FFI RAPPORT

Experimental study of the fragmentation of hard cores of wolfram carbide during penetration in armour steel plates

Moxnes John F, Frøyland Øyvind

FFI/RAPPORT-2004/01884

FFIBM/860/01

Approved
Kjeller 5. January 2005

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Director of Research

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Norwegian Defence Research Establishment

UNCLASSIFIED

P O BOX 25
N0-2027 KJELLER, NORWAY

SECURITY CLASSIFICATION OF THIS PAGE
(when data entered)

REPORT DOCUMENTATION PAGE

1) PUBL/REPORT NUMBER FFI/RAPPORT-2004/ 01884	**2) SECURITY CLASSIFICATION** UNCLASSIFIED	**3) NUMBER OF PAGES** 44
1a) PROJECT REFERENCE FFIBM/860/01	**2a) DECLASSIFICATION/DOWNGRADING SCHEDULE** -	

4) TITLE

Experimental study of the fragmentation of hard cores of wolfram carbide during penetration in armour steel plates

5) NAMES OF AUTHOR(S) IN FULL (surname first)

MOXNES John F, FRØYLAND Øyvind

6) DISTRIBUTION STATEMENT

Approved for public release. Distribution unlimited. (Offentlig tilgjengelig)

7) INDEXING TERMS

	IN ENGLISH:		**IN NORWEGIAN:**
a)	Penetration	**a)**	Penetrasjon
b)	Hard core	**b)**	Hard kjerne
c)	Wolfram carbide	**c)**	Wolframkarbid
d)	Fragmentation	**d)**	Fragmentasjon
e)	Armour	**e)**	Panser

THESAURUS REFERENCE:

8) ABSTRACT

Numerical codes,e.g. Autodyn are widely used for simulation purposes during impact and penetration of projectiles into targets. To validate the computer simulations, an experimental study of fracturing of sintered wolfram carbide-cobalt penetrators have been carried out by shooting inert 12.7 mm MP projectiles into armour steel plates of thickness 22 mm.

We found that with an impact velocity of 950 m/s the hard core penetrated the 22 mm target but fractured. The fracturing most likely took place late in the target or during exit of target. For 820 m/s impact velocity the hard core was observed to penetrate the target. But some shots (25%) indicates undamaged hard cores. The fracturing at 820 m/s most likely took place very late or during exit of target. By studying the fragmentation pattern in the witness plate behind the target, we found that some of the hard cores were weakened due to the penetration through the target, but most likely appear visually as intact.

In general the results indicate that the strength of the hard core is marginal. The different penetration scenarios suggest that the penetration capabilities will be reduced when increasing the impact velocity above 950 m/s due to increased damage of the hard core. Also, increased target strength can reduce the penetration capability significantly.

9) DATE 18. August 2004	**AUTHORIZED BY** This page only Bjarne Haugstad	**POSITION** Director of Research

ISBN 82-464-0920-4

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE
(when data entered)

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Experimental study of the fragmentation of hard cores of wolfram carbide during penetration in armour steel plates

1 INTRODUCTION

Numerical codes, e.g. Autodyn are widely used for simulations purposes during impact and penetration of projectiles into targets. To validate the computer simulations, an experimental study of fracturing of sintered wolfram carbide-cobalt penetrators have been carried out by shooting inert 12.7 mm MP projectiles into armour steel plates of 22 mm. Also a witness plate was inserted 37 cm from the rear part of the armour target plate. Thus the effect of the target on the hard core could be more clearly observed.

The experimental results are delivered as a part of a research to study the penetration capabilities of hard cores of ceramic materials. The material models are complicated and unknown. The producing company typically gives some material parameters. But, in general the delivered parameters are insufficient to construct material models.

We found that with an impact velocity of 950 m/s the hard core penetrated the 22 mm target but fractured. The fracturing most likely took place late in the target or during exit of the target. Thus, often the exit hole of the target was slightly expanded compared to the entrance hole. For 820 m/s impact velocity, the hard core also penetrated the target. The fracturing at this 820 m/s most likely took place during exit or very late in the target. The exit hole of the target was of the same size as the entrance hole. Also, some shots (25 %) indicate undamaged hard cores. By studying the fragmentation pattern in the witness plate behind the target, we suggest that some of the hard cores were weakened due to the penetration through the target, but most likely appear visually as intact.

In general the results indicate that the strength of the hard core is marginal. The different penetration scenarios could indicate that the penetration capabilities can be reduced when increasing the impact velocity above 950 m/s due to increased damaging of the hard core. Also increased target strength could reduce the penetration capability significantly.

2 THE EXPERIMENTAL SETUP

Figure 2.1 shows the experimental setup. The firing range is about 6 m. The target and witness plate is of armour steel and is placed ca. 37 cm behind the target plate of armour steel.

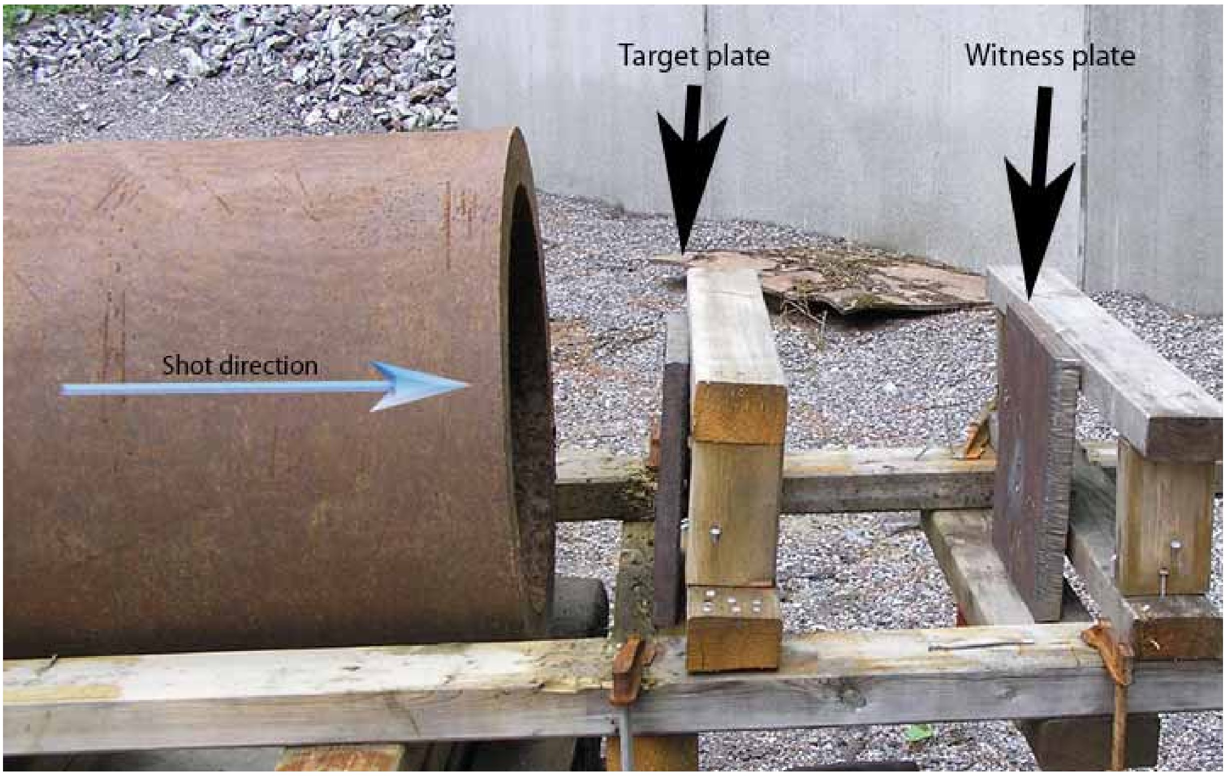


Figure 2.1: The experimental setup of target and witness plate.

3 RESULTS

Two different impact velocities were used to study the fragmentation pattern.

3.1 Shots with impact velocities of 950 m/s at 22 mm armour steel target

The figures below show the holes and the fragmentation pattern for the shots with impact velocities of 950 m/s.

Shot no. 1

Target plate

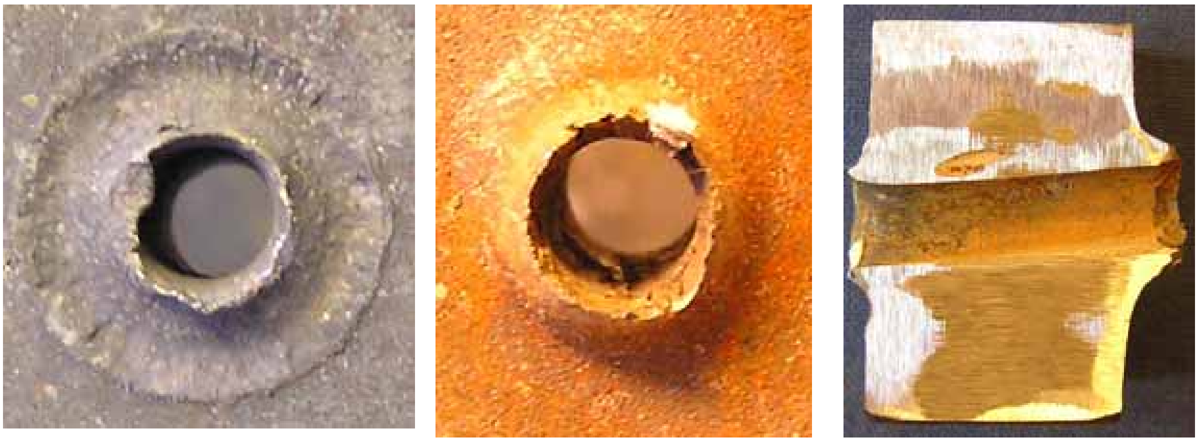

Entry hole Exit hole Cross-section

Figure 3.1

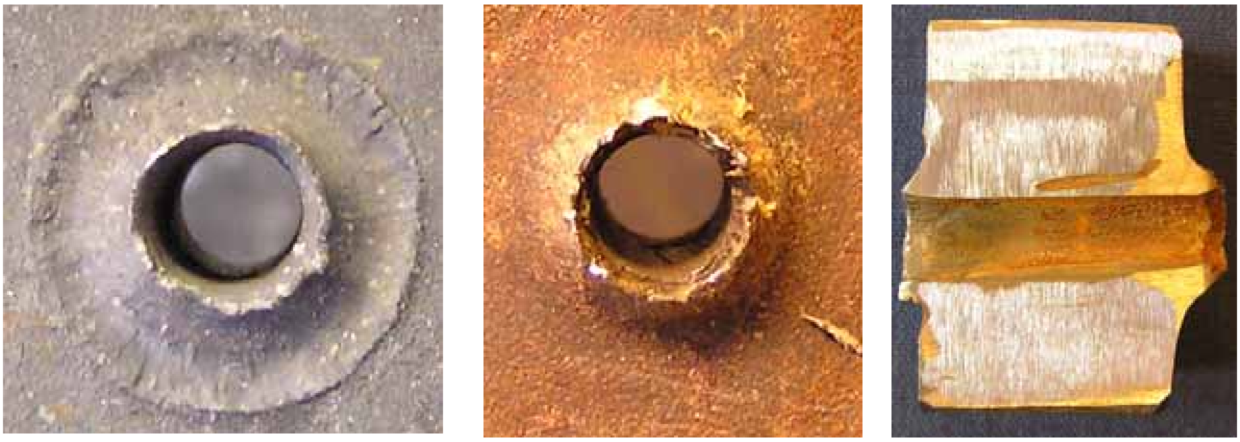
Witness plate

Figure 3.2

Hypothesis: The indefinite mark in the witness plate indicates that hard core was fractured before hitting the witness plate.

