Scaling Effects in Penetration : A Taylor Test Approach

J. Cazamias, S. Bless

► To cite this version:

J. Cazamias, S. Bless. Scaling Effects in Penetration : A Taylor Test Approach. Journal de Physique IV Proceedings, 1997, 07 (C3), pp.C3-115-C3-120. 10.1051/jp4:1997322 . jpa-00255479

HAL Id: jpa-00255479

<https://hal.science/jpa-00255479>

Submitted on 1 Jan 1997

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Scaling Effects in Penetration: A Taylor Test Approach

J.U. Cazamias and S.J. Bless

Institute for Advanced Technology, 4030-2 West Braker Lane, Austin, TX 78759, U.S.A.

Abstract: Taylor Tests with $L/D = 5$ rods (1 cm and 0.2 cm in diameter) were conducted on armor steel (RHA) at 215 to 280 m/s to examine scale effects. AUTODYN-2D calculations confirmed dimensional analysis which predicts that strain rate should scale inversely with size. Yield strengths (Y^d) determined from the Wilkins-Guinan formula were found to be 7 to 9% greater in the smaller specimens which is a little less than the 12% increase predicted from a logarithmic dependence of strength on strain rate.

Résumé: Nous avons effectué des Tests de Taylor pour des échantillons cylindriques d'acier RHA (rapport $L/D = 5$, $D = 1$ cm et 0.2 cm) pour des vitesses allant de 215 à 280 m/s afin d'étudier les effets d'échelle. Des simulations numériques avec AUTODYN-2D ont confirmé l'analyse dimensionnelle qui prédit une vitesse de déformation inversement proportionnelle au diamètre. Nos résultats montrent que la contrainte d'écoulement, déterminée à partir de la formule de Wilkins-Guinan, est 7 à 9% plus grande pour les petits échantillons. Ces valeurs sont proches des 12% d'augmentation prédits par une dépendance logarithmique de la contrainte en fonction de la vitesse de déformation.

1. INTRODUCTION

The effect of test scale in penetration experiments has recently been examined by a number of authors [1-20] with seemingly contradictory results. To the extent that penetration phenomena depend on test scale, strain rate effects have appeared to be a likely cause. In particular, while it has been shown in calculations that logarithmic rate hardening would result in barely perceptible effects, if there is a transition to linear rate hardening at small enough scale, then scale effects might become more evident. Considering the difficulties of interpreting penetration experiments, we have conducted "zero penetration" tests, i.e., Taylor tests [21-22] using common armor steel (RHA). Tests were conducted in the reverse ballistic mode at 215 to 280 m/s. To examine scale effects, two $L/D = 5$ rod sizes with diameters of 1 cm and 0.2 cm were used.

2. REVIEW OF SCALE EFFECTS FOR PENETRATION INTO STEEL TARGETS

Anderson, Mullin and Kuhlman [2] did a computational study of strain-rate effects in penetration using the Johnson-Cook model. They impacted tungsten alloy against armor steel at 1.5 km/s. They found that, over a scale of ten, strain-rate effects changed the depth of penetration for semi-infinite targets, and the residual velocity and length of the projectile for finite-thickness targets by about 5%. They pointed out that damage accumulation is a function of absolute, not scaled time; therefore, small scale armors should outperform large scale armors, but only by a relatively modest amount.

Magness and Leonard [3] presented data from full scale (implying a diameter of approximately 25 mm) ($L/D = 19$) and quarter scale ($L/D = 20$) DU and tungsten alloy penetration experiments. At 1.5 km/s, the P/L increased roughly 20% as the scale increased. Since this difference was larger than could be explained from L/D effects, they then conducted penetration experiments with DU and tungsten alloy $L/D = 10$ penetrators against RHA and 1020 steel at 1/6, 1/4, and 1/3 scales. The DU and tungsten alloy have the same density (18.6 gm/cm^3), but tungsten alloy fails via plastic flow while DU fails via adiabatic shear bands which minimizes the size of the mushroomed head, allowing the penetrator to displace a narrower tunnel in the armor, and thus penetrate more efficiently. They measured P/L and found a very substantial scale effect: the magnitude of performance enhancement as a function of scale was essentially the same for DU and tungsten alloy, about 10% for a scale factor of 2. This also seems to imply that scale-dependent flow and failure of the penetrators are not the scale sensitive parameters (see also Backman *et al.* [13]). However, an increased scale enhanced performance was not observed for the mild steel targets which are extremely strain rate sensitive, and consequently the source of enhancement is left in some doubt.

