23RD INTERNATIONAL SYMPOSIUM ON BALLISTICS
TARRAGONA, SPAIN 16-20 APRIL 2007

REAL TIME-RESOLVED FLASH X-RAY CINEMATOGRAPHIC INVESTIGATION OF INTERFACE DEFEAT AND NUMERICAL SIMULATION VALIDATION

K. Thoma, P. Helberg and E. Strassburger

Fraunhofer-Institute for High-Speed Dynamics, Ernst-Mach-Institut (EMI), Eckerstr. 4, 79104 Freiburg, Germany, KlausThoma@emi.fraunhofer.de

For the time resolved investigation of projectile penetration into a specific target usually a series of experiments has to be conducted, since only few radiographs can be recorded in one test. The combination of the radiographs from the different tests yields pseudo cinematography of the process under investigation. An obvious drawback of this approach is the reproducibility of the experimental conditions, which is difficult to achieve in a series of tests. Therefore, visualization of the penetration process with a high time resolution requires a large number of tests. A novel measurement method provides up to eight flash radiographs from one experiment. A multi-anode flash x-ray tube is utilized and the radiation transmitted through the target is detected with a fluorescent screen. The fluorescent screen converts the radiograph into an image in the visible wavelength range, which is photographed by means of an intensified digital high-speed camera. The new imaging technique has been applied to the investigation of the dwell-penetration transition with steel core projectiles impacting ceramic/aluminum targets.

INTRODUCTION

The penetration of a high-speed projectile into a target material can only be visualized by means of flash-radiography. For this purpose, usually several flash x-ray tubes are arranged around the target and the radiographs are recorded on x-ray film. A simple method is the multi-exposure of one film or alternative detector. Figure 1 gives an example for a triple exposure which was used to observe the acceleration of two plates by high explosive. This method can only be applied when the number of objects is limited and the objects can easily be distinguished. The upper limit of the number of projections is set by the saturation of the detector due to multi-exposures.

A different approach is realized by a set of geometrically separated channels and an array of slits, in order to prevent multi-exposure, as illustrated in Figure 2. Due to geometrical boundary conditions with respect to the target set-up and safe distances the number of channels is usually limited. Therefore, both methods allow only pseudo cinematography of the process to be observed, since the radiographs of several experiments have to be combined in order to get a time-resolved image of the process. However, this requires a high reproducibility of the experiments, which can be difficult to achieve in a series of tests. The lower the reproducibility, the higher is the number of tests needed. For this reason it is desirable to have flash x-ray system that provides a high-number of radiographs in just one experiment. Such a system has been developed at EMI and is presented in the following. The new imaging technique has been applied to the investigation of the dwell-penetration transition with steel core projectiles impacting ceramic/aluminum targets.

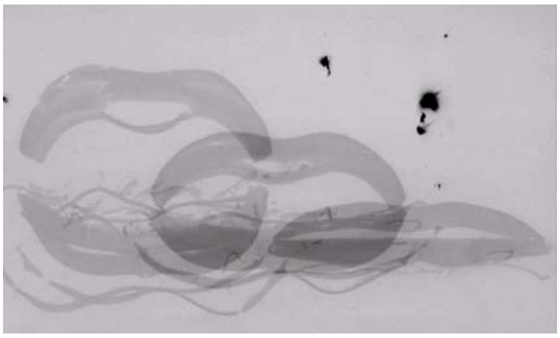

Fig. 1: Acceleration of plates by high-explosive; triple exposure of storage phosphor image plates; overlap of projections

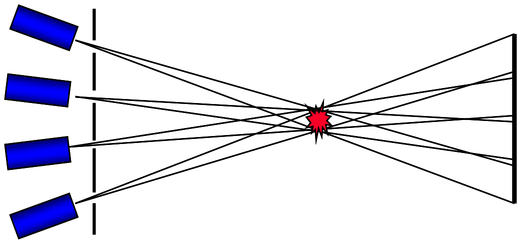

Fig.2: Separated X-ray tubes: The process is x-rayed from different directions without overlap of the projections

