firing = 14.6 GPa = hardness of intact material before firing

Modeling of Firing Experiments

v_0=890 m/s, 40 mm armor steel



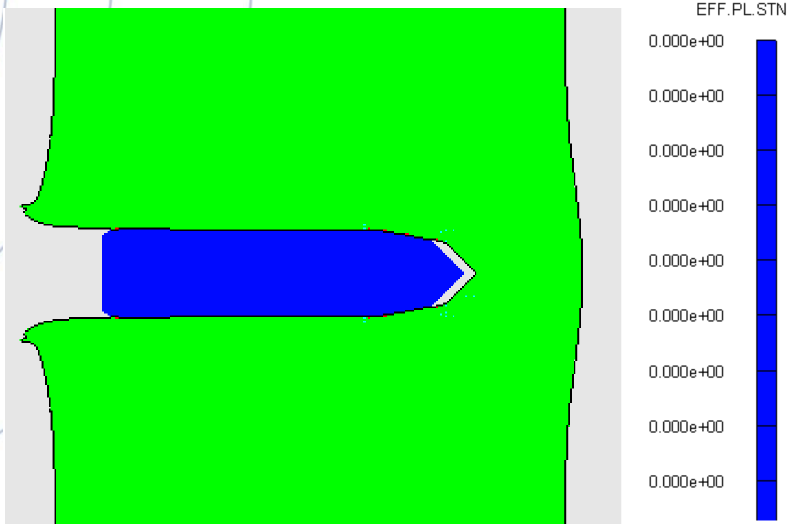
Penetration depth = 32.4 mm (30-31 mm in exp.)

Deviation from experiment assumed due to use of no friction

- Material Model:
  - the quasi-static yield surface fitted into the Johnson-Cook model
  - no strain rate hardening
  - no fracture model
  - no friction was used (Euler target)

Modeling of Firing Experiments

v_0=890 m/s, 40 mm armor steel

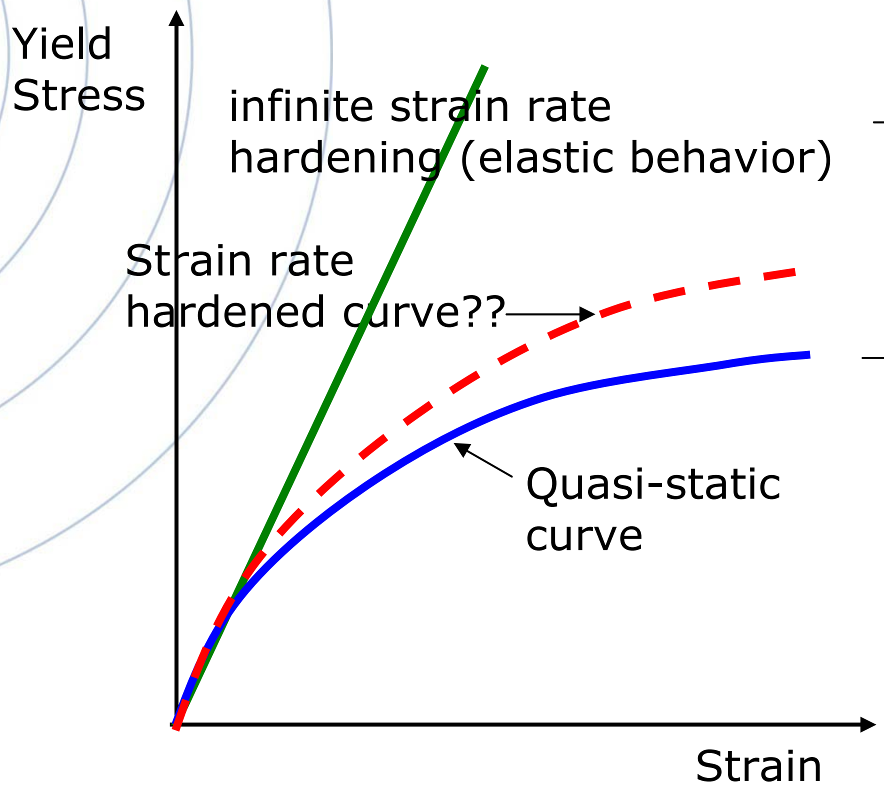


Penetration depth = 33.3 mm

Larger deviation from experiment than with the elastic-plastic model

- Material Model:
  - highest possible strain rate hardening (elastic model)
  - no fracture model
  - no friction

