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CRANFIELD UNIVERSITY

MSc THESIS

Academic Year: 2000

Daniel David Robert Lord

THE EFFECT OF EXPLOSIVES ON MATERIALS

Supervisor: Dr M R Edwards

July 2000

This thesis is submitted in partial fulfilment of the requirements for the degree of Master of Science in Forensic Engineering and Science

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Abstract

Identifying the cause of an explosive accident can sometimes be difficult. Features of explosive debris can be examined to determine this with metal samples showing changes in properties and microstructure when subject to an explosion. Fragments can form identifiable morphologies.

Simulated structures in the form of pipes, plates and boxes were attacked using a variety of explosives. Different parameters such as stand-off were altered to simulate the different effects on metals, which were subsequently examined, using metallography, fractography, fragment analysis and mechanical testing for any changes.

Ammunition containment boxes could be made to fail in a relatively safe manner using specific weld failures to form only one fragment with these fragments clearly identifiable as being from the site of a detonation by their different features. Plate specimens subjected to explosions and deflagrations could be easily distinguished by their changes in physical, mechanical and microstructural properties. Evidence of twinning was recorded for a specimen subject to a military high explosive charge detonation but only when the charge was in direct contact with the metal sample.

The contents of a pipe were found to change the fragmentation behaviour of the metal construction.

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Chapter 1

Introduction

Debris recovered from an apparently explosive accident can be examined for key features to help identify whether the cause was by accidental mechanical fault or explosive means. Explosions can be categorised by type and by explosive. Explosions can commonly differ between dust, gas and vapour explosions to military detonations. In terms of explosive type, high explosives detonate, low explosive deflagrate. High explosives can be military, commercial or even home-made from sources such as fireworks or fertilisers. These explosives, such as PE4 (military plastic explosive) and Gelamex (commercial explosive) are known as secondary explosives and are quite insensitive to initiation. They require the detonation of a more sensitive explosive to set them off. The use of a high velocity of detonation primary explosive, such as lead azide, is usually required. Military detonators tend to be more high performance and increase the power of commercial explosives.

Gas/vapour cloud explosions can occur deliberately, as detonatable military fuel/air mixture or as an accidental detonation or deflagration in the chemical industry. Dust explosions can occur accidentally as deflagrations in flourmills, grain silos or in coalmines, when the concentration of dust in the air reaches an unsafe level. Military explosives tend to be the most powerful, like plastic explosive PE4 while commercial explosives such as dynamite tend to be less powerful, used in quarry blasting and the like.

An aircraft is particularly susceptible to explosive attack. An example of this includes the investigation into the accident to Boeing 747-121, N739PA at Lockerbie, Dumfriesshire, Scotland on the 21st of December 1988. Initially, the cause of the accident was unknown. The aircraft had been in level flight for seven minutes when the last secondary radar return was received just before 19.03 hrs. Radar traces showed multiple primary radar returns fanning out downwind. Major portions of crash debris fell on the town of Lockerbie with lighter debris strewn along two trails, the longest of which extended 130 kilometres to the east coast of England. Upon investigation of the crash debris by forensic scientists, evidence pointed to the detonation of a high explosive on the aircraft (Aircraft Accidents Investigation Branch 1990). Reconstruction of the fuselage showed damage consistent with an explosion on the lower fuselage left side in the forward cargo bay area. A small region of structure had clearly been shattered. This was surrounded by a much larger area of torn fuselage, which formed a "star-burst" fracture pattern. Further analysis of the fractured region close to the shattered zone revealed several more characteristic signs of explosive detonation.

Explosive events are also apparent when considering the chemical industry. An accidental explosion due to a fuel pipe overpressure or accidental ignition can appear, at first glance, to be near identical to a deliberate external detonation.

Similar situations occur with structural explosions- the result of a gas leak and a bombing will both topple a building given the right circumstances.

Chapter 2

Literature Review

The effects of explosion on materials & in particular metals has been investigated in several areas of interest, including in regard to aircraft which are prone to heavy damage due to their distance from the ground and internal pressurisation.

The phenomena, which have been most commonly noted in regard to metallic debris fragments found after an accident, were extensively categorised by Tardif and Sterling (1967).

Several regions of interest were covered including the zone of damage around an explosive event & the features found on fragments.

The characteristic features found when an explosive charge is detonated near a large metal sheet are functions of variables such as stand-off distance, material & charge size & type. The two most commonly observed regions were the shattered zone, caused by the brisance of the explosive charge and the petalled region surrounding this.

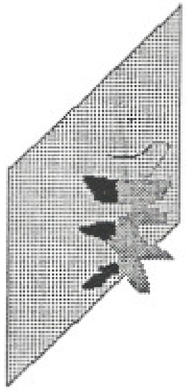


Figure 1. Schematic of petalling effect.

The fragments from the shattered region were generally difficult to recover and often counted as lost material. Barwick and Edwards (1995) estimated the size of holes produced using measurements of material mass lost.

The petalled region of material is observed as being formed by the gas pressure from the explosion. The formation of a petalled, holed region causes the reduction of pressure from the explosive gases, limiting the amount of damage and tearing that would otherwise take place (Edwards and Owen, 1995). The extent of petalling (tearing) is a function of plane stress fracture toughness, as the ease of crack growth

In Tardif & Sterling's examination, the morphology of small fragments were detailed using fragments varying in size between approximately 1/7 and 2 inches (0.3125 and 2.5 cm).

Curved fragments. Very many fragments were approximately rectangular in size but curved along their long axes. These were thought to have been formed by the successive breaking of ribbon like fragments that were bent over themselves when projected outward by the force of the explosion.

Spike-toothed fragments. Other fragments that were also curved showed sharp, parallel protrusions, possibly caused by tearing & shearing type effects. This spiking effect was seen to vary between sharp, short spikes & long wavy spikes.

Curled fragments. Many fragments were found to be completely curled on themselves or deformed in a helical fashion. This was thought to have been caused by a phenomena similar to that which made some fragments to become curved, where the force of the explosion and the hot gases caused the fragments to curl on themselves. Other bending & curling was thought to be achieved by the fragments colliding with other moving or stationary fragments.

Fissured fragments. Many fragments were shown to have heavily cracked or fissured surfaces. Some regions of metal were shown to have deformed in this fashion closely together and in parallel. It is thought that this deformation mode takes place in regions of material where deformation is favoured by excessive stretching rather than by another mode. Deposits of foreign material were also found upon these fragments.

Thin rods. Long structures were thought to have been formed by multiple double shear fractures occurring along a thin section of material. This material was also found to have a characteristic parallelepiped or triangular cross-section due to the multiple shearing.

Reversing slant & stepwise fragments. These features were found on a few small fragments from the shattered zone. This was almost never observed on long shear fractures away from the central zone but frequently on the zone close to the centre of the explosion.