CINEMATOGRAPHY MEASUREMENT SET-UP

A schematic of the measurement set-up for flash X-ray cinematography is shown in Figure 3. Instead of several separate X-ray tubes one multi-anode tube is utilized. In the multi-anode tube eight anodes are arranged on a circle of ≈ 12 cm diameter. This configuration causes only a relatively small parallax for the projections from the different anodes. The process under observation can be X-rayed at eight different times. The radiation transmitted through the target is then detected on a fluorescent screen. The fluorescent screen converts the radiograph into an image in the visible wavelength range, which is photographed by means of an intensified digital high-speed camera. The maximum frame rate that can be achieved with such a system depends on the decay time of the fluorescent screen, the time characteristics of the intensifier and the camera. The brightness of the fluorescent screen is related to the decay time. The slower the decay of the fluorescent image, the higher is the intensity. Thus, the decay constant of the fluorescent screen determines the range of applications with respect to the frame rate. Considering the brightness, the decay constant determines which intensifier/camera system has to be used and which level of amplification is required. Several different set-ups have been realized for different applications, which have been described by Helberg [1, 2, 3].

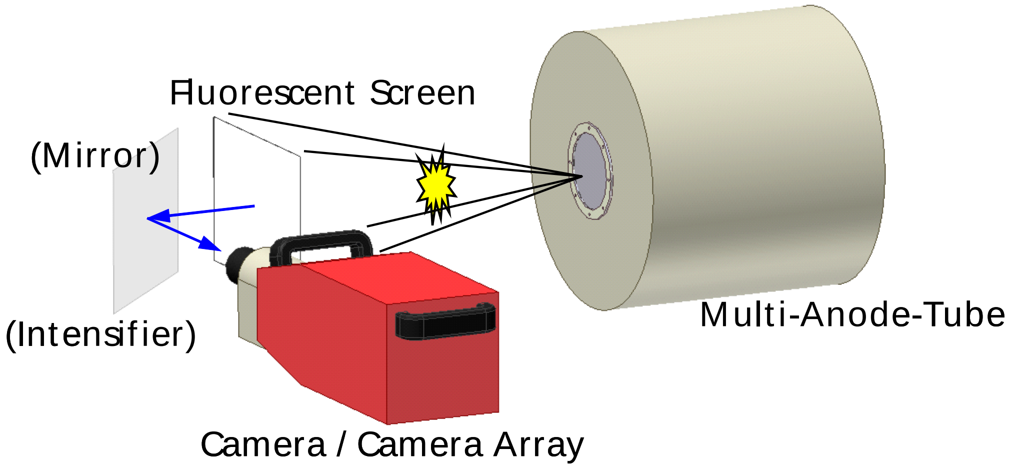

Figure 3: Schematic of typical flash X-ray cinematography set-up

Due to the sensitivity of the high-speed cameras external electronic intensifying is necessary when fast decaying screens are employed. In the tests reported here a device with a second-generation intensifier was used, which is based on a multi-channel plate. The maximum multiplication factor for electrons for this system is 100 000. The spectral sensitivity of the photo cathode ranges from 180 to 850 nm and the decay time of the phosphor is less than 10 μs. Frame rates of 100 000 fps have been achieved with a fast decaying fluorescent screen. The effective spatial resolution of the 100 000 fps detector systems is about 320 x 256 pixels, although the CCDs of the camera have 1280 x 1024 pixels. The degradation of the resolution is caused by the intensifying units. Another important characteristic of an imaging system is its dynamic signal range. The dynamic range is the ratio of the maximum value of detectable signal to the minimum. The dynamic range of the 100 000 fps system is only about 10. However, this is sufficient for many applications as the examples in the following demonstrate.

APPLICATION TO THE DWELL PHENOMEMON

The new X-ray cinematography technique was applied in order to study the dwell-penetration transition with small caliber AP projectiles impacting ceramic/aluminum targets. The phenomenon of dwell with small caliber AP projectiles at impact velocities below 1000 m/s was already observed during the pioneering studies of Wilkins [4], who examined the interaction of 7.62 mm AP projectiles and surrogate steel penetrators with thin ceramic/aluminum targets. Using the classic flash X-ray technique Wilkins observed, that the steel projectiles did nearly not penetrate the ceramics during the first ≈ 20 μs after impact. During this phase the projectiles were eroded to about half of their initial length. The phenomenon, that a projectile does not (or only very little) penetrate a target over a perod of time is designated dwell. However, the term dwell was established during the studies of the interaction of long-rod penetrators with ceramic targets of Hauver [5] and e.g. Lundberg [6]. This phenomenon was observed with long-rod penetrators when shock attenuating layers were in front of the ceramic and the ceramic was pre-stressed by a well fitting confinement. In contrast to the case of KE penetrators dwell can be observed with small caliber AP projectiles with no shock attenuating front layers and no confinement of the ceramic.

