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Expansion of Metallic Cylinders under Explosive Loading

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ABSTRACT

The behaviour of expanding metallic cylinders under explosive loading was studied. Using ultra high speed photography, the expansion characteristics of aluminium and copper metallic cylinders have been evaluated with different *c/m* ratio, and by changing the nature of high explosive. The results obtained are comparable to those predicted by the Gurney's energy and momentum balance equations. A cylinder test has been established for comparative evaluation of the ability of high explosives to accelerate the metal. The relative energies delivered to the metal by octol, TNT, PEK-1, baratol and composition B are calculated. The results are in close agreement with those calculated by Kury *et al.*

1. INTRODUCTION

The motion of the metals driven by detonating explosives is of great importance for designing suitable explosive metal systems, for both armament and civil applications. The ability of an explosive to impart energy to the metal has been referred to as 'brisance'. Many complex computer codes, based on different equations of the state for detonation products, have been worked out to predict the motion of the metal driven under different geometrical conditions, such as plane, spherical and cylindrical configuration. However, the most simple and practical method for estimating the velocity imparted to metal by an explosive is the Gurney Method, based on energy and momentum balances. This method was first devised by RW Gurney[1] in 1943 to compute the velocity of fragments from artillery shells. Inspite of a number of simplifying assumptions, the calculations done by this method often show an excellent correlation with the experimental data, and hence it remains most widely used method especially for calculating the final velocity imparted to the metal elements. In earlier studies at TBRL suitable experimental methods were successfully developed for projecting metallic plates at extremely high velocities with the help of explosives and also for monitoring the motion of these plates[2]. The present study mainly deals with the loading of metallic tubes with different explosives and recording their motion using ultra high speed cameras. Considerable data has been generated, both by varying the wall thickness of the metallic tubes and by changing the explosive composition. A good comparison has been established between the experimental values and those predicted by Gurney's equations.

These results have been used in development of explosive-driven high current generators[3] based on the principle of magnetic flux compression by expanding metallic cylinders. Further, since the experimental configuration used in this study was similar to that used by various authors in 'standard copper cylinder test' for comparative evaluation of the ability of explosives to accelerate metals, the above results could successfully be used for precise relative ordering of a number of explosive compositions for their applications in explosive metal systems.

2. THEORY

The hydrodynamic theory of detonation combined with the assumption that the detonation products follow the constant equation of state ($P = A\rho^{\gamma}$) gives the

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following set of relations among various parameters:

$$P = \rho D^2 / (\gamma + 1) \quad (1)$$

$$U = D / (\gamma + 1) \quad (2)$$

$$C = \gamma D / (\gamma + 1) \quad (3)$$

$$Q = D^2 / 2 (\gamma - 1) \quad (4)$$

where P is the detonation pressure at C-J plane, U the velocity with which the material flows behind the detonation front, C is the sound velocity, D the detonation velocity and Q is the total chemical energy liberated during detonation.

Gurney[1] assumed that out of the total chemical energy released, specific energy E (kcal/g), having a characteristic value for each explosive, is converted from chemical energy in the initial state to kinetic energy in the final state. This value of Gurney energy and heat of detonation are experimentally measured and are available for most of the explosives. It has been observed for most of the explosives that the ratio E/Q lies between 0.61 and 0.76. In the absence of suitable data for calculation of E, one can assume

$$E = 0.7\, Q \quad (5)$$

This kinetic energy is partitioned between the metal and the detonation products. Gurney coupled these assumptions with the law of conservation of energy and momentum, and derived simple relations for estimating the final velocity of the moving particle in different geometrical configurations such as plane, spherical and cylindrical systems. Gurney's relation for velocity[4] of an exploding metallic cylinder is

$$V = \sqrt{(2E)}.[m/c + 1/2]^{-1/2} \quad (6)$$

where V is the terminal velocity imparted to the metal cylinder, m is the metal mass per unit length, c is the explosive mass per unit length and E is the kinetic energy per unit explosive mass also called the Gurney energy. The quantity $2E$ which occurs in the above expression has the unit of velocity and is known as the Gurney characteristic velocity for a given explosive. It is clear from Eqn (6) that for a given explosive, the final metal velocity is a function of only charge-to-metal mass ratio. The final velocity imparted to the metal is a sensitive function of the gas constant γ, in the early stages of expansion and comparatively less sensitive to γ in the later stages of expansion. When the solid explosive is converted into a gas after the passage of detonation wave, the gases have initially the same density as that of the original explosive. The behaviour of the detonation gases is similar to that of a liquid under high pressure. A small initial increase in volume is accompanied by large decrease in pressure, which is consistent with a value of $\gamma > 3$. Hence, a large acceleration is expected in the early stages of the expansion. After the volume of gaseous products has increased a little, the behaviour of the detonation gases will be nearer to that of the normal gas with a value of $\gamma \simeq 1.4$, which suggests a small acceleration in the later stage of expansion.