Spalls. Many fragments were found to be of a thickness much smaller than that of the original sheet & with a finish varying considerably from that of the original sheet. The well-known phenomenon of spalling was thought to be the cause. Reflected tensile stress waves propagate through the material at the rear surface of the sheet and cause a high enough stress to fracture the material on the rear surface. (Covered in more detail)

Other fragments, not from the metal sheets but possibly from casing or housings may be found. In the mass of debris produced by an explosion, it is possible to recover fragments varying from clock parts to wire coverings. Work was carried out by the Royal Armament Research and Development Establishment (RARDE) to determine the degree of fragmentation of detonators (Lidstone, 1964). Most of the sheath was concluded to have broken up into very small fragments, although crimped portions and neoprene covering plugs were sometimes recovered.

Fractographic analysis, on the wreckage of an Indian Airlines Boeing 737 passenger aircraft that was forced by a mid-air explosion into making an emergency landing, was carried out by Krishnan et al (1984) and detailed further effects seen around an explosion and on recovered fragments. In this case, a chemical explosion took place inside the front toilet of the aircraft. By tracing the trajectories of the projectiles produced by the explosion, the location of an explosive device was revealed as being in a waste paper receptacle under a sink.

Indications were found of sharp projectiles passing through floor surfaces along with shattered portions of metal from the washbasin. Fragments were found which matched some of the features noted by Tardif and Sterling (1967), while holed samples and other nondescript samples were also discovered. Petalling and curling of ligaments (of metal) was also found. Metal showing craters with raised rims were found which could not be created by anything but a chemical explosion during an aircraft crash.

The investigation into the Lockerbie accident (Aircraft Accidents Investigation Branch, 1990) highlighted the usefulness of examination techniques in determining the cause of an accident. Material recovered from the "shatter zone" was mostly reduced to just small fragments, with more material available around the "starburst" section. The metal in the immediate locality of the "starburst" was found to be ragged, heavily distorted with the inner surfaces pitted and sooted, described as being if a very large shotgun had been fired through it (see figure 4). Forensic analysis of these sooty residues indicated the presence of explosives. All of the panels in the locality of the explosion had been pulled away and were bent and torn in a manner that showed they had also petalled producing characteristic, tight curling of the sheet material.

Knowledge of Mach-stem phenomenon was used in the investigation to estimate the stand-off distance of the explosive charge from the aircraft skin. Mach-stem effects are caused by the recombination of shockwaves bouncing off of surfaces and give rise (for relatively small charge sizes) to a geometric limitation on the size of shattered region that can be produced by a shockwave. The calculations carried out suggested that the 18-20 inches (45-50 cm) diameter shattered region produced required a stand-off of approximately 25 inches (62.5 cm).

Brisance is the shattering and crushing force of an explosive and is greatly evident when a high explosive (one that detonates) is in direct contact with a material. This is caused by the explosively created shock wave causing intense stress waves in the material. Shock waves travel faster than sound, but the intensity of a shock wave decreases faster than that of a sound wave, because some of the energy of the shock wave is expended to heat the medium in which it travels. The amplitude of a strong shock wave, as created in air by an explosion, decreases almost with the inverse square of distance travelled until the wave has become so weak that it obeys the laws of acoustic waves. Shock waves alter the mechanical, electrical, and thermal properties of solids (Encyclopædia Britannica, 1999).

It is the brisance of the explosion that causes the shattered region found in explosive incident wreckage, while the pressure wave of the hot gases causes the slower tearing effect of petalling. This dynamic pressure at the detonation wavefront is the detonation pressure:

$P_I = 2.5 \times 10^{-7} \rho V_D^2$ (Bailey and Murray, 1989)

Where:

P_I is detonation pressure (GPa)

$\rho(gcm^{-3})$ is explosive density

$V_D(ms^{-1})$ is velocity of detonation (detonation wave speed)

Explosive	**$\rho(gcm^{-3})$**	**$V_D(ms^{-1})$**	**$P_I(GPa)$**
PE4 (military)	1.61	8200	27.06
Gelamex (commercial)	1.45	5000	9.06
Flash powder (commercial)	0.9	550 (deflagration) ~2500 (detonation)	0.07 1.41

Table 1. Detonation pressures for several explosives

Spalling. This occurs due to tensile stresses generated by the collision of two rarefaction waves resulting from an applied shock. (see figure 2 for effect). This was examined in detail by Meyers (1994). Spalling has been studied since the early 1900's, when high-explosive was seen to be "quick" enough to cause the spalling effect (Hopkinson, 1914). Rinehart (1951) found that there was a critical value of normal tensile stress (σ_c) required for different materials to produce spalling. He also identified the phenomenon of multiple spalling and explained it: multiple spalling is produced when a triangularly shaped pulse is reflected with amplitude greater than the spalling stress. Figure 5 illustrates the multi-spall phenomenon.

a dislocation structure is re-ordered and a new grain structure forms. Work softening can be thought of as the reverse process to work hardening.

Twinning is another phenomenon that could be noted from post-explosion debris. Although twinning can occur when a material, such as copper is deformed and heated (annealing twins), deformation twinning can occur when a metal is shock loaded. Twinning is a process that could be said to compete directly with slip, and manifests as "bands" on metallographically prepared microstructures. Twins result from atomic displacements and occur along specific crystallographic directions. The occurrence of twinning is dependent on several factors, which have been described by Meyers (1994). Summarising this:

1. Pressure. It was found by Nolder and Thomas (1963,1964) that twinning occurred in nickel above 35 GPa pressure. Although nickel is not widely used in structural applications, it is quite likely that a set threshold pressure exists for many metals.

2. Crystallographic orientation. Twinning occurs when the stress resolved in the twinning plane & along the twinning direction reaches a critical level. (E.g. If the shock wave in a copper single crystal travels along the [100] crystallographic direction, then 14 GPa is the threshold stress, but if it travels along [111] then it is 20 GPa.)

3. Stacking-Fault Energy. The SFE is the energy stored in a lattice due to stacking sequence faults. As the SFE of FCC metals is decreased, the threshold stress is decreased; therefore the incidence of twinning is increased. The addition of alloying elements tends to decrease the SFE. Pure aluminium has a very high SFE & shows no deformation twins when shocked. This is unfortunate as deformation twinning is normally seen when metals are subject to explosive shock and since almost all aircraft are made from aluminium & its alloys, it is very difficult to prove explosive shock, through evidence of twinning, in serious accidents involving aircraft. Twinning produced by explosive shock cannot even be produced using military high explosive in fcc aluminium. (see Table 1 and Figure 6).

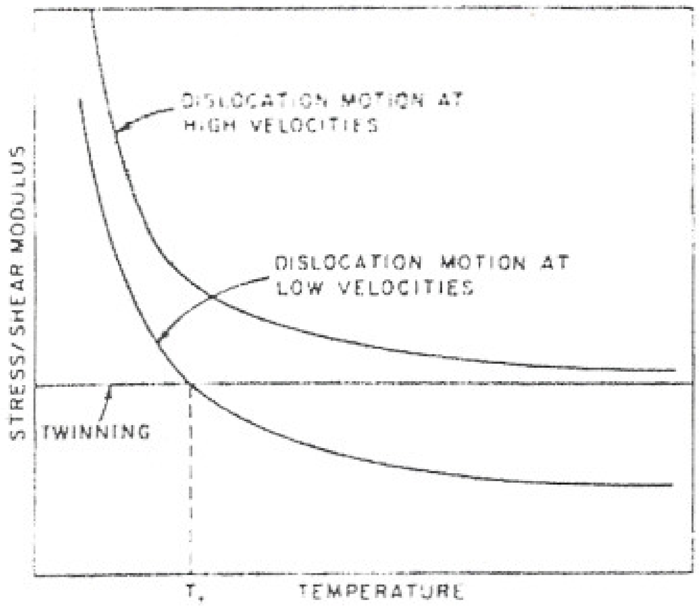


Figure 7. The effect of temperature on the stress requires for twinning and slip to occur. The figure shows low and high strain rates. (From Meyers and Murr, 1981)

Other effect noted under shock loading conditions include diffusionless transformations such as the martensitic transformation and the fact that irregular transformations of material may take place due to the shock wave having to traverse grain boundaries, precipitates and other such microstructural features.

