Информация о номере

Название журнала: Физическая мезомеханика
ISSN: 1683-805X
Издатель: Федеральное государственное бюджетное учреждение науки Институт физики прочности и материаловедения Сибирского отделения Российской академии наук (ИФПМ СО РАН)
Место издания: Томск, Россия
Адрес: Академический пр., 2/4, Томск, 634055, Россия
Сокращенное название: Физ. мезомех.
2025, Том 28, № 3, с. 5–130.
Дата выпуска: 27 июня 2025

1. *Научная статья*

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УДК 539.3, 539.5
DOI 10.55652/1683-805X_2025_28_3_5-21
Поступила в редакцию 14.04.2025; после доработки 21.04.2025; принята к публикации 26.04.2025

Структурно-механические модели материалов, изготовленных селективным лазерным сплавлением, на примере стали 316L (обзор)

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В настоящей работе на примере аустенитной нержавеющей стали 316L, полученной методом селективного лазерного сплавления, рассмотрены модели механического поведения, в явном виде учитывающие структурные особенности аддитивно-изготовленных металлов на разных масштабных уровнях. Представлен обзор экспериментальных исследований особенностей иерархической структуры и механических свойств таких материалов. Рассмотрены основные подходы к построению двумерных и трехмерных моделей. Приведен обзор работ по численному исследованию процессов локализации деформации и концентрации напряжений, связанных с границами раздела различной природы, геометрии и масштаба.

Ключевые слова: селективное лазерное сплавление, сталь 316L, иерархическая структура, конечно-элементные модели пластичности кристаллов.

Microstructure-Based Mechanical Models of Materials Manufactured by Laser Powder Bed Fusion Using Stainless Steel as an Example (Review)

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The The paper reviews numerical models that explicitly consider structural features of additively manufactured austenitic stainless steel 316L at different scales. Experimental studies on hierarchical structures and the corresponding mechanical properties of the material are summarized. Key methods for generating two- and three-dimensional structures are discussed. Numerical studies on the features of plastic strain localization and stress

concentration associated with interfaces of different nature, geometry, and scale in additively manufactured stainless steel 316L are overviewed.

Keywords: laser powder bed fusion, steel 316L, hierarchical microstructure, crystal plasticity finite-element models.

Финансирование

Работа выполнена в рамках государственного задания ИФПМ СО РАН, тема FWRW-2021-0002.

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2. *Научная статья*

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УДК 621.793.1(620.18+620.178.15+620.178.162.4)
DOI 10.55652/1683-805X_2025_28_3_22-34
Поступила в редакцию 15.05.2025; после доработки 2.06.2025; принята к публикации 02.06.2025

Особенности деградации нитридных ионно-плазменных покрытий при трении скольжения

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В работе исследованы покрытия нитридных систем TiAlN и CrAlSiN толщиной 0.8…4.0 мкм, полученных по технологии вакуумного ионно-плазменного напыления. В качестве подложек для осаждения покрытий использованы образцы с азотированной поверхностью из стали 38Х2МЮА и образцы с цементованной поверхностью из стали 12Х2Н4А. Представлены экспериментальные данные физико-механических свойств покрытий, полученных различными методами индентирования, в том числе методом скрэтч-тестирования (царапания), и трибологических свойств покрытий, полученных при испытаниях на трение скольжения. Приводятся также результаты микроструктурного (SEM) и энерго-дисперсионного рентгеновского (EDX) анализа покрытий, в том числе — электронно-микроскопические данные изнашивания покрытий в процессе трибологических испытаний. Показано, что ни одна из физико-механических характеристик (твердость H, модуль упругости E и их отношения H/E, H^3/E^2), полученных при непрерывном или при динамическом (например, критическая нагрузка скалывания покрытия F_N^c, определяемая на скрэтч-тестере) индентировании по отдельности не может оценить износостойкость покрытия в условиях проводимых испытаний. В этом состоит методологическая проблема, которая не позволяет корректно прогнозировать результаты износа покрытий. Предложенное в работе решение проблемы заключается в совместном использовании расчетных величин удельной работы отслаивания покрытия от подложки G и сопротивления покрытия пластической деформации H^3/E^2, которые в совокупности определяют не только суть процесса деградации покрытия, но и процесса потери устойчивости всей системы «покрытие–подложка».

