DAMAGE IN METALS CAUSED BY HIGH-STRAIN-RATE LOADING

JIŘÍ ŠVEJCAR, JAN KREJČÍ, JAROSLAV BUCHAR,
JOSEF BŘEZINA

Damage caused by high-strain-rate loading (explosive loading, perforation of target, various impacts) in metallic materials is described briefly. Mechanism of plastic deformation is different at high strain rates in comparison with quasistatic loading because specific phenomena appear. They are stress and shock waves, strain localization (adiabatic shear bands – ASBs), adiabatic heating etc. Generally, it can be said that at high rates of loading no parameter (strain, strain rate, stress, temperature) remains constant. These specific features are illustrated by few examples: perforation of metallic target by a shaped charge jet, structure of ASBs, and spalling.

Key words: high-strain-rate loading, adiabatic shear bands, spalling, armour steel, copper

POŠKOZENÍ KOVOVÝCH MATERIÁLŮ PŘI VYSOKORYCHLOSTNÍM ZATĚŽOVÁNÍ

Poškození vznikající v kovových materiálech při explozivním zatěžování, perforací kovového terče projektilem nebo při dopadech různých těles je stručně popsáno. Deformační procesy probíhající při vysokých rychlostech deformace se v některých aspektech odlišují od deformace při nižších rychlostech zatěžování (působení napěťových vln, adiabatický ohřev atd.). Tyto odlišnosti jsou ilustrovány na příkladech perforace kovového terče paprskem kumulativní střely, adiabatických smykových pásech a na tvorbě výtrže. Struktura byla studována pomocí optické mikroskopie, rastrovací a transmisní elektronové mikroskopie a rentgenové mikroanalýzy.

Prof. J. Švejcar, Dr. J. Krejčí, Dept. of Structure and Phase Analysis, Fac. of Mechanical Engng, TU of Brno, Technická 2, 616 69 Brno, CR.
e-mail: `svejcar@pime.fme.vutbr.cz`, `krji@form.fme.vutbr.cz`

Prof. J. Buchar, Inst. of Technology, Faculty of Agronomy, Mendel University, Zemědělská 1, 613 00 Brno, CR. e-mail: `buchar@dahlia.mendelu.cz`

Mr. J. Březina, Institute of Physics of Materials, CAS, Žižkova 22, 616 62 Brno, CR. e-mail: `brezina@ipm.cz`

1. Introduction

Applications of high-strain-rate deformation could be roughly divided into three areas:

1. High-energy rate fabrication, including established technologies of explosive welding, cladding, forming, and hardening. New developing technologies are: dynamic consolidation, shock modification of properties, and shock synthesis of new materials. Here also belongs the issue of transport vehicle crashworthiness. For review see, e.g., [1, 2].

2. Defense-related applications which involve:

– Development of armour-defeating projectiles such as kinetic energy penetrators, self-forging fragments, and other novel concepts.

– Development of new armour materials: ceramics, composites, and reactive materials.

– Response of materials to hyper-velocity impacts occurring in space. Impact velocities between 10 and 20 km.s^{-1} can be expected.

The safety issues of nuclear power plants should be also mentioned.

3. Fundamental understanding of the behavior of materials under high-strain-rate conditions.

High-strain-rate deformation is generally associated with different loading modes that involve an instant release of energy. Typical examples are: impact of accelerated object, irradiation by pulse laser, detonation of explosives etc. According to the most frequent method used to exert this type of loading, it is called impact loading [1]. The high-strain-rate deformation exhibits several distinct features that are not observed under quasistatic deformation rates. Most prominent is the existence of stress (shock) waves. Stress waves (tensile or compressive) form upon loading in one (or more) sections of the specimen (machine part) and traverse the specimen. At interfaces (e.g., free surface) they are reflected back and change their sign. Provided that the amplitude of the wave exceeds the yield stress of the material (for the respective strain rate) plastic deformation starts and propagates through the specimen. This is usually described as a plastic wave. The energy of this "disturbance" is used up by the dislocation motion and multiplication, or by other processes of plastic deformation. Thus, both the velocity and amplitude of the plastic "wave" are decreasing during its travel through the specimen.

The high-strain-rate deformation is difficult to analyse because, contrary to the quasistatic deformation, many parameters change in time and place. Namely, strain, strain rate, stress, and temperature (adiabatic heating) might be different locally and change (often rapidly) during the process. Thus, numeric simulations are employed for the evaluation of this type of loading, often based on the assumption that the material behaves in such a way that the laws of hydrodynamics could be applied. Consequently, the structure effects are usually neglected.