The classic flash X-ray technique was refined by Gooch et al. [7] and applied in order to the study the interaction of 7.62 mm APM2 projectiles and tungsten carbide core projectiles with boron carbide/ aluminum targets. Numerical analyses of experiments with APM2 projectiles by Anderson et al. [8] and steel projectiles by Holmquist [9] have demonstrated, that a big part of the kinetic energy of the projectile is reduced during the dwell phase. Thus, the duration of the dwell phase is very important for the total ballistic resistance of a ceramic faced target. In order to improve the protective strength of ceramic composite targets it is important to know the relations between the duration of dwell, the type and thickness of the ceramic material and the influence of the backing. Time resolved flash-Xray cinematography is the appropriate means for studying the influence of the different parameters on dwell and the ballistic resistance.

EXPERIMENTAL RESULTS

Two series of tests have been conducted with boron carbide/ aluminum targets. The projectiles utilized were of the type 7.62 mm x 51 AP FN with a steel core of 3.7 g mass and a total projectile mass of 9.5 gram. The impact velocity was 845 m/s.

In the first series the targets consisted of 9 mm B_4C and aluminum (AlCuMg1) plates of 6 mm thickness. Figure 4 shows a series of eight photographs, resulting from two tests where four photographs could be taken at a frame rate of 10^5 fps, respectively. The photographs in Figure 4 show, that the projectile penetration was very small up to ≈ 20 μs. After this phase of dwell, the projectile penetrated the target at a higher velocity.

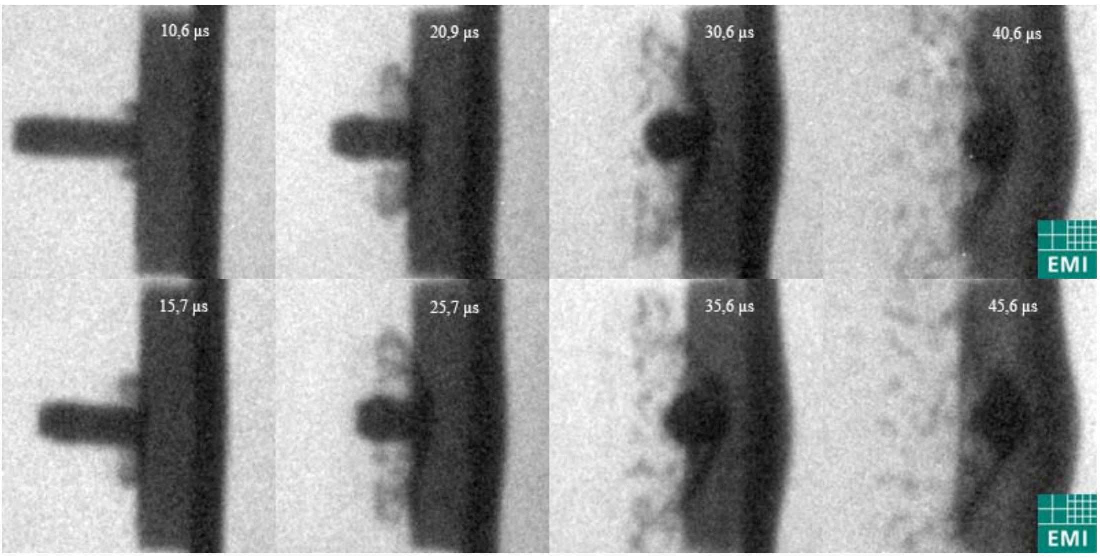

Figure 4: Series of 8 flash X-ray photographs from two tests at a frame rate of 10^5 fps: Impact of 7.62 mm AP projectile on 9 mm B_4C/ 6 mm Al target at 845 m/s

