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Denis Chemezov
Vladimir Polytechnic College
MEng, Honorary Worker of the Education Field of the Russian Federation, Academician of International Academy of Theoretical and Applied Sciences, Lecturer, Russian Federation
https://orcid.org/0000-0002-2747-552X
vpk-science@yandex.ru

Marina Danina
Vladimir Polytechnic College
Student, Russian Federation

Irina Pavlukhina
Vladimir Polytechnic College
Lecturer, Russian Federation

Andrey Kunaev
Vladimir Polytechnic College
Student, Russian Federation

Viktoriya Golik
Vladimir Polytechnic College
Student, Russian Federation

Nikita Zotov
Vladimir Polytechnic College
Student, Russian Federation

Vladislav Zhgarov
Vladimir Polytechnic College
Student, Russian Federation

Arseniy Bezrukov
Vladimir Polytechnic College
Student, Russian Federation

DEPENDENCIES OF THE STRESSED AND DEFORMED STATE OF STEEL ON THE ELONGATION DEGREE OF A SPECIMEN

Abstract: *The article presents the results of testing a standard steel specimen under variable tensile load conditions. Equivalent plastic strain rate of the material was analyzed, depending on the elongation degree of the specimen. It has been established that a high strain rate is characteristic of the elastic state of the material, and a decrease in the strain rate is associated with residual deformations. The minimum and maximum values of the equivalent plastic strain rate and shear stress of the material during tensile characterize the failure of the specimen at the gage length. The values of the tensile force required to break the specimen at various strain rates of steel were also determined.*

Key words: *tensile testing, specimen, elongation, strain rate, failure, stress.*

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1. Introduction

The deformation process of materials is caused by various types of stress [1].

The relative elongation of a specimen during a tensile testing is the amount of stretching that the material undergoes before failure under variable force. It is usually expressed as a percentage of the original length of the standard specimen and provides an indication of the ductility and flexibility of the material being tested. A higher relative elongation indicates a ductile material that can deform significantly before failure, while a lower relative elongation indicates a brittle material with limited deformation before failure. This parameter is important for understanding the material's behavior under tensile and its suitability for various engineering applications.

The strain rate of steel during tensile testing usually depends on the testing conditions, but it typically ranges from 0.001 to 0.1 mm/s for standard testing procedures. The strain rate can affect the behavior of a material: higher rates tend to increase apparent strength and decrease ductility [2-3].

Many studies have been conducted on the plasticity of materials during mechanical tensile testing. For example, the work [4] analyzes the mechanical behavior of two-phase steels by studying their strain hardening rate and strain rate sensitivity during tensile tests at quasi-static strain rates. The author of work [5] explores how changes in strain rate affect the tensile behavior of SAE 4340 steel, emphasizing that higher strain rates tend to increase the strength and ductility of steel. Shin and Kim [6] developed a phenomenological constitutive equation to accurately describe the diverse flow behavior of materials over a wide range of strain rates and temperatures. Naumann and Merklein [7] investigate how the method of optical monitoring of strain rate during tensile testing affects the mechanical properties of sheet metal. Banerjee et al. [8] presented a comprehensive study on the finite element modeling of steel specimens under various loading conditions. Their research focused on modeling the deformation behavior of steel under various mechanical loads, which provided insights into the material's response and failure mechanisms. In another work [9], the authors conducted an experimental and numerical study of the deformation behavior of steels under biaxial tensile tests. The study [10] compares methods for measuring deformations by evaluating the digital correlation of images using finite element analysis software.

By analyzing the scientific literature, we noted that the state of the steel specimen during elongation to failure under the conditions of the tensile testing is less well-documented. Thus, a qualitative analysis of the effect of tensile modes on the stress and strain state of the steel specimen was performed to provide a more comprehensive description of the material's strength characteristics.

2. Materials and methods

The tensile testing of the steel cylindrical specimen was performed using finite element modeling. The standard specimen had the following dimensions: an overall specimen length of 100 mm, a calculated gage length of 60 mm, a diameter of 10 mm, and the specimen head diameter of 20 mm. The following properties of structural steel were specified for the specimen model: heat capacity at constant pressure – 475 J/(kg×K), thermal conductivity – 44.5 W/(m×K), coefficient of thermal expansion – 12.3×10^{-6} 1/K, reference temperature – 293.15 K, melting temperature – 1700 K, temperature exponent – 0.6, density – 7850 kg/m³, Young's modulus – 200×10^{9} Pa, Poisson's ratio – 0.3, initial yield stress – 400 MPa, strength coefficient – 200 MPa, hardening exponent – 0.5, strain rate strength coefficient – 0.12, reference strain rate – 1 1/s, Murnaghan third-order elastic moduli (l) – -3.0×10^{11} Pa, Murnaghan third-order elastic moduli (m) – -6.2×10^{11} Pa, Murnaghan third-order elastic moduli (n) – -7.2×10^{11} Pa, Lamé parameter (λ) – 1.15×10^{11} Pa, Lamé parameter (μ) – 7.69×10^{10} Pa. The plasticity of the specimen model was represented by small plastic strains. The yield function of the deformed material was evaluated using the von Mises stress criterion. The material's behavior during plastic deformation was described by the Johnson-Cook empirical model, which takes into account the effects of isotropic hardening, kinematic hardening, and adiabatic heating. The stretching was performed until the steel specimen model broke.