Shot no. 2

Target plate



Entry hole Exit hole Cross-section

Figure 3.3

Witness plate

Figure 3.4

Hypothesis: Hard core was weakened after penetrating the target plate but most likely appears as intact. The hard core fragmented completely when hitting the witness plate. Small fragments from the hard core are stuck in the witness plate.

Shot no. 3

Target plate

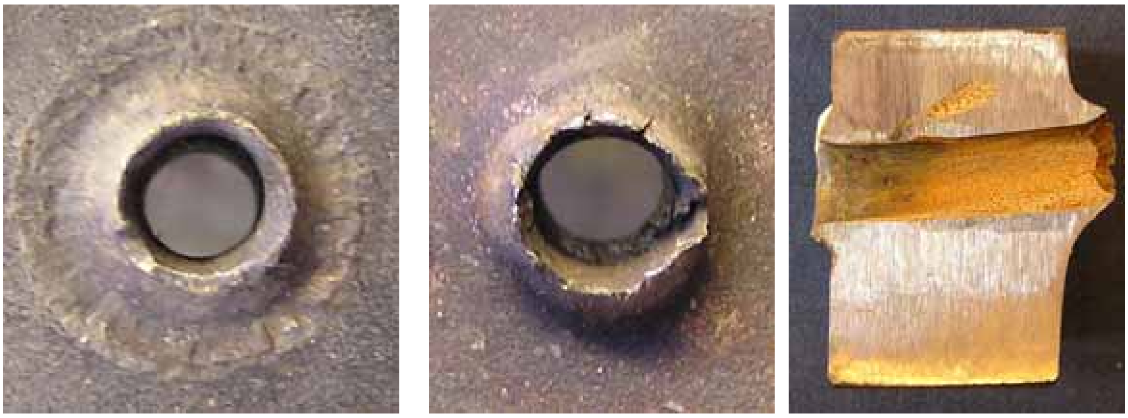

Entry hole
Exit hole
Cross-section

Figure 3.5

Witness plate

Figure 3.6

Hypothesis: Due to multiple marks in the witness plate, the hard core has been fractured before impact with the witness plate.

Shot no. 4

Target plate

Entry hole Exit hole Cross-section

Figure 3.7

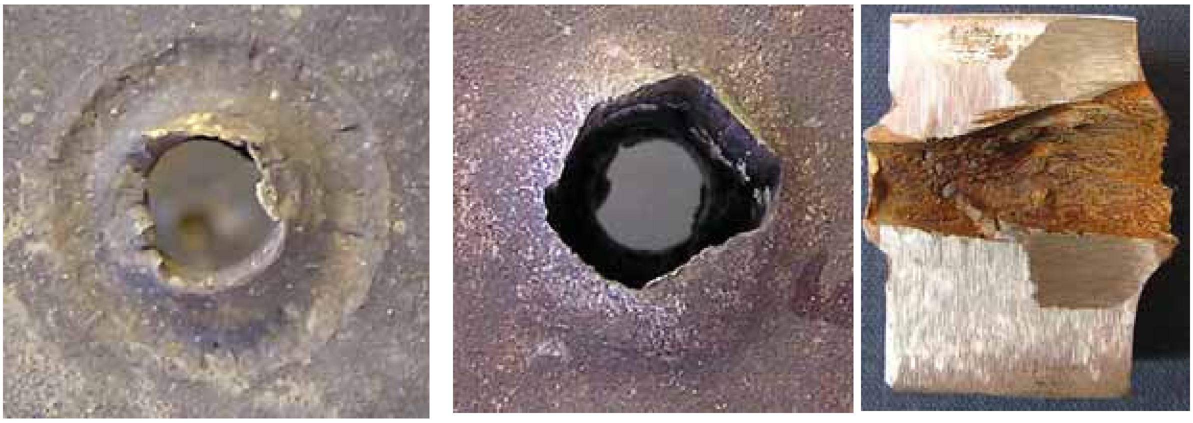
Witness plate

Figure 3.8

Hypothesis: The slightly deformed exit hole indicates that the hard core was fractured before leaving the target plate.

Shot no. 5

Target plate



Entry hole Exit hole Cross-section

Figure 3.9

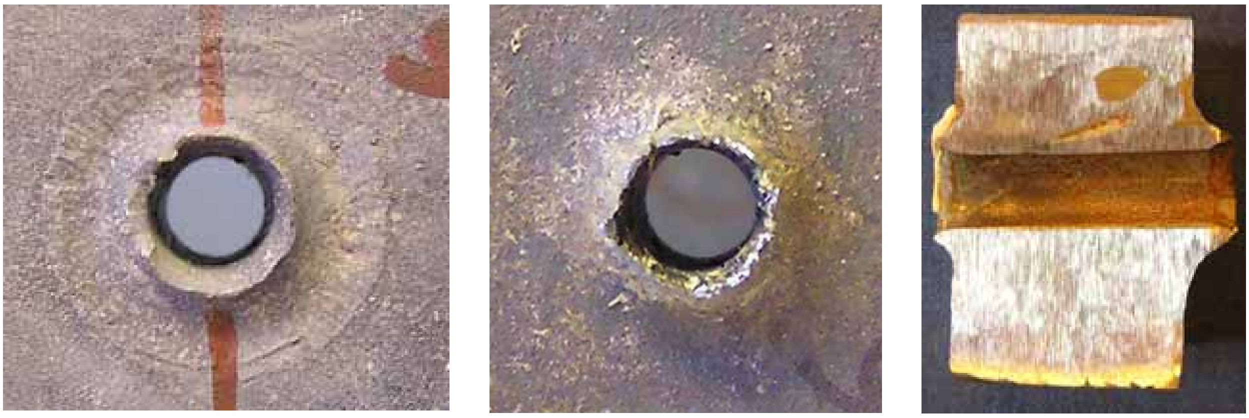
Witness plate

Figure 3.10

Hypothesis: The deformed exit hole indicates that the hard core was broken before leaving the target plate.

Shot no. 6

Target plate



Entry hole

Exit hole

Cross-section

Figure 3.11

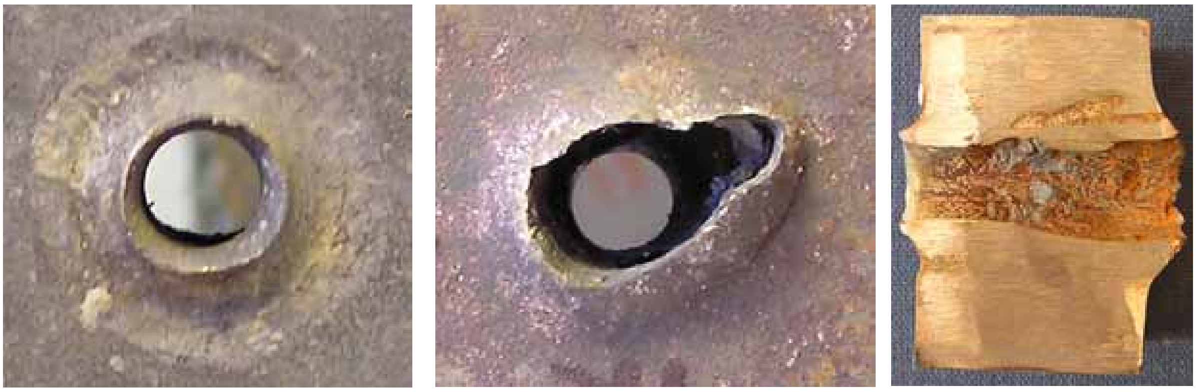
Witness plate

Figure 3.12

Hypothesis: The indefinite mark in the witness plate indicates that hard core was fractured before hitting the witness plate.

Shot no. 7

Target plate



Entry hole

Exit hole

Cross-section

Figure 3.13

Witness plate

Figure 3.14

Hypothesis: The large and deformed exit hole indicates that the hard core was fractured before exit of the target plate.

Shot no. 8

Target plate

Entry hole Exit hole Cross-section

Figure 3.15

Witness plate

Figure 3.16

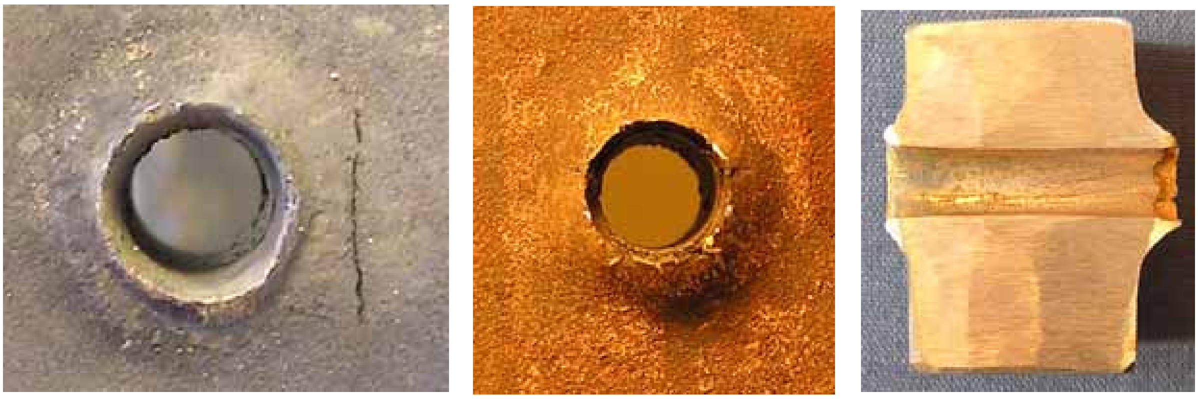
Hypothesis: The hard core was fractured before exiting the target plate, due to the large exit hole. The only visible mark in the witness plate is the shape of a fragment from the hard core with length ~1 cm.

3.2 Shots with impact velocities of 820 m/s at 22 mm armour steel target

The figures below show the holes and the fragmentation pattern for the eight shots with impact velocities of 820 m/s.

