Dynamic material characterization by combining ballistic testing and an engineering model

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Abstract

At TNO several energy-based engineering models have been created for various failure mechanism occurring in ballistic testing of materials, like ductile hole growth, denting, plugging, etc. Such models are also under development for ceramic and fiber-based materials (fabrics).

As the models are energy-based they can be directly compared to experimental results of ballistic tests as the mass and velocities of projectiles are regularly measured. This allows the models to be validated, as has been done for the ductile hole growth model. Using AP-rounds on ductile target materials like many metals, clay and polymers, ductile hole growth (DHG) normally is the major failure mechanism during projectile penetration. When the core of the projectile remains rigid (which is often the case in ductile materials) the loss in kinetic energy of the core is easily measured from its initial and residual velocity. In the DHG-engineering model this energy loss is also calculated but requires that the flow stress at high strain rates is known. Using the experimental results in combination with this engineering model the dynamic flow stress of the target has been quantified.

This procedure has been done for several material (metals, clay types and polymers) and allows the determination of dynamic material properties that are otherwise not easily measured. This method requires a rigid penetration of a projectile through a (thick) plate of the material to be characterized. Hence, no special sample shape or dimension is required.

The dynamic flow stresses that are obtained have been compared to high strain rate (order 1000/s) strength values of the same materials determined by other techniques. As the values are very close to each other, this provides confidence in the approach to use ballistic test results of targets failed by DHG in combination with the engineering model for the characterization of materials at high strain rates.

Keywords: dynamic material properties, characterization, ballistic tests, engineering modeling.

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1.0 INTRODUCTION

For several years TNO has been working on the development of energy-based engineering models that describe the interaction between (armour) materials and projectiles. This has been performed for the main armour material types that are used in armour systems today: fabrics, ceramics and metals. Each model incorporates only the main mechanism that is responsible for the energy exchange between the projectile and a target. Blunt projectiles that hit relatively thin targets tend to lead to denting and finally plugging, while sharp nosed projectile that hit thick walled ductile target materials often penetrate by ductile hole growth. We aim to quantify the energy transfer with an accuracy of at least 90%. This has been reached for our Ductile Hole Growth (DHG) model and is verified here using experimental data obtained from shooting several projectiles to ductile (construction) steel types at normal impact condition.

2.0 Engineering models

2.1 Ductile Hole Growth

Details about the Ductile Hole Growth have been published earlier [1], hence only a short description is provided here. The model assumes normal impact conditions of a non-deforming projectile (like an AP core), while in the target only radial movement is allowed, see figure 1. This time-resolved energy-based model calculates for every time-step the energy required for the target material to be pushed aside by the penetrating (rigid) projectile. The target material is assumed to absorb energy by only two mechanisms: plastic straining energy and radial displacement (kinetic energy). The latter is often overlooked in other models that describe projectile-target interactions. The model input parameters are mass, velocity, diameter and nose shape for the projectile, and density, thickness, Young's modulus and dynamic flow stress for the target. The latter requires a flow stress value for the target material during high strain rate deformation (at a strain rate of approximately 2000/s). Any projectile nose shape is incorporated using its diameters at 25, 50 and 75% of the nose length and is linearly interpolated for the other nose positions.
For any time step the (plastic strain and kinetic) energy absorbed by the target is subtracted from the (residual) kinetic energy of the projectile. From the residual kinetic energy and constant projectile mass the reduced projectile velocity is obtained and multiplied by the time-step to get its new position. Now the procedure repeats until the projectile has lost all its kinetic energy (depth of penetration is known) or the target has been penetrated (residual velocity is known).

