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FEATURES OF DYNAMIC STRAIN AGING DEVELOPMENT IN CARBON STEEL DURING REVERSE LOADING

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Abstract. *The study evaluates the possibility of increasing the ductility of cold-drawn carbon steel by utilizing controlled dynamic strain aging (DSA) processes under alternating deformation. It was found that a change in the deformation sign (compression-tension) leads to a shift in the onset of flow stress serrations toward higher strain levels compared to unidirectional tension. Based on the analysis of the stress of unrevised motion of dislocations and the strain hardening coefficient, it is shown that the suppression of DSA during reverse loading is caused by a disruption in the kinetic relationship between the dislocation waiting time and the duration of their free motion. An optimal temperature range for alternating bending (250–275 °C) was identified, which ensures the realization of kinetic conditions for stabilizing DSA processes to enhance the plasticity of high-carbon wire without compromising its strength properties. It is proved that heating above 275 °C violates this condition, leading to the degradation of mechanical properties. The practical value lies in justifying the necessity of forced cooling of the metal after deformation.*

Keywords: *carbon steel, dynamic strain aging (DSA), dislocation, temperature, strain hardening, plasticization.*

Introduction

Modern technological development leads to a steady increase in requirements for metallic materials, especially those operating under complex thermo-mechanical conditions. Since most engineering components are manufactured using plastic deformation methods, the operational characteristics of such structures are directly determined by structural changes in the metal during its processing. A key process in this context is strain hardening, which reflects the material's ability to resist further deformation.

However, under certain temperature and strain rate parameters, this process becomes unstable, manifesting as non-monotonic stress drops or serrations on loading diagrams [1]. This phenomenon, known in the literature as dynamic strain aging (DSA) or the Portevin–Le Chatelier effect, arises from the specific interaction of dissolved impurity atoms with mobile dislocations [2, 3]. Since intermittent plastic flow can significantly limit the use of alloys in the production of critical components, a thorough analysis of DSA mechanisms is necessary [4, 5]. The development of methods to control metal properties under alternating loading is of particular relevance, as it allows for the mitigation of the negative effects of unstable deformation.

Methods and Data Processing

The objects of the study were carbon steels with a carbon content of 0.1–0.5 % C, as well as industrial high-carbon wire with a diameter of 3 mm and a content of 0.78 % C. To form the initial structural state meeting the requirements of hardware production, the billets were subjected to austenitization followed by isothermal transformation at a temperature of 550 °C, which ensured the production of a fine pearlitic structure. Subsequent cold drawing was performed on industrial machines with a total reduction degree of 78 %.

The experimental procedure involved alternating bending of the specimens in a four-roll device within the temperature range of 225–300 °C at a strain rate of 1 s^{-1}. To distinguish between the effects of dynamic and static strain aging, the metal was subjected to forced air cooling after the deformation. Mechanical properties were determined by tensile testing on an Instron machine at a rate of 10^{-3} s^{-1}. Analysis of true stress-strain curves allowed for the calculation of the stress of irreversible motion of dislocations (σ_0), the strain hardening exponent (m), and the critical strain for the onset of stress serrations (ε_c).

The test results showed that alternating deformation significantly changes the nature of plastic flow compared to unidirectional tension. In particular, a shift in the onset of the first flow stress serrations (ε_c) toward higher strains was established.

Based on the analysis of the parameter σ_0, it was found that the change in the loading sign causes a decrease in the density of mobile dislocations due to their intensive recombination. According to the kinetic model of the process, such a reduction in defect density leads to a shortening of the dislocation waiting time at barriers (τ_0), which disrupts their interaction with impurity atom atmospheres.

The industrial drawing of steel billets is inevitably accompanied by intensive heat generation, where the deformation temperature increases proportionally to the degree of reduction. This creates conditions for the uncontrolled development of aging processes — both dynamic (DSA) occurring directly during deformation and static (SSA) after coiling the wire into bundles — which significantly alters the property profile of the finished metal. With an increase in the degree of cold deformation, the intensive accumulation of crystal lattice defects and the difficulty of internal stress relaxation lead to an increase in strength alongside a simultaneous increase in the brittleness of the steel. To minimize these negative consequences, it is advisable to employ alternating bending, by introducing dislocations of opposite signs, this method allows for the optimization of their total density and spatial arrangement within the structure through recombination processes.

Analysis of the mechanical behavior of cold-drawn metal during heating revealed that at temperatures up to 250 °C, an initial decrease in strength due to softening is observed, followed by its increase resulting from the activation of static aging. In turn, the ductility of the metal begins to significantly degrade once the 250 °C threshold is exceeded. It has been experimentally proven that alternating bending at room temperature only slightly increases ductility, whereas proportional heating of the deformation zone to 250–275 °C provides a unique effect of synchronous increase in both the plastic and strength characteristics of the wire. However, a further temperature rise leads to a disruption of the kinetic conditions for the interaction between dislocations and impurity atoms, accompanied by a sharp decline in the entire complex of the steel's mechanical properties.

Conclusions

In the temperature range of 225–300 °C, alternating deformation shifts the onset of dynamic strain aging toward higher strain levels compared to unidirectional loading.

The suppression of DSA under reverse loading is caused by the disruption of the kinetic relationship between the dislocation waiting time at barriers and the duration of their free path due to changes in defect density.

The optimal plasticization regime for high-carbon wire has been determined: alternating bending at 250–275 °C followed by forced cooling to prevent static embrittlement.

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ОСОБЛИВОСТІ РОЗВИТКУ ДИНАМІЧНОГО ДЕФОРМАЦІЙНОГО СТАРІННЯ ВУГЛЕЦЕВОЇ СТАЛІ ПРИ ЗНАКОЗМІННОМУ НАВАНТАЖЕННІ

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Анотація. *У роботі оцінено можливість підвищення пластичності холоднотягнутої вуглецевої сталі шляхом використання керованих процесів динамічного деформаційного старіння (ДДС) при знакозмінній деформації. Встановлено, що зміна знаку деформації (стиснення–розтягання) призводить до зміщення моменту появи серрацій деформуючого напруження у бік більших ступенів деформації порівняно з односпрямованим розтяганням. На основі аналізу напруження необерненого руху дислокацій та коефіцієнта деформаційного зміцнення показано, що пригнічення ДДС зумовлене порушенням кінетичного співвідношення між часом очікування дислокацій та часом їх вільного пробігу. Виявлено оптимальний температурний інтервал знакозмінного згину*

(250–275 °C), який забезпечує реалізацію кінетичних умов стабілізації процесів ДДС для підвищення пластичності високо вуглецевого дроту без зниження міцності. Доведено, що при нагріві понад 275 °C вказана умова порушується, що призводить до деградації механічних властивостей. Практична цінність полягає в обґрунтуванні необхідності примусового охолодження металу після деформації.

Ключові слова: *вуглецева сталь, динамічне деформаційне старіння (ДДС), дислокація, температура, деформаційне зміцнення, пластифікація.*