Interpretation



→ 33.3 mm

→ 32.4 mm

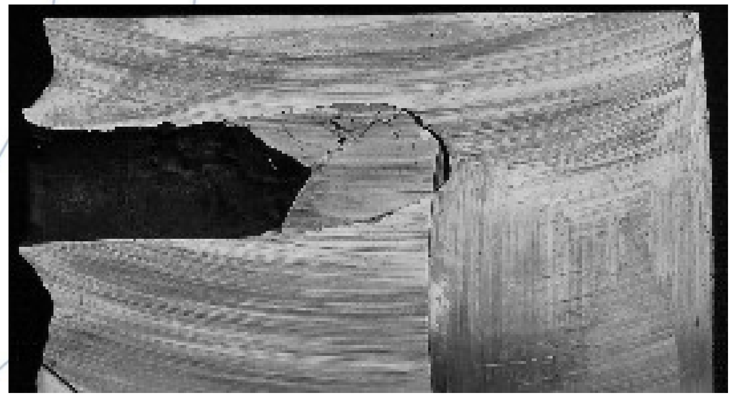
Experiments = 30-31 mm :

Is there any strain rate dependence?

- Question can not be clearly answered from these experiments

Firing Experiments

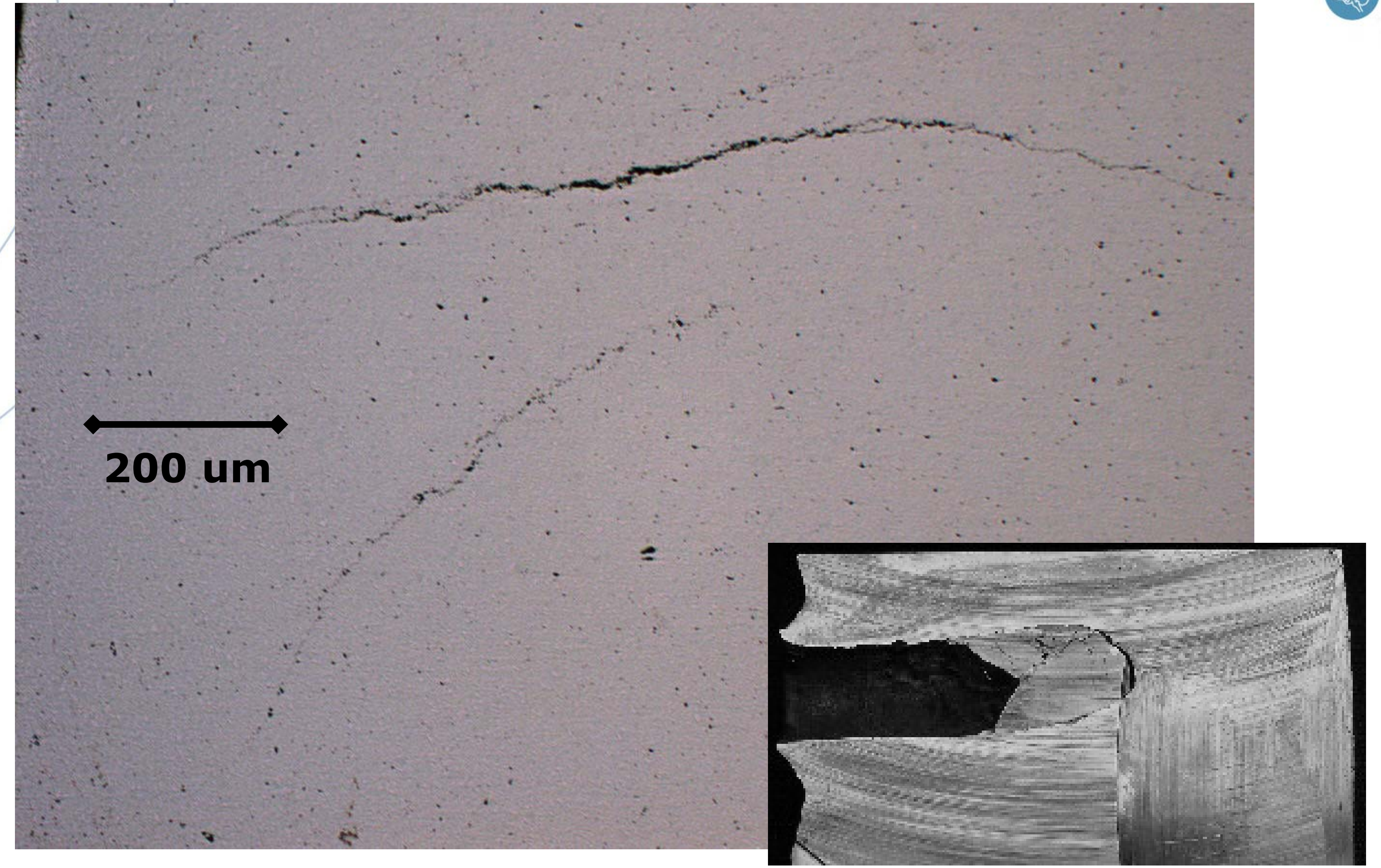
v_0=950 m/s, 40 mm armor steel



- The penetrator has fractured

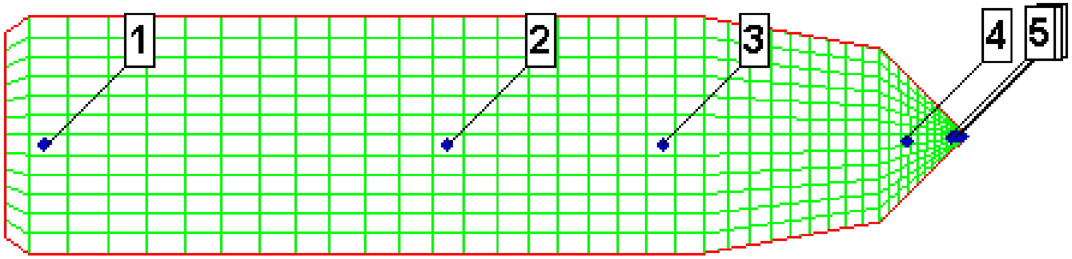
