DEFORMATION BEHAVIOR AND SPALL FRACTURE OF THE HADFIELD STEEL UNDER SHOCK-WAVE LOADING

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Comparative studies of regularities in plastic deformation and fracture of the Hadfield polycrystalline steel upon quasi-static tension, impact failure, and shock-wave loading with rear spall are performed. The SINUS-7 accelerator was used as a shock-wave generator. The electron beam parameters of the accelerator were the following: maximum electron energy was 1.35 MeV, pulse duration at half-maximum was 45 ns, maximum energy density on a target was $3.4 \cdot 10^{10}$ W/cm$^2$, shock-wave amplitude was ~20 GPa, and strain rate was ~$10^6$ s$^{-1}$. It is established that the failure mechanism changes from ductile transgranular to mixed ductile-brittle intergranular one when going from quasi-static tensile and Charpy impact tests to shock-wave loading. It is demonstrated that a reason for the intergranular spallation is the strain localization near the grain boundaries containing a carbide interlayer.

Keywords: Hadfield steel, spall fracture, high-current electron beam.

INTRODUCTION

Hadfield manganese austenitic steel possesses the unique combination of mechanical properties: high wear resistance due to high strain hardening capacity, good ductility, and high impact strength. Because of this, the Hadfield steel is widely used for manufacture of parts of cars working under conditions of shock-abrasive wear. While in service, these parts are subject to shock loading that can cause catastrophic failure. To predict it, it is important to elucidate how the strain rate influences the plastic flow and failure processes. By the present time, the main regularities and mechanisms of the deformation behavior and failure of the Hadfield steel under quasi-static loading have already been established [1–5]. Systematic studies of the behavior of this steel under dynamic loading are limited only by work [6] in which specimens were exposed to shock compression at strain rates of $\varepsilon = (1–8.3) \cdot 10^3$ s$^{-1}$.

Of particular interest are studies of the dynamic deformation and failure of metals at $\varepsilon \geq 10^5$ s$^{-1}$ under shock-wave loading in the regime of rear spall of a target [7, 8]. To form shock waves, nanosecond ion [9] and electron beams with energy density of $10^{10}$–$10^{11}$ W/cm$^2$ [10, 11] are typically used together with high-speed plate impact.

The purpose of the present work is a comparative study of regularities of plastic deformation and failure of the Hadfield steel in three loading regimes that differ significantly by strain rates: quasi-static tension, impact fracture, and shock-wave loading with rear spall.

EXPERIMENTAL

Experiments were performed with the Hadfield steel 110G13 (Fe–14.2 Mn–1.5 Si–1.2 C–0.3 Cr–1.03 Ni–0.0052 S–0.024 P, wt.%) ingots 40 mm in diameter and 100 mm high. The ingots were subject to hot forging, annealing
at 1050°C for 2 h, and subsequent water quenching. Three types of specimens were then cut out by EDM from 10 × 40 × 300 mm plates: 1) 80 × 5 × 5 mm specimens for quasi-static tension, 2) 55 × 5 × 5 mm plates with V-notch for Charpy impact tests, and 3) disks 15 mm in diameter with thickness from 1.5 to 4 mm for shock-wave loading with rear spall. All working specimen surfaces were preliminary mechanically grinded and polished. Quasi-static tests were performed by Shenk testing machine (\( \dot{\varepsilon} = 1.4 \times 10^{-3} \text{ s}^{-1} \)); for impact fracture, a Charpy impact test machine with energy of 50 J (\( \dot{\varepsilon} \sim 10^{2} \text{ s}^{-1} \)) was used.

Experiments on shock-wave loading were performed on the SINUS-7 electron accelerator whose diode system was modernized to increase the current density and hence the shock wave amplitude up to the level necessary for rear spall of bulk targets made of high-strength steels and alloys. An electron beam was formed in a vacuum diode with hemispherical explosive-emission cathode 6 mm in diameter (from 12Kh18N10T steel) in an external longitudinal magnetic field of 17 kOe. The diode current reached 20 kA for cathode voltage of 1.35 MeV and a 7 mm cathode-anode gap. A target was placed behind the grounded graphite aperture 8 mm in diameter and 3 mm thick. The rear surface of the specimen was free. The maximum current density in the focal beam spot was 25 kA/cm², that is, the peak power density was 3.4 \( \times \) 10¹⁰ W/cm²; the electron current pulse duration at half maximum was 45 ns. The beam current density distribution on the target was close to uniform.

Due to the volume character of energy release (the electron penetration depth in Fe is \( \sim 1.2 \) mm), ablation of the target material occurred during single pulse with formation of a crater 6–7 mm in diameter and 0.6–0.8 mm deep. According to estimates based on simulation of shock-wave dynamics for pure metals [10], a quasi-plane shock wave of compression with duration of \( \sim 0.2 \) μs and amplitude of \( \sim 20 \) GPa was formed in the specimen. Due to reflection of the shock wave from the free back surface, a tension wave was formed that caused rear spall of the specimen. The strain rate was \( \sim 10^{9} \) s⁻¹ [10].

The microstructure of the material was investigated by optical microscopy on an Olympus GX 51 microscope and by scanning electron microscopy on a Philips SEM 515 device equipped with an EDAX ECON IV detector. Cross sections were chemically etched in 4% HNO₃ alcohol solution. Fracture studies were performed by scanning electron microscopy. The phase composition of specimens was studied with x-ray diffraction analysis using a DRON-7 diffractometer in filtered CoKα radiation at angles in the range \( 2\theta = 15–150^\circ \) with a step of 0.1°.

Microhardness of specimens after loading was measured with a PMT-3 device for cross sections with a depth step of 100 μm under a load of 0.981 N.

RESULTS AND DISCUSSION

1. Quasi-static loading and impact failure

According to the data of XRD analysis, the 110G13 steel in the initial state has the FCC structure with the lattice parameter \( a = (0.36312 \pm 0.00047) \text{ nm} \), average grain size of 118 μm, and microhardness of 2.7 GPa. The stress-strain diagram has a monotonic parabolic shape. From this diagram it follows that the yield stress of the steel is \( \sigma_{0.2} = 410 \) MPa, ultimate tensile stress \( \sigma_{B} = 940 \) MPa, and percent elongation \( \delta = 33\% \). The microstructure of the longitudinal cross section of the specimen after tensile tests is shown in Fig. 1a.

It can be seen that grains are strongly elongated in the direction of loading. Severe deformation without necking is seen in all grains. Possible deformation mechanisms are sliding and twinning [1, 2, 4, 5]. The average microhardness was 4.33 GPa, that is, strain hardening was \( \sim 60\% \). The fracture surface was perpendicular to the applied load. Fracture had typically transgranular character. From the fractograph shown in Fig. 2a it can be seen that the fracture is ductile one. It is characterized by the presence of fracture regions of two types that differ by the average fracture dimple size. The size distribution of fracture dimples obtained by the secant method is shown in Fig. 3a.

The structure of longitudinal cross section of the specimen after impact fracture is shown in Fig. 1. The fracture, as under quasi-static loading, is transgranular. The fractograph is shown in Fig. 2. It can be seen that the ductile character of failure with alternating regions of large and small fracture dimples is completely retained. The difference is the following: 1) the region of severe deformation extends only to depth of \( \sim 1 \) mm from the fracture surface, 2) the