Shot no. 9

Target plate



Entry hole

Exit hole

Cross-section

Figure 3.17

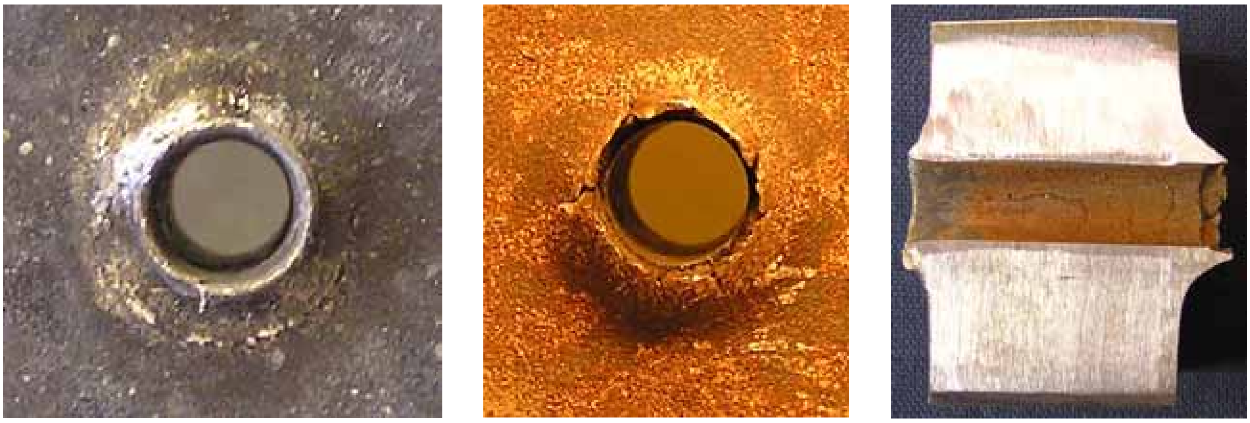
Witness plate

Figure 3.18

Hypothesis: Based on the multiple marks in the witness plate, the hard core must have been fragmented before impact with the witness plate.

Shot no. 10

Target plate



Entry hole

Exit hole

Cross-section

Figure 3.19

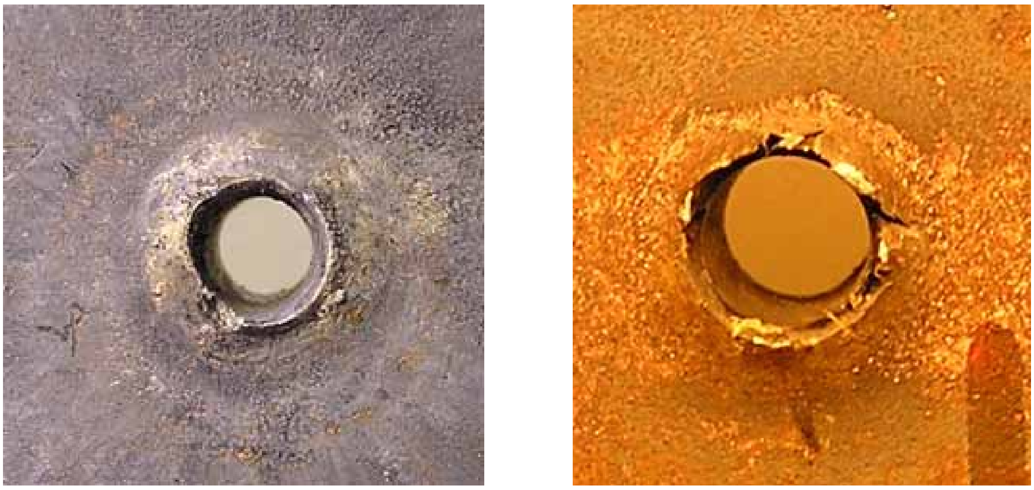
Witness plate

Figure 3.20

Hypothesis: No indication in the witness plate that the hard core was damaged. The hard core was found after the shot and the front part was absent. (Ca. 1,2 cm of the front part was missing.) It is likely the hard core was not fractured before hitting the witness plate.

Shot no. 11

Target plate



Entry hole

Exit hole

Figure 3.21

Witness plate

Figure 3.22

Hypothesis: Fractured before impacting witness plate. By studying the witness plate we observe the indentation of the front of the hard-core with some small marks around. Thus suggesting that only the front part of the hard core was undamaged before hitting the witness plate.

Shot no. 12

Target plate

Entry hole

Exit hole

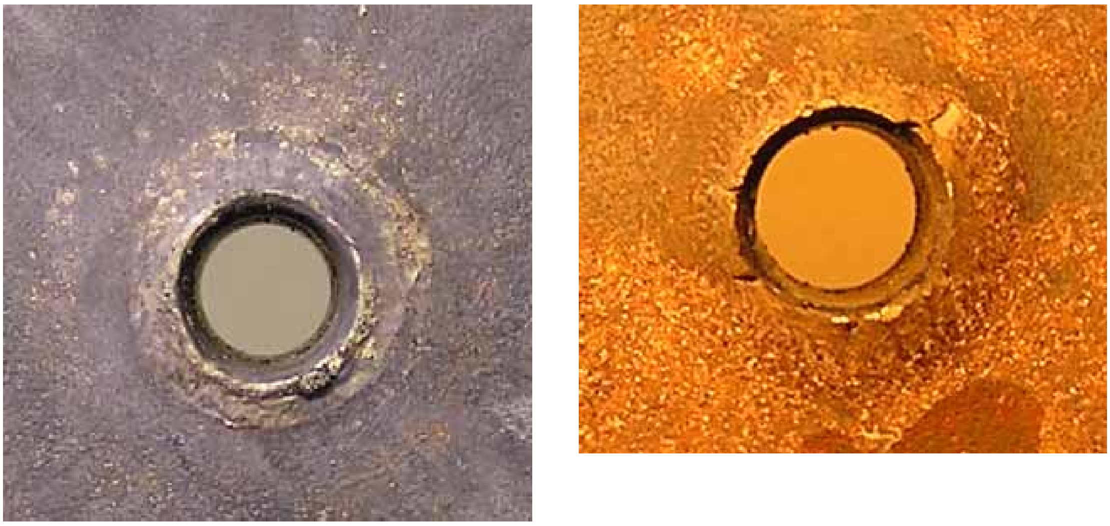


Figure 3.23

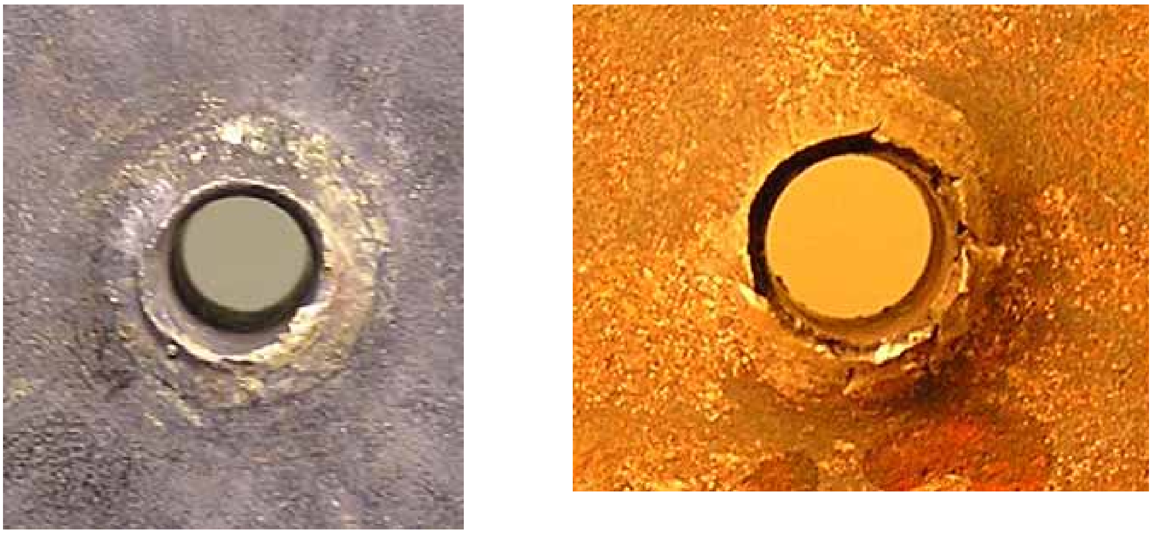
Witness plate

Figure 3.24

Hypothesis: No indication that the hard core was fractured or damaged.
However some small fragments from the hard core was found after the shot. It is likely the hard core was undamaged before hitting the witness plate.

Shot no. 13

Target plate



Entry hole

Exit hole

Figure 3.25

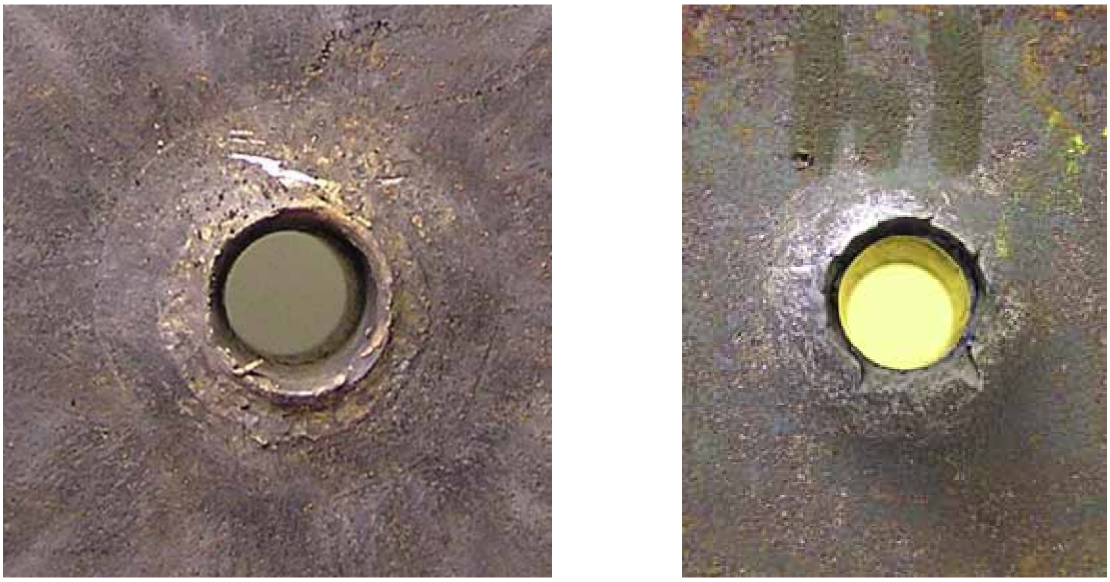
Witness plate

Figure 3.26

Hypothesis: Fractured before impacting the witness plate. The front part of the hard core has been somewhat weakened but not fractured before impacting the witness plate. However, some fragments, most likely from the rear part of the hard core, seem to have broken loose before impact and made the small marks in the witness plate. After impact with the witness plate the front part of the hard core fractured.