- Hardness of penetrator pieces = 13.1 GPa (compared to 14.6 GPa for intact material) => Micro cracks have developed

Microscopy Picture of Micro Cracks



Simulation of Stresses in the Penetrator

Study of the stresses
in different gauge points



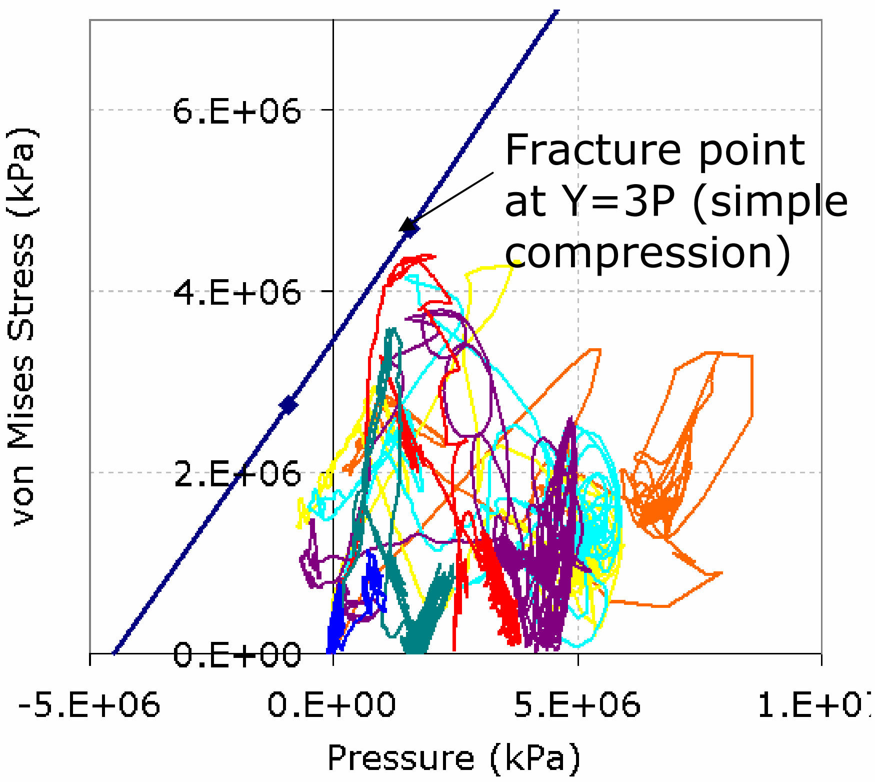
Penetrator modeled with the yield surface established in quasi-static experiments, with no strain rate hardening

