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# Effective depth-of-penetration range due to hardness variation for different lots of nominally identical target material

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## Abstract

The effect of small variations of target hardness on the depth of penetration for nominally identical target material has not been addressed systematically in publications yet and is often neglected. An investigation of this issue for laboratory-scale long rod projectiles penetrating into semi-infinite rolled-homogeneous-armor steel targets was conducted. The tungsten-heavy-alloy penetrators were of length 90 mm and diameter 6 mm. Five lots of armor steel with a nominal hardness range of 280–330 BHN provided material for the targets. The pursued approach consisted of hardness testing of the targets, in total 17 ballistic experiments at velocities in between 1250 m/s and 1780 m/s and data analysis.

A linear regression analysis of penetration vs. hardness shows that a target hardness increase within the given range of 280–330 BHN may result in a reduction of penetration depth of about 5.8 mm at constant velocity. This is equal to a change of −12% at an impact velocity of 1250 m/s. A multiple linear regression analysis included also the influence of yaw angle and impact velocity. It shows that small yaw angles and slight variations of impact velocities provide a smaller variation of the semi-infinite penetration depths than a variation of target hardness within a typical specification span of 50 BHN. For such a span a change in penetration of approximately −4.8 mm due to hardness variation is found, whereas 1° of yaw angle or −10 m/s of velocity variation gives a change of about −1.0 mm respectively −0.9 mm. For the given example, the overwhelming part of the variation is to be attributed to hardness effects – 4.8 mm out of 5.8 mm (83%). For nominally identical target material the target hardness thus influences the ballistic test results more severely than the typical scatter in impact conditions.

*Keywords:* Target hardness; Penetration; Yaw angle; Rolled-homogeneous-armor; Tungsten-heavy-alloy

## 1. Introduction

Many parameters determine the outcome of a ballistic test. Even for depth-of-penetration experiments with tungsten-heavy-alloy (WHA) rod penetrators against semi-infinite rolled-homogeneous-armor (RHA) steel targets, a variety of parameters come into play. Examples are impact velocity, yaw angle, target obliquity and material properties [1–6]. Some of those parameter variations are of statistical nature and controllable in an experiment within some scatter. Others are rather systematic types of error, such as variations between material lots that could occur, e.g. if the quality of a reference target material changes over time.

The target material hardness class is known to have a strong effect on penetration results. A number of investigations are published addressing this issue. For example, the work done by Rapacki et al. [7] analyzes the coarse effects of hardness for large variations of the full relevant armor steel hardness range from below 200 BHN up to 600 BHN. Penetration formulae, e.g. by Lanz and Odermatt [8], take care of those dependencies, too.

We address the case of relatively small variations that are within the range of a single target material hardness class, i.e. that are compatible with the same specification. This is of relevance as often ballistic results obtained with material of different origin in different series are compared or combined rather than repeating expensive tests with same-grade material. From the data correction for hardness effects done by Rosenberg et al. in [9], the significance of this problem for such small hardness differences emerges implicitly. However, we are not aware of a publicly available data set allowing for a more systematic analysis of such effects within a narrow hardness regime.

While actual impact velocities and yaw angles are typically measured in each test, the hardness may not be measured for each target specimen. Rather values are often picked from

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specifications or average values are taken as representative for a lot. For this purpose, we evaluated a test series in a total of 17 experiments conducted with identical penetrators against semi-infinite RHA steel targets from 5 different material lots of the same specification received over the years. Three values representing different impact velocity regimes were considered. The analysis that followed used the data obtained to determine the influence of small hardness variations on the penetration depth.

## 2. Experimental parameters

The present study combines the evaluation of semi-infinite penetration tests and hardness testing. The experimental parameters are summarized in the following.

### 2.1. Target material

A commercially available type of quenched and tempered steel, specified as RHA, was used for the targets. The material is supposed to be in a hardness range of 280–330 BHN and to have a typical yield strength $R_{p0.2}$ of 630 N/mm$^2$ and a typical ultimate tensile strength UTS of 800 N/mm$^2$. Nominally identical material from initially 4 different production lots was used for the penetration tests and the data analysis presented in this paper. The lots are denoted by A, B, C, and D in the following. From those, 17 targets of approximate dimensions of 150 mm × 150 mm × 150 mm were prepared for ballistic tests in total. From each of those target blocks, small elements were extracted and smoothed for hardness measurements. The hardness was determined with 3 separate measurements on each sample in a plane approximately 2 mm below and parallel to the rolling surface using the HBW 2.5/187.5 method.