3. DIRECTION OF METAL PROJECTION

When the detonation wave encounters the metal in a normal angle of incidence, the metal moves in a direction normal to the surface, *i.e.*, in the direction of the detonation wave. However, this is not true when the metal is driven by 'grazing detonation' which propagates parallel to the metal surface. The direction of the metal driven by the grazing detonation is such that it bisects the angle between the normal to the original and the deflected metal wall. If θ is the angle of deflection of the cylinder as detonation wave progresses along the charge axis, the angle of metal projection $\theta/2$ is given by

$$\theta/2 = \mathrm{Sin}^{-1} (V/2D) \quad (7)$$

With the streak camera slit set perpendicular to the rest plane of the charge axis, an apparent velocity V_a measured is given by the relation

$$V_a = D \tan \theta \quad (8)$$

Eliminating D from the above two equations, the relation between the apparent velocity measured V_a and the actual velocity V can be written as

$$V/V_a = \cos \theta / \cos (\theta/2) \quad (9)$$

The apparent velocity measured is only 4 to 7 per cent higher than the actual velocity.

4. EXPERIMENTAL TECHNIQUES

It is clear from the foregoing considerations that the experimental measure of the velocity of residual expansion of a metallic cylinder loaded with the explosive, along with the knowledge of the detonation velocity of an explosive enables to compute the motion of the cylinder, both in magnitude and the direction. The ultra high speed camera was found to be very useful tool for most accurate monitoring of the radial motion of an exploding cylinder. The complete layout is shown

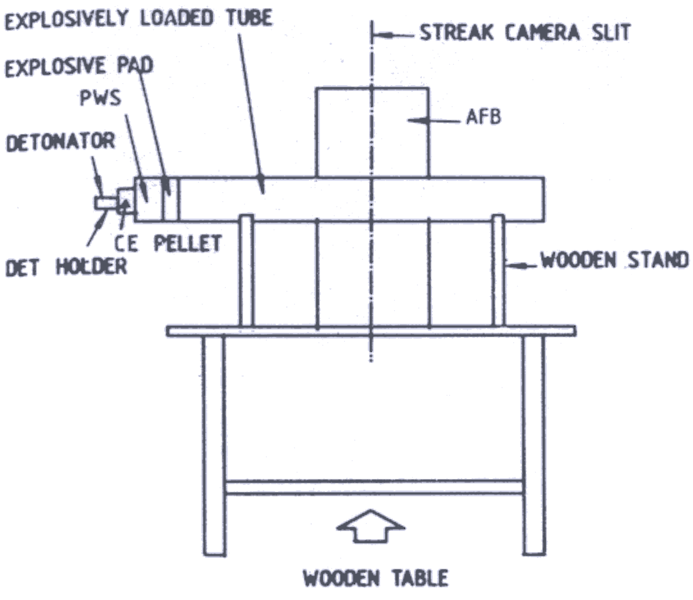

Figure 1. Experimental set-up.

in Fig. 1. A precision machined aluminium or copper cylinder of internal diameter 52 mm, length 200 mm and having wall thickness of 1 to 5 mm filled with high explosive, was placed horizontally on a wooden stand in front of the objective lens of the streak camera. The slit of the camera was adjusted perpendicular to the cylinder axis and was set at a distance of 120 mm from the initiating surface of the explosive. From the theoretical as well as the experimental considerations, it was essential to initiate explosive with a plane detonation wave generator, as shown in Fig. 1. An argon flash bomb was used as a source of back lighting so as to record the motion of the cylinder as a shadowgraph. Both the explosively loaded cylinder and argon flash bomb were fired by means of electronic detonators and their timings were synchronised through the delay generators incorporated in the control systems of the camera. A typical streak camera photographic record

EXPANSION OF ALUMINIUM TUBE

Writing Rate = 1.67 mm/μs

EXPANSION OF COPPER TUBE

Writing Rate = 1.67 mm/μs

Figure 2. Streak camera records of TNT loaded *Al* and *Cu* cylinders of internal diameter 52 mm and wall thickness 4 mm