2.1 Plugging

Blunt projectiles, as well as Ball projectiles that deform upon impact with a hard armour material, will tend to penetrate a thin walled target by plugging rather then ductile hole growth. The impacting projectile pushes the target material out of plane, while the inertia of the target opposes its movement. This leads to a large localized shear loading of the target material at the periphery of the projectile. If this shear load is high enough the target may fail by forming a plug that is pushed in front of the penetrating projectile. As the deformation of the target material is very localized (often by shear bending with a width of only a few microns) the local temperature gets very high and the strength of the target material is thermally reduced. Therefore, the plugging process is assumed to absorb only a minor amount of energy (low strength and small volume that

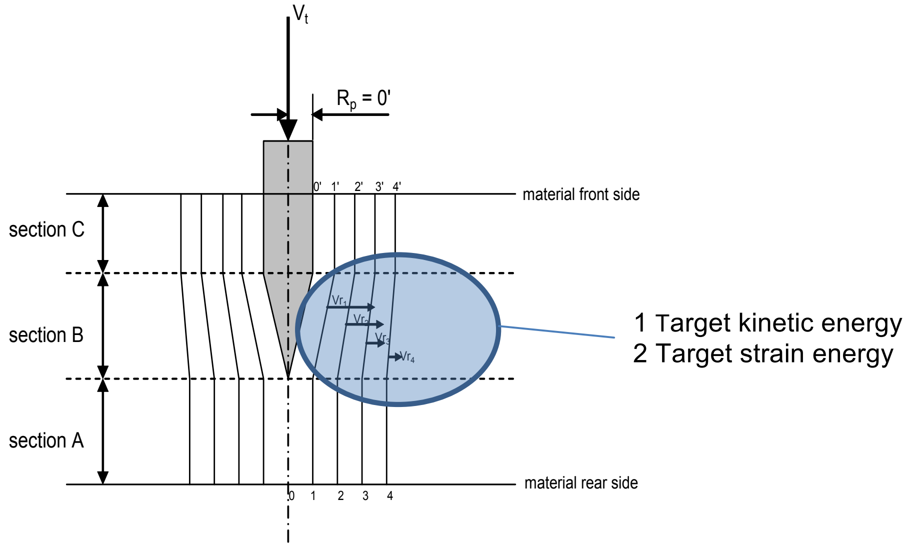

Figure 1: Cross-section showing the target material flow during ductile hole growth

deforms). The conditions required for plugging is determined by the specific impact velocity at which the shear loading of the target exceeds its shear strength (σ_τ). The plugging force F_{plug} equals:

$$F_{plug} = \pi\ D_p\ t\ \sigma_\tau = \pi\ D_p\ t\ Y/\sqrt{3} \qquad (1)$$

Here, D_p is the (effective) diameter of the (deformed) projectile, t the target thickness and σ_τ the shear strength of the target that can be approximated by $Y/\sqrt{3}$ [2], with Y the dynamic flow stress of the target material. If the load by the impacting projectile exceeds F_{plug}, the target will fail by plugging. The load by the impacting projectile is approximated by:

$$F_{dyn.} = P\ A = \rho_p V^2\ \pi\ D_p^2/8 \qquad (2)$$

Where P is the dynamic pressure ($\frac{1}{2}\rho V^2$) and A the cross-section of the projectile ($\frac{1}{4}\pi D^2$)
The critical velocity (V_{50}) for plugging to occur hence is obtained by equating (1) and (2):

$$V_{plugging} = \sqrt{[8\ t\ Y/(D_p\ \rho_p \sqrt{3})]} \qquad (3)$$

It should be stressed that this is only a condition for plugging to occur and is not a time-resolved energy-based model for the plugging process itself. As described the plugging process is not expected to absorb much of the kinetic energy. Other phenomena like the deformation of the projectile during the target loading and the acceleration of the plug to the residual projectile velocity will absorb (kinetic) energy but are not taken into account here.

3.0 Ballistic experiments

3.1 Target materials

Table 1 shows plate thicknesses A to J with increasing thickness between 0 and 30 mm and the steel types, as well as their mechanical properties. These readily weldable construction steels are very ductile (strain to fracture of about 50%). The LRA steel is somewhat weaker than the DH36 and EH36 steel types that are quite comparable in mechanical properties. As the failure mechanisms that occur in ballistic testing result in high strain rates of the material, the dynamic properties are more relevant than the QS properties. Therefore, in our engineering model we use a dynamic flow stress of the material, that is also provided in table 1. At high strain-rates the strength of the steel types has significantly increased. Nemat-Nasser et al. measured a flow stress of about 550 MPa for EH36 steel at a strain rate of 3000/s [3]. Although comparable to the value obtained by high speed tensile tests, the dynamic flow stress as used in this work (see 4.1) is obtained from fitting the strength input parameter to one of the experimental results. This means one can obtain the (flow) strength of a ductile material at high strain rate by using the engineering model and ballistic test results using a rigid penetrator.

