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Metallurgical Investigation of HSLA Steel Subjected to Underwater Explosion

The metallurgical behaviour of HSLA steel subjected to underwater explosion is of prime importance because of its structural applications in underwater vehicles. HSLA steel plates 300 × 250 × 4 mm were subjected to single and repetitive shock loadings and the point of rupture was identified. Test plates exhibited mode-I (large ductile deformation) and mode-II (tensile tearing) macroscopic failures. Electron micrographic and fractographic examination showed that the initiation of fracture was due to adiabatic shearing and the microscopic mode of failure was ductile. Plates subjected to single shock showed an increase in residual hardness and at the point of rupture it was approximately one-third higher than the initial residual hardness.

INTRODUCTION

The ability of a material to withstand large plastic deformation before it fractures is a major criterion in underwater structural applications (Sumpter, 1987). The Explosion Bulge Test (EBT) has been used as the final qualification test to verify the dynamic plasticity of structural materials (Porter, 1988). Explosive loading promotes brittle fracture by taking advantage of the high strain rate influence on the material's flow properties (Ahmad, Wong, and Porter, 1989). Performance of steel plates and weldments subjected to a high level of dynamic plastic deformation from explosive shock has been studied extensively by various authors. Early research on the explosive response of ship steel was carried out by Fox (1950) at the Admiralty Research Establishment (ARE), United Kingdom, by subjecting air-backed plates to underwater shock loading. Subsequent work on the response of weldments of low alloy, high tensile, firebox steel, fully killed mild steel, and silicon killed firebox steel was done by Hartbower and Pellini (1951a,b) at the Naval Research Laboratory (NRL), USA. MIL-STD-2149A (SH) (1990) formulated by the U.S. Navy recommends airblast as the source of explosive energy to evaluate the resistance of the base material and the weldments to fracture under rapid loading conditions. It also recommends repetitive shock loading on the test plate with a reduction in thickness for each shot until final strain to fracture. Defence Research Establishment Atlantic (DREA), Canada, and ARE independently developed underwater EBT to minimise the charge and the environmental noise nuisance. DREA adopted the concept of single shot to qualification to avoid the influence of change in material properties during intermediate deformation steps (Ahmad et al., 1989), whereas ARE studied the propagation of dynamic cracks in fatigue precracked notched

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submarine weld panels using the Flawed Bulge Explosion Test (FBET) (Sumpter, 1991).

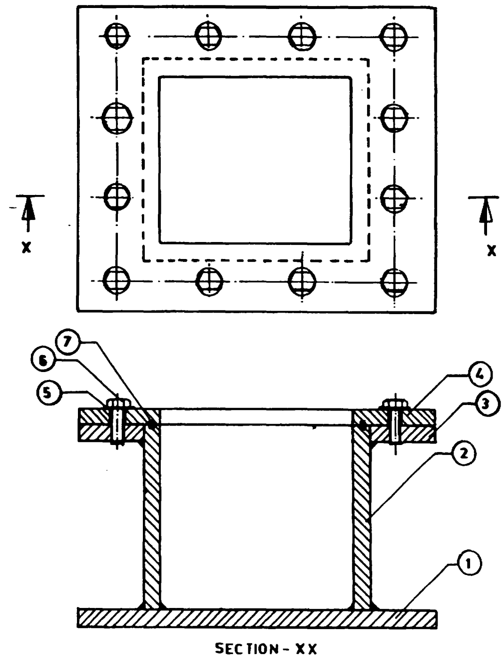
In this work, underwater EBT was carried out on high strength, low alloy (HSLA) steel plates of 4-mm thickness. The experimental work was planned in two stages to study the possible dynamic deformation processes of the material. In the first stage, a single shot was exploded against separate plates with increasing charge weight until fracture. In the second stage, successive shots of increasing shock intensity were exploded on a single plate until fracture.

Plates subjected to both single and repetitive shock exhibited mode-I (large ductile deformation) macroscopic fracture and there was a shift to mode-II (tensile-tearing) macroscopic fracture as the peak pressure increased, as observed by Olson, Nurick, and Fagnon (1993). Plates subjected to repetitive shots failed at almost half the plastic strain of the plates failed in single shock. In addition, just before fracture, the depth of bulge at the apex of the plate in single shot was considerably larger when compared to that of repetitive shock. This shows that there is loss of ductility after shock loading due to work hardening of the plate. Hence, the change in residual hardness of the plates subjected to single shock was measured to study the behaviour of shock hardening. Electron micrography and fractography were carried out to understand the mechanism of failure.