Shot no. 14

Target plate



Entry hole

Exit hole

Figure 3.27

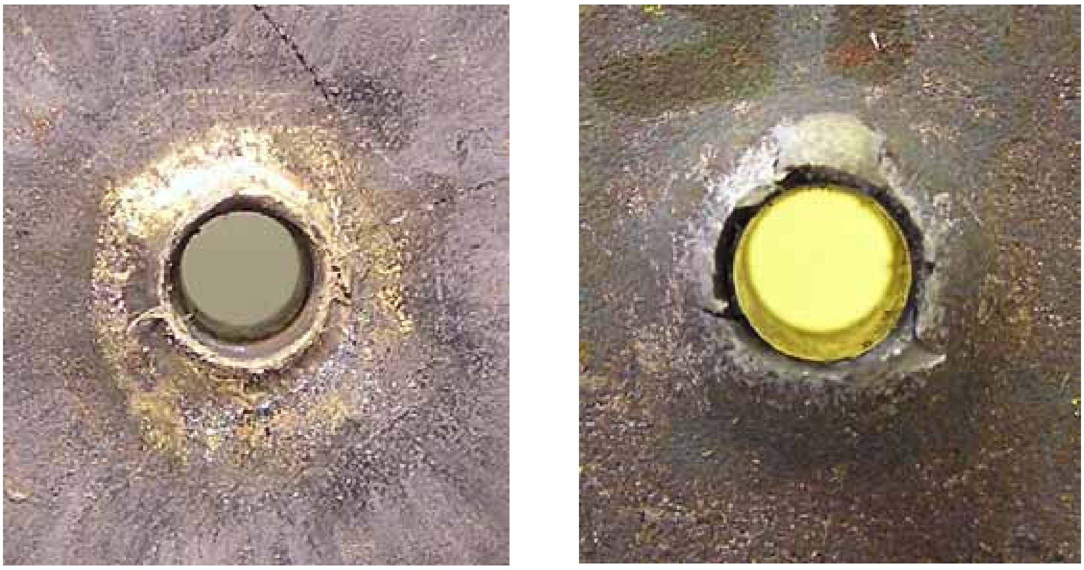
Witness plate

Figure 3.28

Hypothesis: The hard core has not been fractured but weakened before hitting the witness plate. At impact the rear part of the hard core fragmented, thus making the fine radial marks around the impression. A larger fragment from the hard core has ripped off a flake from the witness plate.

Shot no. 15

Target plate



Entry hole

Exit hole

Figure 3.29

Witness plate

Figure 3.30

Hypothesis: Fractured before impacting the witness plate. The indefinite mark in the witness plate strongly suggests this interpretation.

Shot no. 16

Target plate

Entry hole

Exit hole

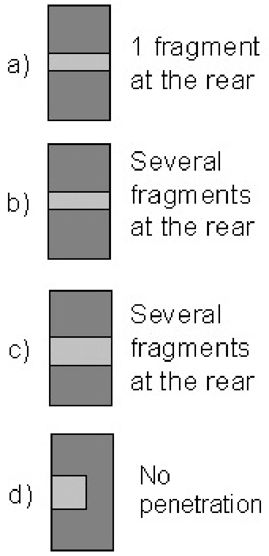
Figure 3.31

Witness plate

Figure 3.32

Hypothesis: Hard core was not fractured, but was weakened before impacting the witness plate. At impact with the witness plate, the rear part fragmented and the fragments made the small marks in the plate. The front part of the hard core fractured and was stuck in the plate.

3.3 Summary, 22 mm armour steel target



820 m/s: 8 shots, inert projectiles

- 4 cases of a), 2 did not fracture, 2 fractured in witness plate
- 4 cases of b), fractured before witness plate

Suggestion: Fracturing after exit.

950 m/s: 8 shots, inert projectiles

- 1 case of a), fractured in witness plate (b?)
- 3 cases of b), fractured before witness plate
- 4 cases of c), fractured in target
- 0 cases of d)

Suggestion: Fracturing in target or during exit.

The hard cores that supposedly fractured in the witness plate were most likely weakened before impact. The hard cores that supposedly fractured before witness plate, fractured on exit of the target plate or very late in the target plate.

Table 3.1 show calculated exit hole radii by assuming a constant entrance hole and an exit hole corresponding to the frustum of a cone. Shots 11-16, at a velocity of 820 m/s, are not shown in the table, but they give equal exit and entrance holes as shot 9 and 10. Exit holes with no deformation have a diameter of 3.5 mm. Shot no. 8 has the largest exit hole which is approximately twice the radius of the entrance hole. None of the shots at 820 m/s has deformed exit holes.

Date	Shot no.	Velocity [m/s]	Volume of hole [mL]	Exit hole radius [mm]*
26-Nov-2003	1	950	1.12	3.5
	2	950	1.12	3.5
	3	950	1.12	3.5
	4	950	1.6	4.7
	5	950	2.2	6.0
27-Nov-2003	6	950	1.12	3.5
	7	950	1.8	5.2
	8	950	2.9	7.1
1-Dec-2003	9	820	1.12	3.5
	10	820	1.12	3.5
	11	820	1.12	3.5
	12	820	1.12	3.5
	13	820	1.12	3.5
	14	820	1.12	3.5
	15	820	1.12	3.5
	16	820	1.12	3.5

*Table 3.1: Cavity volume in target. (*Calculated from volume measurements and an entry hole diameter set to 7 mm)*

Table 3.2 shows calculated radial expansion velocities of the fragments behind the target plate for MP 12.7 mm projectiles and inert projectiles. The shots in table 3.2 are not a part of the shooting series in chapter 3.1 and 3.2. The expansion velocity 1 correlate to distance 1 and so forth.

		Expansion area 1*		Expansion area 2**		Residual velocity [m/s]	Expansion velocity 1 [m/s]	Expansion velocity 2 [m/s]	Expansion velocity 3 [m/s]	Expansion velocity 4 [m/s]
Date	Ammunition	Distance 1 [cm]	Distance 2 [cm]	Distance 3 [cm]	Distance 4 [cm]					
11.11.2003	MP (penthrite)	5,3	4,3	2,2	0,8	400	59	48	24	9
"	MP (penthrite)	11,3	11,2	1,5	1,4	400	126	124	17	16
12.11.2003	MP-T (penthrite)	10	8,4	1,4	1,5	400	111	93	16	17
"	MP-T (penthrite)	6,5	10,7	1,3	1,7	400	72	119	14	19
"	MP-inert	5	8,4	0,6	1,8	400	56	93	7	20
"	MP-inert	5,6	4,1	1,1	1	400	62	46	12	11
"	MP-inert	Malfunction, failed to hit target plate								
"	MP-inert	6,4	8,5	2,7	2,3	400	71	94	30	26
"	MP-inert	6,2	4	2,6	2,6	400	69	44	29	29

Notes: *Expansion area 1: The whole area of fragment hits in the witness plate enclosed in a quadrangle area.

**Expansion area 2: The two largest penetration holes in the witness plate enclosed in a quadrangle area.

The distances are measured from the centre to each side of the quadrangle. All distances are in [cm]

Distance to witness plate 37 cm.

Table 3.2: Expansion of sintered WC-Co projectiles after penetration of armour steel plates

3.4 Shots with impact velocities of ~970 m/s at 40 mm armour steel targets

The figures below show the holes and the fragmentation pattern for the four shots with impact velocities of ~970 m/s against 40 mm armour steel targets (ARMOX 370).

Figure 3.33

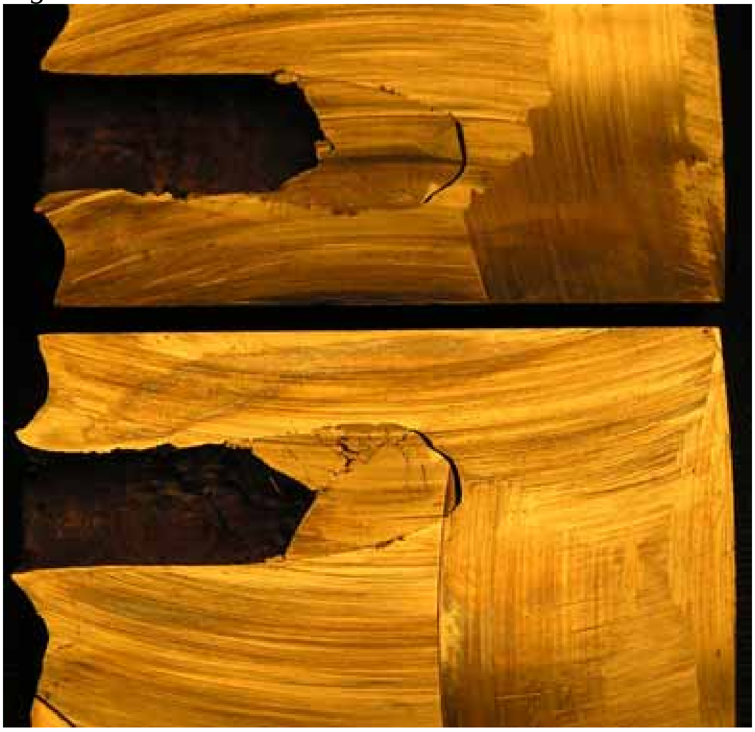


Figure 3.34

Figure 3.35

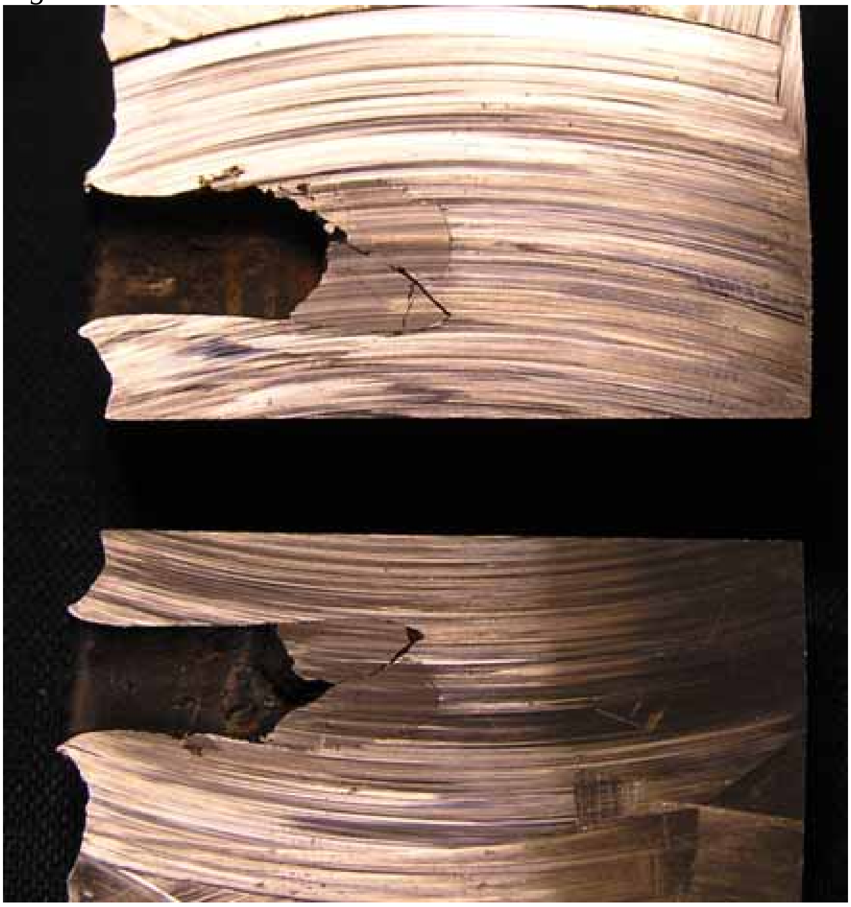


Figure 3.36

3.5 Shots with impact velocities of ~950 m/s at 40 mm armour steel targets

The figures below show the holes and the fragmentation pattern for the three shots with impact velocities of ~950 m/s against 40 mm armour steel targets (ARMOX 370).

