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Microstructural changes caused by penetration of shaped charge jet into steel targets

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Resumé: On étudie l'effet de l'impact des jets métalliques sur le comportement. Des travaux ont été entrepris sur le comportement d'un acier (0.37C, 0.80Mn, 1.04Cr, 1.38Ni, 0.24Mo) et l'impact des jets métalliques. La microstructure est examinée par microscopie électronique à balayage.

Abstract: The interaction of the shaped charge jet with low alloyed high strength steels subjected to different heat treatment along with low alloyed bainitic and cast austenitic steel has been studied. The structure affected by jet penetration was evaluated by means of light and scanning electron microscopy and X-ray microanalysis. The microstructural features and their changes are described (perforation surface layer, cracking, adiabatic shear bands etc.)

1. INTRODUCTION

A shaped charge is a cylinder of an explosive with a conical cavity lined by a thin layer of metal, glass, ceramics etc. [1]. Upon ignition of the explosive, the detonation wave spreads through the explosive engulfing the cavity. The material of the liner is accelerated by high detonation pressure and the metal cone collapses. During this process part of the liner material forms a jet, which moves forward at a very high velocity (typically around 8000 ms^{-1}). When a jet strikes the target it induces high pressures, around 30 GPa, and forces the target material to flow plastically away from the impact site. Most of papers, dealing with this type of penetration, treat it in the framework of the hydrodynamic concept. This approach evidently overlooks the role of structure, both of the target and of the jet.

A better explanation of the material characteristics effects on jet penetration requires more information on the structural changes caused by the penetrating jet.

The aim of the present paper is the analysis of structure alterations which occur during the penetration of copper jets into steel targets.

2. EXPERIMENTS

Experiments were done mainly on low alloyed high strength steel (Czech equivalent of AISI 4340 steel) with composition: 0.37C, 0.80Mn, 1.04Cr, 1.38Ni, 0.24 Mo - in wt%. Discs 60 mm in diameter and 10 mm thick, were austenitized at 840°C (1100°C), quenched and tempered at different temperatures

between 180°C and 700°C. Discs were stacked to form a layered target. In a similar way cylinders (diameter 60mm, length 150mm), used as compact targets, were processed. Heat treatment and some relevant mechanical properties are given in Tab.1. Further the low-alloy bainitic steel (0.13C, 0.59Mn, 0.16Si, 1.99Cr, 0.61Mo, 0.15V, 0.023P, 0.015S - all wt.%), Y.S. = 380 MPa, UTS = 560 MPa (discs 55 mm thick) and cast austenitic steel (18/8) were used.

For comparison, perforations caused by solid projectiles (WC+Ni) in bainitic steel targets were also studied.

The structure was examined by light microscopy, scanning and transmission electron microscopy, X-ray microanalysis and hardness measurement.

3. RESULTS

The impact surface of the target and the shape of the entrance opening made by a jet depend on the target material (mechanical) properties. Macroscopic features of perforation can be described as follows. The shape of perforation is wavy, the particular contour depends on target structure and dimensions (Fig.1).

Fig.1 The perforation caused by copper jet in "soft" target. 1x

Penetration depth and volume are in Tab.1. The perforation surface is covered by a layer containing both the target and jet material. Depending on the structure of the target, a very hard layer (up to 900 HV) forms in the vicinity of the perforation surface, Fig.2. This layer was encountered especially in "hard" specimens. Its structure is apparently caused by intense shear deformation and resembles the structure surrounding the core of adiabatic shear bands (ASB) [2]. Macrocracks that appear in the material around the perforation are more frequent in "hard" specimens. The cracks are either inclined to or parallel with the perforation surface. The latter forming on the cylindrical surface with its axis matching to the perforation axis. If these cracks are connected with the perforation surface, then usually mixed material partly fills them. The already existing cracks filled with Cu+Fe mixture are later in the process subjected to the stress that cause their opening, Figs 3 and 4. In hard discs, cracks perpendicular to the target axis are sometimes observed under the bottom of incomplete perforation. Hard discs are in a stressed state after the perforation (they often break when cutting is attempted). The hardness of target material is increased, the maximum value and extent of the affected region depend on the structure of target.

Fig.2. Hard (dark) layer at the perforation surface (bottom) and corresponding mapping in Cu K α .

Fig.3. Crack near the perforation filled with Cu+Fe alloy subsequently opened (bottom). Corresponding mapping in Cu K α line. 500 x

Under the bottom of the perforation, the increased hardness gradually falls to the original value. The increase in hardness is larger in "soft" than in "hard" specimens, so that the final value near the perforation is almost identical.

On a finer scale we observed ASB and intense deformation around the perforation, Fig.5. ASB do not necessarily serve as crack nucleation sites.

Fig.4. Microanalysis along the line perpendicular to the perforation surface

The thickness, extent and composition of the surface layer containing both jet and target material depend on several factors. Its thickness and extent decrease with target hardness and distance from impact surface (depth of penetration). Its composition varies especially in deep regions of perforation, sometimes even isles of target material can be observed embedded in the mixture matrix (Fig.6). The bottom of the incomplete perforation is covered by a compact layer of mixed Cu+target material.

4. Discussion

The existence and location of the cracks proves that stress waves play an important role in the process of perforation. The dominant mechanism is apparently erosion and friction that produces perforation and the layer containing both target and jet material. Comparing the features of perforation caused by a shaped charge jet with that produced by a solid projectile (WC+Ni), it can be seen that all features are present in both events, and these impacts differ only quantitatively. We can assume that stress waves which propagate in the material with higher velocity than the projectiles (jet or solid) damage the target's material and thus make its penetration easier. Penetration itself is the result of erosion of target (and projectile) material. The process is not completely smooth - the waviness of perforation in compact targets suggest that slow erosion alternate with faster penetration of already damaged material.

Fig.5. Light microscopy of the region adjacent to the perforation 50 x (top) and 200 x (bottom)

Fig.6. Surface of perforation near the bottom. Target material embedded in the mixed layer and corresponding mapping in Cu K α

References:

[1] Walters W.P. and Zukas J.A, Fundamentals of Shaped Charges. (John Wiley, New York 1989).
[2] Krejci J. et al., *Scripta Metal. et Mater.* 27 (1992) 611 - 615

Tab.1 Heat treatment, mechanical properties of the target steel (LAHS) and depth of perforation

Austenitization	Tempering	R _{p0.02} [MPa]	R _m [MPa]	HV10	Depth [mm]	Volume [mm ³]
840°C/30'/oil	180°C/145'	1530	1978	550	78	
840°C/30'/oil	250°C/145'	1472	1732	480	81	
840°C/30'/oil	320°C/45'	1450	1620	477	88	
840°C/30'/oil	400°C/45'	1402	1518	439	90	
840°C/30'/oil	500°C/35'	1220	1256	389	96	
840°C/30'/oil	600°C/35'	1073	1104	345	97	
840°C/30'/oil	650°C/35'	888	929	287	105	
840°C/30'/oil	700°C/35'	747	867	270	106	4400
1100°C/30'/oil	180°C/145'	1377	1812	600	85	2819
840°C/30'/oil	180°C/145'			607	107	2345
840°C/30'/oil	400°C/45'	compact target		512	115	
840°C/30'/oil	700°C/35'	compact target		283	126	4241
Compact targets with mixed structure Mixed layered targets: soft → hard hard → soft hard → hard soft → hard hard → soft hard → medium → hard				400	108	3448
				390	87	5107
				434	102	3788
				569	78	
				404	81	4634
				410	97	2878
				492	88	