Ключевые слова: вакуумная ионно-плазменная технология, нитридные тонкие пленки, сканирующая электронная микроскопия, индентирование, скрэтч-тестирование (царапание), механические свойства покрытий, трибологические испытания, трение скольжения, адгезия, износостойкость.

Degradation Features of Ion-Plasma Nitride Coatings under Sliding Friction

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The paper studies nitride coatings of the TiAlN and CrAlSiN systems with a thickness of 0.8…4.0 μm deposited by the vacuum ion-plasma technology. Specimens of nitrided 38Cr2MoAlN steel and carburized 12Cr2Ni4N steel were used as substrates for coating deposition. Experimental data are derived on the physical and

mechanical properties of the coatings by various indentation methods, including scratch tests, as well as on their tribological properties in sliding friction tests. The results of microstructural (SEM) and energy-dispersive X-ray (EDX) analysis of the coatings are also presented, including electron microscopic data on coating wear in tribological tests. It is shown that none of the physical and mechanical characteristics (hardness H, elastic modulus E, and their ratios H/E, H^3/E^2) determined by continuous or dynamic (for example, critical load F_N^c for coating spallation in scratch tests) indentation can separately describe the wear resistance of a coating under the test conditions. This is the methodological problem that does not allow an accurate prediction of the coating wear. The problem is solved by the joint use of the calculated specific work of coating delamination from the substrate G and the coating resistance to plastic deformation H^3/E^2, which together determine not only the coating degradation process, but also the loss of stability of the entire coating–substrate system.

Keywords: vacuum ion-plasma technology, nitride thin films, scanning electron microscopy, indentation, scratch testing, mechanical properties of coatings, tribological tests, sliding friction, adhesion, wear resistance.

Финансирование

Работа выполнена при финансовой поддержке Российского научного фонда (проект № 21-79-30007-П).

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3. *Научная статья*

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УДК 669.017
DOI 10.55652/1683-805X_2025_28_3_35-44
Поступила в редакцию 26.08.2024; после доработки 01.10.2024; принята к публикации 01.11.2024

Влияние скорости охлаждения при кристаллизации на микроструктуру квазибинарного сплава Al-Cu-Gd в литом и гомогенизированном состояниях

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Проведено исследование влияния скорости охлаждения при кристаллизации на микроструктуру квазибинарного сплава Al-6Cu-3Gd после литья и гомогенизации. Различные скорости охлаждения реализованы путем поверхностного лазерного плавления (ПЛП), кристаллизации в холодной и подогретой изложнице и с печью. Показано, что увеличение скорости охлаждения с 0.02 К/с до 10^5–10^7 К/с приводит с существенному измельчению размера дендритной ячейки со 126 до 0.5 мкм и интерметаллидных фаз с 0.2–4 мкм до 0.05–0.1 мкм, что обеспечивает рост твердости слитков с 25 до 75 HV. Зависимость размера дендритной ячейки точно описывается эмпирическим уравнением, полученным на доэвтектическом силумине. В микроструктуре идентифицированы дисперсная эвтектика ((Al) + Al_8Cu_4Gd (τ1)) и отдельные включения фазы $(Al,Cu)_{17}Gd_2$ (τ4), которые демонстрируют высокую термическую стабильность в процессе гомогенизации при 590°C. В микроструктуре после ПЛП выявлено наличие сетки более крупных частиц размером около 1 мкм, в то время как основная доля частиц размером 0.1–0.2 мкм однородно распределена в объеме. В сплавах, полученных с промежуточными скоростями охлаждения 1–15 К/с наиболее близкими к промышленным, процессы фрагментации и сфероидизации протекают практически одинаково: размер частиц изменяется с 0.1–0.2 мкм в литом состоянии до 0.5–3 мкм после 1–24 часов гомогенизации. В сплаве, охлажденном с минимальной скоростью 0.02 К/с, частицы практически не изменяют своей морфологии.