Figure 3.37

Figure 3.38

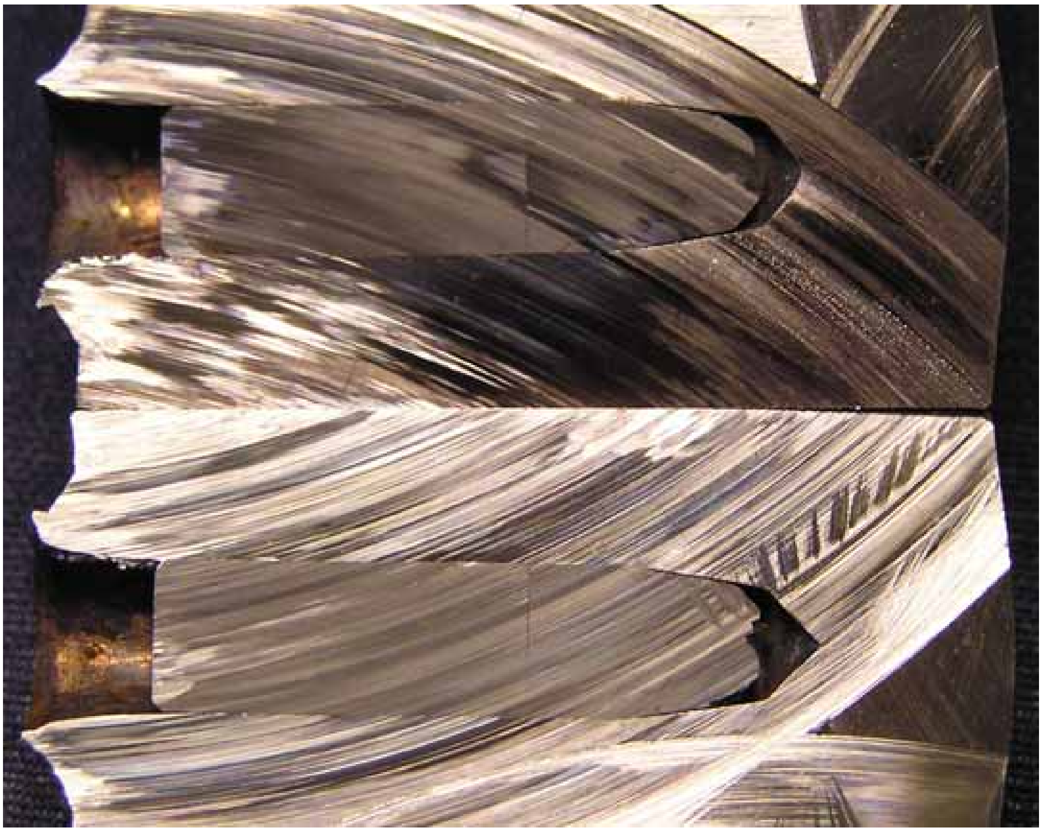


Figure 3.39

3.6 Shots with impact velocities of ~940 m/s at 40 mm armour steel targets

The figures below show the holes and the fragmentation pattern for the eight shots with impact velocities of ~940 m/s against 40 mm armour steel targets (ARMOX 370).