The second series of tests was conducted with targets consisting of 10 mm B_4C and 10 mm aluminum backing. Three tests were performed with equal targets and impact conditions at a frame rate of 10^5 fps. Eight flash X-ray photographs were taken in each test. The times of the X-ray flashes were shifted by 3 µs from test to test, i.e. the flash times in the first test were 0 µs, 10 µs, 20 µs, 30 µs…, 3 µs, 13 µs, 23 µs ... in the second test and 6 µs, 16 µs, 26 µs etc. in the third test. Figure 5 shows a selection of 12 photographs from this test series. In this case the projectile was stopped. The analysis of the projectile movement, deformation and penetration is being discussed in the following paragraphs.

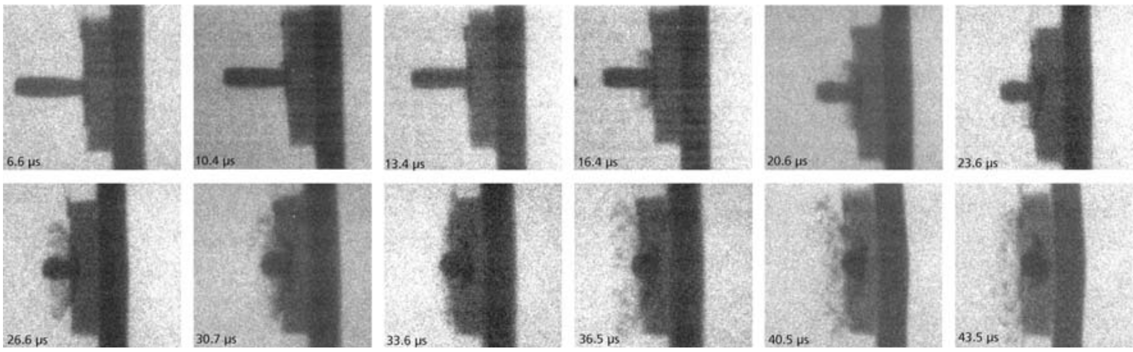

Figure 5: Selection of twelve flash X-ray photographs showing the dwell-penetration transition from impact of a 7.62 mm AP projectile on 10 mm B_4C + 10 mm Al

NUMERICAL SIMULATION

The experiments with the 9 mm B_4C/ 6 mm Al targets have been simulated using a commercial hydro-code with a SPH solver. Only the steel core of the projectile and the ceramic have been represented in the model. The influence of the projectile jacket was regarded as negligible. The effect of the aluminum backing has been approximated by boundary conditions. For the ceramic a polynomial equation of state (EOS) was chosen. The strength and failure of the ceramic were simulated using the Johnson-Holmquist model. For the projectile's steel core a linear EOS and the Johnson-Cook strength model were applied. All models and material data were taken from literature, thus the results can be a first approximation, only. The positions of the materials determined from the simulation are depicted in Figure 6, superimposed to the flash X-ray photographs from the experiment. A good agreement can be observed with respect to the position of the steel core tip and the lateral extent of the eroded and ejected material. The difference in the positions of the projectile rear in the simulation and the experiment is due to the projectile jacket, which was not represented in the simulation.

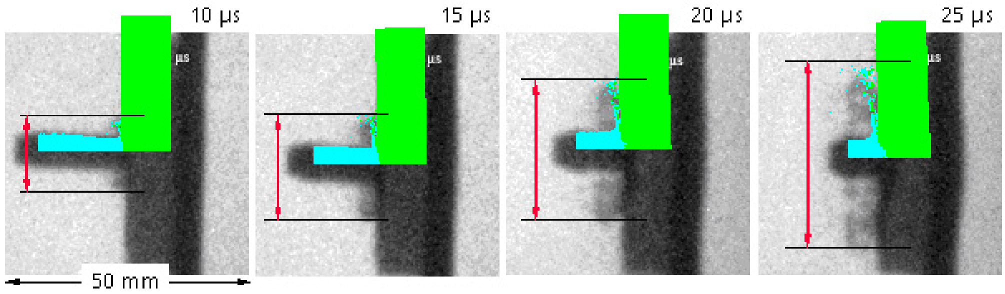

Figure 6: Superposition of simulation and experiment (9 mm B_4C/ 6 mm Al): positions of the materials (projectile and ceramic)

Figure 7 shows the simulation result with respect to damage in the ceramic, superimposed to the radiographs from the experiment.

