Deformation and fracture of porous iron under dynamic loading

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Abstract. The aim of this work was to study the microstructural features of the process of dynamic deformation and fracture of porous iron under fast loading with a relatively simple and economical device (a cumulative "knife").

1. Introduction

Highly porous materials have been used for a long time in various industries [1,2]. In recent years, interest in them has increased, which is associated, among other things, with the development of self-propagating high-temperature synthesis (SHS-method) of their manufacture [3,4]. The advantage of porous metallic materials over porous ceramic materials is their high energy absorption capacity and increased ductility, which allows them to be subjected to high-speed impact, including with a sharp change in temperature. Therefore, for example, they are used to make effective devices for localizing explosive and shock loads [5]. The increasing use of porous metallic materials necessitates an adequate calculation of dynamically loaded structures made of these materials, and, consequently, adequate modeling and analysis of physical processes occurring in a porous medium under fast and ultrafast loading. However, due to the complexity of the processes of the response of a porous medium to a shock-wave effect, the choice and development of physical and mathematical models of the behavior of porous materials under such an effect causes certain difficulties. Even if a certain model is selected and empirical macrocharacteristics of a porous medium are selected, which allow a sufficiently accurate description of the behavior of a structure under a certain impact, this does not guarantee adequate prediction of the behavior of a structure under other loading parameters.

The physical processes occurring in the thickness of the sample materials under high-speed action are rather weakly amenable to instrumental study. The available results of pulsed X-ray diffraction of processes are not very informative from the point of view of obtaining data on physical phenomena in samples. The results of metallographic studies of samples after external exposure require careful analysis, since they are post-factor observations. Nevertheless, metallographic studies provide today the most reliable data on the physics of processes under dynamic loading of materials [6, 7].

However, it should be noted that today the overwhelming majority of metallographic studies of materials are performed after their loading in the range of strain rates $\dot{\varepsilon} = 10^3$–$10^6$ s\(^{-1}\). Loading of materials at high deformation rates is associated with technical difficulties in obtaining such rates. As
a rule, loading at strain rates $\dot{\varepsilon} = 10^7 - 10^9$ s$^{-1}$ is carried out using light-gas, electric and electromagnetic accelerators, as well as with the help of various radiation sources: laser, electron and ion beams, etc. [8-10]. And since such experimental installations, which are expensive in themselves, require a certain, often unique, hardware equipment and highly qualified service personnel, the research of materials on such installations is of a single nature. At the same time, as shown by studies of materials carried out under fast and ultrafast loading ($t \leq 10^{-7} - 10^{-9}$ s), there is a fundamental difference in the behavior of materials under such loading from loading at shorter durations.

2. Material, experimental techniques and justification of loading duration

2.1. Material under investigation
The study of samples in the form of parts of a semi-cylinder made of porous iron grade PA-Zh GOST 26802 - 86 with a thickness of $H = 4.0$ mm was carried out. The samples were subjected to the effect of a cumulative "knife" formed during the detonation of an elongated shaped charge of the 2TSn-3 grade [11, 12]. The impact of a cumulative "knife" led to the division of the half-cylinder into two parts.

The structure of the porous iron under study consisted of rather large miscellaneous ferrite grains with a size of (20 - 50) $\mu$m $\times$ (140-170) $\mu$m, there were also equiaxial grains with a diameter of 150 - 170 $\mu$m, and there were also regions of dynamic recrystallization (figure 1a), where the grain decreases to a size of 0.5 to 1.5 $\mu$m. In addition, the structure contained twins of different sizes and orientations (figure 1b), including intersecting ones. The pore size was in the range of 2 - 15 $\mu$m.

2.2. Justification of loading duration
The cumulative "knife" used to influence the samples is a set of plane cumulative jets [13], the speed of the head-parts of which (for our case) is $V_0 \approx 2,8$ km/s, and the speed of the closing parts is $V_f \approx 1,4$ km/s. The elongated shaped charge was installed on the inner side surface of the half-cylinder at the optimal focal length of 3 mm, so the length (height) of the flat jet was $l_j = 3$ mm. As a result of the intrusion of the cumulative knife, as mentioned above, the half-cylinder was divided into two parts.

The average velocity of a plane jet was estimated by the ratio [14]

$$\langle V \rangle = V_0 \sqrt{\frac{1 + V_f / V_0 + (V_f / V_0)^2}{3}}$$

(1)
The calculation according to the relation (1) gives the value of the average speed of the jet \( \langle V \rangle = 2.14 \) km/s. As mentioned above, the thickness of the split sample (barrier) is 4.0 mm. Even if we assume that the motion of a plane cumulative jet in a porous medium is equivalent to the motion of a body (simulating a jet) in a liquid (as was done in [15]), then the thickness of the separable obstacle in the framework of the hydrodynamic theory of penetration should be equal, according to the classical M.A. Lavrentiev’s formula [13, 14]

\[
H = l \sqrt{\rho_j / \rho_s},
\]

(2)

(here \( \rho_j, \rho_s \) are the densities of the materials of the jet and the obstacle, respectively) \( H = 3.2 \) mm.

But relation (2) is true for the depth of penetration of the jet into an obstacle of semi-infinite thickness; in our case, the thickness of the obstacle has a finite value, therefore, the thickness of the separable obstacle should be estimated by the relation [16]

\[
H = H_p + H_s,
\]

(3)

where \( H_p \) is the depth of penetration of the jet; \( H_s \) is the thickness of the spall part of the barrier. However, examination of the rear of the barrier did not reveal characteristic signs of spalling.