Rosenberg, Kreif and Dekel [6] performed $L/D = 10$ penetration experiments with copper and tungsten

alloy penetrators against 4340 steel at quarter scale and half scale. They found that copper penetration scaled geometrically while with the tungsten alloy there was again a significant enhancement of P/L by about 10% at half scale. They postulated that tungsten (and in addition DU) do not scale due to their semi-brittle nature. They argued that the plastic zone in front of crack tips is proportionally smaller at the larger scale, and this results in a more "brittle" failure mode.

Lundberg and Holmberg [7] conducted penetration experiments with tungsten alloy $L/D = 15$ projectiles against armor steel. They shot at 1.5 (0.5, 2, 5, 10 and 15 mm in diameter) and 2.5 km/s (0.5, 2, 5 and 10 mm in diameter). They found no scale effects in crater depth, crater diameter, residual projectile length, or hardness distribution around the penetration crater. The residual projectile length for the smallest scale ($D = 0.5$ mm) was considerably smaller than for the larger scales, and the authors attributed this to the fact that at this scale the shots were performed reverse ballistically while shots at the other scales were performed in direct ballistic mode. The general appearance of the craters did not show any scale dependence.

Sorensen *et al.* [12] compiled data for tungsten alloy penetration into semi-infinite RHA at quarter scale, half scale and full scale. The P/L versus impact velocity showed good correlation with a hyperbolic fit, i.e. no scale effect was readily apparent. Holmberg, Lundberg and Westerling [14] shot $L/D = 15$ tungsten alloy rods (2, 5, 8 mm in diameter) against steel plates (60° obliquity and 1500 m/s). They found no scale dependence in the normalized residual velocities and normalized residual lengths. Ferguson [10] found a small scale effect which he attributed to strain rate effects. Specifically, he observed a 3.5% increase in penetration for a scale difference of 10 at 2000 m/s.

3. THE TAYLOR TEST

During World War II, Taylor [21] and Whiffen [22] conducted tests (the Taylor test) to characterize the dynamic compressive yield strength of a variety of metals. They shot metal rods against "rigid" anvils and then measured the change in length of the rods to determine a *minimum* value of the dynamic compressive yield strength. Assuming an elastic-perfectly plastic response, Taylor came up with closed form equations to describe the process. For his model, he considered an elastic wave and a plastic wave traveling down the bar. The elastic wave which is traveling faster than the plastic wave is reflected from the rear surface of the bar and comes back to relieve the plastic wave. Later Wilkins and Guinan [23] presented a different analysis which better models the experimental data. This analysis assumes that the rate of change of the length of the rod is given by:

$$\frac{dL}{dt} = -U, \quad (1)$$

where U is the impact velocity. Using $F = ma$ for the force exerted on the specimen by the rigid wall, one gets:

$$Y^d A = -\rho_0 L A \frac{dU}{dt}, \quad (2)$$

where Y^d is the dynamic compressive yield strength, A the cross sectional area, and ρ_0 is the original density. Solving for dt in (2) and substituting into (1), one obtains:

$$\frac{dL}{L} = \frac{\rho_0 U}{Y^d} dU. \quad (3)$$

Wilkins and Guinan observed in numerical simulations that the plastic front moves to a fixed distance h from the rigid boundary. The distance h is assumed to be independent of velocity and proportional to L_0 , the original length. In general, they found $h/L_0 = 0.12$. Integrating the left-hand side of (3) from $L_0 - h$ to $L_f - h$, where L_f is the final length, results in:

$$\frac{-\rho_0 U^2}{2 Y^d} = \ln \frac{\frac{L_f}{L_0} - \frac{h}{L_0}}{1 - \frac{h}{L_0}}, \quad (4)$$

which is the equation that is used for the analysis in this paper.

Partom [24] pointed out that for rate sensitive materials, Y^d does not generally represent the actual material response. Partom derived a one dimensional flow problem that can easily be solved numerically once one has the functional form of Y^d . Erlich and Chartagnac [25] observed that in work hardening materials, the strength determined from (4) is the flow stress, rather than the initial yield stress.