EXPERIMENTAL

The HSLA steel used in this investigation was cold-rolled, not heat treated (chemical composition and mechanical properties are given in Table 1).

The schematic of the box model fixture used for the underwater EBT is shown in Fig. 1. The test plate (550 × 450 × 4 mm) was inserted between top plate I and II with an exposed area of 300 × 250 mm and clamped with case hardened bolts and nuts. A rubber gasket was provided between the top plate-I and the test plate to prevent water leaking into the assembly. The photographic view of the assembly is shown in Fig. 2.



1. BOTTOM PLATE
2. RECTANGULAR BOX
3. TOP PLATE-I
4. TOP PLATE-II
5. WASHER
6. HEXAGONAL BOLT
7. RUBBER GASKET

FIGURE 1 Schematic of the EBT fixture.

PEK-1 (1.19 TNT equivalent) explosive was used for all tests and the detonation was by an electronic detonator. The explosive was weighed, shaped to a cylinder, inserted into a plastic container, and positioned from the charge holder (angle projecting from the fixture) at the

Table 1. Chemical and Mechanical Properties of HSLA Steel

Chemical Composition (Wt. %)							
C	Mn	Ni	Cr	S	Si	Cu	P
0.12	0.6–0.8	0.8–1.1	0.6–0.9	0.035 max	0.5–0.8	0.4–0.65	0.35 max

Mechanical Properties		
σ_y(MPa)	σ_u(MPa)	Elongation (%)
400	560	32.58

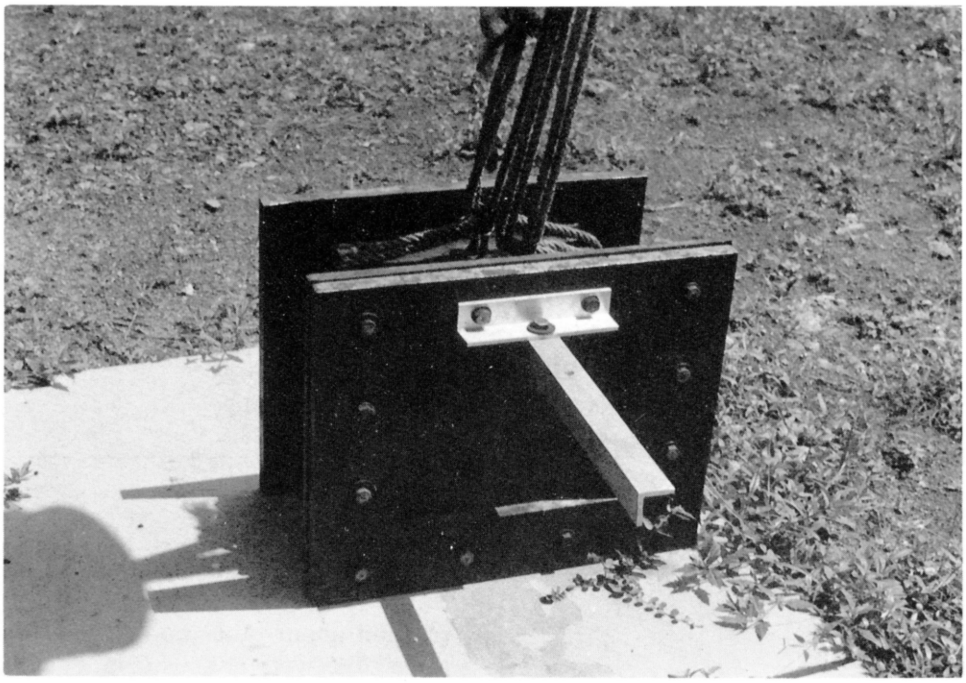


FIGURE 2 Photographic view of the EBT fixture.

required stand-off of 150 mm with the centre of gravity of the explosive coinciding with the centre of gravity of the plate. The electronic detonator was then inserted into the explosive with the firing cable leading to the firing circuit located in a control room at a distance of 50 m from the underwater shock tank. The whole set-up was immersed into the shock tank (15 × 12 × 10 m).

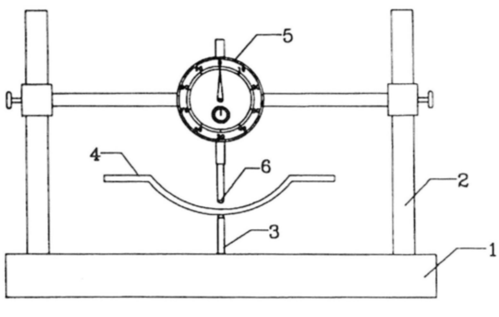
EBT assembly was taken out of the shock tank after each explosion, brought to the preparation bay, dismantled, and the test plate was removed. A special dial gauge (with an accuracy of 0.01 mm) arrangement was made on the existing shock test machine (MTS-886-360A). The depth of bulge and reduction in thickness of the plate were measured as shown in Fig. 3.