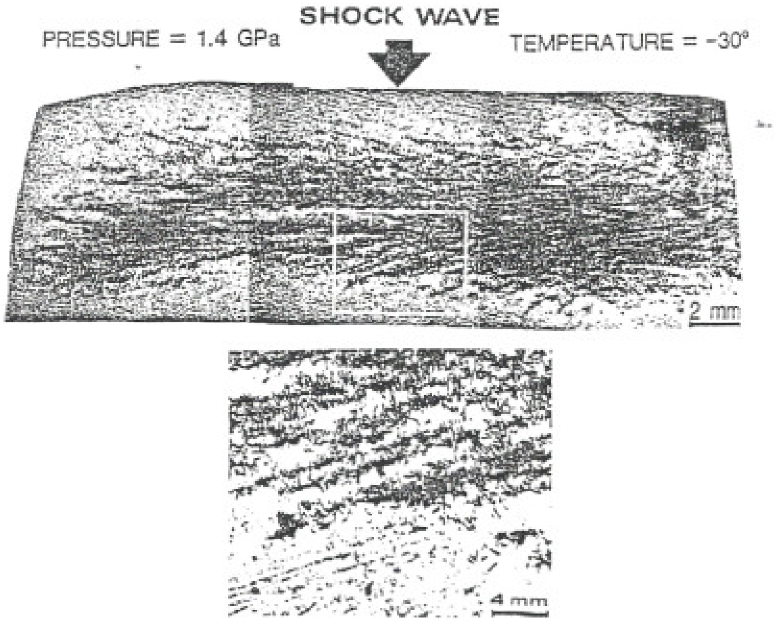


Figure 8. Cross section of specimen (Fe-32%Ni-0.035%C). The structure shows the irregular transformations that occur due to the inhomogeneities of a reflected shock wave. The shock wave was produced when a tensile pulse was reflected of the metals free surface. (From Thadhani et al., 1985)

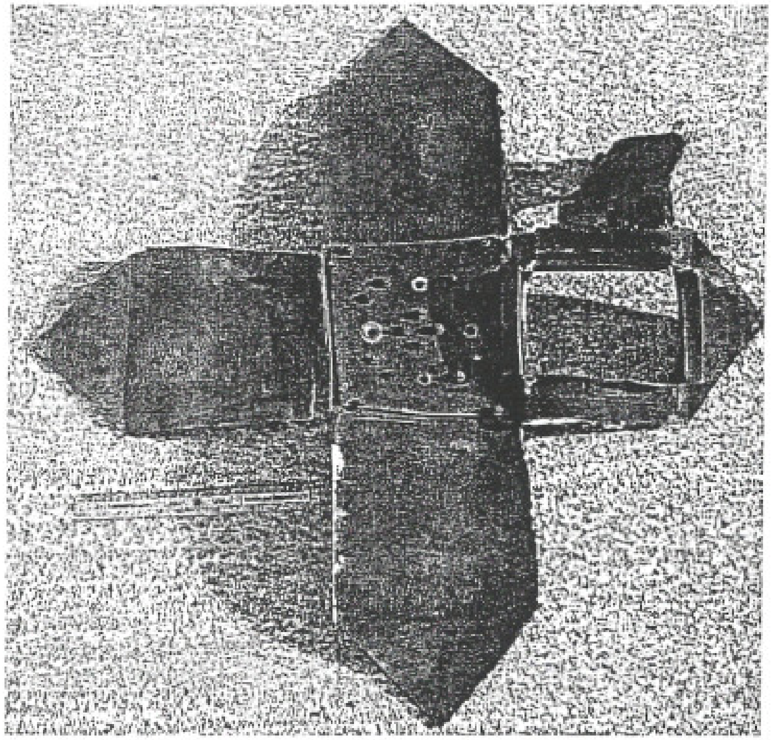
CHAPTER 3

EXPERIMENTAL

3.1 Ammunition storage box

Constructed of BS 4360 50D, structural (non alloy) steel. For approximate composition see appendix 2. The box was made using folds & welds to create a structure which, upon an explosion event occurring inside, would fail and form one large fragment only.

Four boxes were tested, with three only forming one, large fragment while one box failed along a fold and formed two.
Each box was subject to the detonation of 150g of PE4 military plastic explosive; this caused collapse of the box structures and for the failed box, tearing of one edge forming two fragments. Examination of the fractured regions and failed edge were necessary to determine the reason for this unforeseen failure.



Photograph 1. The two fragments of the ammunition box. The left hand wall is torn off from the main body.

were subject to the same metallographic procedures as carried out on the samples produced from the ammunition box.
The detonations were classified as follows:

3.2.1 Attack on Plate (AP)

A metal plate was "attacked" with explosive. Each plate was 8mm thick mild steel, composition approximating that of the box. Smaller fragments were captured from AP4 using strawboards placed inside the supporting pipe for plate specimens and stood-off by a metre next to the set-up for the charge holder fragments. The samples were then metallographically examined as above and hardness tested in several areas.

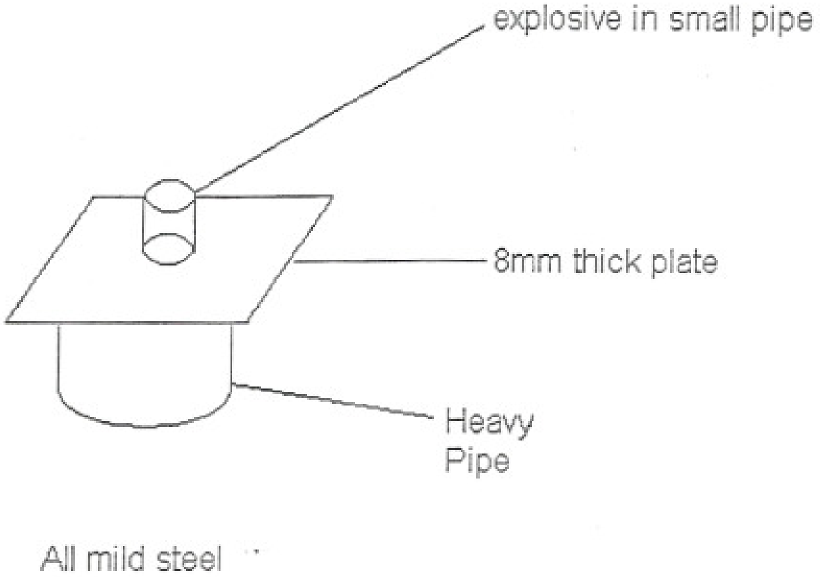


Figure 11. The set-up for the plate tests. The stand-off was achieved using a 12mm thick layer of sand between the charge holder and the plate. (See photograph 2.)