4. EXPERIMENTAL PROCEDURES AND DATA

Taylor tests are performed in a reverse ballistic mode (from a single stage light gas gun) at the Institute for Advanced Technology's (IAT) Hypervelocity Launch Facility. The gun has a diameter of 56 mm and shots were conducted in the 215 to 280 m/s velocity range. The gun fires a lexan sabot with a hardened 4340 steel flyer plate (nominal hardness of 50 Rockwell C). The plate is 9.5-mm thick and approximately 50 mm in diameter with two drill holes for attachment to the lexan. Velocity is measured by an optical technique (Simha [26]). Reflective bands are placed on the sabot and a laser beam and detector are located at the end of the barrel. As the sabot passes beneath the laser, the light is reflected into a photodiode and the output is read by an oscilloscope. Measuring the time between signals and the distance between bands allows the velocity to be calculated.

Two different size $L/D = 5$ rods were impacted. The lengths were 50 mm and 10 mm. The longer rods were caught in celotex tiles with no effort made to stop the flyer plate. The shorter rods were also caught in tiles, but this time a stripper plate was added to stop the projectile. Inspection of the long rods did not show evidence of additional interactions with the flyer plate. The shorter rods had a tendency to be recovered bent when there was not a stripper plate present. In addition, the stripper plate simplified finding the short rods after the shot. The RHA rods were cut from a single RHA plate of the same stock as those used in IAT's penetration experiments. A total of seven shots were performed (Table 1). One specimen from each scale was selected for metallographic study. Knoop microhardness characterization was performed using a Tukon microhardness tester with a five hundred gram load. The full scale specimen had an average hardness of 310 ± 16 , and the 1/5 scale had an average hardness of 321 ± 16 . Photomicrographs were taken (Figures 1a and 1b) to determine if differences in flow lines could be observed in the two specimens. No notable difference in the flow lines was observed.

Table 1: Experimental Data

Shot	Scale	Impact Velocity (m/s)	$\frac{L_f}{L_i}$	Y^d (GPa)
1	1	249	0.879	1.63
2	1	256	0.871	1.61
3	1	219	0.894	1.46
4	1	277	0.855	1.66
5	1/5	272	0.869	1.79
6	1/5	216.5	0.905	1.60
7	1/5	249	0.885	1.73

Figures 1a and 1b: Photomicrographs of full scale (left) at 6.6x and 1/5 scale (right) at 36x.

5. DIMENSIONAL SCALING

Strain rate is inversely proportional to scale. A simple way to see this is through dimensional analysis. Strain rate has units of s^{-1} . Viewing impact velocity (v) and either length (L) or diameter (D) of the projectile as the relevant physical parameters, one obtains.

$$\dot{\epsilon} \propto \frac{v}{L} \text{ or } \frac{v}{D} . \tag{5}$$

Therefore as size decreases, strain rate increases. To test the validity of this assumption, AUTODYN-2D computations were performed for RHA rods against 4340 steel plates at 250 m/s (Figure 2a). At large scale, a strain rate of approximately $4 \times 10^4 s^{-1}$ was observed. At 1/5 scale, a strain rate of approximately $2 \times 10^5 s^{-1}$ was observed. This is roughly a factor of 5 larger thus supporting the dimensional argument for strain rate. Small scale simulations were also performed at 220 m/s and 270 m/s (Figure 2b) showing that the strain rate scales with velocity. The strain rates in these experiments are in the range of interest for ballistics tests. For penetration tests, in which the strain rate associated with cavity formation in the target is approximately the penetration velocity divided by cavity diameter, the strain rates for quarter scale penetrators are about $10^5 s^{-1}$ for impact velocities of 1.5 to 2.5 km/s. Thus, the Taylor experiments reproduce most of the ballistic strain rates of Section 2.

Figures 2a and 2b: 2a is a plot of effective plastic strain rate versus scaled time for the two different scales at 250 m/s where scaled time for the 1/5 scale experiment is actual time multiplied by a factor of five. Notice that the strain rates vary effectively by a factor of five. 2b looks at effective strain rate versus time as a function of impact velocity. Notice that the strain rates scale with the impact velocity.

6. ANALYSIS

Yield strengths are plotted in Figure 3; 3a connects points at the same impact velocity for varying scale and 3b connects points at the same scale for varying velocity. Both are seen to consistently affect the flow stress. These data may not be absolutely accurate since there was a slight indentation of the flyer plates in these tests (about 1/4 mm), and the mass of the flyer plate is only a little less than five times the mass of the rod. Nevertheless, the range of flow stresses measured, 1.5 to 1.7 GPa, is consistent with the value reported by Gray *et al.* [27] for RHA at a strain rate of $3.5 \times 10^4 s^{-1}$ to $7.0 \times 10^4 s^{-1}$, i.e., 1.5 GPa. However, the goal of these tests, which was to search for rate effects in two experiments that differ solely in geometry, and not in loading technique, does not require an absolute measurement of flow stress.