Peak pressure of the shock wave incident on the test plate was calculated using the empirical formula given by Cole (1948)

$$P_{\max} = 55\left(\frac{W^{1/3}}{R}\right)^{1.13} \qquad (1)$$

where $P_{\max}$ is peak pressure in MPa, W is (the TNT equivalent of) charge weight in kg, and R is stand-off in m.

Samples were prepared from fractured surfaces for scanning electron microscopic (SEM) fractographic examinations. Samples were also prepared from the fractured edges by polishing and etching with 2% nital solution for observing adiabatic shear. A JEOL model T330 scanning electron microscope (SEM) was used. Samples were made from the apex of the plates subjected to single shock and their hardness was measured using a Vickers Crayford Kent instrument.



1. TABLE 2. SUPPORT COLUMN
3. SUPPORT PIN 4. TEST PLATE
5. DIAL GAUGE 6. PROBE

FIGURE 3 Schematic of the dial gauge set up for thickness and bulge depth measurement of exploded plate.

Table 2. Rupture Results of HSLA Steel

Shot No.	PEK-1 Weight (g)	P_{max} (MPa)	Depth of Bulge (mm) Single Shot	Depth of Bulge (mm) Repetitive Shot	Thinning (%) Single Shot	Thinning (%) Repetitive Shot
1	5	64	12	12	1.25	1.25
2	10	83	23	23	2.50	2.50
3	15	96	26	29	3.75	4.00
4	20	108	32	33	4.75	4.75
5	30	125	46	47	6.25	7.50
6	40	139	50	58	7.25	10.00
7	50	151	52	—	12.50	12.00[a]
8	60	162	65	—	16.25	—
9	70	172	72	—	21.25	—
10	80	194		—	22.50[a]	—

[a]Plate ruptured.

RESULTS AND DISCUSSION

Rupture

The underwater EBT results on HSLA steel plates are summarised in Table 2. A series of photographs of the test plates subjected to single shock loading is shown in Fig. 4. On close examination of the boundary lines, there is evidence of shear lift of the top surface that corresponds to mode-I macroscopic fracture as observed by Olson et al. (1993). Initiation of mode-II macroscopic fracture along a side is observed in Fig. 5 and corresponds to rupture of the plate subjected to single shock and a peak pressure of 193.5 MPa. Tearing on a corner and two sides with rotation about other corners and tearing of all three sides were noticed (Fig. 6) and correspond to mode-II fracture in repetitive shock.

For single and repetitive shock the reductions in thickness after rupture were 22.5 and 12%, respectively. Percentage reduction of thickness of the plates as a function of depth of bulge is shown in Fig. 7, and it can be observed that the depths of bulge before rupture were 72 mm in single shock and 58 mm in repetitive shock. The inferior plastic deformation performance of the plate subjected to repetitive shock is due to the

FIGURE 4 Mode-I fracture in single explosive loading.

