EFFECT OF PRE-STRAIN ON THE FRAGMENTATION OF HYDROGEN-CHARGED STEEL 45 UNDER EXPLOSIVE LOADING

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This paper presents the results of an experimental study on the effect of preliminary elastic–plastic deformation and hydrogen charging of steel on the fragmentation intensity of cylindrical shell structures under internal explosive loading. The preliminary deformation was carried out by pressing a steel ball along the axis of a cylindrical specimen, creating local plastic zones and damage. Part of the specimens, after deformation, was subjected to hydrogen charging in a special chamber to reduce the material's plasticity. Prepared hydrogen-charged and control (uncharged) specimens, in the form of scaled projectile models, were filled with explosive charges and tested at a proving ground. The results showed that the specific fragmentation parameter for the hydrogen-charged specimens was more than 2.4 times higher than that of the uncharged ones. The proposed approach provides a technologically simple method for controlling the fragmentation of shell structures without the use of complex geometric stress concentrators.

Keywords: shell fragmentation, elastoplastic deformation, hydrogen embrittlement, explosive loading, number of fragments, shell structures, steel, hydrogen charging, hydrogen concentration, stress-strain state, elastioplastic deformation

Introduction. The fragmentation of shell structures under explosive loading is a key factor determining the effectiveness of their application in both defense and industrial fields. The efficiency of structural failure directly depends on the number of fragments formed and their geometrical characteristics. Traditional methods of controlling fragmentation include the use of geometric stress concentrators; however, their production is complex, costly, and does not always ensure a uniform distribution of fragments [1].

An alternative approach is the application of preliminary elastic–plastic deformation in combination with hydrogen charging, which induces internal embrittlement of the metal. It is well known that hydrogen, when diffusing into the metal, reduces its plasticity and promotes brittle fracture. Preliminary elastic–plastic deformation, in turn, produces local microdefects and traps for atomic hydrogen, which facilitate and intensify hydrogen embrittlement [2].

In recent years, a number of studies have confirmed the critical role of hydrogen charging combined with prior mechanical loading. It has been demonstrated that the combination of pre-straining and hydrogen charging leads to a significant decrease in the plasticity of the material and results in the transition to a brittle fracture mechanism [3]. Similarly, in steels such as 22K, the combination of pre-strain and hydrogen charging has been shown to reduce fracture energy under static loading conditions [4].

In the context of shell fragmentation, these findings are particularly relevant. For example, in studies on 60S2A steel, a fragmentation parameter

P (the ratio of the number of fragments ≥ 5 g to the total mass) was introduced, and hydrogen charging led to an increase of approximately 25% in this parameter [5]. This demonstrates the effectiveness of hydrogen treatment in controlling fragmentation.

Methods of Research. For the experimental investigations, cylindrical specimens of steel 45 were manufactured with an outer diameter of 30 mm and a height of 60 mm. The inner diameter of the specimens was varied within 21, 22, and 22.5 mm. This variation allowed the creation of different stress–strain states during subsequent testing.

Preliminary elastic–plastic deformation of the specimens was performed by pressing a spherical steel ball with a diameter of 22 mm into the inner channel of the cylinder. This approach enabled the reproduction of different levels of elastic and elastic–plastic states in the specimen wall material, depending on the initial inner diameter.

Fig. 1. Scaled model of a cylindrical shell before experiments

To determine stresses and strains during indentation, an optical–digital image correlation system was applied. The method made it possible to register displacements on the outer surface of the cylindrical specimen in two coordinate directions. Based on these measurements, local strain was calculated within control areas of 0.5 mm. This approach provided spatial distribution of local strains and allowed the evaluation of inhomogeneity in the stress–strain state across the shell wall.

The obtained results were used for quantitative assessment of the degree of preliminary elastic–plastic deformation, which became the baseline parameter for subsequent hydrogen charging and explosive testing of the prepared specimens.

Before testing, the internal cavities of the cylindrical specimens were filled with explosive material. The subsequent fragmentation was carried out under field conditions at a specially equipped testing site. All experiments were performed under identical conditions, which excluded the influence of external factors and allowed the comparison to be focused solely on the differences arising from the degree of prior hydrogen charging of the material.

Results and discussion. Preliminary elastic–plastic deformation of the cylindrical specimens ensured the achievement of an equivalent strain level of about 19.7%. This method of deformation by pressing a spherical ball into the inner channel of the cylinder is of fundamental importance, since it promotes a uniform distribution of microdamage and plastic zones throughout the shell wall. As a result, it prevents the formation of localized stress concentration areas that typically arise under other loading modes, and instead produces a more homogeneous defect field within the bulk of the material.

Subsequent hydrogen charging of a portion of the specimens in a special chamber for 48 hours led to the diffusion of atomic hydrogen into the steel and its accumulation in the traps generated during pre-deformation. As a consequence, the hydrogen concentration in the metal reached approximately 3.8 ppm, significantly altering the fracture mechanism and enhancing brittle embrittlement.

The fragmentation properties were evaluated through the analysis of the fragment groups formed after explosive loading (Fig. 2). For this purpose, static methods were employed: fragments were collected and weighed, and their number as well as mass–size distributions were determined. Only fragments with a mass exceeding 5 g were included in the statistical evaluation, as this threshold corresponds to the accepted criterion of effective damaging capability. This approach made it possible to compare the fragmentation intensity of hydrogenated and non-hydrogenated specimens using an objective quantitative basis. To enable an objective comparison, the specific fragmentation index was applied:

$$P_f = \frac{n_f}{m_\Sigma}, \qquad (1)$$

where n_f - is the number of fragments with a mass greater than 5 g; m_Σ - is the total mass of all collected fragments.

In the case of hydrogen-charged specimens, the value of this parameter was more than 2.4 times higher compared to the non-charged specimens. This confirms that hydrogen charging after prior elasto-plastic deformation reduces the plasticity of steel 45 and promotes the development of a brittle fracture mechanism, which leads to the formation of a larger number of fragments effective by mass.

a b

Fig. 2. Fragmentation of cylindrical Steel 45 specimens after explosive tests for hydrogen-free (a) and hydrogen-charged (b) specimen.

Conclusions. The proposed methodology, which combines prior elastoplastic deformation with hydrogen charging of steel 45, makes it possible to purposefully modify the fracture behavior of cylindrical shell specimens under internal explosive loading. Pre-strain of the sample ensured an average level of local strain on the outer surface of the shell of about 19.7%, creating favorable conditions for the formation of defects and traps for atomic hydrogen in the metal. Hydrogen charging of the specimens for 48 hours resulted in a hydrogen concentration of approximately 3.8 ppm, which significantly affected the fracture mechanism of the steel and promoted its brittle embrittlement. Fragmentation analysis showed that, in hydrogen-charged specimens, the specific fragmentation index was more than 2.4 times higher compared to the control specimens. This indicates that hydrogen charging following prior elastoplastic deformation promotes the formation of a greater number of fragments effective by mass.

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