Examining the scale effect, we find that the flow stress does indeed increase with strain rate, and all the values of dY^d/Y^d lie between 7 and 9%, with a mean of 8.5%. If we hypothesize a logarithmic dependence of flow stress on strain rate, e.g., $Y^d \propto \log \dot{\epsilon}$, then $dY^d/Y^d = (d \log \dot{\epsilon})/(\log \dot{\epsilon})$, which is of the order of 12%. Thus, the amount of rate hardening is, if anything, less than logarithmic. As discussed in Section 2, it is well established that scale effects, when they occur, are greater than can be accounted for by logarithmic rate effects. Thus, strain rate effects on flow stress (for the target) can be ruled out as a cause of scale effects in penetration experiments.

We find that the change of flow stress with velocity is approximately $(\Delta Y^d/Y^d)/(\Delta v/v) = 1.1 - 1.2$. This is a considerably larger effect than would be expected from strain rate alone. About half of this increase could be due to the higher total strains associated with higher impact velocities. However, at least part of this apparent hardening is probably due to imperfections in the experiment—namely the relatively greater indentation and deceleration of the flyer plate at higher impact speeds.

Figures 3a and 3b: Plots of yield strength versus scale and velocity.

7. CONCLUSIONS

Taylor tests were performed on common armor steel in the reverse ballistic mode at 215 to 280 m/s to examine scale effects on yield strengths using $L/D = 5$ rods of 1 cm and 0.2 cm diameter. AUTODYN-2D calculations showed that strain rate scales inversely with size and directly with velocity in agreement with dimensional analysis. Yield strengths (Y^d) of RHA were determined to be 1.46 to 1.79 GPa using the Wilkins-Guinan formula (4). It was found that the strength of the smaller specimens was 7 to 9% more than the larger specimens. This is nearly what would be expected from a logarithmic dependence of strength on scale (strain rate), which predicts an increase of 12%. The yield strengths also exhibited a dependence on impact velocity of $(\Delta Y^d/Y^d)/(\Delta v/v) = 1.1 - 1.2$, which is much greater than would be expected from strain rate alone. There was no noticeable difference in deformed microstructure between the two scales.

ACKNOWLEDGMENTS

The authors would like to acknowledge Dr. Yehuda Partom, who suggested the experiments, and Mr. Hari Simha and Mr. Steve Myers who helped carry out the work. This work was supported by the U.S. Army Research Laboratory (ARL) under contract DAAA21-93-C-0101.

REFERENCES

- [1] Gurson A.L., *Int. J. Impact Eng.*, **10** (1990) pp. 213-229.
- [2] Anderson C.E., Mullin S.A., Kuhlman C.J., *Int. J. Impact Eng.*, **13** (1993) 35-52.
- [3] Magness L., Leonard W., "Scaling Issues for Kinetic Energy Penetrators", 14th International Symposium on Ballistics, Québec, Canada 26-29 September 1993, M.J. Murphy and J.E. Backofen Eds. (American Defense Preparedness Association, Arlington, VA, 1993) pp. 281-289.
- [4] Olsson P.-O., Lundberg P., Ragnarsson K., "Post-Mortem Studies to Investigate Replica Modeling of Alumina Targets", 15th International Symposium on Ballistics, Jerusalem, Israel 21-24 May 1995, M. Mayseless and S.R. Bodner Eds. (American Defense Preparedness Association, Arlington, VA, 1995) pp. 307-314.