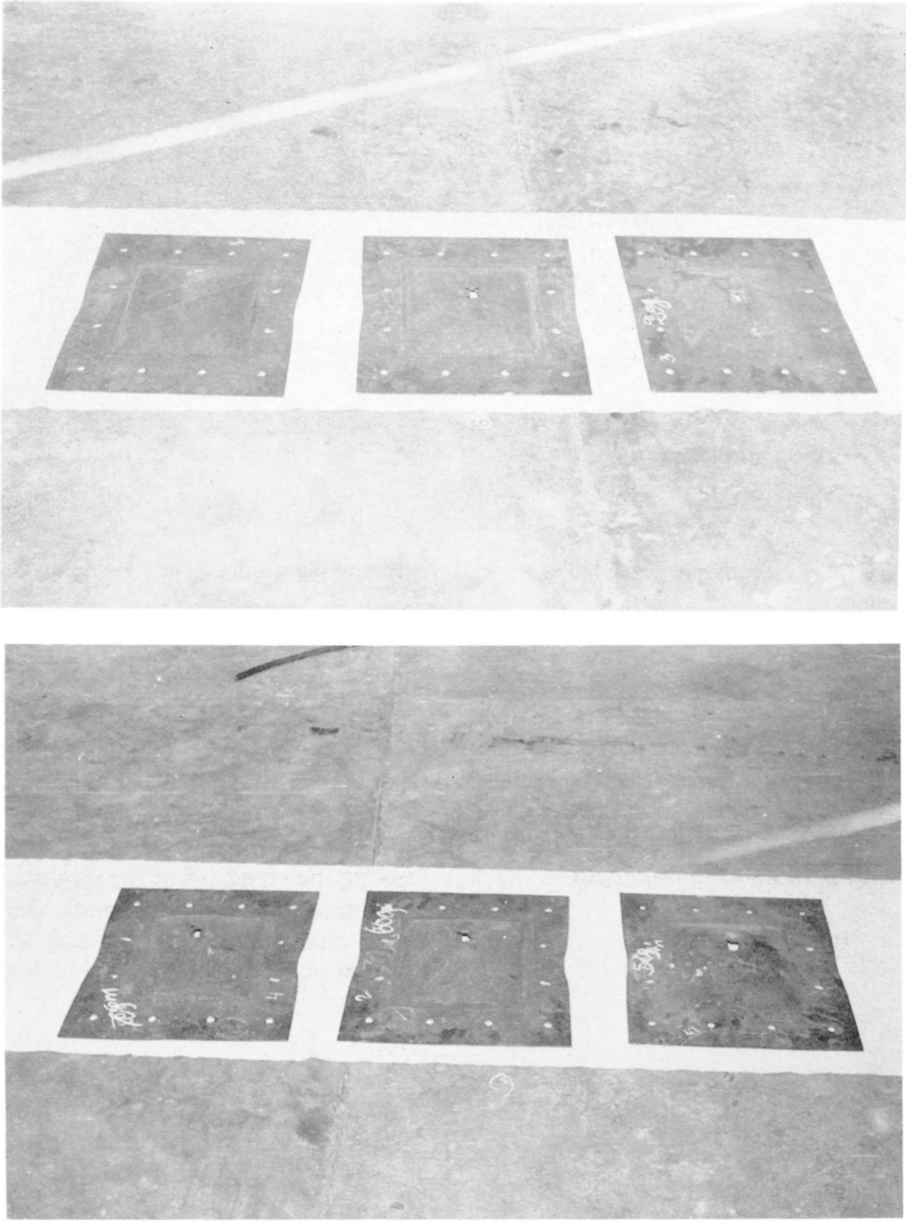


FIGURE 4 (*Continued*)

fact that after each explosion the plate was work hardened (Murr, 1983) resulting in increased flow stress and decreased ductility. The immediate conclusion that can be derived is that the MIL-STD-2149 (SH) standard is conservative in its approach. Further, from Fig. 7 it can be observed that the depth of bulge and the reducton in thickness are almost linear in relation to repetitive shock and parabolic in relation to single shock. The empirical relations governing the deformation characteristics are given by

$$T = 0.195D - 1.554 \quad \text{for repetitive shock} \quad (2)$$

and

$$T = 0.0024D^2 + 0.171D - 3.86 \quad \text{for single shock} \quad (3)$$

where T is the percentage thinning and D is the depth of bulge at the apex of the exploded plate in mm.

The effect of peak pressure on the depth of the bulge for single and repetitive shock is shown in Fig. 8 for which the empirical relation is

$$D = 0.55P_{\max} - 22.17. \quad (4)$$

FIGURE 5 Tearing at one edge in mode-II fracture of plate subjected to single explosive loading.

From Eq. (4) it can be inferred that there exists a threshold peak pressure (40.3 MPa) for which the depth of bulge is zero. In other words, the permanent deflection of the plate takes place only above this peak pressure. Substituting this in Eq. (1), the following parameter is obtained:

$$\left(\frac{W^{1/3}}{R}\right) = 0.7594. \tag{5}$$

This nondimensional number, which may be called a dynamic yield number (DYN), is material, thickness, and fixture specific and can be used for evaluating the onset of dynamic yield for the given explosive and stand-off. For example, taking the stand-off of the explosion experiments as reference value (150 mm), the weight of the TNT charge explosive that can set dynamic yield is 1.48 g. Alternately, if the value of $(W^{1/3}/R)$ is