Another reason for such a high value of the thickness of the separated target (sample) may be that the cumulative "knife" is, in fact, a wedge-shaped striker. And then, in the process of its penetration into a rather fragile barrier, a crack is formed in front of the wedge-shaped striker (figure 2), the speed of which can be comparable to the penetration rate of the striker itself, which leads to such a high value of the thickness of the separated barrier.

![Figure 2. Scheme of motion of the cumulative knife](image)

The total time of the separation process can be estimated \( t_H \geq 0.5 H / \langle V \rangle < 1 \) mks. Such a phenomenally low value of the process time (the time of direct penetration of the jet is less than 0.5 mks) without the use of unique loading devices, along with sufficiently high values of the loading parameters of the porous medium, makes it possible to reveal the microstructural changes occurring in the material (porous iron) under extreme conditions.

3. Results of microstructural studies of samples and their analysis

The intrusion of a plane cumulative jet into the sample led to the following changes in its structure. First, near (~ 0.5 mm) of the frontal surface (from the beginning of the motion of the cumulative jet), areas with a dendritic structure were observed (figure 3), which indicated that the melting temperature in local regions (grains) of the sample was reached, while the propagation rate of the temperature front had to reach \( \sim 10^9 \) – \( 10^{10} \) ºC/s. However, the melting of iron corresponds to a shock compression pressure of 140 GPa [17], and in our case, as shown by the rough estimates from the ratios...
\[ p \approx \rho_0 c_p u \]  

or  

\[ p = u \frac{\rho_0 c_1}{\rho_1 c_1 / \rho_0 c_2 + 1} \]  

Here, \( \rho_0 \) is the initial sample density, \( c_p \) is the plastic wave velocity in the sample, \( u = \langle V \rangle \) is the stress wave mass velocity, \( \rho_1 \) is the impactor material density, \( c_{1,2} \) are the speeds of sound in the material of the striker (cumulative jet) and in the material of the sample, respectively, giving a pressure value in the range of 60 - 80 GPa. Since dendritic structures were observed only in individual grains, it can be assumed that higher additional pressure values (80 - 60 GPa) were achieved in them due to the volumetric compression of such grains by neighboring (surrounding) grains. In addition, it is necessary to take into account that the factor of ultrafast heating of the near-contact surface of the sample is associated with the nonequilibrium distribution of energy between the structural elements of the solid [18].

![Figure 3. Dendritic structure of porous iron (a) \times 1000 C_DIC; (b) x 1000](image)

Secondly, in the structure of porous iron in the same near-contact layer in some grains near their boundaries, martensitic transformations have occurred (\( \alpha \rightarrow \varepsilon \rightarrow \alpha \) transition), and acicular (lenticular, truss-shaped, or twinned) martensite appeared in them (figures 4a, 4b, and 4c, respectively). In addition, the appearance of adiabatic shear bands (figure 4b) and partially fragmented structures (figure 4b) should be noted.
Figure 4. Martensitic transformations in the sample after the introduction of a cumulative jet: (a), (b) - × 1000 C_DIC, (c) × 500

By analogy with the works [19 - 24], it can be assumed that the emerging martensite crystals at a supersonic speed penetrate the grain volume, forming perturbation fronts, some of which overtake the shock wave that initiated the transformation, i.e., in fact, we have a certain analogy with detonation process [24]. In this case, the supersonic velocity of the martensitic transformation is analogous to the velocity of the detonation wave D. In the first approximation, we define this velocity. Let us write in the framework of the Zeldovich-Neumann-Döring theory [25] the momentum conservation equation

$$p = \rho_f DU,$$

where $\rho_f$ is ferrite density; $U$ is ferrite mass velocity; $p$ is pressure at the shock front. The density of $\alpha$-Fe is 7570 kg/m$^3$, and $\gamma$-Fe is 7750 kg/m$^3$ [24], let us take the pressure at the front of the wave of propagation of martensite in accordance with the above estimate $p = 60 - 80$ GPa, and $U = u = 2140$ m/s. As a result, from (6) we obtain 3700–4940 m/s, which is quite comparable with the detonation velocity of initiating explosives [25].

Third, the deformation of the barrier material was accompanied by rotational movements of the microstructural volumes of the medium, as evidenced by circular (almost closed) cracks (figure 5).
Figure 5. Examples of rotary motion of microvolumes of the medium: (a), (b) x 1250, (c) x 1000 CDIC

In addition to circular cracks, there were individual cracks oriented at an angle of ~45° to the fracture surface (figure 6). Similar cracks during the penetration of a cumulative knife were observed in titanium alloys [26]. Their formation is associated with the wedging effect, and the orientation with a complex stress state in the zone where the crack propagates.

Figure 6. Cracking in the zone of motion of the cumulative jet (x 1000 CDIC)

4. Conclusions

Thus, the ultrafast action of the cumulative jet on the porous iron barrier led to intense structure formation of the mesoscale level in the near-surface layer of the sample.

In principle, the results obtained do not contradict the wave theory of martensitic transformation and indicate that the processes of dynamic deformation under conditions of ultrafast loading occur under conditions of strong nonequilibrium, leading to energy redistribution and melting of individual structural elements, and structure heterogenization.
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