Nonetheless, there is experimental evidence that the influence of the real structure of the material plays a major role in the deformation process, especially in the plastic response. The structure development leads to the formation of different types of damage related to the specific material. The changes have characteristic threshold values and growth kinetics. They influence in a specific way the stress waves and consequently the final stress state of the impact loaded body.

This paper contains few examples of damage caused by high-strain-rate loading, with attention focused on the structure effects.

2. The structure affects shaped charge jet perforation of steel targets

Fig. 1 shows the results of a shaped charge (copper liner) jet penetration into various steel targets. The impact velocity of Cu jet was $\sim 7000\ \mathrm{m \cdot s^{-1}}$. Armour

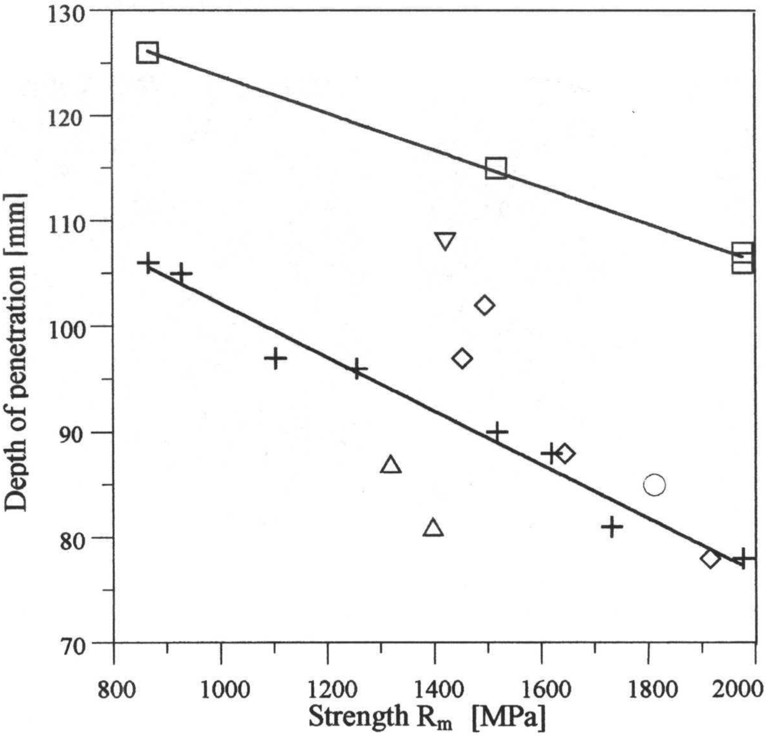

Fig. 1. Depth of penetration of shaped charge jet (Cu) into armour steel. + – layered targets of the same heat treatment (mechanical properties), ○ – higher austenitization temperature (1100 °C/OQ/180 °C), △ – target formed by discs with different HT – stacking order soft-hard material, □ – hard-soft material, ◇ – compact specimens (cylinders), ▽ – cylinders quenched from one face (mixed structure).

steel (Czech standard 41 16341) (0.37 C, 0.8 Mn, 1.04 Cr, 1.81 Ni, 0.24 Mo – in wt. %) discs and cylinders were heat treated so that hardness varied from 270 HV10 to 600 HV10 (austenitization 840 ℃/30′ + oil quench + tempering at 180–700 ℃). Discs with different mechanical properties (i.e., microstructure) were stacked to form targets. The depth of penetration depends not only on mechanical properties of individual discs but also on the stacking order. The surface of the perforation is covered by mixture of copper and target material. Further structural changes depend on the mechanical properties of individual discs.

Soft material exhibits thick mixed layer at the perforation surface followed by deformed layer. With increasing material hardness the thickness of mixed layer on the surface decreases. Under this layer tenths of microns thick band appears. The band has properties (hardness, etching response) similar to that of adiabatic shear bands. Numerous cracks both parallel and perpendicular to the perforation axis appear, Fig. 2a,b. Moreover, hard discs have very high internal stresses.

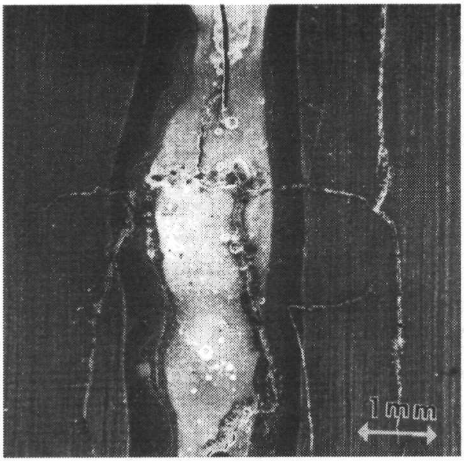

Fig. 2a. "Hard" disc (left) – dark region surrounding central perforation has properties similar to the ASB.

