Hypervelocity impacts into graphite

S Latunde-Dada, C Cheesman, D Day, W Harrison and S Price

AWE Plc, Aldermaston, Reading RG7 4PR, UK

E-mail: seyi.latundedada@awe.co.uk

Abstract. Studies have been conducted into the characterisation of the behaviour of commercial graphite (brittle) when subjected to hypervelocity impacts by a range of projectiles. The experiments were conducted with a two-stage gas gun capable of launching projectiles of differing density and strength to speeds of about 6 km s⁻¹ at right angles into target plates. The damage caused is quantified by measurements of the crater depth and diameters. From the experimental data collected, scaling laws were derived which correlate the crater dimensions to the velocity and the density of the projectile. It was found that for moderate projectile densities the crater dimensions obey the ‘2/3 power law’ which applies to ductile materials.

1. Introduction

The normal impact of spheres into semi-infinite targets is a problem that has been studied extensively in the laboratory and through the use of numerical hydrocodes with in-built material models. Most of these studies have been done with ductile targets examples of which can be found in [1, 2] and a few with brittle targets, an example of which is [3]. In these studies, the dimensions of the craters formed have been used to characterize the damage to the target and scaling laws with impact velocity have been derived. Typically, due to the large deformations prevalent in the hypervelocity regime, detailed mathematical analysis of this problem has proved too difficult to derive scaling laws theoretically. Therefore, simple power laws relating the crater dimensions to the governing parameters of the problem have been developed by fitting experimental or numerical data.

In this paper, an attempt will be made to derive scaling laws for the dimensions of the craters formed from experimental data generated by normal hypervelocity impacts of spherical projectiles into a graphite target.

In section 2, the cratering process is discussed and contrasted with the morphology of craters formed in ductile and brittle targets such as graphite. Next, in section 3, the impact experiment is described and the experimental data presented in appendix A. From this data, in section 4, the variation of crater depth against impact velocity is studied and compared with the 2/3 power law characteristic of impacts into ductile targets. In section 5, the correlation of the crater diameter with velocity is studied and hence, a power law obtained for the variation of the crater volume with impact velocity. In section 6, the effects of projectile density on the correlations are studied and predictions made for the crater dimensions formed by polypropylene and cellulose acetate projectiles which are compared to data. Finally in section 7, a summary and some conclusions are reported.

2. Cratering process and morphology for normal impacts

The process of crater formation from normal hypervelocity impacts can be divided into four phases: shock, steady state, cavitation and recovery [4]. At the instant of impact, the particles at the impact surface of the projectile are instantaneously brought to rest by the target particles. Shock waves are produced at this surface which propagate into both the target and...
back into the projectile, causing large scale plastic deformations accompanied by melting or vaporization. This is the **shock phase** which ends when the rarefraction waves relieve the shock pressures. These rarefaction waves originate from reflection of the shock waves from free surfaces where there is a zero-pressure boundary condition. In semi-infinite targets where the lateral and rear surfaces are too far away to generate the rarefraction waves, the shock is primarily released by the rarefraction waves generated from the free surfaces of the projectile. In thinner targets, on the other hand, both the projectile and target rarefraction waves relieve the shock wave in the target. Accompanying this release is the ejection of target particles at high speeds.

During the shock phase, the projectile, being subjected to pressures much greater than its yield stress, begins to erode and effectively becomes a fluid which is now the primary cause of crater formation. This is the **steady state phase** during which the governing parameters of crater formation are the density and velocity of the projectile. The duration of this phase depends on the dimensions of the projectile. For spherical projectiles travelling at hypervelocities, this phase can be very short.

After the projectile has completely eroded, the crater continues to expand under its inertia until it is unable to overcome its own intrinsic resistance. This is the **cavitation phase**.

Finally, once the crater has reached its maximum extent, its dimensions may diminish slightly due to an elastic rebound which produces tensile stresses. This is the **recovery phase** which signals the end of cratering.

Typically, in brittle materials, due to their low tensile strength, cratering lasts longer than in ductile materials and hence the damage is more extensive. This because the shock and rarefraction waves last longer during the shock phase due to the low intrinsic resistance. In addition, due to their relative tensile strengths, the target material ejected during this phase forms the characteristic raised lip in ductile materials which is absent in impacts on brittle targets.

Likewise, during the cavitation phase, the low resistance of brittle materials causes subsurface cracks to develop which can result in surface cracks and spallation around the initial crater unlike in ductile materials. This results in relatively wider craters which are therefore shallower in terms of the ratio of the crater depth to its diameter.