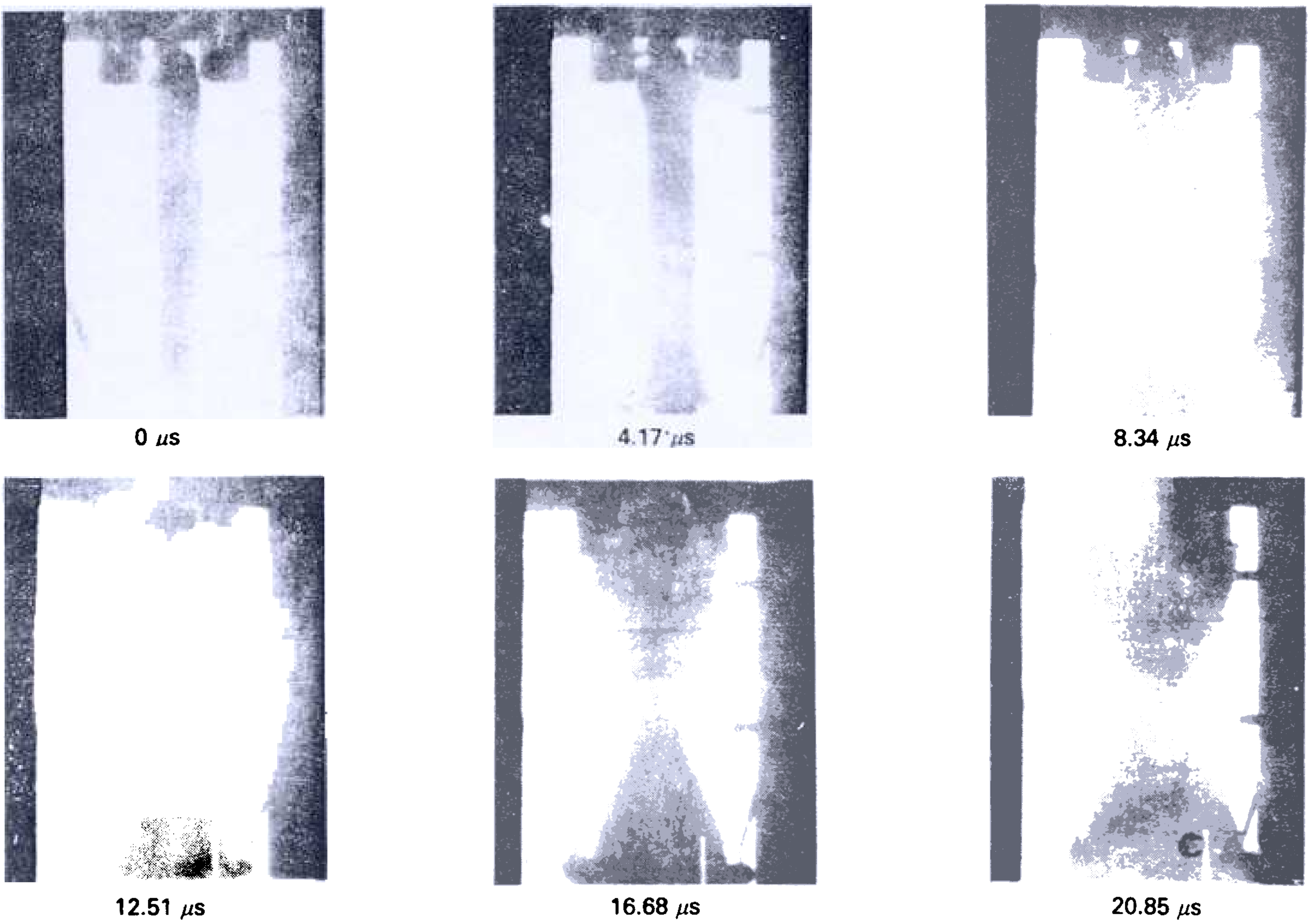

Figure 3. Framing camera record of RDX/TNT loaded *Al* cylinder of internal diameter 5 mm and wall thickness 1 mm.

taken on Beckman and Whitley Model 770 (nanoseconds camera) at a writing rate of 1.67 mm/s is shown in Fig. 2. The experiment was repeated several times by varying the wall thickness of the aluminium and copper cylinders and for different explosive compositions. In separate experiments, the detonation velocities of the explosives used were also measured.