3.2 Projectiles

The following bullet types have been used in the ballistic tests:

- 7.62 x 39 API-BZ (core mass 4.0 gram)
- 7.62 x 51 Ball (Sintox)
- 0.50 APM2 (core mass 25.4 gram)
- 0.50 Ball

The 0.50 bullets only differ in dimension (hence mass) as their calibre is 0.50 inch (12.7 mm). The Ball and AP bullets differ quite a lot in hardness of their core material. The core of the Ball projectiles consists of a weak, ductile metal (lead for 7.62 and steel for the 0.50 projectile). While the core of the AP rounds consist of a hardened steel type, that is much harder (stronger) than the construction steel types that are used as target material in this research. The relative strength (hardness) between the projectile core and the steel plate target will determine which will deform (fail) first. This means that the Ball projectiles are expected to deform upon impact creating a lower kinetic energy density on the target as well as a larger effective diameter, while the AP cores are expected to remain rigid (constant nose shape) during the whole projectile-target interaction.

3.3 Experimental results

Both AP projectiles generated a crater without plate denting or fragments escaping the ductile steel targets indicating ductile hole growth (plastic deformation) as the main failure mechanism. In Table 2 the observed 7.62 API-BZ V_{50} values for the combinations of plate steel type and

Table 1: Overview of the target materials and their thicknesses

Steel type	Thicknesses [mm]	Yield [MPa]	Ultimate [MPa]	$Y_{flow, dyn.}$ [MPa]
DH36/EH36	A, B, C/ D, E, F, G, H, J	431 / 407	568 / 529	500 / 500
LRA	B, C, E, G, H, I	315	454	450

thickness are provided in black and grey (estimated values). In cases with only target perforations the V_{50} value has been estimated using the quadratic relationship by Recht and Ipson [4] $[V_{50}= \sqrt{(V_o^2- V_r^2)}]$ for the impact versus residual velocity. Figure 2 shows such extrapolation for the impact (V_{hit}) versus residual velocity of the 0.50 APM2 projectile at normal impact on DH36 steel (thickness H), leading to an estimated V_{50} of 373 m/s. Table 3 shows the V_{50}'s (estimated values indicated in grey, measured in black) of the thicker target plates shot with 0.50 APM2.

The shots using both Ball type projectiles resulted in another failure mechanism (plugging) of the target plates and the residual projectiles where plastically deformed, see figure 3. The V_{50} values for both Ball projectiles are provided in tables 4 and 5, respectively.

The 0.50 Ball projectiles locally dented the target plates by this projectile-target interaction.

Table 2: Calculated (left) versus observed (right) V_{50}'s for steel types against 7.62 API-BZ (± 15 m/s)

Steel type /Thickness	A	B	C	D	E	F	G	H	J
DH 36	317/264	349/277	386						
EH 36				413/367	444/436	468/462	501/527	541/558	-
LRA	-	-	369/308	-	425/421	-	479/462	518/539	558/583

Table 3: Comparison between V_{50}'s from experiments (right) and DHG-model (left) for 0.50 AP

Steel type/thickness	H	I	J
EH 36 Y=500 MPa	388/373	-	566/541
LRA Y=450 MPa	379/357	385/388	-