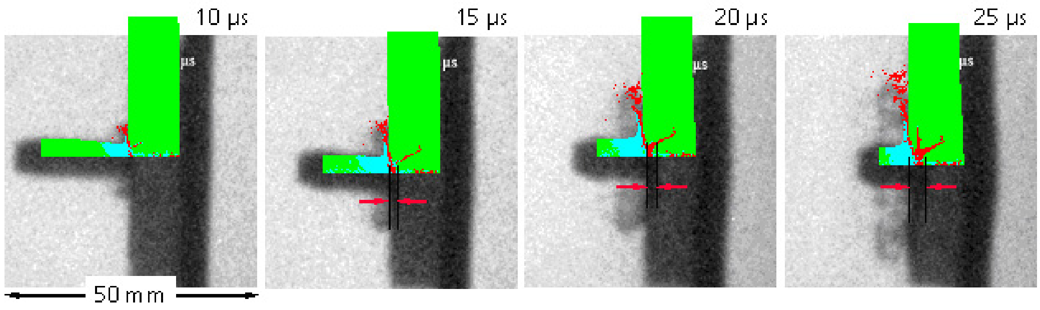

Figure 7: Superposition of simulation and experiment (9 mm B_4C/ 6 mm Al): ceramic damage

ANALYSIS AND DISCUSSION

Figure 8 shows the position-time histories of the projectile nose, center of gravity, tail and target rear surface for the target consisting of 10 mm B_4C with 10 mm aluminum backing (experiment see Fig. 5). The center of gravity position was calculated assuming a cylindrical shape of the eroded projectile. Up to 24 data points for each position measurement could be recorded from the three experiments.

Only very little penetration was observed up to about 15 µs after impact. Then the penetration velocity increases, accompanied by the beginning deformation of the backing, observed at the rear surface. The penetration velocity decreases after ≈ 50 µs. The velocity of the center of gravity of the projectile decreased continuously and the projectile was stopped.

An excellent set of data and analysis of the penetration of a 7.62 mm B_4C ceramic with 6.6 mm aluminum backing by an 7.62 mm APM2 projectile was provided by Anderson and Burkins et al. [11]. They used a classic 1 MeV flash X-ray system to obtain time-resolved images of penetration. The test series comprised of eleven tests which delivered 11 data points for the position-time histories (see Figure 9).

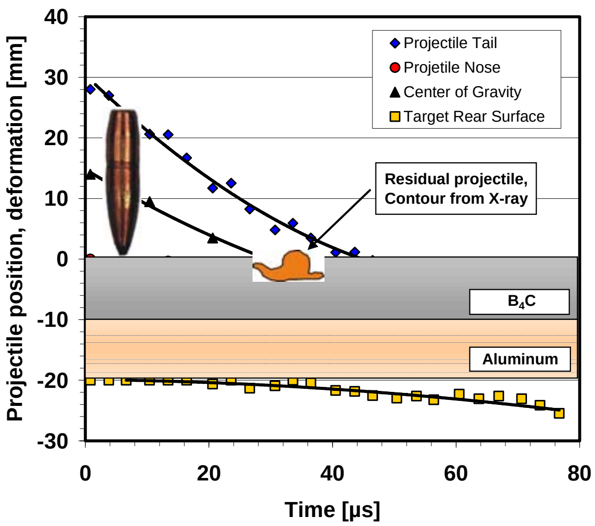

Figure 8: Position-time histories projectile nose, tail and rear target surface for 10 mm B_4C + 10 mm Al target