Up to this stage it was assumed that either the velocity of detonation of the explosive used was known or it was measured from separate set of experiments. The knowledge of velocity of detonation was essential to compute the angle of deflection of the metallic wall. Hence, in the absence of such knowledge, it may not be advisable to use streak camera as it would not give sufficient information for monitoring the motion. However, in such a situation the answer for replacing streak camera by a suitable ultra high speed framing camera was found, which recorded motion in space coordinates, thereby making it possible to compute the angle of deflection without measuring the velocity of detonation. The experimental set-up was similar to that described above and a typical set of framing pictures taken by a Beckman and Whitley Model 189 (a framing camera at a framing rate of 2,40,000 frames) is shown in Fig. 3. In this experiment the explosive was initiated from both the ends simultaneously.

5. RESULTS AND DISCUSSION

In Fig. 4 the experimental radius-time curves for aluminium cylinder loaded with composition B are plotted. Wall thickness of the metal cylinder was the only variable with internal diameter of the tube fixed at 52 mm. It is clear from the curves that for a large *c/m* ratio the acceleration phase is quickly over and the cylinder expands with more or less a constant velocity with small accelerations whereas, for a small *c/m* ratio

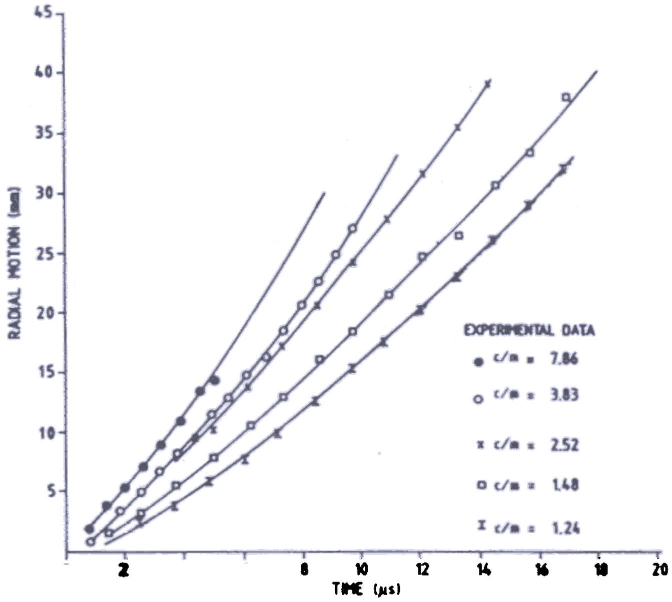

Figure 4. Expansion characteristics of *Al*, RDX/TNT loading.

Table 1. Expansion characteristics of aluminium cylinders

c/m	Wall thickness (mm)	Deflection angle θ(°)	Apparent velocity V_a (mm/µs)	Corrected velocity V (mm/µs)	Velocity Gurney's relation (mm/µs)
Octol					
1.091	7	15.41	2.26	2.2	2.35
1.293	6	15.86	2.33	2.26	2.48
1.584	5	16.06	2.5	2.43	2.63
1.981	4	18.48	2.74	2.63	2.79
2.76	3	19.35	2.88	2.76	3.01
4.10	2	22.64	3.42	3.22	3.25
8.46	1	24.05	3.66	3.42	3.56
Composition B					
1.041	7	15.41	2.15	2.09	2.24
1.235	6	16.77	2.35	2.27	2.37
1.488	5	17.17	2.41	2.33	2.5
1.896	4	20.26	2.88	2.74	2.67
2.518	3	20.65	2.94	2.8	2.86
3.832	2	22.43	3.22	3.03	3.11
7.857	1	23.86	3.45	3.22	3.42
TNT					
0.96		15.14	1.84	1.79	1.91
1.157	6	15.84	1.93	1.87	2.03
1.597	5	18.0	2.21	2.13	2.23
1.743	4	18.16	2.23	2.15	2.29
2.364	3	19.81	2.45	2.34	2.47
3.554	2	20.63	2.56	2.43	2.68
7.53	1	23.1	2.9	2.72	2.98
PEK-1					
1.586		16.07	2.19	2.13	
2.138		17.18	2.35	2.27	
3.2	2	18.28	2.51	2.41	
6.733	1	20.56	2.85	2.71	
Baratol					
1.394		17.1	.6	.55	
2.033	5	18.5	1.74	.67	
2.582	4	19.68	1.86	78	
3.487	3	20.07	1.9	1.81	
11.06		24.78	2.4	2.23	