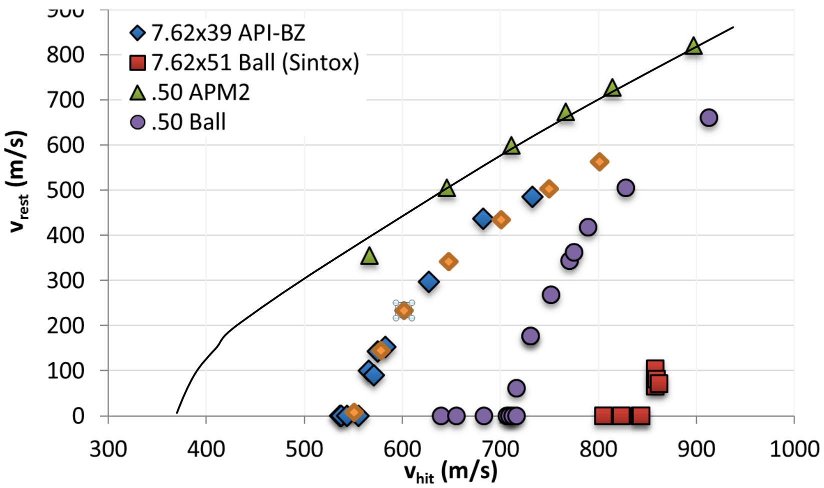

Figure 2. Example of the calculated residual velocity (orange squares) using the DHG model versus impact velocity for the 7.62 API-BZ (core) impacting a EH36 target of thickness H.

Table 4: Calculated (top) versus observed (below) V_{50}'s for steel types against 7.62 Ball (± 15 m/s)

Steel type	A	B	C	D	E	F	G	H
DH 36 Y=500	485/510	534/548	589/592					
EH 36 Y=500				599/606	678/662	715/711	764/757	820/847
LRA Y=450	-	507/535	560/565		643/651	-	725/719	778/845

4.0 Comparison between experimental results and calculations

As mentioned before, the engineering models are energy based and centred around a single failure mechanism. Therefore, in order to identify which model to use, it is important to analyse the target plates for the (main) failure mode responsible for the perforation process.
An easy one to identify is plugging, as it leaves plugs of target material in the shooting range (together with the residual projectiles). The plugged target plate is (apart from the obvious hole/crater) practically undeformed. Another easily identified failure mechanism is denting. This does not create a hole/crater in the target, but a considerable local out-of plane deformation of the plate. Ductile hole growth, in its purest form, creates a hole/crater in the target plate without removal of target material (therefore the plate mass is unchanged before and after shooting, no matter how many shots have penetrated the plate). The projectile (core) has penetrated practically without deformation or erosion, hence the projectile (core) mass and nose-shape are constant. This frequently happens with the penetration of armour piercing (AP) bullets, if one takes the core into account (the jacket is often stripped off at the strike-face of the target).
Indeed it was observed that the two AP rounds (7.62 and 0.50) penetrated the steel targets by DHG, while the Ball projectiles produced dents and plugs in the same targets.

Figure 3: Deformed 7.62 Ball (left) and 0.50 Ball projectiles (right) after impact on steel targets

4.1 Ductile hole growth (AP projectiles)
All steel targets used in this work are ductile, hence the shots using AP-projectiles (7.62 x 39 API-BZ and 0.50 APM2) are expected to penetrate the steel plates by the ductile hole growth mechanism. Table 2 and 3 show the V_{50} values for these projectiles, of which indeed undeformed cores have been recovered from the shooting range. The mass of the target plates has not been measured, but no chips of target material were missing from the deformed areas around the craters (no mass loss). A single plate thickness was selected from the middle of the thickness range, and the mechanical properties for steel (density 7800 kg/m^3 and E=200 GPa) were used, together with the projectile parameters of the 7.62 API-BZ core used. This leaves the dynamic flow stress of the target material as free parameter to tune in order to obtain the observed V_{50} for this combination of bullet with plate thickness and steel type. The value of 500 MPa served best for both the EH and DH36 steel types, for the LRA a lower value of 450 MPa had to be used. The value of 500 MPa for EH36 (as appears from this work) is in good agreement with that obtained by Nemat-Nasser et al. [3] using high speed tensile testing.
As the dynamic flow stress of the steel type is known, now the engineering model can be used to calculate V_{50} values for other plate thicknesses of the same steel and bullet-type. After adjusting the projectile parameters (mass, diameter and nose-shape), also the V_{50} values for other AP bullets can be calculated for any plate thickness of the same steel type.
Tables 2 and 3 show the experimentally obtained V_{50}'s compared to the calculated ones using the Ductile Hole Growth (DHG) engineering model. For the 7.62 mm AP round the agreement between the experimentally obtained values and the calculated ones is striking. Only for the thinnest metal plates the calculated V_{50}'s are above the estimated ones, indicating that for thin plates (thickness A to C) ductile hole growth no longer forms the main energy dissipating mechanism. Probably, less energy dissipating failure mechanisms like petalling take over. Using the same dynamic flow stresses for EH36 and LRA, respectively, also for the 0.50 APM2 core the calculated V_{50}'s are in agreement with the observed or estimated values. The DHG-model not only allows the calculation of the V_{50} for a certain plate thickness, but can also calculate the depth of penetration for a stopped projectile, or the residual velocity in case of a perforation of the target. The latter is shown in figure 2 by the yellow icons for the 7.62 API-BZ on a EH36 target plate with thickness H. It shows proper residual velocity results over a wide range of impact velocities (V_{hit}), when using a single test result in combination with the DHG calculation model.