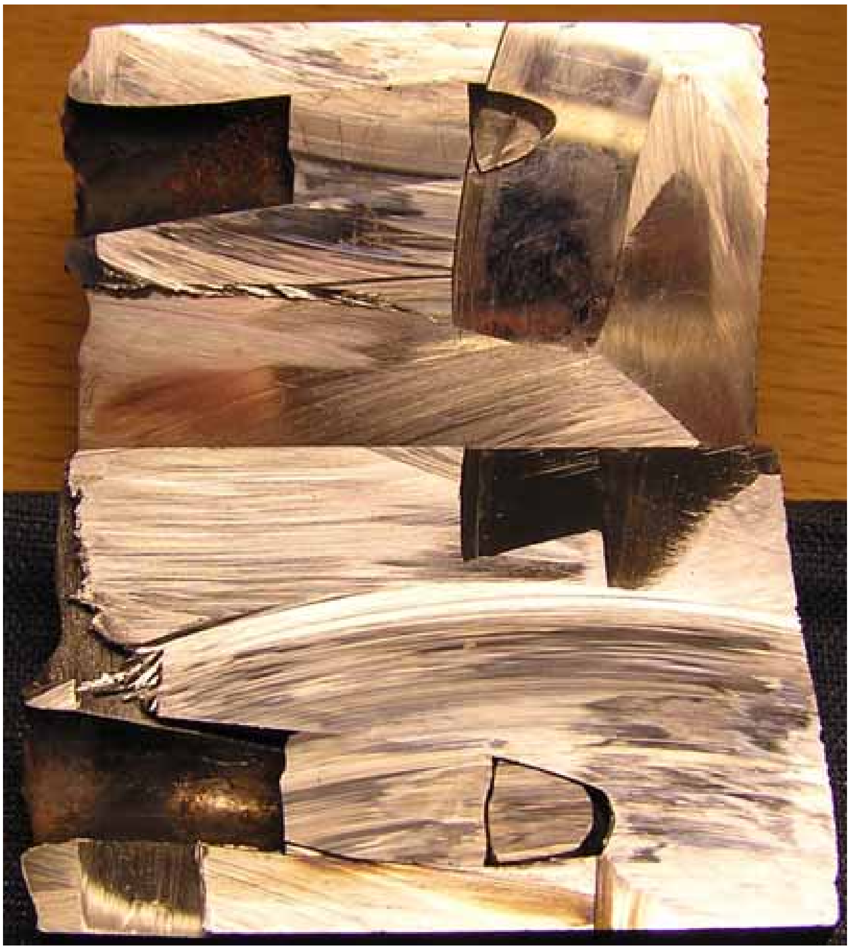


Figure 3.40

Figure 3.41

Figure 3.42

Figure 3.43

Figure 3.44

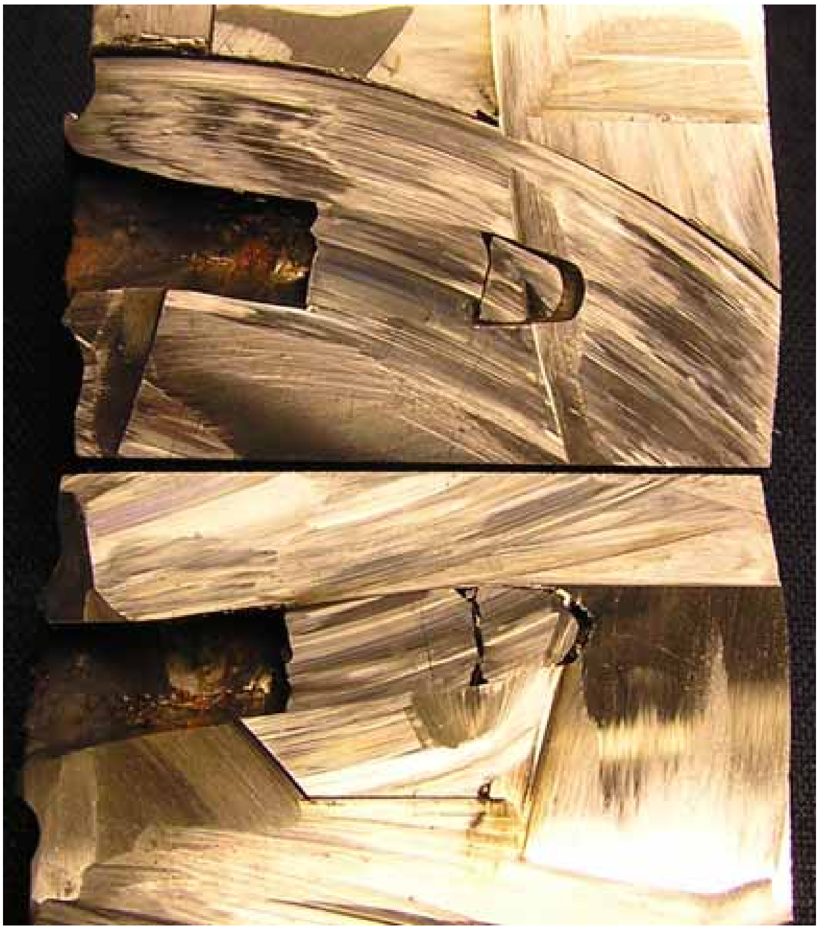


Figure 3.45

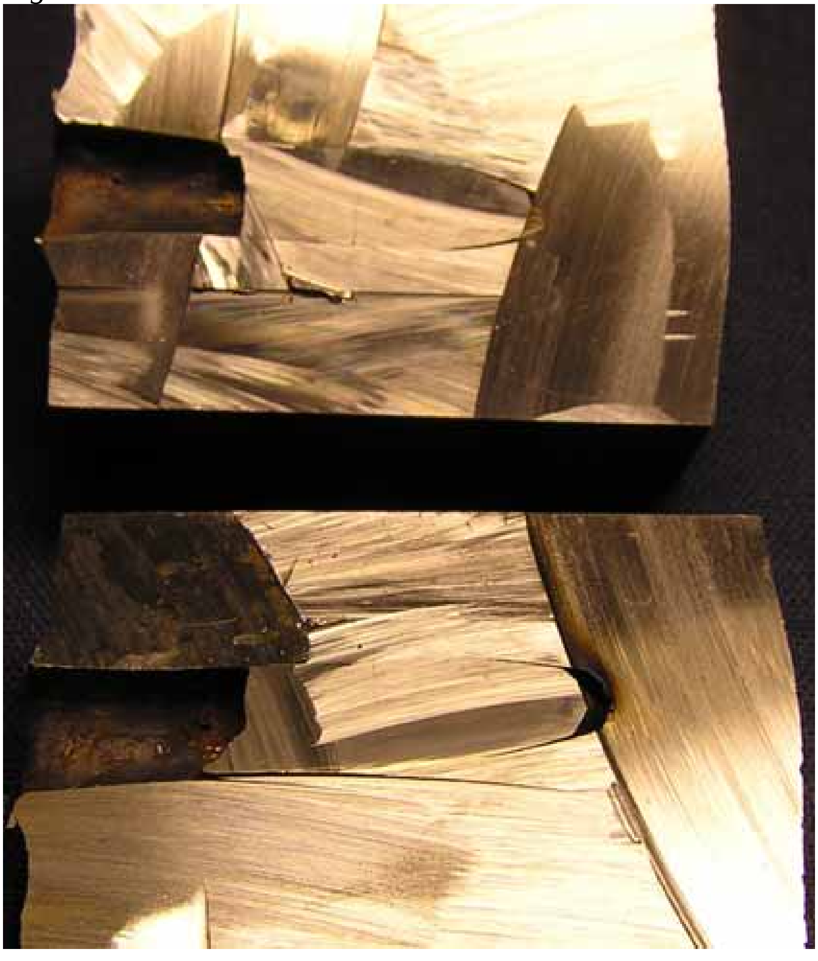


Figure 3.46

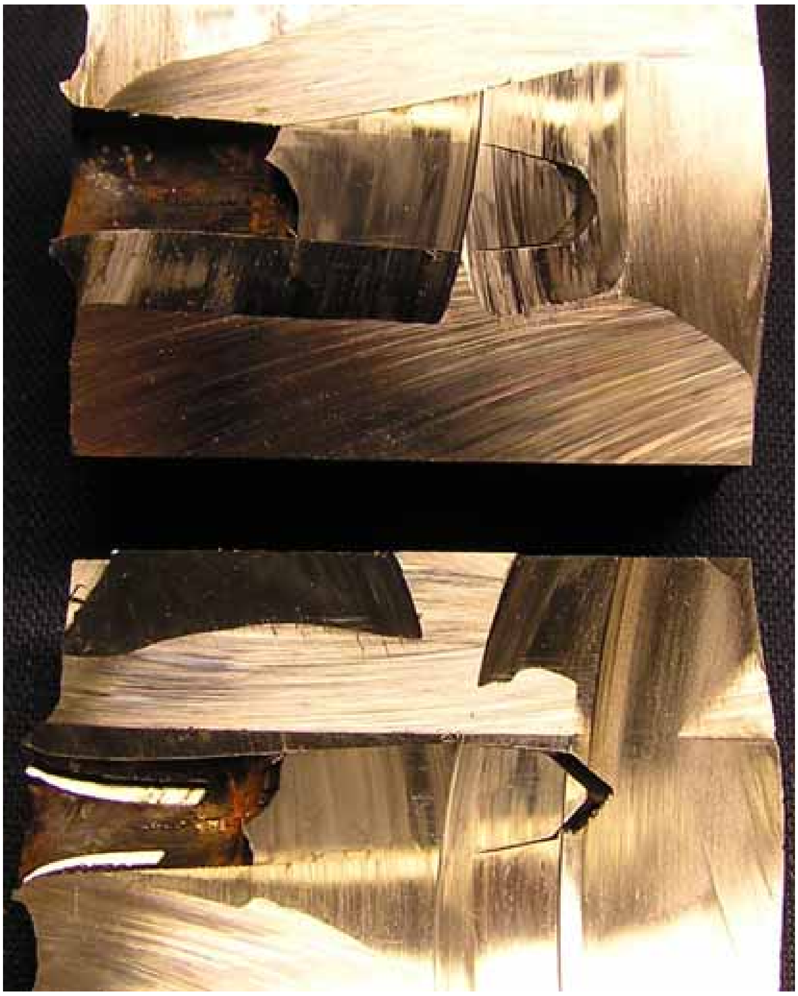


Figure 3.47

3.7 Shots with impact velocities of ~890 m/s at 40 mm armour steel targets

The figures below show the holes and the fragmentation pattern for the three shots with impact velocities of ~890 m/s against 40 mm armour steel targets (ARMOX 370).

Figure 3.48

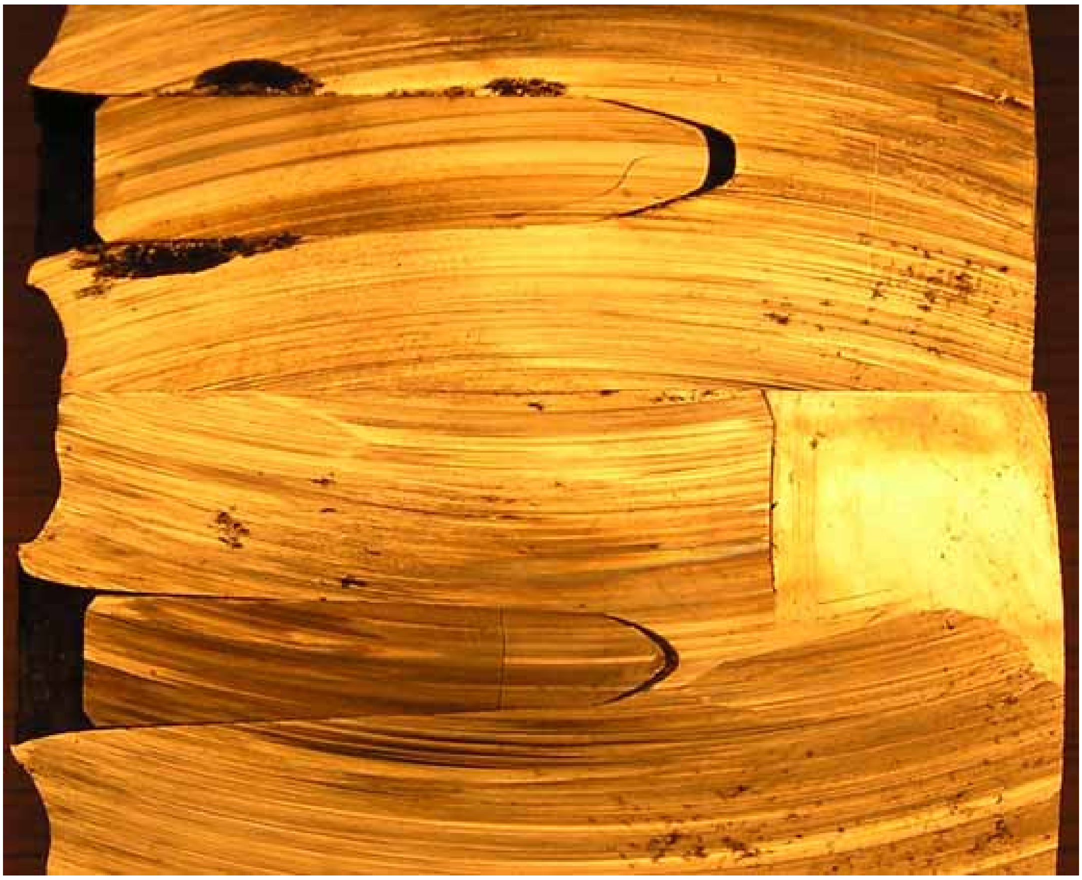


Figure 3.49

Figure 3.50

3.8 Shots with impact velocities of ~870 m/s at 40 mm armour steel targets

The figures below show the holes and the fragmentation pattern for the two shots with impact velocities of ~870 m/s against 40 mm armour steel targets (ARMOX 370).

Figure 3.51

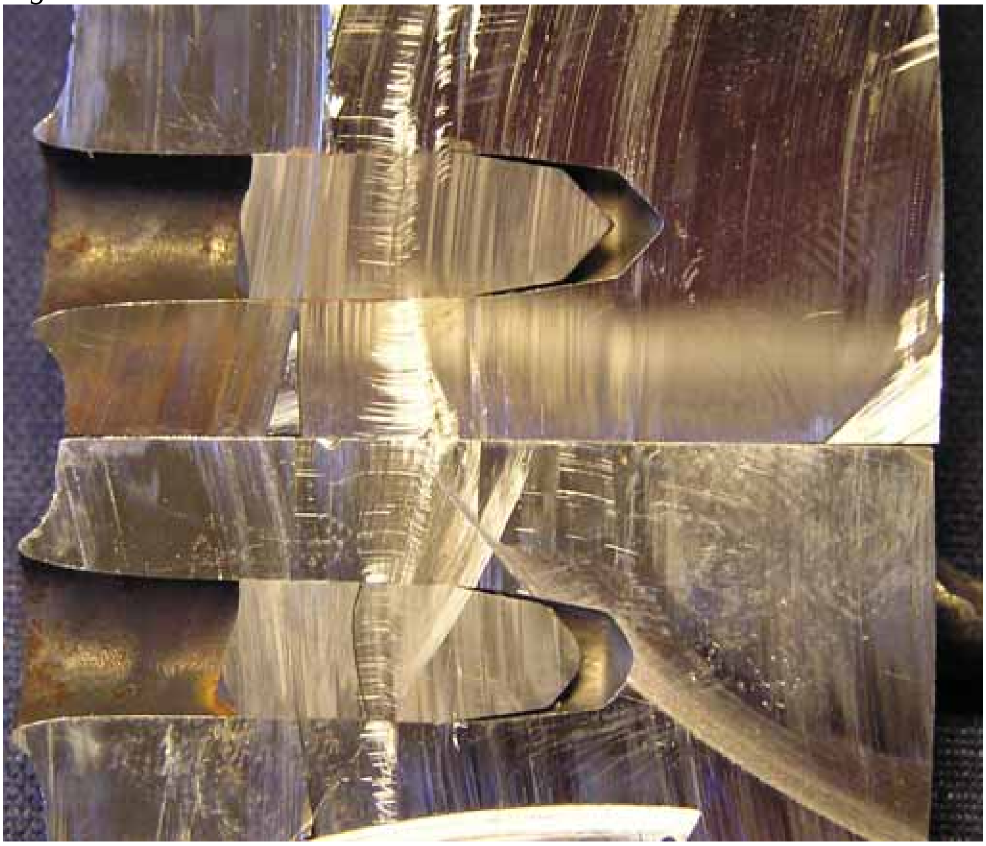


Figure 3.52

3.9 Shots with impact velocities of ~860 m/s at 40 mm armour steel targets

The figures below show the holes and the fragmentation pattern for the eight shots with impact velocities of ~860 m/s against 40 mm armour steel targets (ARMOX 370).