### 2.2. Penetrator properties

The projectiles used were laboratory-scale WHA long rod penetrators. The penetrator dimensions are given by an overall length L of 90 mm, a diameter D of 6 mm, and a truncated nose as shown in Fig. 1.

According to the supplier, the WHA has a density of 17.55 g/cm$^3$, a yield strength $R_{p0.2}$ of 1290 N/mm$^2$ and an ultimate tensile strength UTS of 1360 N/mm$^2$. All projectiles were produced from the same WHA material lot.

### 2.3. Experimental set-up

The penetrators were accelerated with a powder gun using sabots. The basic idea underlying the structure of the test matrix was to consider 3 different impact velocities. The nominal impact velocities were chosen as 1250 m/s, 1560 m/s, and 1780 m/s. These velocities cover the parameter range most relevant for the penetration of WHA rod penetrators into steel. For all chosen velocities, an observable influence of material strength is to be expected, i.e. all velocities are well below the regime of purely hydrodynamic behavior [1]. We expected that for the highest investigated velocity of 1780 m/s, the effects of hardness are less pronounced than at the lower end of the velocity range at 1250 m/s. For this reason, most of the tests were done at the lower velocity.

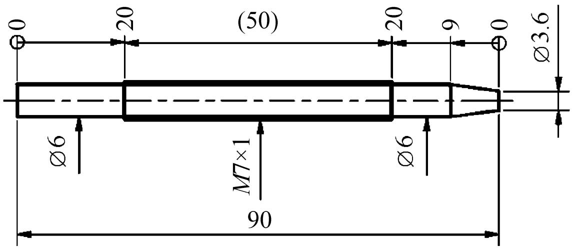

Fig. 1. Drawing of $L/D = 15$ laboratory penetrator with truncated nose.

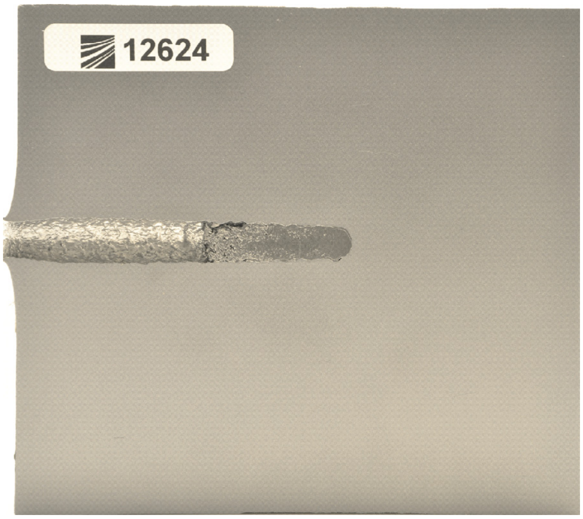

Fig. 2. Example of the cross-section of an impacted target (impact velocity 1780 m/s).

The impact velocities and yaw/pitch angles were measured in front of the targets by flash X-ray images. Total yaw angles were calculated from the measured yaw/pitch angles. These are shown in the results and used in the data analysis. In the experiments the penetrators impacted the targets at the rolling surface.

After the impact experiments the blocks were cut in half along the shot axis and ground for measurement of penetration depth (Fig. 2). For the given parameters and dimensions of targets and projectiles, the targets can be considered as effectively semi-infinite, i.e. the obtained penetration crater has sufficient distance to the lateral and rear target edges in all performed experiments [10].

## 3. Results

### 3.1. Hardness testing

Table 1 shows the hardness of each target and each lot. Prior and after the hardness testing of the samples, 3 measurements

Table 1
Results of Brinell hardness testing.

| Lot | Number of targets | *BHN* (individual target) | *BHN* (mean of lot) |
|---|---|---|---|
| A | 3 | 307, 311, 313 | 310 |
| B1 | 2 | 321, 323 | 322 |
| B2 | 3 | 283, 295, 300 | 293 |
| C | 5 | 326, 341, 344, 344, 345 | 340 |
| D | 4 | 323, 337, 337, 337 | 334 |