- The target is modeled using a cavity expansion theory boundary condition for the stresses on the penetrator
- This was done to ensure no unphysical spikes

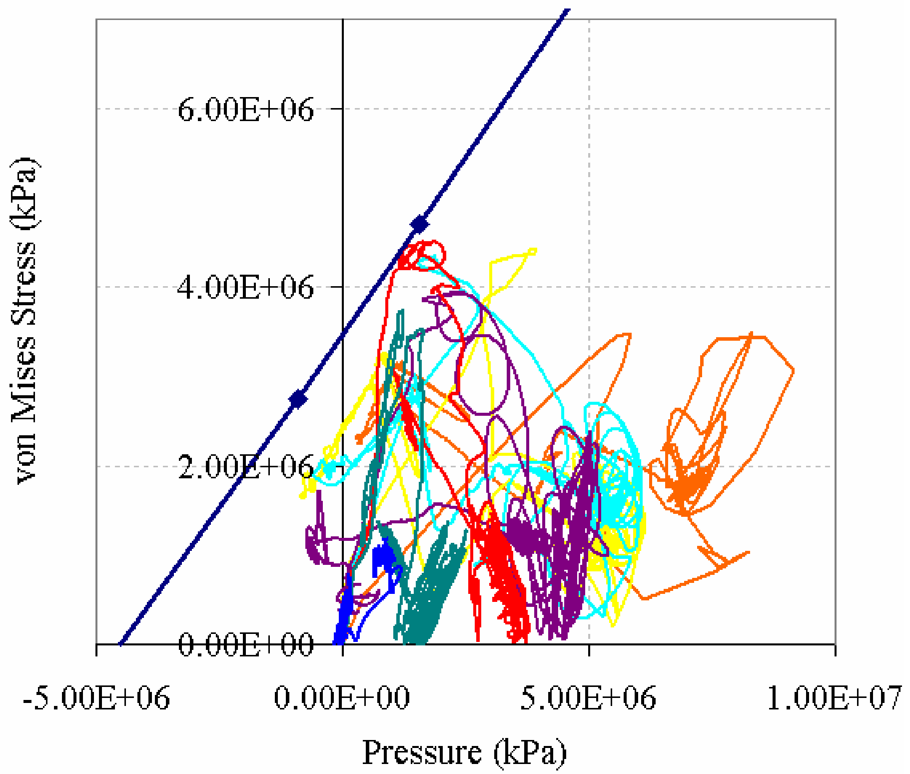
von Mises Stress vs. Pressure

- Also shown in the figures are two fracture points found from quasi-static experiments (not applied in the simulation)