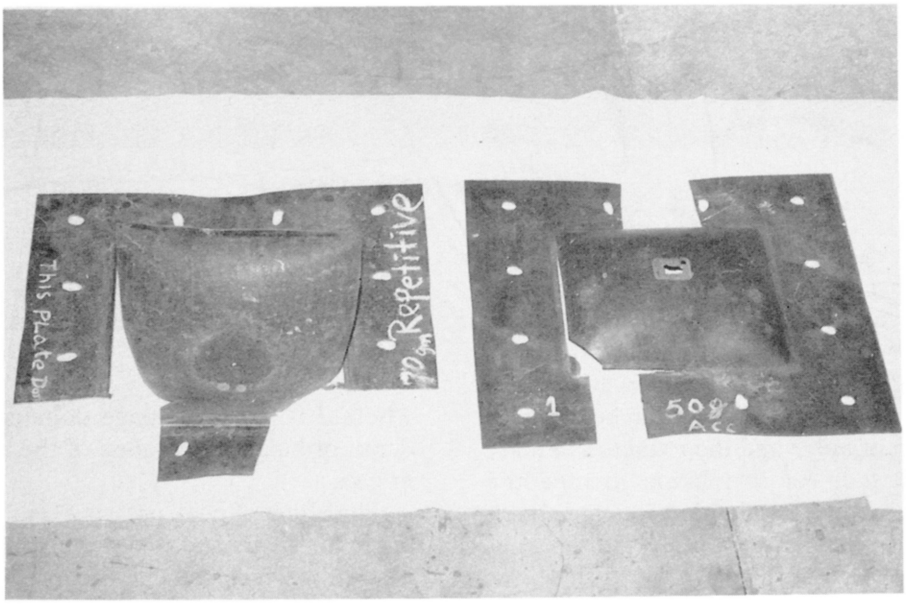


FIGURE 6 Mode-II fracture of plates subjected to repetitive shock.

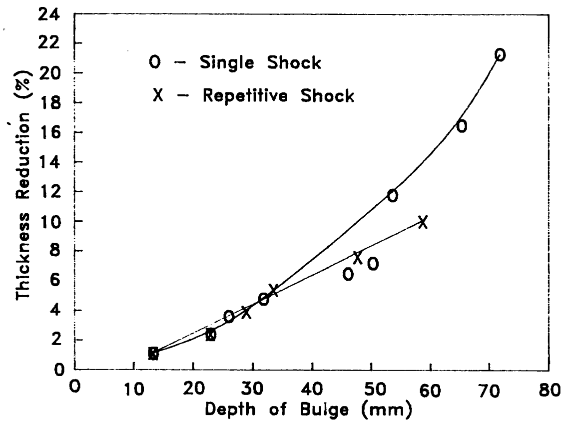


FIGURE 7 Dependence of percentage thinning on depth of bulge for single and repetitive shock.

less than DYN, the explosive response of the material is within its yield limit. If $(w^{1/3}/R)$ is more than DYN, the permanent deformation is set in the material.

Adiabatic Shear

The deformation of the test plate during explosive loading is a rapid process that introduces a high rate of strain. The work of plastic deformation during explosive loading is converted almost entirely into heat that is not dissipated to the surroundings due to short duration and raises the temperature in the strain concentrated zones of microstructure. The plate under dynamic loading experiences thermoplastic instability because the flow stress increment due to work hardening is compensated by the flow stress decrement due to thermal softening as observed by Sundararajan (1984). Aided by this flow instability, localisation of strain takes place within a band of microstructural inhomogeneity that leads to permanent fracture. Formation and propagation of a crack and multiple crack propagation at the edge of the exposed area of the plate due to adiabatic shear are shown in Fig. 9 (a, b). It was observed that microstructural features are different at the shear cracks. This is because the molten metal rapidly solidified at phases that are different from the parent material. Physical observation of the fractured edges showed a brownish yellow colour suggesting heavy oxidation during melting.

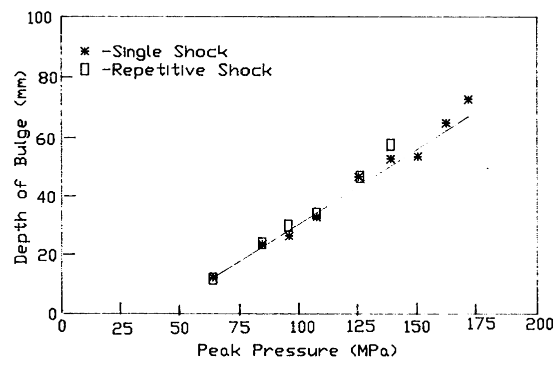


FIGURE 8 Dependence of depth of bulge on peak pressure for single and repetitive shock.