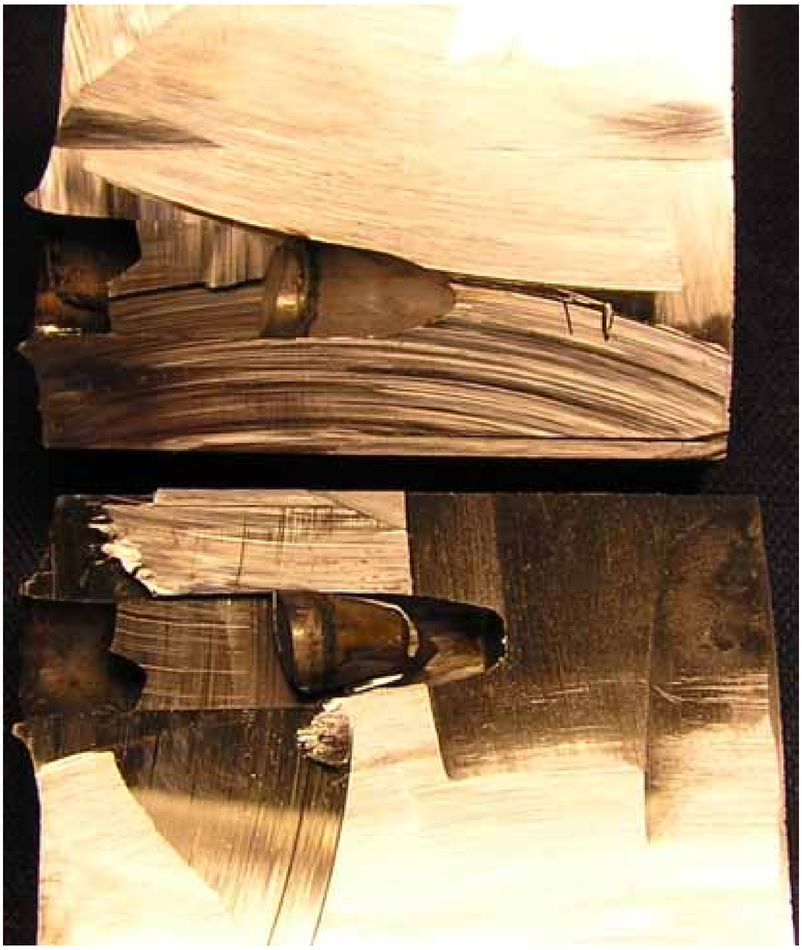


Figure 3.53

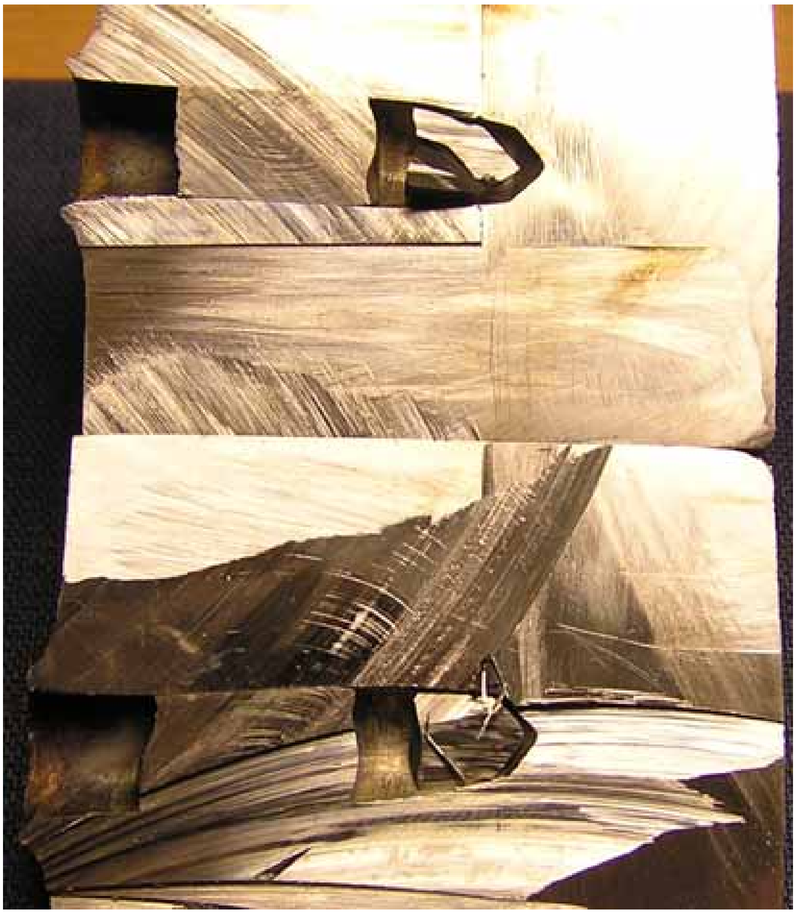


Figure 3.54

Figure 3.55

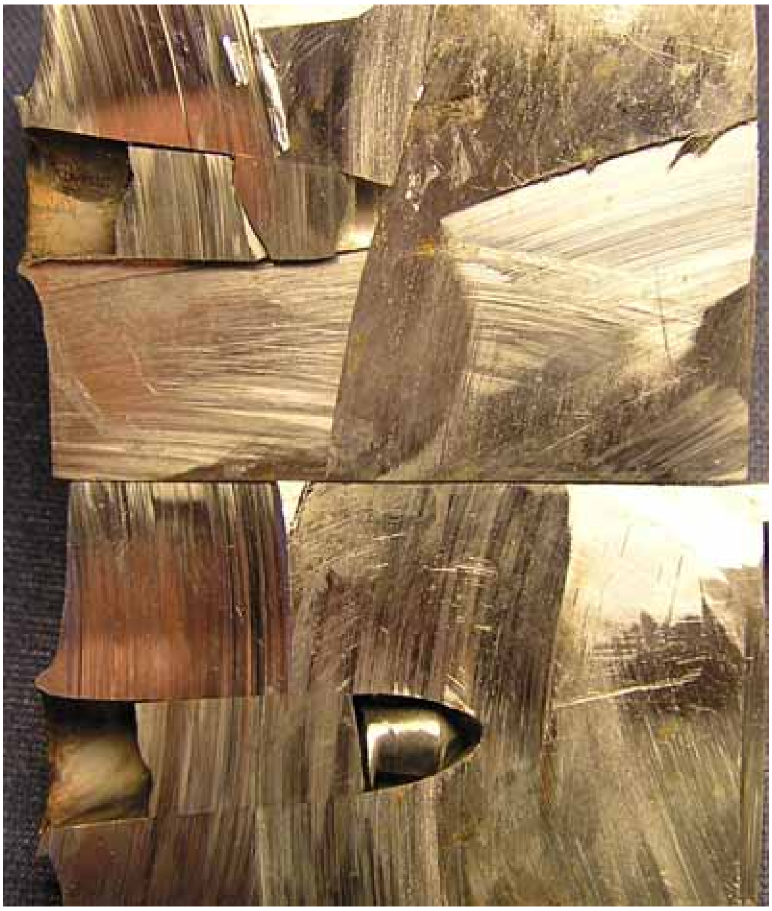


Figure 3.56

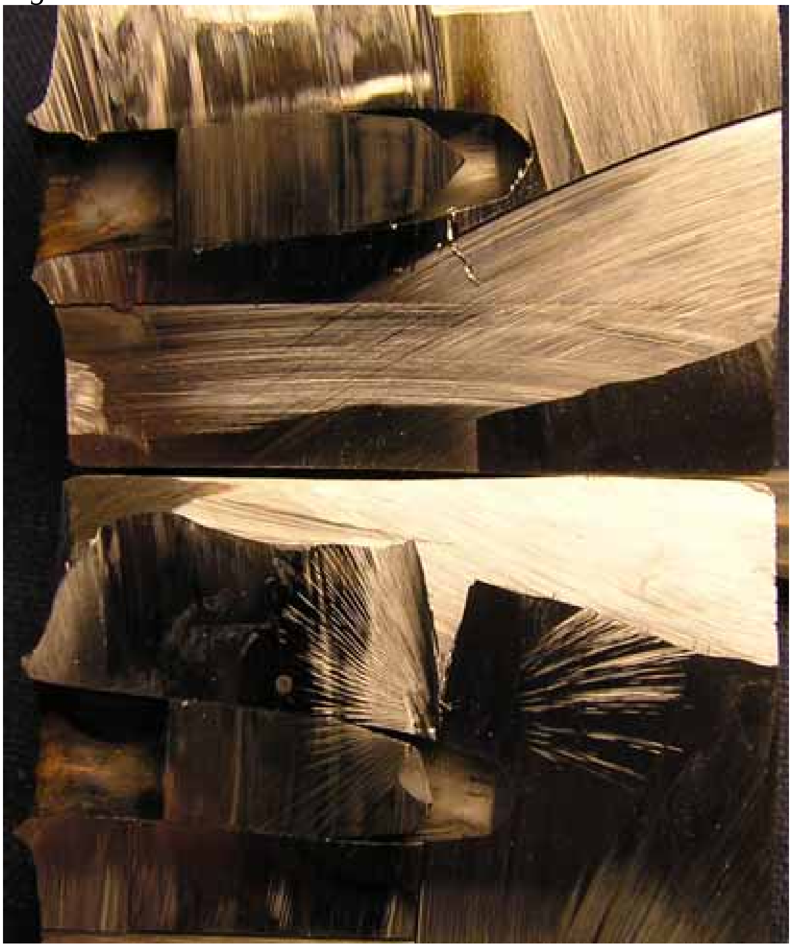


Figure 3.57

Figure 3.58

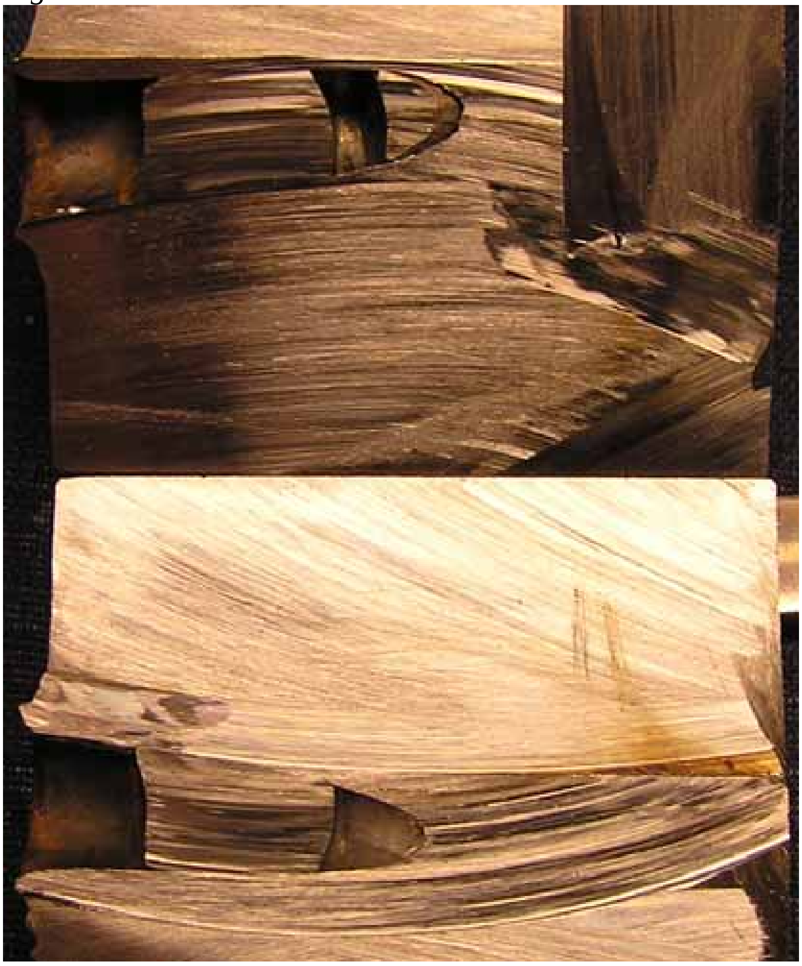


Figure 3.59

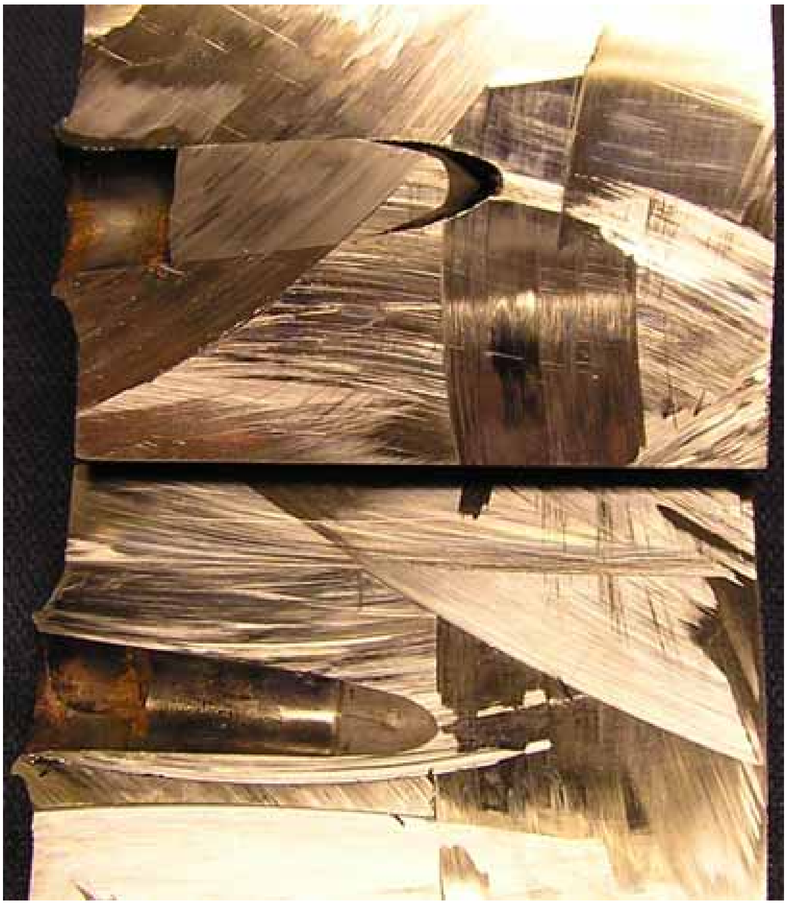


Figure 3.60

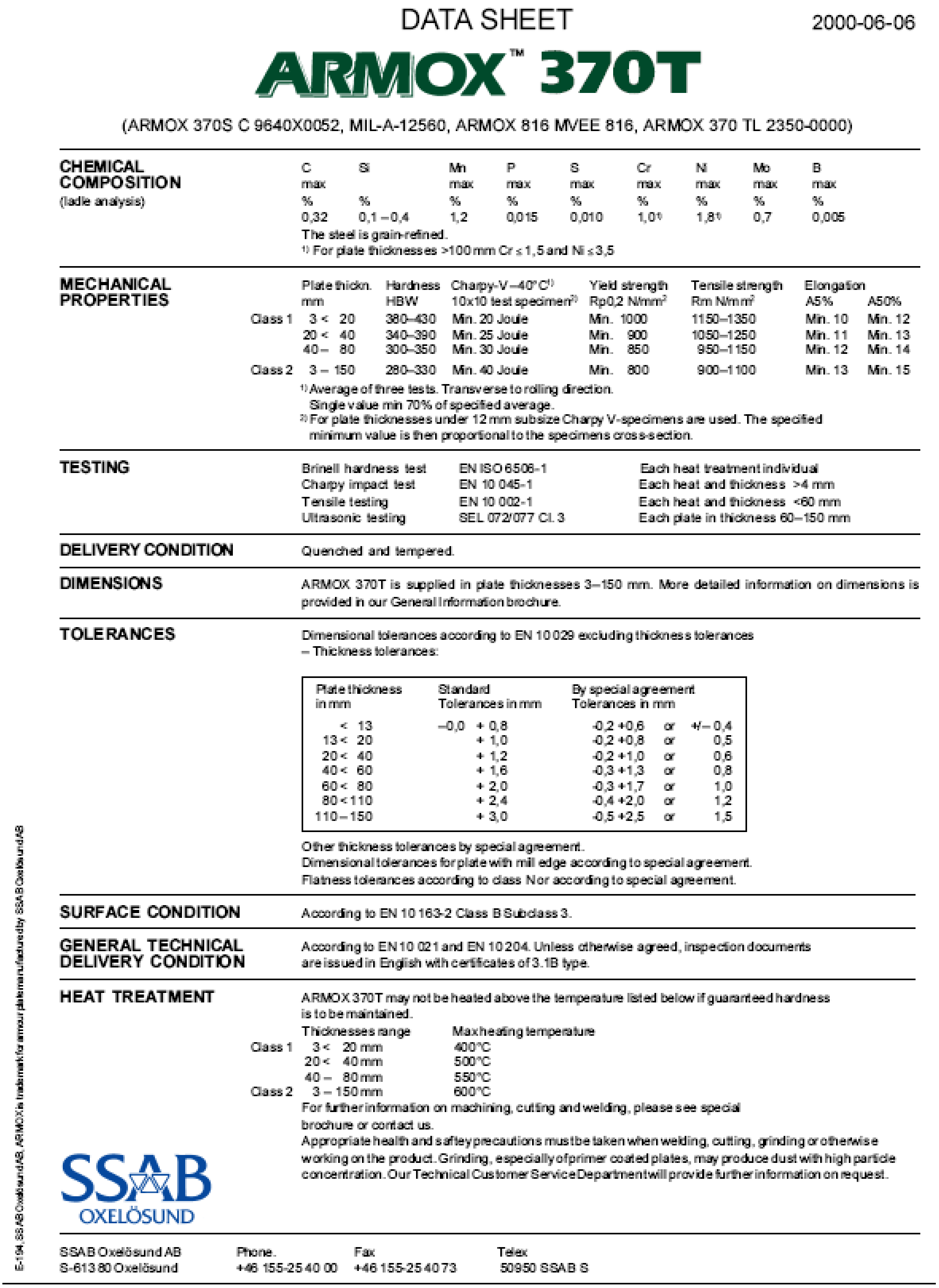
4 CONCLUSIONS

With an impact velocity of 950 m/s the hard core penetrated the 22 mm thick target, but it fractured. The fracturing most likely took place late in the target or during exit of the target. Thus, often the exit hole of the target where expanded compared to the entrance hole.
For an impact velocity of 820 m/s, the hard core also penetrated the target. The fracturing at this velocity most likely took place during exit of the target. The exit hole of the target was of the same size as the entrance hole. Also some shots (25 %) indicate undamaged hard cores. By studying the fragmentation pattern in the witness plate behind the target, we suggest that some of the hard cores were weakened due to the penetration through the target plate, but most likely appears as intact.
Above 950 m/s the hard core showed large plastic flow and fracturing in the 40 mm target. By comparing with the strength model of the hard core established from quasi-static compression experiments, we conclude that the strain rate dependency is small and most likely negligible.

In general the results indicate that the strength of the hardcore is marginal. The different penetrations scenarios could indicate that the penetration capabilities can be reduced when increasing the impact velocity above 950 m/s due to increased damaging of the hard core. Also increased target strength could reduce the penetration capability significantly.

APPENDIX

The armour steel plate has the following material properties



DATA SHEET

2000-06-06

ARMOX™ 370T

(ARMOX 370S C 9640X0052, MIL-A-12560, ARMOX 816 MVEE 816, ARMOX 370 TL 2350-0000)

CHEMICAL COMPOSITION

(ladle analysis)

C max %	Si %	Mn max %	P max %	S max %	Cr max %	Ni max %	Mo max %	B max %
0,32	0,1 – 0,4	1,2	0,015	0,010	1,0[1]	1,8[1]	0,7	0,005

The steel is grain-refined.

[1] For plate thicknesses >100 mm Cr ≤ 1,5 and Ni ≤ 3,5

MECHANICAL PROPERTIES

	Plate thickn. mm	Hardness HBW	Charpy-V –40°C[1] 10x10 test specimen[2]	Yield strength Rp0,2 N/mm²	Tensile strength Rm N/mm²	Elongation A5%	A50%
Class 1	3 < 20	380–430	Min. 20 Joule	Min. 1000	1150–1350	Min. 10	Min. 12