Figures 1 (a) and (b) show the morphologies of ductile and brittle craters labelled with the crater dimensions. In figure 2, a photograph of the brittle crater formed by a 4mm diameter alumina projectile impacting a graphite target at 3.02kms$^{-1}$ is shown.

![Figure 1](image1.png)  
**Figure 1.** Typical morphologies of crater formed by hypervelocity impacts into (a) ductile and (b) brittle targets.

![Figure 2](image2.png)  
**Figure 2.** Photograph of a brittle crater

3. **The experiment**

The experiments were conducted with a two-stage light gas gun which is used to accelerate small spherical projectiles to hypervelocity speeds (approximately 1–7kms$^{-1}$) into target plates. It operates by the ignition of a propellant charge to force a piston forward into a breech filled with hydrogen gas at pressures of 200–500psi. This pressure rapidly increases until a
bursting disc ‘petals’ and the sabot containing the projectile is launched forward. The sabot is
stripped either by a metal obstruction or gas pressure and the speed of the projectile is
measured by lasers just prior to impact into the target plate.

The spherical projectile materials used include HDPE, alumina, aluminium, soda glass and
steel with diameters ranging from 1-4.76mm. The thickness of the blocks used varied from
25mm to 50mm to 100mm. The target blocks were made of commercial graphite (Graphite
25) which is a brittle and porous material with a porous density of 1.83gcm\(^{-3}\) and a compact
density of 2.13gcm\(^{-3}\).

The primary method of quantitative damage comparison between each impact is the
measurement of the crater depth, diameter and volume using a laser scanner which generates
profiles of the craters. Due to the irregular nature of the craters, the depth and diameter are
taken in two perpendicular planes and the averages of each are found. The crater volumes are
also calculated. The experimental data obtained from these experiments are tabulated in
appendix A.

4. Correlation of crater depth \(p\) with impact velocity \(v\)

In previous studies of hypervelocity impacts, the dimensionless form \(p/d_p = \Phi(v)\) has been
used for the correlation where \(p\) is the crater depth, \(d_p\) is the diameter of the projectile, \(v\) is its
impact velocity and \(\Phi\) is the correlation to be determined [5]. This convention will be adopted
here since as can be seen in the data tables in appendix A, \(d_p\) has been varied for certain
projectile-target configurations.

Previous studies on normal hypervelocity impacts on semi-infinite ductile targets have
demonstrated two fundamental concepts about the correlation of crater depth with impact
velocity [1, 2]. Firstly, as the impact velocity is increased, it has been observed that the crater
tends to a hemispherical shape i.e. the ratio of the crater depth \(p\) to crater diameter \(d_c\)
approaches 1/2. The direction of the approach to this regime was found to be dependent on
the ratio of the density of the projectile to the target. For projectiles denser than the target,
\(p/d_p\) starts off greater than 1/2 and vice versa for projectiles of a lower density than the target.
In addition, the greater the difference between the densities of the projectile and the target, the
slower is the approach to the hypervelocity regime and the greater the velocity at which
hypervelocity phenomena dominate the cratering process.

Secondly, a number of studies have suggested that the crater volume becomes proportional
to the kinetic energy of the projectile in the hypervelocity regime. Coupling these two
observations together, the following relations are arrived at:

\[
\begin{align*}
V_c &= \frac{4}{3} \pi p^3 \\
E_p &= \frac{2}{3} \pi p d_p^3 v^2 \\
V_c &\propto E_p \\
\therefore \frac{p}{d_p} &= K_p \frac{2}{3} v^3
\end{align*}
\]

where \(V_c\) is the crater volume, \(E_p\) is the kinetic energy of the projectile, \(\rho\) is its density and \(K_p\)
is a constant of proportionality. This is the 2/3 power law which has been verified for a
variety of ductile materials. It is worth noting that some fits to experimental and numerical
data have provided velocity exponents between 1/3 and 2/3 which is indicative of a mixture
between energy scaling and momentum scaling i.e. scaling in which the momentum rather
than the kinetic energy is proportional to the crater volume [1].

Impacts in brittle materials like graphite have undergone much less investigation.
However, as discussed in section 2, most of the differences between the brittle and ductile
cratering processes are related to the crater width and not the depth. Hence, a similar scaling
law is expected for the depth of craters in graphite.
Figure 3. Correlation fits from experimental data.