Fractography

The fractography of the plates failed in repetitive shock is shown in Fig. 10. It is observed in Fig. 10(a) that void and inclusion of a hexagonal particle served as microcrack nucleation sites. The growth of microvoids and their coalescence is observed as dimple features in Fig. 10(b). These characteristic features show that the test plate failed in the ductile mode, absorbing an enormous amount of energy before fracture (Dieter, 1988). Ductile failure is obviously desirable from the ship designer's point of view because the resistance of the plate material to underwater explosive damage depends on its ability to absorb energy and undergo large plastic deformation before the onset of fracture (Sumpter, 1987). The transition from the ductile to brittle mode of fracture during explosive loading is influenced tremendously by lowering the test temperature as observed by Sumpter (1991). However, studying the effect of temperature on the material under investigation is beyond the intended scope of this work.

Shock Hardening

Shock loading, different from conventional loading (Murr, 1983), results in significant hardening and strengthening that arises from shock wave propagation while the residual strains are small. There is a particular residual hardness associated with the plate after passage of a particular intensity of shock wave. The dependence of residual hardness on peak pressure is shown in Table 3 and Fig. 11. It was observed that there was an increase in hardness from 1700 to 2280 MPa for plates subjected to single shock, which is nearly 35%. The reduced ductility of the plate subjected to repetitive shock loading was attributed to shock hardening associated with plastic deforma-

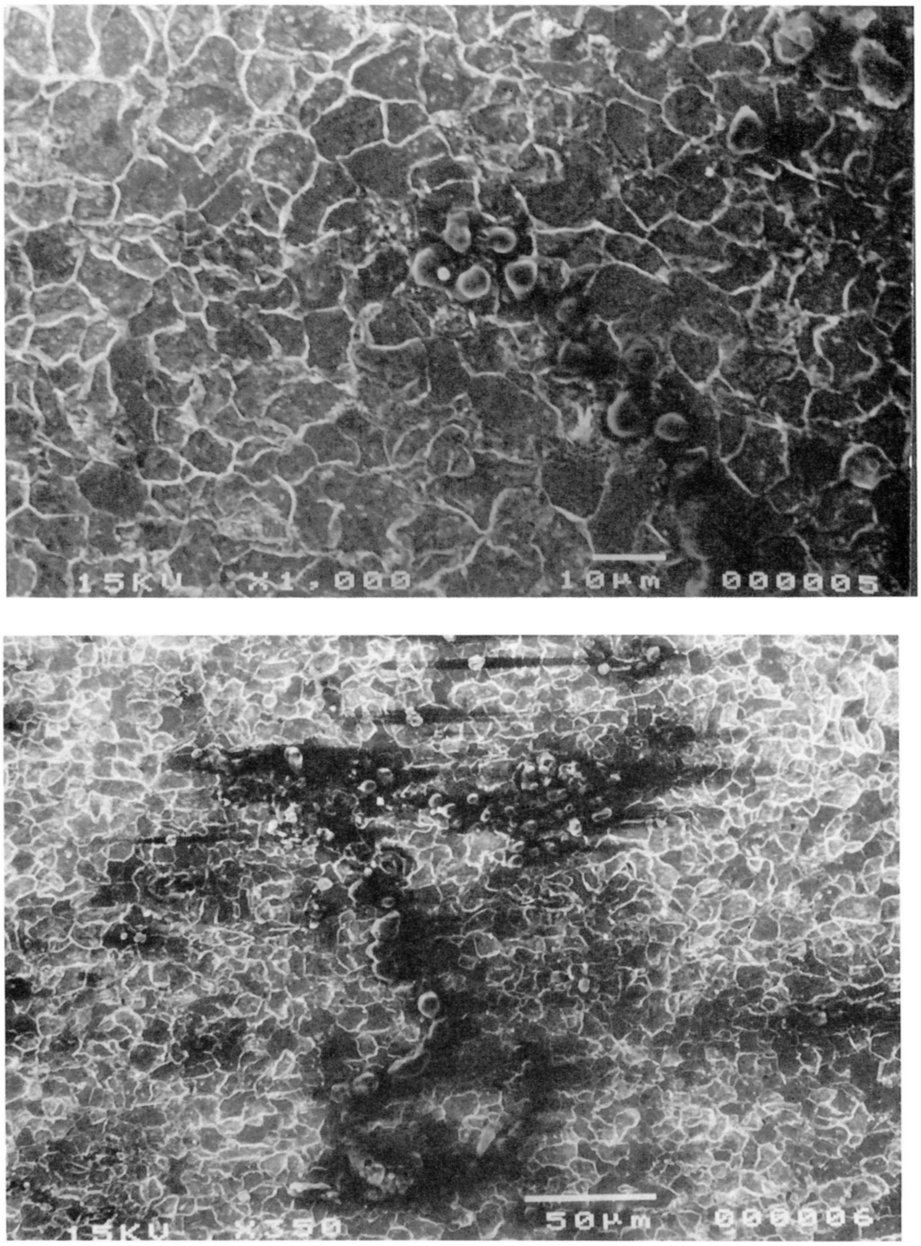


FIGURE 9 Scanning electron micrograph of adiabatic shear: (a) initiation and propagation of a crack and (b) multiple crack propagation.