AP	Explosive	Detonator	Stand-off
1	117g flash powder	Match head fuse	None
2	234g flash powder	Match head fuse	None
3	117g flash powder + shaped charge	Match head fuse	None
4	227g PE4	Military L1A2	12mm
5	227g PE4	Military L1A2	None
6	Gelamex	Military L1A2	12mm

Table 2. The different configurations for the plate tests.

PB	Explosive	Detonator
1	117g theatrical maroon	Match head fuse
2	117g theatrical maroon	Match head fuse

Table 3. Pressure burst configurations.

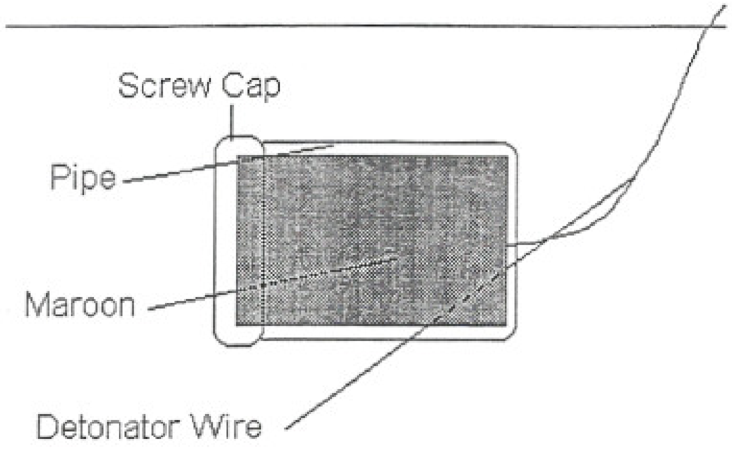


Figure 12. Schematic of maroon pressure burst tests.

Chapter 4

Results

4.1 Plate observations

The plate samples were affected as follows:

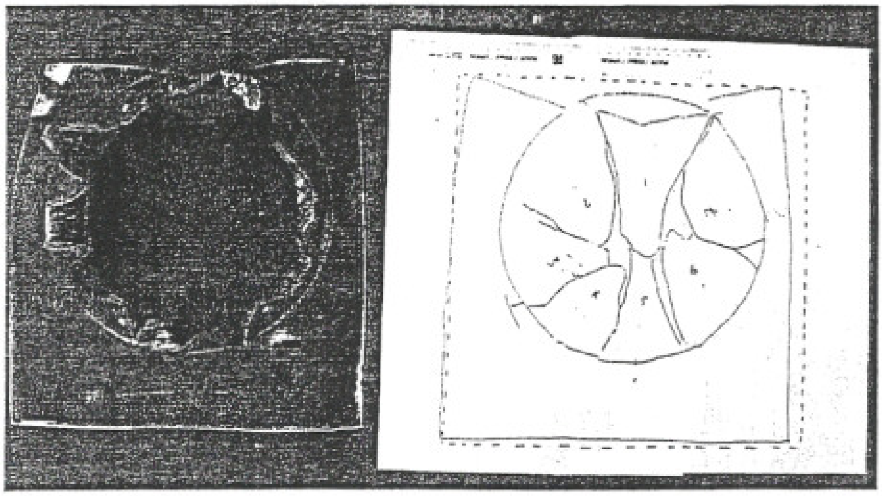
Sample	Explosive	Stand-off	Effect
AP1	117g flash powder	None	Bulged, no fracture
AP2	234g flash powder	None	Bulged, no fracture
AP3	117g flash powder + shaped charge	None	Bulged, no fracture
AP4	227g PE4	12mm	Large, petalled hole
AP5	227g PE4	None	Shattered zone, no petals
AP6	Gelamex	12mm	Large, petalled hole

Table 5. Results of attack on plate tests.

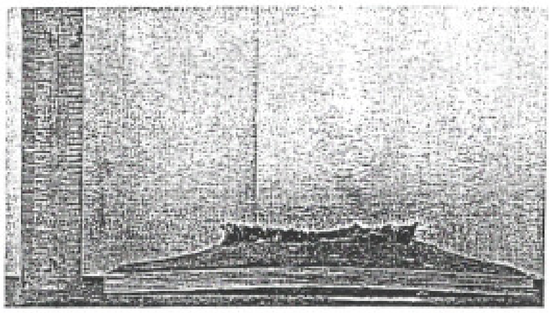
4.2 Plate deflections

AP	Deflection (mm)	Original cross-sectional length (mm)	Deformed cross-sectional length (mm)	Change in cross-sectional length (mm)
1	35	340	348	8
2	44	340	360	10
3	36	340	347	7

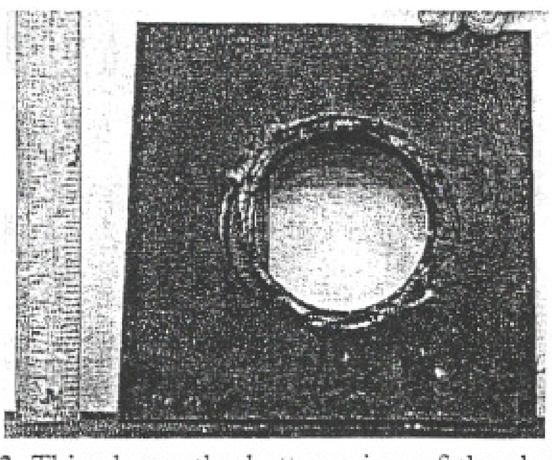
Table 6. Changes in deflection from the normal of plates that did not fracture.



Photograph 10. Plate AP4 on the left with approximate petalled lengths illustrated on paper model. Paper sheets were traced against petal lengths and orientated to match their positions as if they were folded flat. The paper model illustrates the amount of plastic deformation that has occurred during petalling. Some of the petals appear to overlap the shattered region, indicating an increase in original length and therefore reduction in thickness.



Photograph 11. Side view of central region of plate AP5. This illustrates the absence of petalling with a large shattered region. Of particular note is the lipped rim of the shattered hole.



Photograph 12. This shows the bottom-view of the shattered centre region (AP5). No petalling is apparent, although the central shattered region can be clearly seen. Lip formation and curling of the shattered zone edge is also evident, with a rough fracture surface finish.