Figure 3 shows the correlation fits obtained from the experimental data recorded in tables A1-A6 in appendix A. In table 1, the velocity exponents $n_p$ obtained for the depth correlations are presented for the various projectiles under study. The values of the proportionality constants $K_p$ and the correlation coefficients $R^2$, of the global fits are also presented. $R^2$ is a measure of the goodness of fits of the global trend lines.

| Projectile Material | $\rho$/gcm$^{-3}$ | $n_p$   | $K_p$  |
|---------------------|-------------------|--------|--------|
| HDPE                | 0.969             | 0.6972 | 0.7837 |
| Soda Glass          | 2.48              | 0.6319 | 0.9292 |
| Aluminium           | 2.71              | 0.6059 | 1.0754 |
| Alumina             | 3.69              | 0.6022 | 1.0512 |
| Steel               | 7.8               | 0.87   | 0.9434 |

From the table, it appears that except for steel projectiles, the velocity exponents obtained agree with the 2/3 power law if some momentum scaling is allowed for. The higher value of $n_p$ observed for steel projectiles may be attributed to the inclusion in the fits, of data from outside the hypervelocity regime since, as mentioned earlier, the speed of approach to the hypervelocity regime is expected to be slower for denser materials. This will be discussed further in appendix B. It should be noted also that this trend should not be surprising as a previous study into hypervelocity impacts on glass targets gave a velocity exponent of 0.8 [6].

5. Correlation of crater diameter $d_c$ with impact velocity $v$

As discussed in section 4, for ductile targets, the crater formed from a hypervelocity impact tends to a hemispherical shape. This implies that, the crater diameter $d_c$ scales as the penetration depth $p$ does with velocity i.e.

$$\frac{d_c}{d_p} \propto v^\frac{2}{3}$$

(2)

In brittle targets however, as explained in section 2, the correlation is not so straightforward due to the shallow craters formed by the subsurface cracks and spallations characteristic of such materials and hence the craters formed are not hemispherical. To illustrate this, scatter plots of the ratio of the crater diameter to its depth $d_c/p$ as a function of velocity as shown in figure 4.
It is important to note though that despite the irregularities of the cracking process, \( \frac{d_c}{p} \) stays relatively constant with velocity and ranges from an average value of about 2.8 for HDPE to 3.4 for alumina. The average values \( \langle \frac{d_c}{p} \rangle \) and standard deviations \( \sigma \) are recorded in table 2.

**Table 2.** Means and standard deviations of the ratios of crater diameter to crater depth.

| Projectile Material | \( \langle \frac{d_c}{p} \rangle \) | \( \sigma \) |
|---------------------|-----------------|--------|
| HDPE                | 2.86            | 0.29   |
| Soda Glass          | 3.15            | 0.43   |
| Aluminium           | 3.34            | 0.35   |
| Alumina             | 3.39            | 0.2    |
| Steel               | 3.13            | 0.32   |

This suggests that crater diameter should have a similar variation with impact velocity as crater depth. This is demonstrated in table 3 where \( n_d \) represents the velocity exponents for the normalized crater diameter correlations (see figure 3) and \( K_d \) and \( R \) are the proportionality constant and correlation coefficient respectively.

**Table 3.** Correlation parameters for crater diameter with impact velocity.

| Projectile Material | \( \rho \)/g/cm\(^3\) | \( n_d \) | \( K_d \) |
|---------------------|-----------------|--------|--------|
| HDPE                | 0.969           | 0.718  | 1.9498 |
| Soda Glass          | 2.48            | 0.5818 | 3.0603 |
| Aluminium           | 2.71            | 0.6655 | 3.1472 |
| Alumina             | 3.69            | 0.6686 | 3.2256 |
| Steel               | 7.8             | 0.9308 | 2.7355 |

The values of \( n_p \) for the depth correlations obtained in section 4 can now be compared to \( n_d \). As mentioned in section 2, during the cratering process in brittle targets, an initial crater is formed which then subsequently expands in diameter as the tensile strength of the target is overcome and cracks propagate. The scaling of \( d_c \) and hence the crack length, \( l \), therefore suggests that the energy absorbed by crack propagation (as well as the spallation of the target
material above the crack) is proportional to the projectile energy as well as volume of target material spalled which scales roughly as .

As an aside, it is interesting to note that for impact velocities above \( 2.5 \text{km/s} \), the velocity exponents for steel approach \( 2/3 \) as shown in table 4.