Table 3. Shock Hardening Effects on HSLA Steel

Sl. No.	P_{max} (MPa)	Vickers Hardness (MPa)
1	0	1700
2	83	1720
3	96	1770
4	108	2090
5	125	2130
6	139	2180
7	151	2250
8	162	2260
9	172	2280

tion after each shot. The change in dislocation density, the formation of twins, and their correlation to shock is beyond the scope of this work.

CONCLUSIONS

Mode-I and mode-II macroscopic fractures were observed distinctly in plates subjected to single and repetitive shock.

The dynamic plasticity of the plate subjected to repetitive shock was adversely affected due to

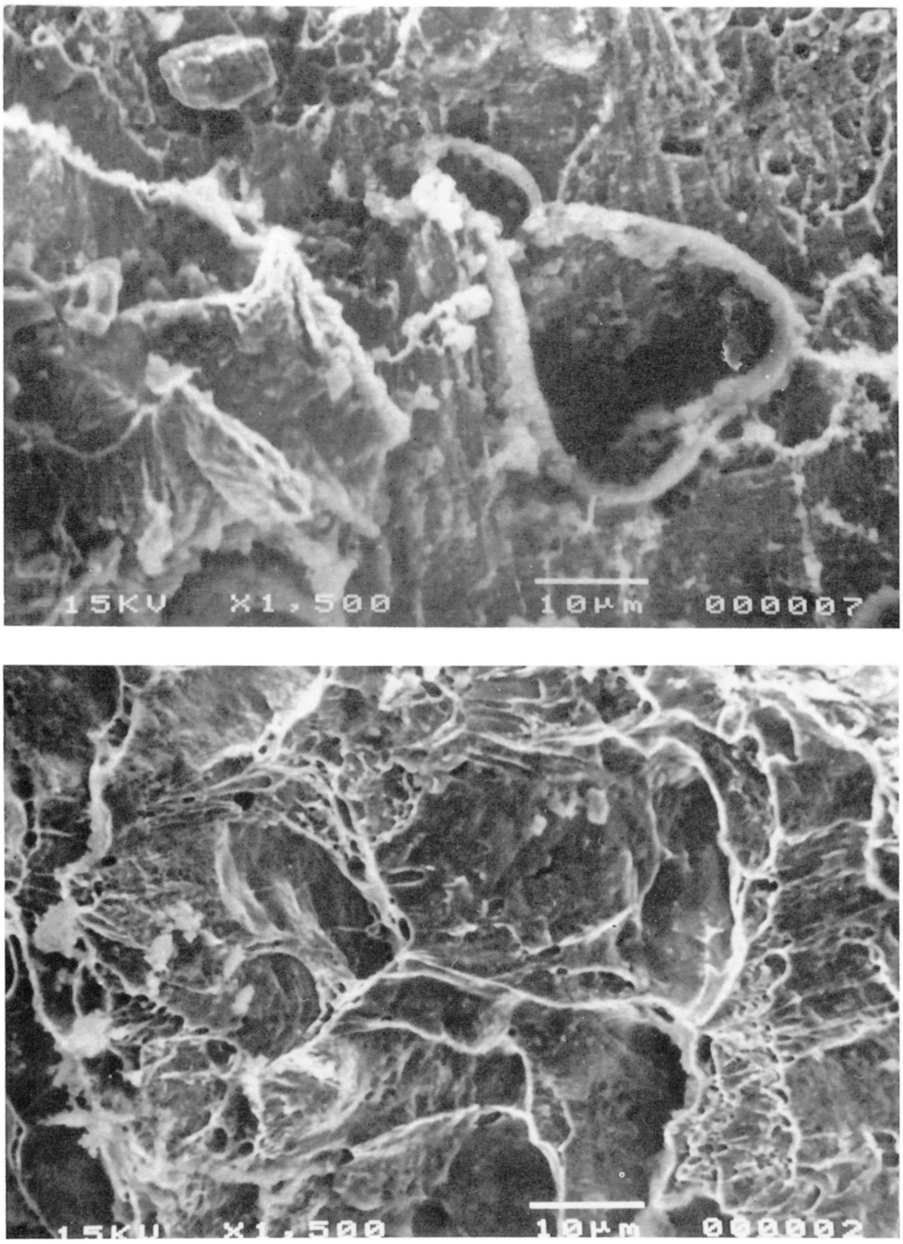


FIGURE 10 Fractography of plate failed in repetitive shock: (a) hexagonal particle inclusion and initiation of microcrack from void and (b) dimple features.

shock hardening. MIL-STD-2149A (SH) specification that recommends successive shock loading with thinning of the plate after every shot, thus seems to be a conservative material qualification procedure.