Inner diameter of cylinder = 52 mm

the tube takes few microseconds to attain the terminal velocity. In the early stages of expansion, streak camera records slightly high velocity due to spray[5] ejected from the metal surface on the arrival of the shock wave. Due to these reasons, the starting experimental points lie above the radius-time history. The theory suggests that the expansion of about two radii are required to approach the hydrodynamic terminal state. However, cylinders tend to burst after some finite expansion and the motion may be perturbed before the terminal state is obtained. The expansion velocity was measured at R/R_0 = 1.7 and the results are given in Table 1. Experimental values of the expansion velocity are slightly less than that estimated from Gurney relation (Eqn (6)). Possible sources of this discrepancy may lie in the effect of the compressibility of the metal or because the true terminal state has not been reached at R/R_0 = 1.7. Expansion velocity with different *c/m* ratio for different explosives are plotted in Fig. 5. The values of Gurney's characteristic velocity[4] taken for octol, composition B and TNT are 2.8, 2.71 and 2.37 respectively. Most of the experimental points in the study lie slightly below the Gurney's curves, though the difference is within 10 per cent. The results of expanding copper cylinder with different *c/m* ratio and with different explosives are given in Table 2.

For relative evaluation of the ability of explosives to impart energy to the metal a copper cylinder of internal diameter 52 mm and external diameter of 60 mm was exploded with five different high explosives, such as octol, composition B, TNT, PEK-1, and baratol. Radius-time history for different explosives is plotted

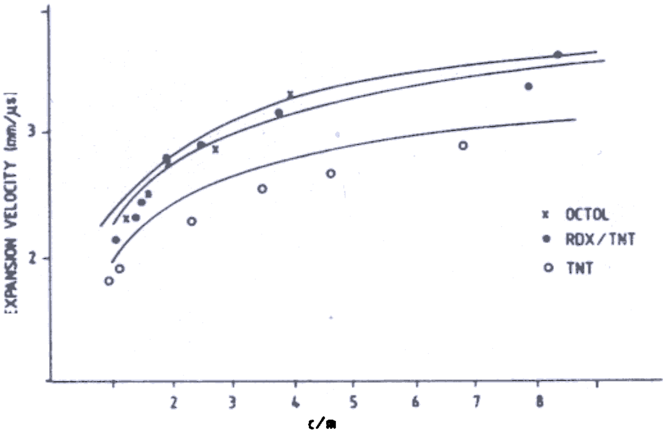

Figure 5. Gurney's curves vs experimental data.

Table 2. Expansion characteristics of copper cylinders

c/m	Wall thickness (mm)	Deflection angle θ(°)	Apparent velocity V_a (mm/μs)	Corrected velocity V (mm/μs)	Velocity Gurney's relation (mm/μs)
Octol					
0.61	4	13.04	1.9	1.861	1.91
0.821	3	14.82	2.17	2.12	2.23
1.265	2	15.8	2.32	2.26	2.46
2.5	1	18.92	2.81	2.69	2.95
Composition B					
0.447	5	11.31	1.56	1.54	1.64
0.57	4	12.5	1.73	1.7	1.8
0.776	3	13.83	1.92	1.88	2.03
1.172	2	16.43	2.3	2.23	2.33
2.31		19.16	2.71	2.6	2.81
TNT					
0.531	4	12.2	1.47	1.44	1.53
0.736	3	13.88	1.68	1.64	1.74
1.13	2	15.77	1.92	1.87	2.01
PEK-1					
0.51	4	11.16	1.5	1.48	
0.668	3	12.18	1.64	1.61	
1.033	2	13.96	1.89	1.85	
1.922		16.84	2.3	2.23	
Baratol					
0.81	4	13.62	1.24	1.23	
1.097	3	15.78	1.47	1.43	
1.7	2	17.9	1.68	1.62	
3.388	1	20.26	1.92	1.83	