**Table 4.** Correlation parameters for impact velocities above \( 2.5 \text{km/s} \).

| Projectile Material | \( n_p \) | \( K_p \) | \( n_d \) | \( K_d \) |
|---------------------|--------|--------|--------|--------|
| Steel \( (v < 2.5 \text{km/s}) \) | 0.6468 | 1.3449 | 0.6265 | 4.5084 |

Therefore it appears that, for steel projectiles, the hypervelocity regime includes speeds of above about \( 2.5 \text{km/s} \), although this can not be confirmed with conviction because of the relative paucity of data used in these new fits.

In the data tables of appendix A, the crater volume is also recorded. During the measurements, it was observed that the craters formed were roughly conical in shape. This can be verified by comparing the volume of a cone of height \( h \) and diameter \( d_c \) which is given by \( \pi d_c^2 h / 12 \) with the measured values. Figure 5 shows scatter plots of the volume ratio \( V_c / V_{measured} \) from which it can be seen that a cone does give a good description of the crater shape. The mean of this distribution is 0.97 with a standard deviation of 0.12.

![Cone approximation](image)

**Figure 5.** Scatter plot for conical volume ratio

6. **Projectile density correlations**

The differences in the velocity exponents and proportionality constants obtained for the different projectiles may be attributed to their varying densities since as discussed in section 4, the density of the projectile relative to the target’s determines the speed at which hypervelocity phenomena becomes important.

Looking at tables 1 and 3, it can be noted that in general as the density increases, so do the proportionality constants \( K_p \) and \( K_d \) with the velocity exponents (excepting steel’s) remaining relatively constant. Assuming a power law variation for the exponents \( n \) and constants \( K \) with \( \rho \) and ignoring the values for steel, the following correlations are obtained for a projectile of density \( \rho \);

\[
\frac{p}{d_p} = 0.791 \rho^{0.2339} \sqrt[0.6936]{\rho^{-1.1146}}; \rho < 3.69 \text{g/cm}^3,
\]

\[
\frac{d_c}{d_p} = 2.02 \rho^{0.4061} \sqrt[0.6974]{\rho^{-0.0776}}; \rho < 3.69 \text{g/cm}^3.
\]

(3)

With these equations, predictions were made for four experiments which were excluded from the fits. The results are compared to the experimental measurements in table 5 and both can be seen to agree to within at least 90% accuracy.
Table 5. Experimental and predicted crater dimensions.

| Projectile Material | \( \rho / \text{g/cm}^3 \) | \( v / \text{km/s} \) | \( \frac{p_{\exp}}{d_p} \) | \( \frac{p_{\text{pred}}}{d_p} \) | \( \frac{d_{c,\exp}}{d_p} \) | \( \frac{d_{c,\text{pred}}}{d_p} \) |
|---------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Cellulose acetate   | 1.273           | 3.015           | 1.72            | 1.76            | 5.27            | 4.74            |
| Cellulose acetate   | 1.273           | 5.928           | 2.53            | 2.78            | 7.07            | 7.54            |
| Polypropylene       | 0.881           | 3.204           | 1.64            | 1.74            | 4.26            | 4.36            |
| Polypropylene       | 0.881           | 1.415           | 0.98            | 0.99            | 2.45            | 2.43            |

7. Summary and conclusions

In summary, this study into the hypervelocity impact of projectiles into graphite targets has:

- Developed power laws for the correlation of crater dimensions with the impact velocity for a wide range of projectiles.
- Confirmed that projectiles up to the density of alumina (3.69g/cm\(^3\)) obey the 2/3 power law approximately. Investigation of the data from the steel impacts also hint at an obedience of the 2/3 power law at impact velocities greater than 2.5km/s\(^{-1}\).
- Confirmed that the craters were roughly conical in shape with a height and diameter equalling the crater depth \( p \) and diameter \( d_c \).
- Calculated the density variation of the velocity exponent and proportionality constant and tested this against experiments with success.

The hypervelocity impact data has provided a valuable insight into the laws of cratering in graphite targets. However, the study will benefit from the inclusion of more data in the fits from normal impacts of steel at velocities above 2.5km/s\(^{-1}\) to determine the onset of the hypervelocity regime.

Acknowledgements

The author would like to acknowledge the valuable help received from Nigel Thomas during the compilation of this report. This work was funded by AWE Plc, Aldermaston, Reading, Berkshire RG7 4PR.

Appendix A. Experimental data

The experimental data obtained from the impact experiments are presented in tables A1-A6. The notation below has been applied for the parameters.