3. Results and discussion

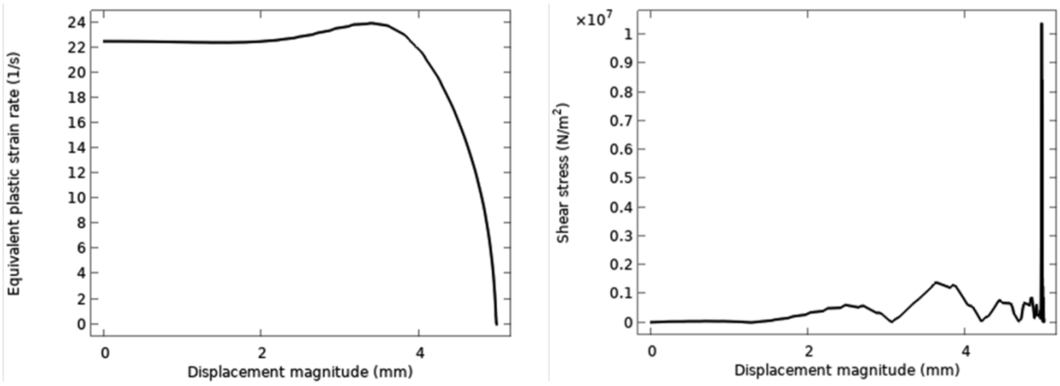
By analyzing the deformed model of the standard cylindrical specimen after tensile, it was noted that the von Mises stress of the material volume of the specimen (the calculated gage length) is 600 MPa, which is 1.5 times higher than the equivalent stress of the material volume in the area of radius connection between the diameters of the gage and the specimen head.

The elongation of the standard specimen before its failure was 5 mm. The specimen elongates by a specified amount at tensile forces of 35.3, 35.4, 38, and 47.5 kN at strain rates of 0.1, 0.01, 1, and 10 1/s, respectively. Therefore, it can be concluded that lower rates of strain during tensile lead to the breaking of the specimen when a smaller tensile force is applied.

Strain of the specimen material due to stress will also depend on the strain rate. The deformation of the specimen at low rates in the plastic deformation zone is characterized by low stresses in the material in the range of 400-450 MPa and a higher value of the strain coefficient up to 0.275. The deformation of the specimen at high rates (10 1/s) in the plastic deformation zone is characterized by high stresses (570-615 MPa) and a lower value of the strain coefficient up to 0.22.

The results of calculating the stress and strain state of the standard specimen model during sequential tensile are presented graphically in the Figure 1.

The graphs show that the equivalent plastic strain rate of steel is maximum (22-24 1/s) before the specimen elongates by 3.5 mm. A slight increase in the equivalent plastic strain rate is due to the transition of elastic steel deformations into plastic deformations. A sharp decrease in the equivalent plastic strain rate demonstrates the process of metal flow before it failure. The shear stress of the material changes abruptly (from 0 to 1.5×10^7 N/m^2) over the entire range of elongation to a maximum value that determines the failure of the specimen.



a ***b***

Figure 1. Dependencies: *a* – equivalent plastic strain rate of the material from the elongation of the specimen; *b* – shear stress of the material from the elongation of the specimen.

4. Conclusion

Based on a critical analysis of the research results, the following conclusions can be drawn:

1. At steel strain rates of 0.01 and 0.1 1/s, the axial stress in the material remains virtually unchanged and is 450 MPa at the moment of failure of the specimen. With an increase in the strain rate of the specimen to 10 1/s under tensile conditions, the axial stress increases by 25%. The strain coefficient of steel at low strain rates is 18.18% higher than at higher strain rates.

2. The failure of the standard specimen occurs in the tensile force range of 35.3…47.5 kN. The minimum value in the range characterizes the failure of the material at a strain rate of 0.1 1/s, the maximum value in the range characterizes the failure of the material at a strain rate of 10 1/s.

3. The transition boundary between elastic deformations and residual deformations occurs at a strain rate of 23.6 1/s, which corresponds to an elongation of the specimen by 3.5 mm. Subsequent elongation of the specimen results in metal flow until it ruptures at an elongation of 5 mm. Shear stress of the material over the entire range of elongation changes abruptly to a maximum value instantly, which determines the failure of the specimen.

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