Inner diameter of cylinder = 52 mm

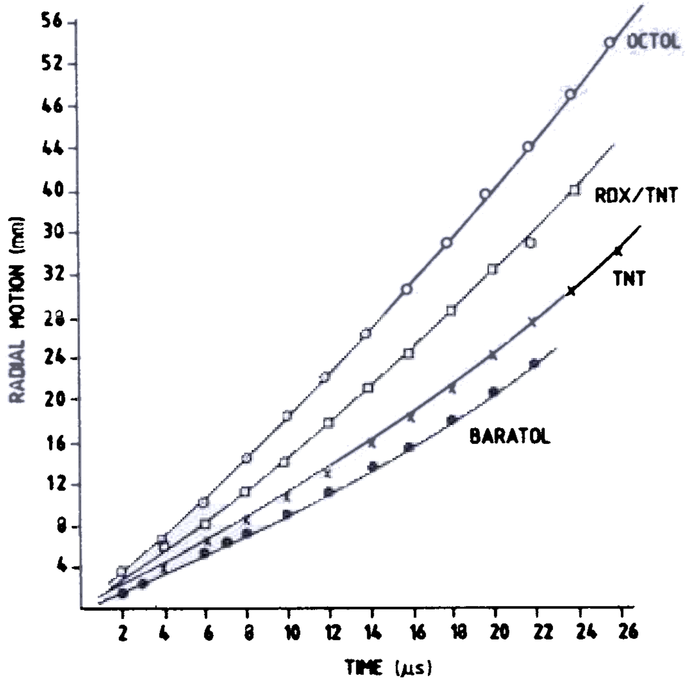

Figure 6. Radial expansion of 4 mm thick explosive loaded *Cu* tube.

in Fig. 6 and the expansion velocity measured at R/R_0 = 1.7 for all five explosives is given in Table 3. Relative energy delivered to the metal by an explosive was found by squaring the cylinder wall velocity at R/R_0 = 1.7 for that explosive and comparing it to that of composition B for the same expansion. Relative energy values for octol, composition B and TNT are in close agreement with that calculated by Kury *et al* [6]. The values of Gurney's characteristic velocity for PEK-1 and baratol are not given, but from the experimental data the calculated velocity values for PEK-1 and baratol are 2.4 and 1.8, respectively.

Table 3. Relative grading of different explosives on the basis of cylinder test

Explosive	Rate of expansion at R/R_0=1.7	Relative energy delivered	Relative energy values by Kury *et al*[6]
Composition B (RDX/TNT (60:40))	1.7	1.0	1.0
Octol (HMX/TNT (70:30))	.86	1.2	1.15
TNT	1.44	0.72	0.74
PEK-1	1.48	0.76	
Baratol	1.23	0.52	

Wall thickness of copper cylinder = 4 mm

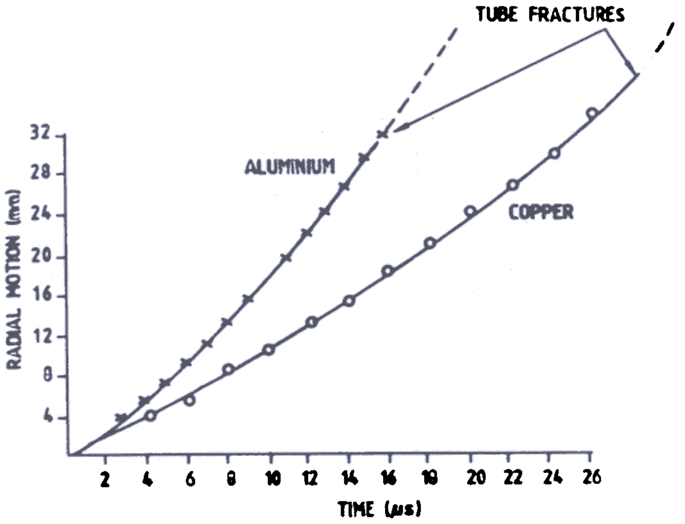

Figure 7. Expansion of 4 mm thick(ID/OD = 52/60 mm) *Al* and *Cu* cylinders under TNT loading.

Figure 2 shows the streak camera records of the expanding aluminium and copper cylinders of inner diameter 52 mm and wall thickness 4 mm. Radius-time history of each record is plotted in Fig. 7; the broken part of the curves indicate the fracture of the tube. Aluminium being light and brittle is accelerated at a faster rate and fractures quickly (16 μs) whereas, copper being heavier and ductile can be expanded slowly before it fractures (27 μs). Therefore, copper is preferred to aluminium for the cylinder test.

6. CONCLUSION

A large amount of data on the radial expansion of copper and aluminium has been generated for various explosive metal systems. The present data has been successfully used in the design and development of explosive-driven current generator based on the principle of magnetic flux compression by expanding metal cylinders. The cylinder test has been established for relative evaluation of the ability of various explosive compositions to impart energy to the metals. With the help of this test five high explosives have been graded; but a novel technique has been established for future studies on various plastic-bonded explosives.

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