Table A1. Notation for data tables.

| Symbol | Description                      |
|--------|----------------------------------|
| \( v \) | Impact velocity of projectile    |
| \( t \) | Thickness of the graphite block  |
| \( d_p \) | Diameter of spherical projectile |
| \( p \) | Average penetration depth of the crater |
| \( d_c \) | Average diameter of the crater (normal impact) |
| \( V_c \) | Crater volume |

7
Table A2. Experimental data for normal impacts of HDPE projectiles into graphite.

| $v$/kms$^{-1}$ | $t$/mm | $d_p$/mm | $P$/mm | $d_c$/mm | $V_c$/mm$^3$ |
|----------------|---------|-----------|--------|----------|-------------|
| 0.729          | 50      | 4.75      | 2.54   | 7.13     | 45.06       |
| 1.076          | 50      | 4.75      | 4.36   | 9.68     | 87.91       |
| 1.342          | 50      | 4.76      | 4.85   | 11.78    | 334.1       |
| 1.995          | 50      | 3.15      | 3.83   | 10.00    | 103.7       |
| 2.97           | 50      | 3.15      | 5.03   | 13.08    | 237.9       |
| 2.97           | 50      | 3.15      | 5.17   | 13.03    | 249.2       |
| 3.02           | 100     | 3.15      | 4.76   | 14.25    | 334.1       |
| 3.09           | 100     | 3.15      | 4.75   | 14.73    | 294         |
| 4.01           | 50      | 3.15      | 5.49   | 14.6     | 389.2       |
| 4.44           | 50      | 3.15      | 6.32   | 17.68    | 531.9       |
| 4.88           | 100     | 3.15      | 5.97   | 19.75    | 554         |
| 4.92           | 100     | 3.15      | 6.67   | 20.69    | 795.7       |
| 5.94           | 50      | 3.15      | 6.85   | 21.38    | 818.9       |
| 6.21           | 50      | 3.15      | 7.27   | 20.88    | 889.2       |

Table A3. Experimental data for normal impacts of soda glass projectiles into graphite.

| $v$/kms$^{-1}$ | $t$/mm | $d_p$/mm | $P$/mm | $d_c$/mm | $V_c$/mm$^3$ |
|----------------|---------|-----------|--------|----------|-------------|
| 1.46           | 50      | 4         | 4.74   | 13.28    | 509.8       |
| 3.03           | 100     | 3.95      | 6.65   | 25.49    | 1199        |
| 4.89           | 100     | 3.95      | 7.99   | 25.57    | 1626        |
| 5.44           | 50      | 2         | 5.98   | 18.74    | 268.6       |
| 6.01           | 100     | 2         | 5.96   | 16.55    | 499.1       |
| 0.794          | 50      | 3.95      | 3.6    | 12.1     | 167.8       |
| 1.048          | 50      | 3.95      | 3.3    | 11.35    | 137.9       |
| 3.963          | 50      | 3.95      | 10.8   | 29.25    | 2382        |

Table A4. Experimental data for normal impacts of aluminium projectiles into graphite.

| $v$/kms$^{-1}$ | $t$/mm | $d_p$/mm | $P$/mm | $d_c$/mm | $V_c$/mm$^3$ |
|----------------|---------|-----------|--------|----------|-------------|
| 1.25           | 50      | 3.95      | 4.66   | 13.78    | 332.4       |
| 2.04           | 100     | 2.05      | 3.2    | 9.3      | 80.65       |
| 2.04           | 100     | 2.05      | 3.2    | 11.06    | 102.2       |
| 2.7            | 50      | 3.95      | 7.93   | 30.38    | 2248        |
| 3.45           | 50      | 2.05      | 4.5    | 15.48    | 253.2       |
| 3.68           | 100     | 2.05      | 4.86   | 15.3     | 329.1       |
| 5.88           | 50      | 2.05      | 5.88   | 21.67    | 814.4       |
| 0.78           | 50      | 3.94      | 3.75   | 10.61    | 112.2       |
| 1.03           | 50      | 3.95      | 4.47   | 12.25    | 184.5       |
| 3.968          | 50      | 2.04      | 5.83   | 14.8     | 335.4       |
| 4.391          | 50      | 2.05      | 5.7    | 15.2     | 370.9       |
| 5.076          | 50      | 2.05      | 6      | 16.95    | 538.7       |
Table A5. Experimental data for normal impacts of alumina projectiles into graphite.