4.3 Hardness tests

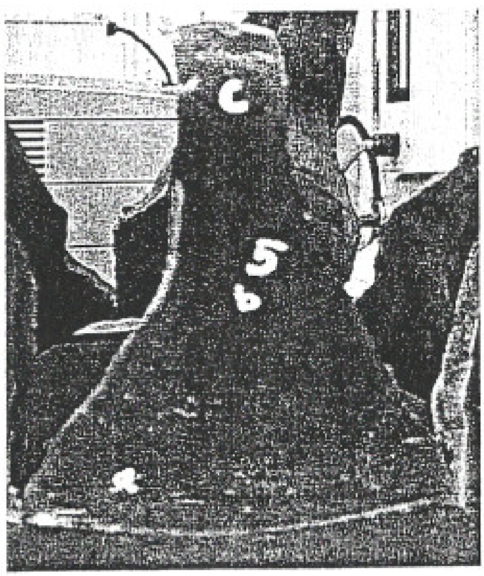
Hardness tests were carried out in different positions along the plates. The plates were low carbon non-alloy and not heat treated (not including normalising).

Vickers hardness tests (Load 30 kg)		Original hardness = 146
Sample	Hardness	Comments
AP1 centre	158	No hole
AP1 edge	167	No hole
AP2 centre	153	No hole
AP2 edge	203	No hole
AP3 centre	156	No hole
AP3 edge	160	No hole
AP4 petal end	211	Petals
AP4 edge	158	From plate edge
AP5 centre	235	Hole (from hole edge)
AP5 edge	150	From plate edge
AP6 petal end	219	Petals
AP6 edge	156	From plate edge

Table 7. Results of the hardness tests taken after the detonations.

Photograph 18. Petal 3 from plate AP4 showing a broken end.

Photograph 19. Petal 4 from plate AP4 showing some bending and twisting.



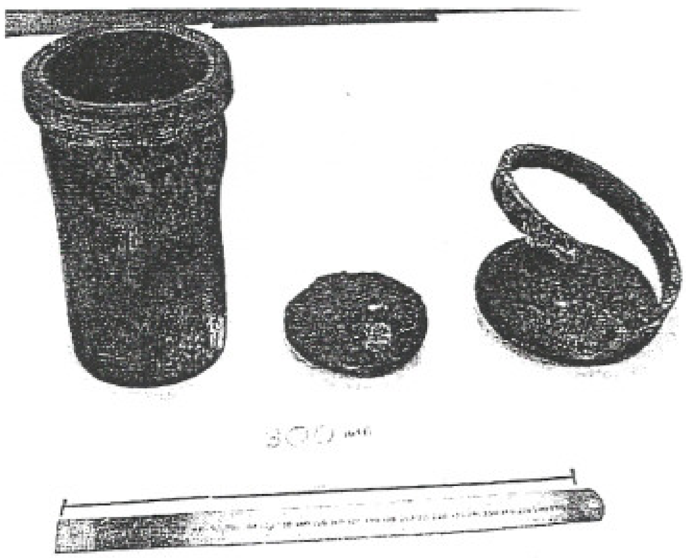
Photograph 20. Petal 5 from plate AP4 showing narrowing towards the ligament end with some curling and bending.

Petal	Position a (mm)	Position b (mm)	Position c (mm)	Max % reduction	Position d (mm)	Notes
1	8.05	7.08	6.94	13.79		
2	7.85	7.95	6.06	24.72	7.95	
3		7.62	6.75	16.15		Truncated petal
4	7.7	7.39	7.86	2.36		short petal
5	8	7.4	5.98	25.71		
6	7.9	7.41	5.37	33.29		
7		7.57	6.07	24.60		truncated petal
Plate original thickness = 8.05						

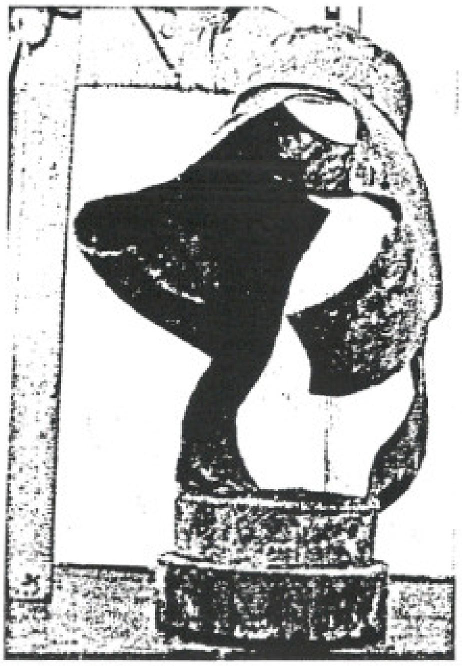
Table 8. Results from the thickness measurements of the petals. The max % reduction indicates the maximum amount of reduction that occurred along the petal length when compared with the original plate thickness. Gaps appear in the table due to the different shapes of the petals, with only those measurements thought relevant or necessary taken.

4.5 Pressure burst

For PB1 the end-cap fractured, with the pipe bulging.
For PB2 the pipe fractured, as the end-cap was constructed to be more heavy-duty.



Photograph 23. The fragments from test PB1. The actual cylinder showed no fracture, with some bulging near to the end cap. The end cap and welded end both fractured. The end cap split from the top of the screw thread and around the inner circumference at the weld until the top split. The bulge indicated that either the pressure was greater or the material was weaker or hotter at the bottom near the end



Photograph 25. The pipe fragment from test PB2 was physically stretched out using a lifting hook and vice until it was straightened to a length approaching the original length of the pipe. This photograph shows the extensive tearing that occurred along both the circumference and length of the pipe.

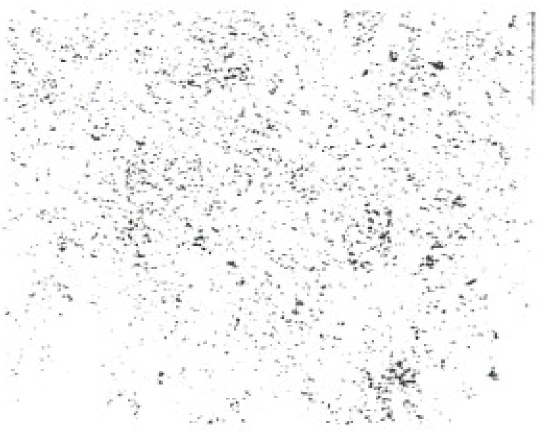
4.6.2 Plates

The microstructures for the samples AP1-3 were all very similar, so only selected microstructures have been included.

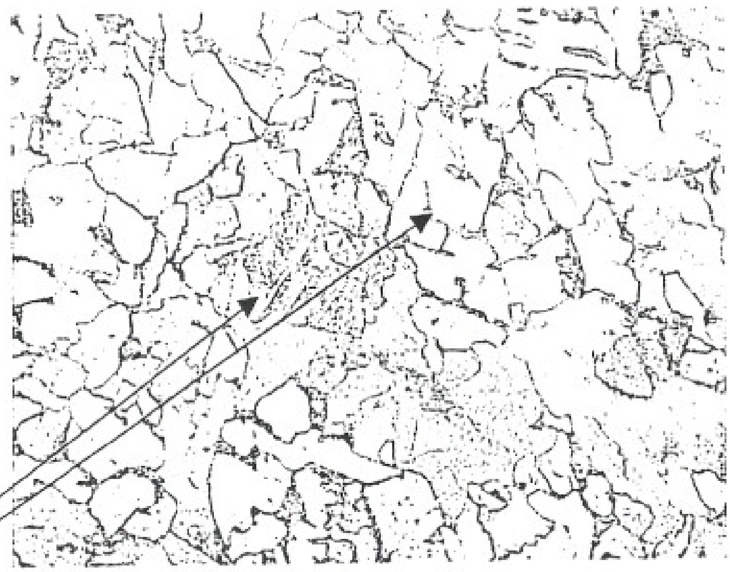
Micrograph 5.
AP2 centre (x500)
A fine grain structure with a ferrite-grained matrix with regions of pearlite, consistent with a low-carbon steel.