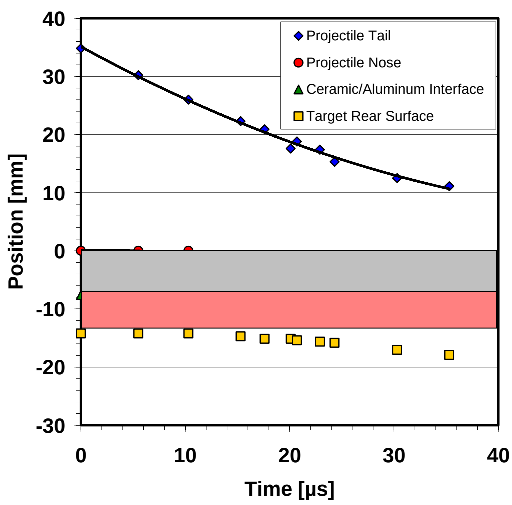

Figure 9: Position-time histories of APM2 penetration into 7.62 mm B_4C + 6.6 mm Al from Anderson and Burkins [11]

A very similar sequence of dwell and penetration can be recognized from the data in Figure 9. Erosion stopped after ≈ 25 µs, which is indicated by the equal slope of the curves for the projectile nose and tail. However, the slopes of the curves after ≈ 35 µs indicate that the target was perforated with a residual velocity of ≈ 300 m/s.

A comparison of the data sets obtained with the cinematography set-up and the classic flash X-ray set-up reveals a slightly higher scatter of the position data with the cinematography set-up, which can be attributed to the lower resolution of the images. However, all main features of the dwell and penetration phase were captured with three tests, compared to eleven tests with the classic method.

CONCLUSION

A novel flash X-ray imaging method has been developed at EMI, which provides up to eight flash radiographs in one experiment. A multi-anode flash X-ray tube is utilized with this method, and the fluorescent image of the transmitted radiation is photographed by means of a high-speed digital camera. The capability of the method has been demonstrated by applying it to the investigation of the dwell-penetration transition with steel core projectiles impacting B_4C/aluminum targets. All main features of the dwell and penetration phase were captured with only three tests.

REFERENCES

[1] P. Helberg, K. Michael : High-Speed Flash X-Ray Computed Tomo-Cinematography; Proc. 22nd Int. Symposium on Ballistics, DEStech Publications, Lancaster, Pennsylvania, 2005

[2] P. Helberg, S. Nau, K. Thoma : High-Speed Flash X-Ray Cinematography. In: ASNT 15th Annual Research Symposium 2006 Paper Summaries CD-ROM. Orlando : The American Society for Nondestructive Testing, 2006

[3] P. Helberg, S. Nau, K. Thoma : High-Speed Flash X-Ray Cinematography; 9th European Conference for Nondestructive Testing. Berlin, September 2006

[4] M.L. Wilkins: Third Progress Report on Light Armor Program; UCRL-50460, Lawrence Livermore Laboratory, Livermore, CA, USA, 1968

[5] G.E. Hauver et al.: Interface Defeat of Long-Rod Projectiles by Ceramic Armor, U.S. Army Research Laboratory Report, ARL-TR-3590 (2005)

[6] P. Lundberg, R. Renström, B. Lundberg: Impact of metallic projectiles on ceramic targets: transition between interface defeat and penetration; Int. J. of Impact Engineering 24 (2000) 259-275

[7] W.A. Gooch, M.S. Burkins, P. Kingman, G. Hauver, P. Netherwood, R. Benck: Dynamic X-ray imaging of 7.62-mm APM2 projectiles penetrating boron carbide, Proc. 18th Int. Symp. on Ballistics, Vol. 2, pp. 901-908, Technomic Publishing Company Inc., Lancaster, PA, 1999

[8] C.E. Anderson Jr., J.D. Walker: Ceramic dwell and defeat of the 0.30-Cal AP projectile, Proc. 15th U.S. Army Symp. On Solid Mech., pp. 17-28, Battelle Press, Columbus, OH, 2000

[9] T.J. Holmquist, G.R. Johnson: A detailed computational analysis of interface defeat, dwell and penetration for a variety of ceramic targets; Proc. 20th Int. Symp. on Ballistics, Vol. 2, pp. 746-753, DEStech Publications, Lancaster, PA, 2002

[10] Century Dynamics Autodyn v6.0.01, Materials Data base (2005)

[11] C.E. Anderson, Jr., M.S. Burkins, J.D. Walker, W.A. Gooch: Time-Resolved Penetration of B_4C Tiles by the APM2 Bullet, Computer Modeling in Engineering & Science, Vol.8, No. 2, pp. 91-104, 2005