| $v$/kms$^{-1}$ | $t$/mm | $d_p$/mm | $p$/mm | $d_v$/mm | $V_c$/mm$^3$ |
|---------------|--------|-----------|-------|---------|-------------|
| 0.797         | 50     | 4         | 4.1   | 11.75   | 164.1       |
| 0.994         | 50     | 4         | 6     | 16.15   | 366.3       |
| 1.27          | 50     | 4         | 3.7   | 12.38   | 166.9       |
| 2.02          | 50     | 4         | 4.93  | 18.58   | 496.2       |
| 2.35          | 50     | 3         | 4.45  | 16.16   | 285.6       |
| 2.82          | 50     | 4         | 7.65  | 23.8    | 1003        |
| 3             | 50     | 2         | 3.18  | 11.07   | 97.32       |
| 3.02          | 100    | 4         | 8.2   | 26.73   | 1404        |
| 4.1           | 100    | 4         | 10.94 | 37.71   | 4321        |
| 4.13          | 100    | 4         | 11.63 | 39.49   | 4442        |
| 4.31          | 50     | 3         | 8.55  | 29.14   | 1852        |
| 4.54          | 50     | 4         | 11.95 | 36.5    | 4729        |
| 5.03          | 100    | 2         | 6.07  | 18.97   | 566.7       |
| 5.89          | 50     | 2         | 5.64  | 19.67   | 752.5       |
| 5.92          | 50     | 2         | 5.61  | 19.58   | 746.7       |
| 6.24          | 50     | 2         | 6.78  | 23.34   | 1019        |

Table A6. Experimental data for normal impacts of steel projectiles into graphite.

| $v$/kms$^{-1}$ | $t$/mm | $d_p$/mm | $p$/mm | $d_v$/mm | $V_c$/mm$^3$ |
|---------------|--------|-----------|-------|---------|-------------|
| 0.774         | 50     | 3.99      | 3.2   | 9.69    | 90.5        |
| 0.964         | 50     | 3.99      | 4.4   | 11.55   | 130.4       |
| 1.3           | 50     | 3         | 2.65  | 8.98    | 54.32       |
| 1.65          | 50     | 3         | 3.75  | 11.18   | 96.24       |
| 2.06          | 50     | 4         | 6.99  | 18.87   | 589.5       |
| 2.515         | 50     | 3.01      | 7     | 20.6    | 750.6       |
| 3.394         | 50     | 3         | 8.9   | 29.45   | 1850        |
| 4.032         | 50     | 4         | 7.21  | 20.77   | 830.2       |
| 4.51          | 50     | 3         | 11.25 | 35.43   | 4361        |
| 5.54          | 50     | 2         | 7.47  | 27.17   | 1695        |
| 6.15          | 50     | 2         | 18.7  | 27.5    | 1924        |

Appendix B. Low velocity impacts

Since alumina and steel are much denser than graphite, the approach to the hypervelocity regime is expected to be slower than less dense materials which might explain why the velocity exponents obtained for these projectiles fall out of the range $1/3 < \psi_n < 2/3$ predicted by momentum and energy scaling. To understand this further, the velocity dependence of craters formed by low velocity impacts will be investigated.

At low velocities, the equation of motion of the indenting sphere of mass $m_p$ and diameter $d_p$ is given empirically by,

$$m_p \frac{d^2 p}{dt^2} = m_p v \frac{dv}{dp} = -Yp \frac{d^2}{4} \approx -Ypd_p$$

(B.1)

where $t$ is the time, $v \approx v$ is the velocity, and $Y$ is the mean pressure of resistance of the target to penetration. We have assumed that $d_v^2 \approx 4pd_p$, which is true when $p \ll d_p$ is small. Solving equation (10), the following correlation for the depth $p$ with impact velocity $v$ is obtained,
\[ \frac{p}{d_p} \propto v, \]  

which suggests a velocity exponent of 1 for low velocity impacts. Thus, the large velocity exponents obtained from the steel projectile correlations might be due to the influence of low velocity data in the correlation fits.

**References**

[1] Shanbing Y, Gengchen S and Qingming T 1994 *Int. J. Impact Eng* **15** 1 67-77
[2] Cour-Palais B G 1987 *Int. J. Impact Eng* **5** 221-237
[3] Taylor E, Kay L and Shrine N 1997 *Adv. Space Res.* **20** 8 1437-1440
[4] Hermann W and Wilbeck J S 1987 *Int. J. Impact Eng* **5** 307-322
[5] Holsapple K 1987 *Int. J. Impact Eng* **5** 343-355
[6] Burchell M J and Grey I D S 2001 *Material Science and Engineering* **A303** 1340141