4.2 Plugging (Ball projectiles)
Using the dynamic flow stress as determined by a fit of the experimental results of AP rounds with the DHG-model (see Table 1), equation 3 was used to calculate the V_{50} for the failure by plugging. First the results using the 7.62 Ball projectile are analysed. Due to the huge deformation of this projectile (in fact the projectile was turned inside out) the effective diameter is much larger than its caliber. For the effective diameter of the 7.62 Ball projectile the diameter of the plugs (about 14 mm) was used. For the density of the projectile a value of 2.45 g/cm^3 was shown to provide the best results, however this value has little to do with the density of the projectile materials involved (copper jacket and lead core, which have significantly higher mass densities). The discrepancy is probably induced by the hollow shape of the deforming projectile upon striking the much harder steel targets, see figure 3. Table 4 shows the calculated values again in red, which are in good agreement with the experimentally obtained V_{50}'s.
Second, the results of the 0.50 Ball projectile was assessed. Denting of a (thin) plate involves a combination of bending and biaxial stretching of the plate material. For this combination of

deformation mechanisms an engineering model is not available yet. Therefore, no calculated values for the V_{50} are provided for this projectile-target combination.

5.0 Conclusions

In this work the experimental results of ballistic tests using 4 projectiles at normal impact on construction steel targets are compared to calculations using engineering models that have been developed at TNO. The experimentally obtained V_{50} values for the armor-piercing projectiles (cores) could very well be reproduced using the Ductile Hole Growth model for all steel types and plate thicknesses using a single dynamic flow stress value for each steel type. Also residual velocities can be reproduced over a wide range of impact velocities using only a single AP-steel plate test result. The agreement between the calculated and experimentally obtained V_{50}'s, as well as the agreement between the dynamic flow stress as obtained using the DHG-model and the reported dynamic yield stress [3], indicate that the dynamic flow stress obtained by a combination of ballistic tests and DHG-model represents an intrinsic target material parameter.
For the Ball projectiles the situation is more complicated; not only do these projectiles deform upon impact, they initiate a number of failure mechanisms in the target like plugging, bending and stretching.
Although engineering models for such mixed mode target failure are still lacking, the V_{50} values for the 7.62 Ball could be calculated reasonably well, assuming the target to be plugged by the pressure of the impacting deformed projectile (using an effective projectile diameter and density) and the same dynamic flow stress of the target material.
The result of this work is a great reduction in shots required to determine penetration parameters of an unknown material. All we have to do is to determine the dynamic flow stress with a certain level of accuracy at one target thickness. After that, other thicknesses can be assessed using the ductile hole growth model. Furthermore, from the dynamic flow stress obtained with one (rigid) projectile, extrapolations can be made to other calibres. So, we do not have to shoot a whole range of calibres, one representative calibre is enough. In order to verify simulation results, it is recommended to perform some shots for validation at strategically chosen target thicknesses and projectile calibres.

6.0 Acknowledgements

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7.0 References

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