- [5] Farrand T.G., Polesne J.T., Abell J.M., "Prediction of Behind Armor Debris Generated for Kinetic Energy Penetrators Against Light Armors", 16th International Symposium on Ballistics, San Francisco, CA, 23-27 September 1996, R. Brown and D. Baum Eds. (American Defense Preparedness Association, Arlington, VA, 1996) pp. 59-68.
- [6] Rosenberg Z., Krief R., Dekel E., "On the Geometric Scaling of Long-Rod Penetration", 16th International Symposium on Ballistics, San Francisco, CA 23-27 September 1996, R. Brown and D. Baum Eds. (American Defense Preparedness Association, Arlington, VA, 1996) pp. 321-328.
- [7] Lundberg P., Holmberg L., "Replica Modeling Experiments with Long Rod Projectiles into Homogeneous Armour Steel", 16th International Symposium on Ballistics, San Francisco, CA, 23-27 September 1996, R. Brown and D. Baum Eds. (American Defense Preparedness Association, Arlington, VA, 1996) pp. 329-338.
- [8] Anderson C.E., Mullin, S.A., Piekutowski A.J., Blaylock N.W., Poormon K.L., *Int. J. Impact Eng.*, **18** (1996) pp. 1-22.
- [9] Lundberg P., Westerling L., Lundberg B., *Int. J. Impact Eng.*, **18** (1996) pp. 403-416.
- [10] Ferguson G.L., *Int. J. Impact Eng.*, **16** (1995) pp. 571-583.
- [11] Hörz F., Cintala M., Bernhard R.P., See T.H., *Int. J. Impact Eng.*, **15** (1994) pp. 257-280.
- [12] Sorensen B.R., Kimsey K.D., Silsby G.F., Scheffler, D.R., Sherrick T.M., De Rosset W.S., *Int. J. Impact Eng.*, **11** (1991) pp. 107-119.
- [13] Backman M.E., Finnegan S.A., Schulz J.C., Kenneth, J., "Scaling Rules for Adiabatic Shear Populations", Metallurgical Applications of Shock-Waves and High-Strain-Rate Phenomena, Portland, Oregon 28 July 1985, L.E. Murr, K.P. Staudhammer and M.A. Meyers Eds. (Marcel Dekker Inc., New York, 1986) pp. 675-687.
- [14] Holmberg L., Lundberg P., Westerling L., "An Experimental Investigation of WHA Long Rods Penetrating Oblique Steel Plates", 14th International Symposium on Ballistics, Québec, Canada 26-29 September 1993, M.J. Murphy and J.E. Backofen Eds. (American Defense Preparedness Association, Arlington, VA, 1993) pp. 515-524.
- [15] Tvrdik C., Hill T., IAT Report 0125, 1996.
- [16] Orphal D.L., Franze R.R., Piekutowski A.J., Forrestal M.J., *Int. J. Impact Eng.*, **18** (1996) pp. 355-368.
- [17] Yatteau J.D., Recht R.F., "High Speed Penetration of Spaced Plates by Compact Fragments", 9th International Symposium on Ballistics, Shrivenham, England 29 April - 1 May 1986, (American Defense Preparedness Association, Arlington, VA, 1986) pp. 365-374.
- [18] Alexander M.D., Finnegan S.A., Zimmerman R. A., "A Study of Scaling Effects in the Modeling of Multiple Fragment Impacts", 10th International Symposium on Ballistics, Orlando, Florida 27-29 October 1987, W. Reinecke Ed. (American Defense Preparedness Association, Arlington, VA, 1987).
- [19] Orphal D.L., Wagner M. H., Vivian C.E., "Low Angle Impact and Penetration of Thin Laminated Targets by Spheres", 1982 Symposium on Ballistics, Aberdeen Proving Ground, Maryland November 1982, pp. 213-229.
- [20] Hall D.L., "Scaling Laws for KE Penetrators", 5th International Symposium on Ballistics, Toulouse, France 16-18 April 1980, (American Defense Preparedness Association, Arlington, VA, 1980).
- [21] Taylor G., *Proc. R. Soc. A*, **194** (1948) pp. 289-299.
- [22] Whiffen A.C., *Proc. R. Soc. A*, **194** (1948) pp. 300-322.
- [23] Wilkins M.L., Guinan M.W., *J. Appl. Phys.*, **44** (1973) pp. 1200-1206.
- [24] Partom Y., "Modeling Taylor's Anvil Test for Hardening and Rate Sensitive Materials", 13th International Symposium on Ballistics, Stockholm, Sweden 1-3 June 1992, Å. Persson, K. Andersson and E.B. Björck Eds. (American Defense Preparedness Association, Arlington, VA, 1992) pp. 291-297.
- [25] Erlich D.C., Chartagnac P.F., "Determination of Dynamic Flow Curve of Metals at Ambient and Elevated Temperatures by Rod Impact Techniques", DYMAT 85, Paris, France 2-5 September 1985, J. Philibert Ed. (Les Éditions de Physique, Les Ulis, 1985) pp. 455-62.
- [26] Simha C.H.M., IAT Technical Note 54, 1995.
- [27] Gray III G.T., Chen S.R., Wright W., Lopez M.F., LA-12669-MS, January 1994.