Micrograph 6.
AP2 edge (x500)
Very similar to the grain structure from the centre region, possibly slightly finer and more equiaxed, confirming that the centre portion was deformed in some way.

Micrograph 7.
AP3 centre (x500)
More deformed than that of AP2, confirming that the shape charge caused a greater level of damage, even with the lower charge.

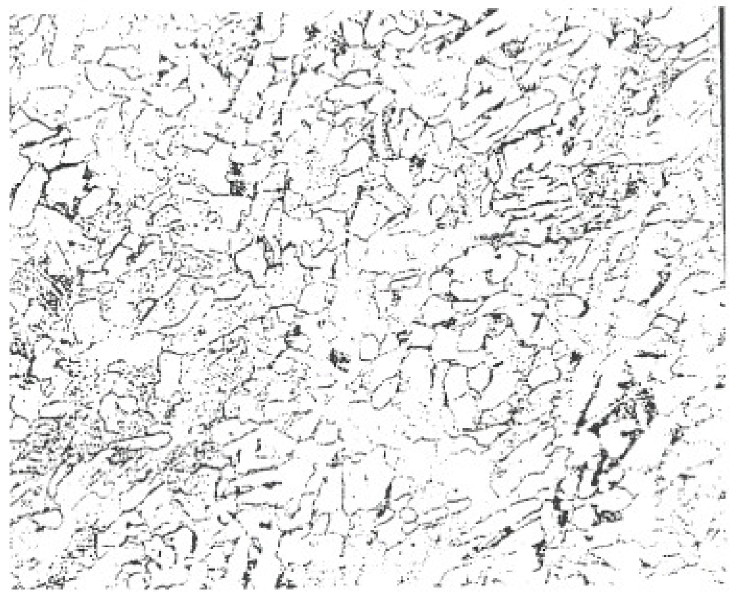


Micrograph 9.
AP5 near hole (x1000)
The microstructure shows Clear evidence of deformation twinning as bands in the same direction where twinning occurs in the same grains. This indicates an explosive shocking. only possible when a high military explosive is close enough to cause a high pressure.



TWINS

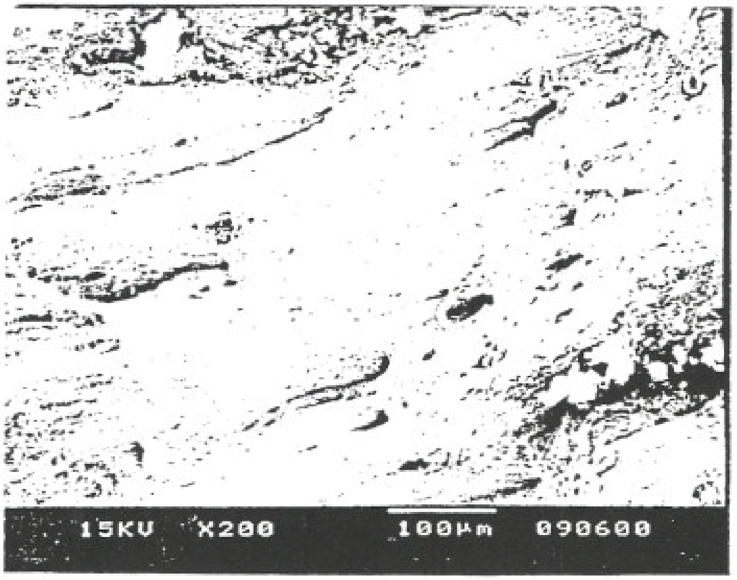
Micrograph 10.
AP5 near hole (x500)
This shows further evidence of twinning.



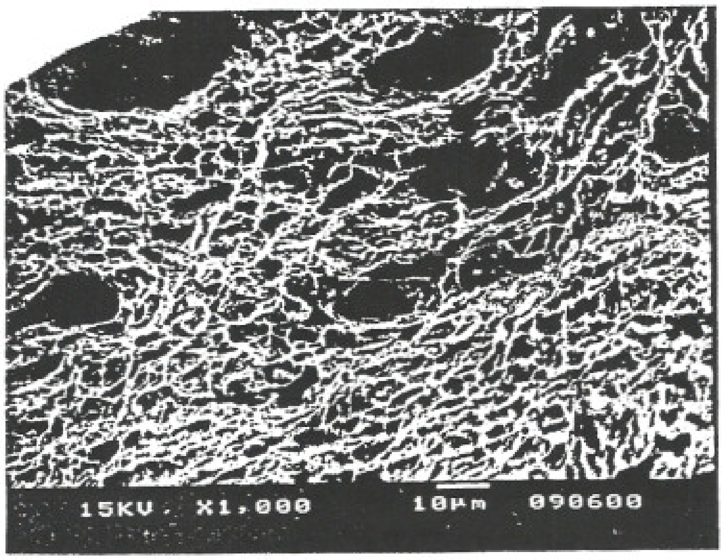
Micrograph 11.
AP5 near hole (x1000)
More twinning. This clearly indicates that explosive shocking has taken place.

4.8 SEM fractographs

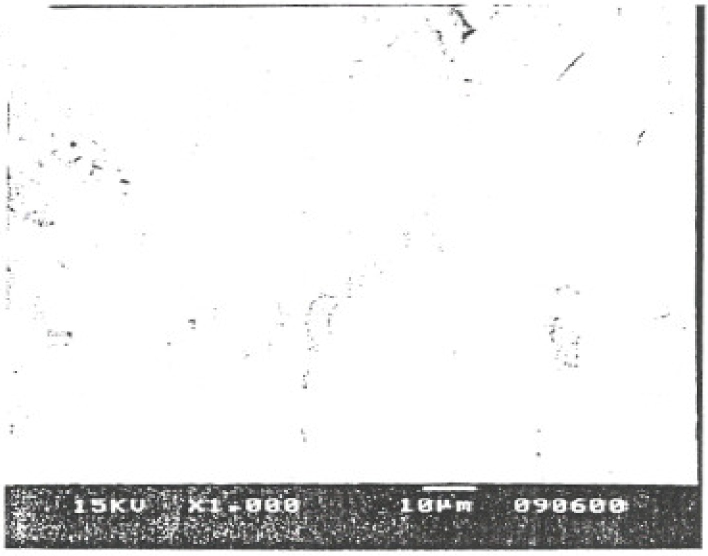
Fractograph 2.
AP6 petal fragment edge
This scanning electron micrograph shows a ductile surface with some pitting and chevron marking, indicating tearing and holing, possibly caused by regions of instability due to inclusions or from high velocity gases or particles. This was taken near the skin surface (darker, ductile regions of fractograph 1).



