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Experimental Determination of the Surface Energy of a Metal Composite Based on Crack Development Parameters

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Abstract: The paper proposes and tests a method for measuring the surface energy of an alloyed steel with a fibrous ferrite-martensite composite structure. The method is based on the cleavage test and the measurement of the material's mechanical characteristics based on the development of a crack. The relationship between the material parameters, surface energy, and crack length was described in accordance with the Griffiths and Irwin fracture criteria, expressed through the invariant integral. The crack developed under flat deformation conditions with low values of the average radius of the plastic zone at the crack tip. In this case, the fracture mechanism is quasi-elastic or elastoplastic. Using analytical expressions for fracture criteria and experimental data on crack formation, the values of the surface energy of the steel composite were obtained. The results are in good agreement with known experimental data for single crystals of polymorphic iron modifications, which demonstrates the correctness and applicability of the proposed methodology. In the future, it will be possible to account for the delamination of ferrite during crack growth and, by determining the thicknesses of the ferrite and martensite layers, to determine their surface energies.

Keywords: Crack formation, Tensile strength, Ferritic-martensitic composite, Elastic-plastic deformation, Surface energy

Introduction

To ensure the safety and durability of materials, understanding the mechanical and thermodynamic factors of crack development is critical. The study of crack formation processes in composite materials is an important research area based on experimental data and a rigorous theoretical approach to their analysis (Shvechkovet al., 2020). The process of crack formation involves the simultaneous formation of two free surfaces. Griffiths was the first to analyze the relationship between mechanical characteristics and the surface energy of a solid. However, his model, which was confirmed by experiments, is only applicable to brittle amorphous bodies. Further development of the theory of material failure has allowed us to move from the description of brittle failure to failure under elastoplastic deformation (Astafiev, et al., 2001).

It should be noted that several well-known methods are used to experimentally determine the surface tension (energy) of solid metals, including the cleavage method, which is based on the Griffiths model and its modern interpretation. The surface energy of solids is a determining parameter not only in the mechanics of destruction, but primarily in all processes and phenomena occurring on the surface – adsorption, adhesion, cohesion, wetting, hydrophobicity of materials, sintering, etc. It depends on the temperatures of phase transitions, and therefore, on the technologies of processing materials. Today, theoretical approaches to determining the surface energy of solid crystalline bodies are being developed. However, there is a lack of experimental data on surface tension (energy) even for pure metals, and the data often have a wide range (Aref'eva, 2022). For alloys, such data is almost non-existent in both reference books and scientific literature. This highlights the need for a

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technically feasible method for measuring the surface tension (energy) of metals and alloys. As know, the Griffiths and Irwin criteria have been formulated for brittle fracture. A crack propagates when the released energy intensity or stress intensity factor reaches a critical value (Astafiev et al., 2001).

The critical values of the surface energy density of a body with a crack and the stress intensity factors are material constants that characterize its crack resistance under given external conditions, and they must be determined experimentally. The higher the values of these parameters, the better the material's resistance to crack growth and the higher the threshold for brittle failure. The failure of metals occurs with the formation of a zone of plastic deformation at the crack tip.

The energy of the localized field of plastic deformations significantly exceeds the surface energy of the formation of a new free surface. In this case, the application of Griffith's theory becomes incorrect. However, if the size of the plastic zone is small compared to the crack length, the failure of metals can often be considered quasi-brittle. The Griffiths criterion for brittle failure, formulated using the Ashlby-Cherepanov-Rice invariant J-integral (Bondar et al., 2023; Chernavin et al., 2023), can be extended to include elastoplastic deformation.

The study focused on layered composites, which are characterized by a specific ratio of the volume fractions of their structural components and a discrete length of the reinforcing fiber. The aim of the work was to determine the surface energy of a metal composite using the Griffiths theory for elastoplastic deformation by determining the mechanical parameters of fracture.

Method

To obtain the mechanical parameters of fracture, the work carried out an analysis of the development of a crack of fatigue cyclic destruction of a composite material based on steel A414(F) with an oriented layered ferrite-martensite structure (Figure 1). The strict orientation of the phase structural components was obtained using a technological regime (Pustovoit et al., 2020, Egorov & Egorova, 2022) consisting of quenching from the intercritical temperature interval (730°C) followed by low-temperature tempering (200°C). The volume fraction ratio of ferrite and martensite was 70 / 30, respectively, and the length of the strengthening fiber was lкр =160 µm. (Duka & Aref'eva, 2025)

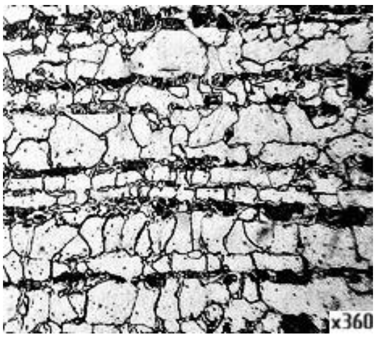

Figure 1. Microstructure of a ferrite-martensite composite based on A414(F) steel

A special installation was used to study the kinetics and mechanism of fracture. This installation was designed to induce a fatigue crack and study the kinetics of its development under cyclic loading (Pustovoit et al., 2020). The samples used for the study had a four-sided prismatic shape (10x10x100mm) with a pre-applied "U"-shaped concentrator (r=0.25mm, depth=1.5mm). To exclude the possibility of the crack banks hardening during its growth, the cyclic bending tests were carried out according to the non-zero loading cycle, in which the bending moment led only to tensile stresses arising in the sample, compressive stresses in this case were equal to zero.