There exists a nondimensional parameter (DYN) that is material, fixture, and thickness specific. In underwater shock loading this DYN can be used to evaluate the dynamic yield onset for the given explosive weight and stand-off.

Rapid loading in underwater explosion resulted in adiabatic shearing of the plate due to localised melting and solidification of the microstructure at inhomogeneities. Single and multiple shear crack initiation and propagation were observed due to adiabatic shearing. The microstructure of the shear cracks was distinctly different from the parent material.

Fractographic examination of the failed plates showed that the microscopic fracture was in the ductile mode with dimple features and microcracks initiating from voids and inclusions.

There was significant influence of the propagation of shock wave on the residual hardness of

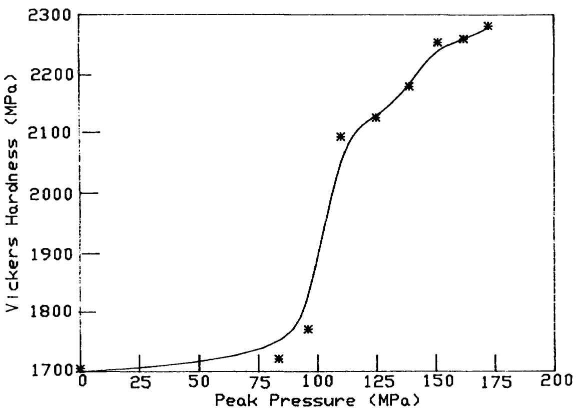


FIGURE 11 Dependence of residual hardness on peak pressure.

the HSLA steel. Although the microstructural changes associated with shock hardening were not studied, it could be concluded that there was a 35% increase in hardness in the ruptured plate.

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REFERENCES

Ahmad, J., Wong, K., and Porter, J., 1989, "Nonlinear Dynamic Analysis Assessment of Explosively Loaded Submarine Hull Panels," *60th Shock and Vibration Symposium,* Vol. 1, pp. 139–171.

Cole, R. H., 1948, "Underwater Explosions," Princeton University Press, Princeton, NJ.

Dieter, G. E., 1988, *Mechanical Metallurgy,* McGraw–Hill Book Company, Singapore.

Fox, E. N., 1950, "A Review of Underwater Explosion Phenomena," in *Compendium of British and American Report of Underwater Explosions Research,* Vol. 1, Part 1, pp. 60–62.

Hartbower, C. E., and Pellini, W. S., June 1951, "Explosion Bulge Test Studies on Deformation of Weldments," *Welding Journal,* Vol. 29, pp. 307s–318s.

Hartbower, C. E., and Pellini, W. S., October 1951, "Investigation of Factors Which Determine the Performance of Weldments," *Welding Journal,* pp. 499s–511s.

Murr, L. E., 1983, "Metallurgical Effects of Shock and Pressure Waves in Metals," in *Explosive Welding, Forming and Compaction,* Applied Science Publishers, London and New York.

Olson, M. D., Nurrick, G. N., and Fagnon, J. R., 1993, "Deformation and Rupture of Blast Loaded Square Plates—Predictions and Experiments," *Int. J. of Impact Engineering,* Vol. 13, No. 2, pp. 279–291.

Porter, J. F., 1988, "Response of SMA and Narrow Gap HY80 Weldments to Explosive Shock Loadings," Technical Memorandum, 88/206, Defence Research Establishment, Atlantic.

Sumpter, J. D. G., 1987, "Design Against Fracture in Welded Structures," *Journal of Naval Science,* Vol. 13, No. 4, pp. 258–270.

Sumpter, J. D. G., 1991, "Fracture Avoidance in Ships and Submarines," in *Advances in Marine Structure-2,* pp. 1–22, North-Holland, Elsevier.

Sundararajan, G. 1984, "Shear Bands and Dynamic Fracture," in *Advances in Fracture Research,* Vol. 5, Pergamon Press, Great Britain.

U.S. Navy, MIL-STD-2149A (SH), 1990.