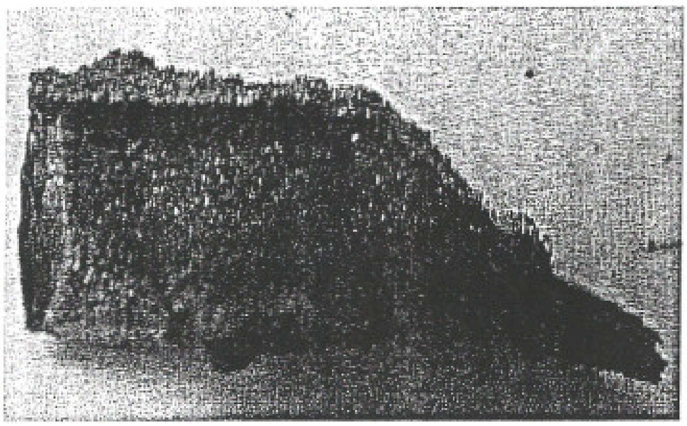
Fractograph 3.
AP6 petal fragment edge.
A ductile surface from a region inside the boundaries of fractograph 2. The ductile fracture is characterised by its dimpled appearance.



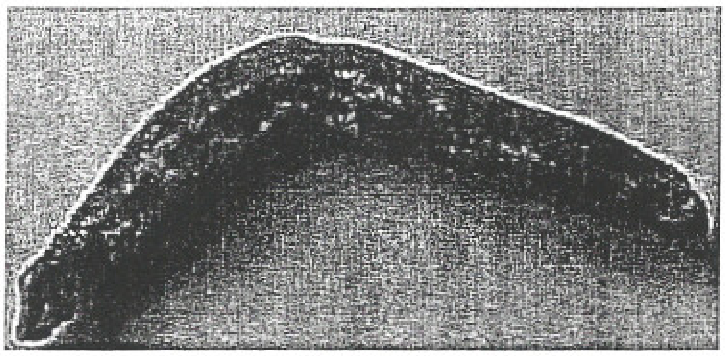
Fractograph 4.
AP6 petal fragment edge.
This shows a brittle fracture surface from near the middle of the fracture. The brittle fracture is characterised by its sharp facets and cracked appearance.



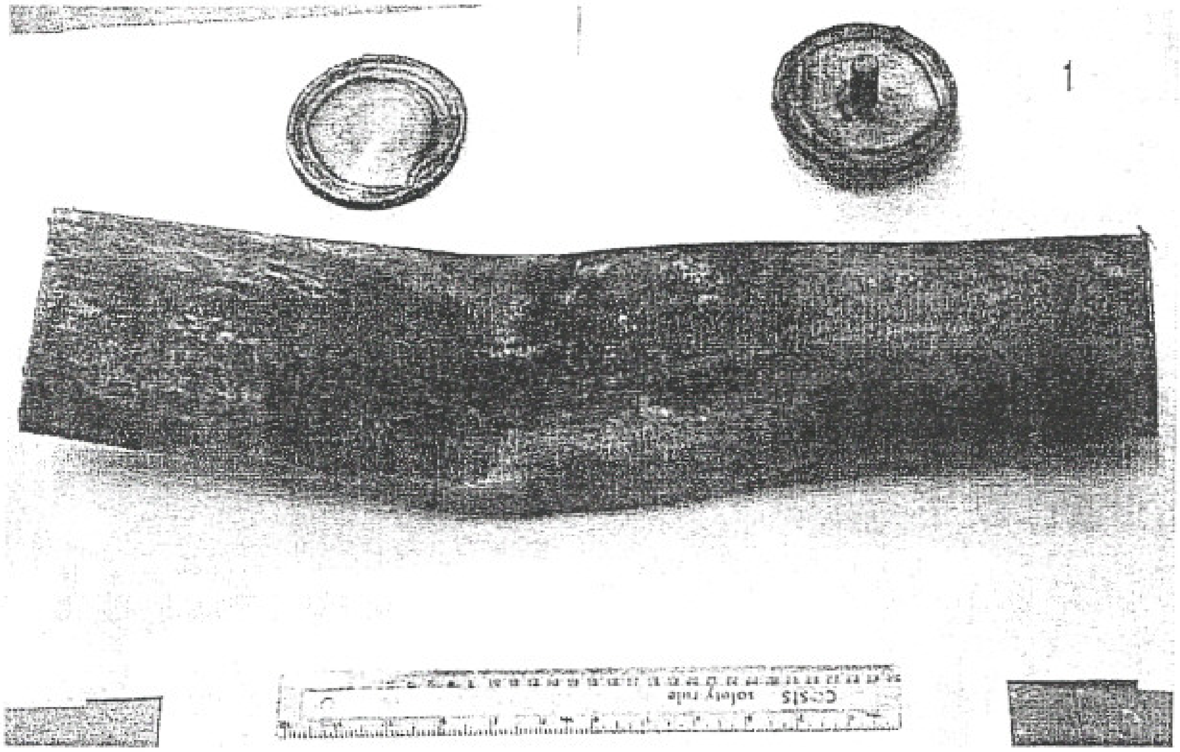
Photograph 29. An AP6 plate fragment, showing a smooth surface from collision with the supporting pipe.



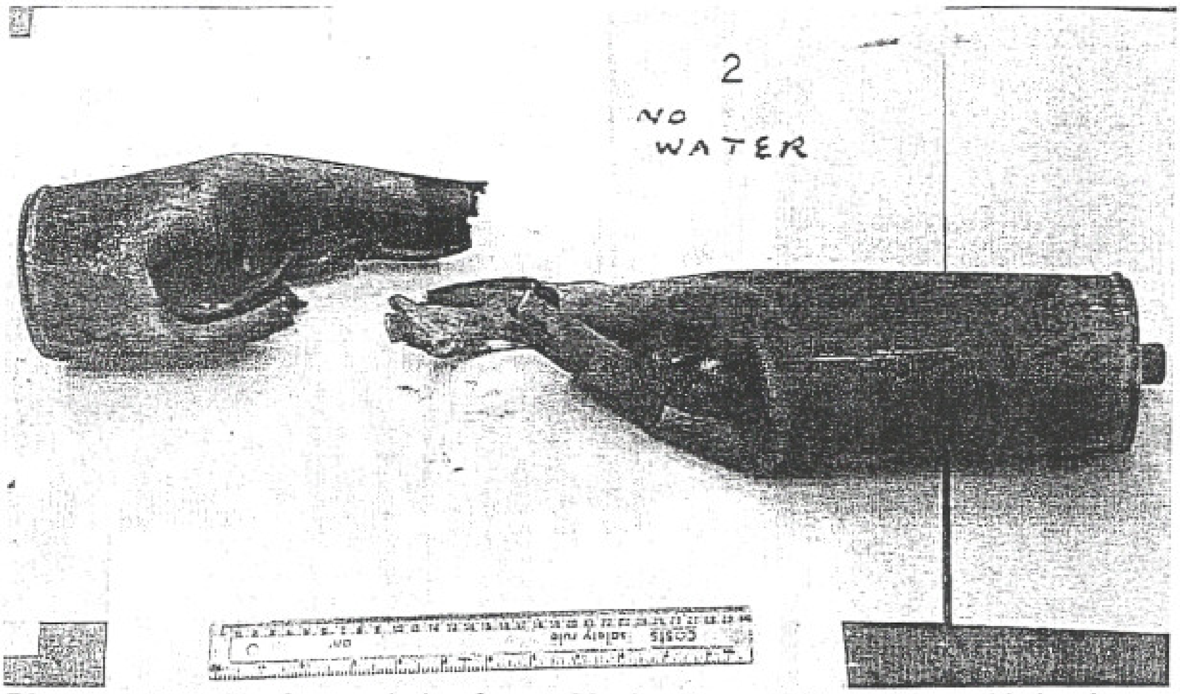
Photograph 30. An AP4 plate fragment showing fissuring and cratering.