890 m/s



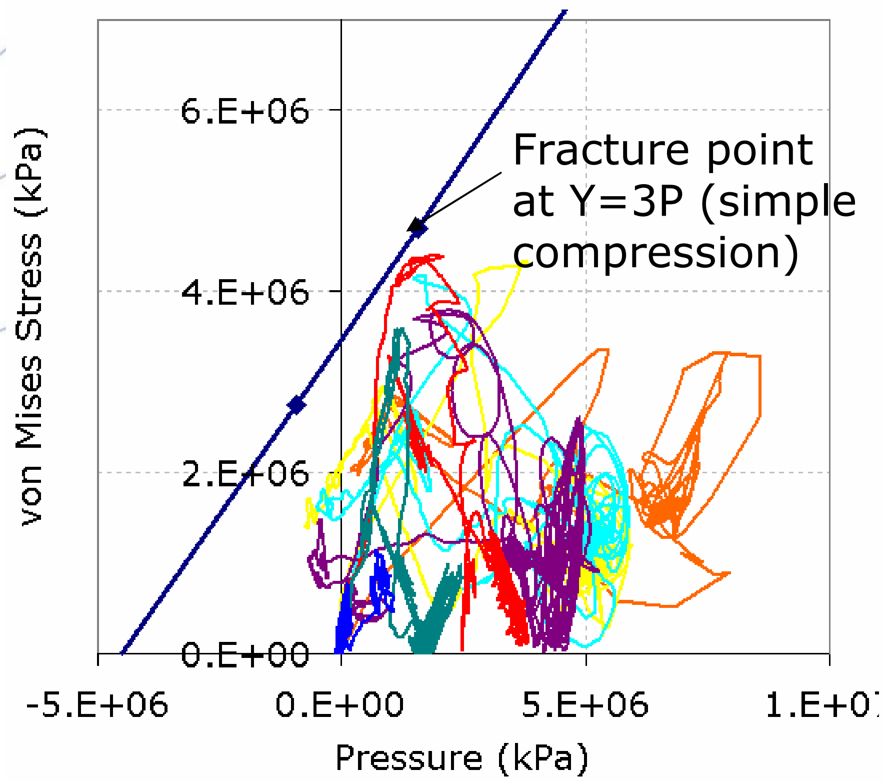
950 m/s



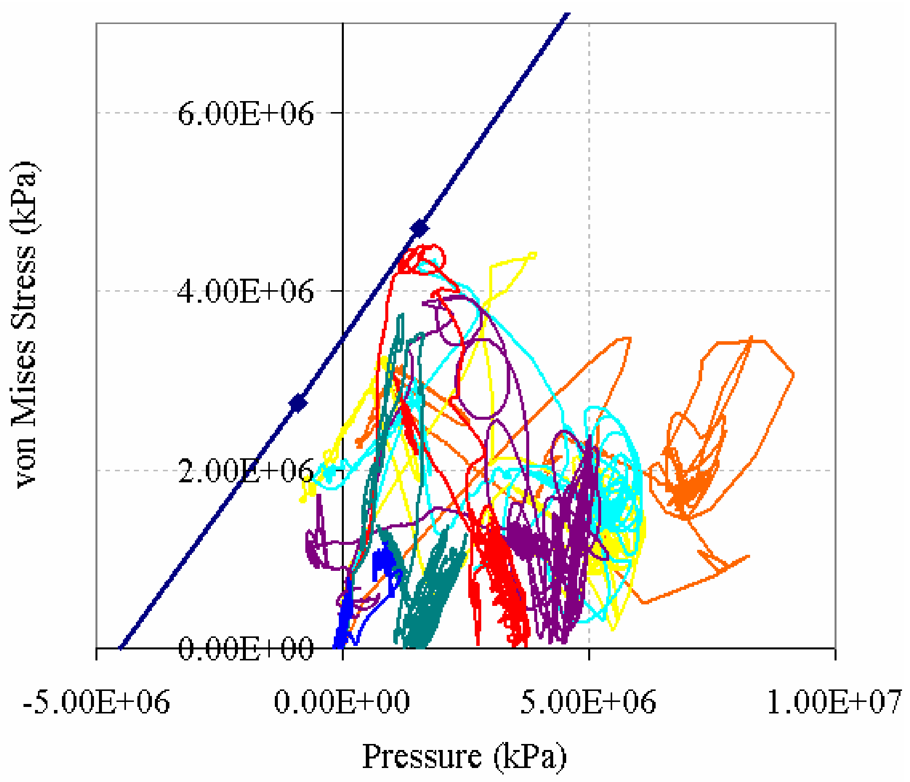
von Mises Stress vs. Pressure

Good agreement with experiments with no strain rate hardening of the fracture and the yield surfaces