The process of measuring crack growth was carried out by the method of potential difference. In the process of the crack growth, the dependence "potential difference - time" was automatically recorded. For the interpretation of the obtained data, a calibration graph was used, which connected the potential difference with the crack length. (Pustovoit et al., 2022; Gurdjiev et al., 2024). This graph was constructed based on the millivolt meter readings, taking into account the cross-section of the sample, the current value, and the crack length in Figure 2 (Pustovoit et al., 2022).

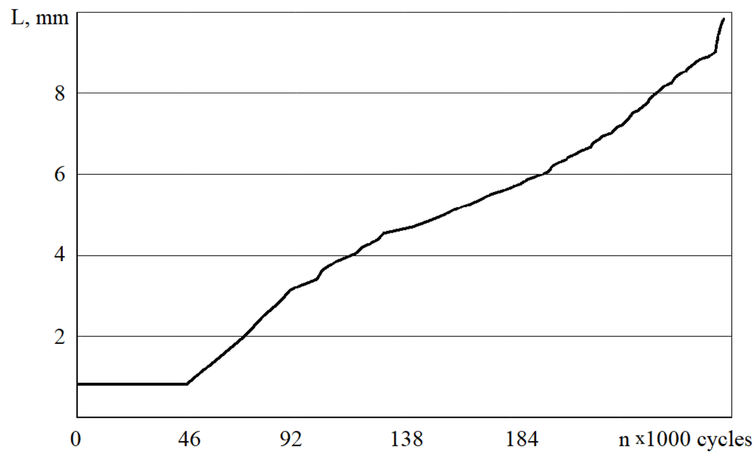

Figure 2. Dependence of crack length on the number of loading cycles in A414(F) steel

The relationship between the tensile strength σ, the crack length L, and the surface energy γ is expressed analytically using the Griffiths criterion

$$G = 2\gamma = \frac{K_I^2(1-\mu^2)}{E},$$

where μ is the Poisson's ratio and E is the modulus of elasticity.

Thus, the surface energy of a metal can be obtained from the experimental data of the crack length and the tensile strength:

$$\gamma = \frac{\pi(1-\mu^2)L\sigma^2}{2E}.$$

In the case of elastic-plastic deformation for a plane crack, the radius of the plastic zone is added to the half-length, expressed through the substance constants and the yield strength (Babeshko et al., 2022).

Results and Discussion

Earlier in the work of Pustovoit with co-authors (Pustovoitet al., 2022; Pustovoit et al., 2023) it was established that the growth of a crack occurs in steps, i.e. in the process of cyclic loading of the sample, first a zone of plastic deformation of the metal arises, and after the accumulation of stresses of a certain magnitude in it, their relaxation occurs in the form of the occurrence of a crack and its jump-like growth. Sliding occurs in the {110} and {112} planes, and the effective length of the sliding line is quite long, which leads to the rapid formation of flat dislocation clusters at the ferrite-martensite interphase boundary, local overstressing in this area, the formation of a crack nucleus, and the destruction of the martensitic layer. Based on the data from the above-mentioned work, the surface energy of A414(F) steel with a ferrite-martensitic structure was calculated.

The average radius of the plastic zone at the crack tip is small in relation to the total crack length and is 3.8 mm. The value of the surface energy was obtained for two cases of fracture mechanisms: brittle (ideal, used for comparison) and elastoplastic (real). In our calculations, the delamination of the ferrite phase was not taken into account. It should be noted that the results are obtained at room temperature, as the crack development occurred in steel without heating. In the first case, the surface energy value is 1308 mJ/m^2, and in the second case, it is 1949 mJ/m^2.

Our results were compared with known experimental data that were recommended as reference data. The surface energy of α-iron for the (110) face is 1480 mJ/m^2, γ-iron for the (100) and (111) faces is 2145 and 1370 mJ/m^2, δ-iron for the (110) face is 1407 mJ/m^2, and for a polycrystal is 1624 mJ/m^2 (Schönecker, et al., 2015). The surface tension of γ- and δ-iron was determined using the "zero" creep method and is 2170±330 and 2320±80 mN/m, respectively (Schönecker et al., 2015).

Conclusion

The work performed measurements of the surface tension of the alloyed steel A414(F) by a method similar to the cleavage method and based on the measurement of the crack length in the composite material. The analytical relationship between the material parameters, surface energy and crack length were described in accordance with the Griffiths and Irwin criteria of fracture, expressed through the Ashlby-Cherepanov-Rice integral. The established averaged radius of the plasticity zone under plane deformation allows us to consider the considered mechanism of destruction to be quasi-elastic or elastoplastic and to apply the above criteria for assessing the surface energy.

From the analysis of the results obtained, it can be concluded that the proposed and tested technique allows for a good accuracy to determine the value of the surface tension of a polycrystalline material and, in particular, is applicable to composites with a fibrous structure. It is possible that in the future, by taking into account the delamination of ferrite during crack development and knowing the thickness of the phase layers, it will also be possible to estimate the surface energy of ferrite and martensite.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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