Photograph 31. An AP4 charge holder fragment showing bending and curling.



Photograph 34. The deformed pipe from AC1, showing no fracturing of the main pipe, but failure of the welded end-caps.



Photograph 35. The fractured pipe from AC2, showing no failure of the welded end-caps. This indicated that the presence of water inside the pipe may help distribute the pressure of an external blast to the ends.

Chapter 5

Discussion

5.1 Ammunition storage box

The ammunition storage box was designed to tear along selected welds to form only one fragment, which it failed to do. Welds are parts of (normally metal but can be plastic) structures that have been constructed using heat to join regions of parent metal, combined with weld metal to hold the structure together. They are generally weaker than folds if produced in a normal fashion.

There are many different types of welding technique and welding materials available. Commonly, welding is carried out using a source of intense heat, such as an electric arc or gas welding torch and a weld metal such as tungsten or a composition that differs slightly from the parent. The welding is normally carried out in an inert gas stream to prevent oxidation and pollution of the welded surface. The weld and the area immediately surrounding it are subject to intense heat and therefore a likely change in properties. Many modern metals are heat-treated; the effect of welding on this heat treatment would be effectively to undo it. Welding can also cause a change in local composition. If a stainless steel plate was to be welded incorrectly, it would likely cause degradation of the steels corrosion resistance properties – the formation of chromium carbides would lower the amount of chromium free in the metal to form protective oxide coatings. The formation of other carbides and impurity inclusions can also cause defects and weakening of the alloy.

Areas such as welds are generally incorporated intelligently into a design, but even then, do not always perform as expected. The weld metal in the ammunition boxes would likely be composed of a low carbon steel which was cooled to give moderately sized grains with ductile properties, although they wouldn't be too weak to tear easily. The weld metal also showed less evidence of pearlite than the parent metal did, indicating that much care was taken to produce a high quality welded structure.

The microstructures indicated that the parent metal possessed a larger average grain size than the weld metal but was more heavily distorted on detonation and subject to a greater size change and possible strain than the weld metal. The strain caused by the explosion, coupled with the strain already induced by the folding may have caused regions of folded metal to break. Any defects, stress concentrators or regions of brittle pearlite present could also initiate failure.

To improve the performance of the boxes it would be necessary to facilitate the free tearing of the welded areas with no fracture of any other areas. It would be ideal if the welds all failed simultaneously so to release the blast pressure more rapidly. This change in performance could be achieved by making sure that no brittle regions exist in the metal folds while the welds are less strong. To assure that no brittle material remained in the folds, it would be necessary to carry out a stress relieving heat

The evidence of twin occurrence in the plate with no stand-off indicates that even using a military explosive, any stand-off will produce no or very little twinning. This means that, in the case of an explosion, the absence of twinning does not mean that a detonation did not cause it. Deformation twin formation requires a very high pressure and relatively low temperature. The very nature of explosions, in particular the heat released, makes incidences of twinning less common.

5.2.3 Plates showing no fracture

The results of the tests indicated that the flash powder samples, even with the addition of a shaped charge, were insufficient to cause fracturing of the plate. The plate deflections indicated that the increase in charge size between AP2 and AP1 caused a greater impact, while the shaped charge caused a sharper "bump" but only a small increase in deflection.

The degree of deflection caused by these tests produced considerable enough plastic deformation to cause work hardening. Using the relationship between true stress, true strain and the strain-hardening exponent, hardness can be approximated for low carbon steel (appendix 1).

$$\sigma_T = K\,\varepsilon^n_T$$

Where:

σ_T is the true stress
ε_T is the true strain
K is a material constant =530 MPa
N is the strain-hardening exponent = 0.26

To calculate the true stress, the true strains must be calculated using:

$$\varepsilon_T = \ln\left(\frac{l_1}{l_0}\right)$$

Where:

l_1 is the strained length
l_o is the original gauge length

The hardness can be calculated by the rule that the hardness is a 1/3 of the tensile stress, which will be approximated as the true stress plus the yield stress (~295 MPa) for this case.

5.4 Attacks on pipes

These showed the effect of a fluid contained in a pipe. The presence of a fluid, in this case water, caused some transference of the pressure to the ends of the pipe and preventing fracture in the case of the gelamex. The more powerful military high explosive still caused fracture, even with a stand-off.

Chapter 6

Conclusions and Recommendations

6.1 Conclusions

With minor treatment, a welded ammunition box can be made to fail as only one fragment, by fracture of the welds, using a minor heat treatment or weld alteration.

The damage caused to structures and materials by detonations can be differentiated from accidental damage using metallography, fractographic analysis, mechanical testing and fragment analysis.

The effect of twinning can be detected in samples suffering extreme brisance effects with no stand-off, although its absence is not a clear marker to an explosion being an accident.

The characteristics of detonated fragments can be clearly recognised using basic equipment.

Hardness cannot be reliably used to test for deflagration, only to identify detonation where shattering or petalling has taken place. Softening can take place in the region nearest to the charge.

The contents of a pipe, which is attacked by explosive charge from its exterior, can affect the fracture behaviour of the pipe metal.

6.2 Recommendations for further work

Further work should include the use of a wider variety of materials, with explosives of differing power, using a variety of stand-off distances.

More investigation into the nature of the twinning effect and its relation to explosive charge parameters should be carried out.

The effect of explosive detonation temperature on the hardness and other mechanical properties should be investigated.

More experiments regarding the softening effect of certain charge compositions on the metal plates should be carried out.

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APPENDIX 1

Material	Strain-hardening co-efficient, n	Constant, K (MPa)
Low carbon steel – annealed	0.26	530
Alloy steel – type 4340, annealed	0.15	640
Stainless steel – type 304, annealed	0.45	1275
Aluminium – annealed	0.20	180
Aluminium alloy – type 2024, heat treated	0.16	690
Copper – annealed	0.54	315
Brass – 70Cu/30Zn, annealed	0.49	895

Table showing the strain-hardening co-efficient and related constants for a selection of materials. (S. Kalpakuian, 1991)

Appendix 2

BS 4360 50D Structural Steel.

C wt%	Si wt%	Mn wt%	P wt%	S wt %
Max 0.20	Max 0.55	Max 1.60	Max 0.035	Max 0.035

Table showing the approximate elemental composition of a low-carbon steel. (Stahlschlüssel, ????)