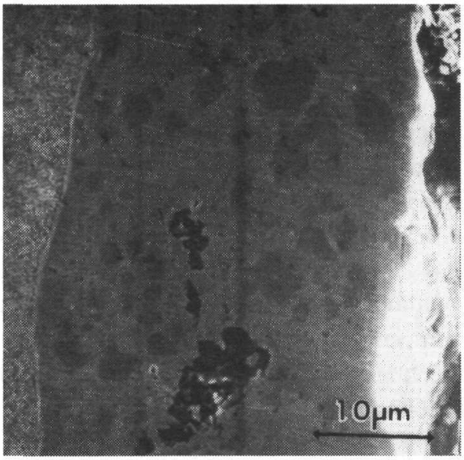

Fig. 2b. "Soft" disc (right) – mixed layer (Cu + steel) around the perforation contains fragments of target material.

3. Adiabatic shear band (ASB)

The structure of adiabatic shear bands is often discussed. These bands appear after high-strain-rate deformation but similar features are observed after forming and some other types of loading. Their main macroscopic property is high resistance against metallographic etchings. High resistance against etching in ferritic

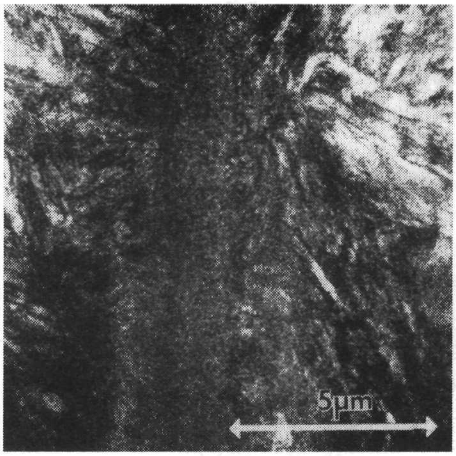

Fig. 3. Dark field STEM image of ASBs in armour steel. It can be seen that the core of ASBs is formed by a very fine grained material.

Fig. 4. Optical micrograph of the steel target impacted by a solid projectile (perforation at upper left). Original microstructure was that of tempered martensite (400 °C).

steels was often explained by adiabatic heating above austenitization temperature followed by rapid quenching in "cold" surrounding matrix. Usually, authors do not account for shift of critical temperatures with heating rate (rapid heating – higher A_1 and A_3, A_c temperatures). ASBs are also considered to be the initiation sites of the cracks.

Electron diffraction and recrystallization experiments proved that no martensite is present in ASBs [3]. The structure of ASB in austenitic steels is similar to that in ferritic (Fig. 3), namely very fine grained core, surrounded by heavily deformed region. Chen and Vecchio proved on Al-Li that temperature reached due to the adiabatic heating in ASBs is lower than 400 °C [4].

As far as the crack initiation is concerned, it is necessary to distinguish two cases. If an ASB forms due to geometrical constraints (e.g., punching and other forming procedures that cause sharp deformation inhomogeneities), then it is usually related to the cracking of material. On the other hand, if ASB forms due to relatively free movement of stress waves, then no "affinity" between crack and ASB is observed.

Fig. 4 illustrates complicated pattern of plastic deformation as indicated by bands of chemical heterogeneity (bands with higher Cr content are bright). These bands are originally parallel to each other – the result of rolling, and they could be utilized to measure local deformation. ASBs are white lines that separate individual regions of relatively low shear strain gradients. Fig. 5 is an example of a crack in the vicinity of ASB. Many observations on different alloys show that there is no direct interaction between ASBs and cracks. On the other hand, when ASBs arise due to geometrical constraints, cracks follow the ASBs.

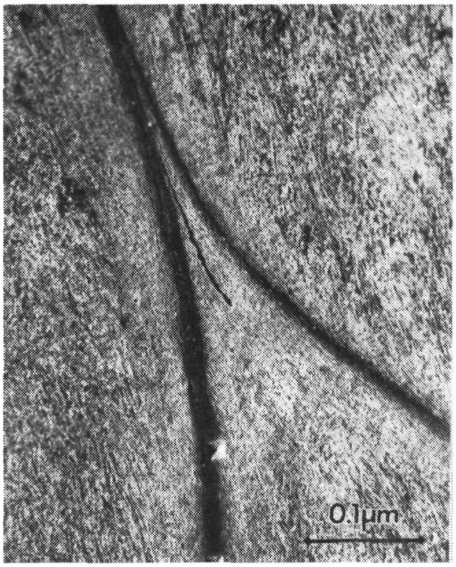

Fig. 5. SEM micrograph of the steel target perforated by a shaped charge jet. Original structure: Tempered (350 °C) martensite.