	20 < 40	340–390	Min. 25 Joule	Min. 900	1050–1250	Min. 11	Min. 13
	40 – 80	300–350	Min. 30 Joule	Min. 850	950–1150	Min. 12	Min. 14
Class 2	3 – 150	280–330	Min. 40 Joule	Min. 800	900–1100	Min. 13	Min. 15

[1] Average of three tests. Transverse to rolling direction. Single value min 70% of specified average.

[2] For plate thicknesses under 12 mm subsize Charpy V-specimens are used. The specified minimum value is then proportional to the specimens cross-section.

TESTING

Brinell hardness test	EN ISO 6506-1	Each heat treatment individual
Charpy impact test	EN 10 045-1	Each heat and thickness >4 mm
Tensile testing	EN 10 002-1	Each heat and thickness <60 mm
Ultrasonic testing	SEL 072/077 Cl. 3	Each plate in thickness 60–150 mm

DELIVERY CONDITION

Quenched and tempered.

DIMENSIONS

ARMOX 370T is supplied in plate thicknesses 3–150 mm. More detailed information on dimensions is provided in our General Information brochure.

TOLERANCES

Dimensional tolerances according to EN 10 029 excluding thickness tolerances
– Thickness tolerances:

Plate thickness in mm	Standard Tolerances in mm		By special agreement Tolerances in mm		
< 13	–0,0	+ 0,8	-0,2 +0,6	or	+/– 0,4
13 < 20		+ 1,0	-0,2 +0,8	or	0,5
20 < 40		+ 1,2	-0,2 +1,0	or	0,6
40 < 60		+ 1,6	-0,3 +1,3	or	0,8
60 < 80		+ 2,0	-0,3 +1,7	or	1,0
80 < 110		+ 2,4	-0,4 +2,0	or	1,2
110 – 150		+ 3,0	-0,5 +2,5	or	1,5

Other thickness tolerances by special agreement.
Dimensional tolerances for plate with mill edge according to special agreement.
Flatness tolerances according to class N or according to special agreement.

SURFACE CONDITION

According to EN 10 163-2 Class B Subclass 3.

GENERAL TECHNICAL DELIVERY CONDITION

According to EN 10 021 and EN 10 204. Unless otherwise agreed, inspection documents are issued in English with certificates of 3.1B type.

HEAT TREATMENT

ARMOX 370T may not be heated above the temperature listed below if guaranteed hardness is to be maintained.

	Thicknesses range	Max heating temperature
Class 1	3 < 20 mm	400°C
	20 < 40 mm	500°C
	40 – 80 mm	550°C
Class 2	3 – 150 mm	600°C

For further information on machining, cutting and welding, please see special brochure or contact us.

Appropriate health and saftey precautions must be taken when welding, cutting, grinding or otherwise working on the product. Grinding, especially of primer coated plates, may produce dust with high particle concentration. Our Technical Customer Service Department will provide further information on request.

SSAB OXELÖSUND

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