890 m/s



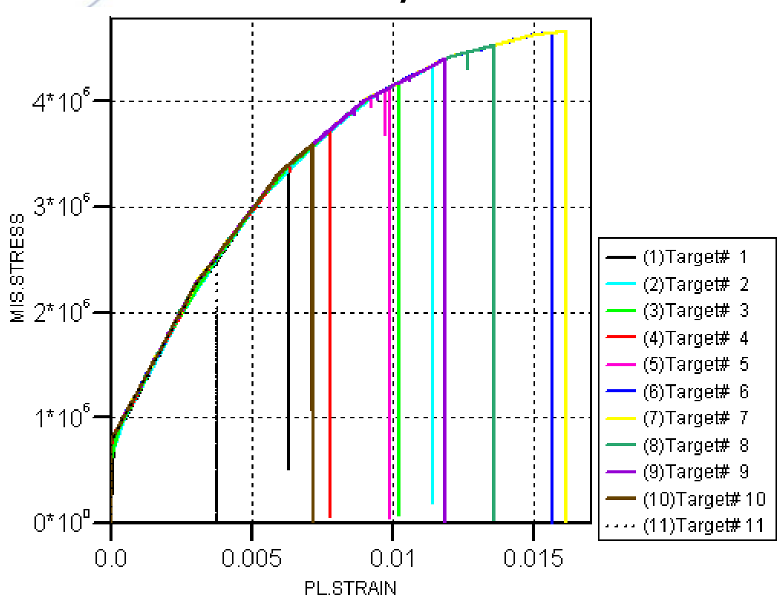
950 m/s



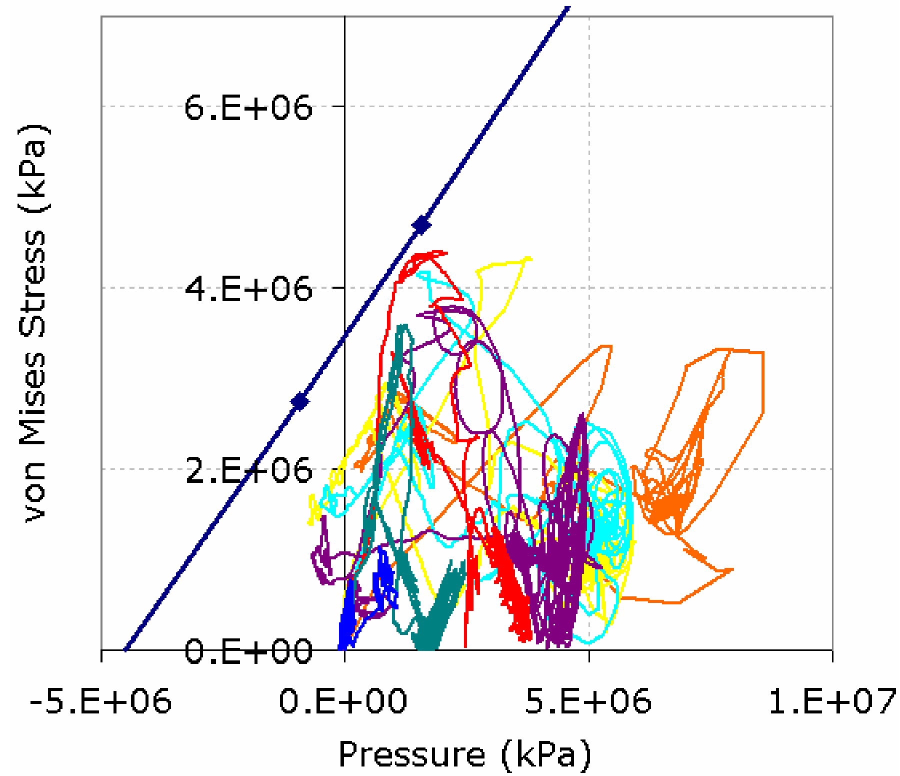
Interpretation

- The yield surface can not strain rate harden if the fracture surface does not strain rate harden at the same time

890 m/s



890 m/s



Interpretation

- If the fracture surface strain rate hardens, the yield surface must also strain rate harden at the same time

Conclusions, strain hardening

- The WC-Co material shows a strain hardening effect, and is more ductile than most ceramics
  - The fracture strain was 2% during a simple compression test
- If a Johnson-Holmquist damage model is used, it should be combined with a strain hardening model of the plastic yield surface as a function of strain

Conclusions, strain rate hardening

- The constitutive model with no strain rate dependency gave good agreement with experiments for strain rates below 10^4 -10^5 /s
- Strain rate hardening of the fracture surface is possible if and only if there is a strain rate hardening of the plastic yield surface
- Further studies on strain rate dependency will be performed in a Split Hopkinson Bar equipment