4. Spall

Spallation is tensile fracture caused by the reflection of a short-duration compressive pulse from a free surface.

This effect was probably first utilized during the Second World War, when critical need to eradicate Japanese concrete fortifications arose. During the war, projectile, labeled HESH (high-explosive squash head) was developed for use against armour.

Although newly developed armours made projectiles HESH obsolete, the study of spalling remains of an interest in military research. The reason is that spalls accompany penetration of different projectiles. The study of this fracture is also important for various technologies which make use of impact loading.

Most important difference between the spalling and fractures arising from more conventional types of loading is decisive role of the reflected stress pulse. It is necessary to bear in mind that these pulses are not reflected on free surfaces only. Generally, the reflection takes place on all interfaces between materials with different acoustic impedance. This effect may cause failure of complex components under impact loading. Structural studies show that during the spalling the following sequence of events takes place:

a) microdefects nucleation (microcracks, cavities) – see Table 1
b) growth of these and initially existing defects
c) mutual interaction and coalescence of defects
d) formation of continuous fracture surface and eventually fragmentation

The extent and significance of the particular process depend on the material used. For example, rocks and ceramic materials contain high density of primary defects and therefore the stage a) is of far lesser importance in these materials than, e.g., in metal single crystals.

Table 1. Different modes of microdefects nucleation

Nucleation site	Nucleation mechanism	Parameters affecting nucleation
Existing defects	Defect growth	Tensile stress and plastic deformation
Inclusions and other phase particles	Inclusion fracture, interface decohesion fracture of matrix in inclusion vicinity	Tensile stress and plastic deformation
Grain boundary	Vacancy clusters GB sliding	Tensile stress and plastic deformation
Sub-grain boundaries	Dislocation pile-ups	Shear deformation

Comparing the low-strain-rate tensile test with impact loading, apparently the differences between the two fracture processes are mainly in the number of microdefects and mechanism of their growth. The fracture of tensile test specimen is caused by initiation of few defects and then by the expansion of magisterial crack, while spalling requires a large density of microdefects that grow very rapidly on small distance.

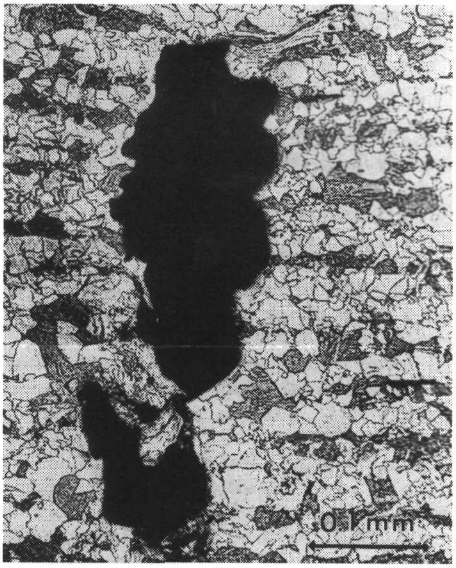

Fig. 6. Detail of the cavity formed in copper disc impacted by a low-velocity projectile (gas gun test). In this test the strain rate approaches the ones encountered during some forming processes.

It is also necessary to take into account the plastic deformation that may, and usually is, taking place earlier, during the time the stress pulse traverses through the specimen. Further effects accompanying the stress pulse movement are, e.g., ASBs formation, or the phase transformations. All structural changes may be operative simultaneously. Each of them possesses its own kinetics and influences the stress-wave transmission in its own way.

Fig. 2 (left) shows cracks produced

by spall mechanism in hard (steel) material. The tensile stress prerequisite for their formation arises from reflection on various sides of disc. In Fig. 6 the cavity is formed by spall mechanism in soft material under relatively low-strain-rate conditions.

Concluding notes

It seems clear that high-strain-rate processes depend on the original structure and its development during the deformation. Adiabatic shear bands may cause failure in case there are severe geometrical constraints. Otherwise, they do not significantly interact with the cracks. Spalling, the formation of internal fracture surface, is again dependent on the material structure. It is not present only in military applications but, as the technology advances, it could be encountered in ordinary production.

This article has been written to commemorate the 60th anniversary of late Professor Vojtěch Karel's birthday.

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