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Temperature Effect on Deformation and Fracture Mechanisms under Impact Loading of 17Mn1Si Steel with Explicit Accounting Structural Heterogeneity

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Abstract

The effect of the microstructure parameters as well as the testing temperature on the impact toughness of 17Mn1Si steel has been studied. The interrelation between the testing temperature during impact bending and deformation and fracture energy consumption has been studied. The relation between fracture energy characteristics at high-rate impact bending and the microstructure of the steel has been established. It is shown that the decrease of the testing temperature leads to almost linear reduction of the impact toughness.

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Keywords: transportation systems, impact toughness, main pipeline, steel 17Mn1Si, fracture, failure

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1. Introduction

Within the methodology of physical mesomechanics, a relationship between processes developing at various scale levels is to be taken into account to build hierarchical models of deformation and fracture [1]. A special attention has to be paid to understand the local response at the mesoscale level where stress-strain state is very inhomogeneous. The mesoscale is related to the large number of interfaces, nucleation and development of deformation defects [1, 2]. Processes of plastic flow followed by nucleation of defects and discontinuities are initiated in the vicinity of structural inhomogeneities [3]. Also, the free surface should be treated as an additional structural level of deformation where plastic flow processes are predominantly initiated [4]. The explicit account has to be given to interaction between independent 2D-planar subsystems (the surface layer and all interfaces) and 3D-crystalline ones (grains, inclusions, precipitations, etc.) [1].

17Mn1Si structural steel is widely used in pipeline engineering. Its properties have been comprehensively studied and documented. [5] However, ensuring safe operation of products made of this steel with regard to fracture resistance under various conditions, especially at low temperatures, is still an important research and engineering problem. In particular, the relatively low fracture toughness of individual grains or their conglomerates (hereinafter aspects of the local damaging and/or exhaustion of plasticity will also be discussed) may be the reason that the reliability of a pipeline as the engineering construction is determined by the properties of its "weakest link" [6]. The problem of plastic deformation development across the grain conglomerates has been widely studies in the literature [7, 8]. In those papers, the role of deformation mechanisms at the microscale level is taken into account through the use of appropriate phenomenological relations. Nevertheless, the results of multiscale deformation and fracture studies of pipe steels are not sufficiently covered in the literature. At the same time, establishing the relationship between microstructural parameters and mechanical (macro) characteristics of pipeline materials is of significant scientific and practical interest.

Thus, the present paper is aimed at experimental study and theoretical understanding of the relationship between the microstructure parameters, mechanical properties, features of impact induced deformation and fracture of Charpy specimens of 17Mn1Si pipe steel in the temperature range from ambient one down to –60 °C.

2. Experimental research technique

Charpy specimens for impact bending tests with the dimensions of 10 × 10 × 55 mm were cut out of 30 mm thick steel sheet by electro spark erosion. 2 mm long V-shaped notches were induced mechanically by the Blacks Charpy cutting machine (UK). The impact strength was measured using the automated pendulum Instron 450 MPX equipped with an instrumented striker. The software for the data processing makes it possible to divide the fracture energy into components by converting the "loading-time" ($P - t$) dependence into "load-bending" ($P - s$) one [9]. Deformation and fracture topography were investigated using the scanning electron microscope LEO EVO 50 (Zeiss, Germany).

3. Simulation technique

The original developed simulation technique is based on the theory of stress field evolution that initiates reversible structural-phase transformations as well as formation of vortex structures at the interfaces. This theory has been successfully developed on the basis of physical mesomechanics [1, 4]. Within the multiscale approach the material is represented as a set of spatial elements comprising of the 3D-crystalline subsystems and the 2D-planar one. The latter are the paths where rotational-wave flows of mass and energy are developed. In doing so the latter should be highly pronounced under dynamic (and localized) loading. These rotational deformation modes emerge under the effect of local moments of forces.

A series of numerical experiments was conducted to analyze the temperature effect on the dynamic deformation behavior of ductile 17Mn1Si steel specimens. The modified hybrid approach combines the methods of excitable cellular automata and continuum approach (ECA). Each active element of the automata is characterized by a certain set of neighbors at the first coordination sphere, as well as numerical parameters corresponding to the material