Ключевые слова: алюминиевые сплавы, гадолиний, микроструктура, скорость охлаждения.

Effect of the Cooling Rate on the Microstructure of a Quasi-Binary Al-Cu-Gd Alloy in the As-Cast and Homogenized States

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The paper studies the effect of the cooling rate during solidification on the microstructure of the quasi-binary Al-6Cu-3Gd alloy after casting and homogenization. Different cooling rates are implemented by surface laser melting (SLM), solidification in a cold or heated mold and with a furnace. It is shown that an increase in the cooling rate from 0.02 K/s to 105–107 K/s leads to a significant refinement of dendritic cells from 126 to 0.5 μm and intermetallic phases from 0.24 μm to 0.05–0.1 μm, which improves the hardness of ingots from 25 to 75 HV. The dependence of the dendritic cell size is accurately described by an empirical equation obtained for hypoeutectic silumin. The microstructure contains a dispersed eutectic ((Al) + Al_8Cu_4Gd (τ1)) and individual inclusions of the $(Al,Cu)_{17}Gd_2$ (τ4) phase, which demonstrate high thermal stability during homogenization at 590°C. The microstructure after SLM contains a network of larger particles of about 1 μm in size, while the main proportion of particles 0.1–0.2 μm in size is uniformly distributed throughout the volume. In the alloys obtained at the intermediate cooling rates 1–15 K/s, which are close to industrial ones, the processes of fragmentation and spheroidization occur almost identically: the particle size changes from 0.1–0.2 μm in the cast state to 0.5–3 μm after 1–24 h of homogenization. In the alloy cooled at the minimum rate of 0.02 K/s, the particle morphology remains almost unchanged.

Keywords: aluminum alloys, gadolinium, microstructure, cooling rate.

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УДК 669.295:539.5

DOI 10.55652/1683-805X_2025_28_3_45-54

Поступила в редакцию 02.09.2024; после доработки 03.10.2024; принята к публикации 03.10.2024

Исследование усталостной прочности титанового сплава Ti-10V-2Fe-3Al с частицами карбида титана

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Методами Исследовано сопротивление усталости при одноосной циклической нагрузке прутков из сплава Ti-10V-2Fe-3Al с различным содержанием углерода (0.031 и 0.063 мас. %). В структуре сплава с 0.063 мас. % углерода присутствуют частицы карбида титана аналогичные по морфологии частицам первичной α-фазы размерами в среднем около 2-3 мкм. По результатам испытания на усталость установлено, что предел выносливости сплава на базе 3 млн. циклов с частицами карбида титана составляет 1000 МПа. При исследовании поверхности разрушения образцов обнаружено, что усталостное разрушение образцов вблизи предела выносливости подповерхностное, очаги разрушения представлены фасетками со скоплением частиц первичной α-фазы, инициирующими зарождение трещины. Экспериментально показано и подтверждено численными расчетами, что наличие частиц карбида титана в структуре не влияет на усталостную прочность сплава.

Ключевые слова: титановый сплав, усталость, карбид титана, прочность, РЭМ.

Study of Fatigue Strength of the Ti-10V-2Fe-3Al Titanium Alloy with Titanium Carbide Particles

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The fatigue strength of rods made of the Ti-10V-2Fe-3Al alloy with different carbon contents (0.031 and 0.063 wt %) under uniaxial cyclic loading was studied. The structure of the alloy with 0.063 wt % C contains titanium carbide particles similar in morphology to those of the primary α phase with an average size of about 2-3 μm. It was experimentally found that the 3 million cycle fatigue strength of the alloy with titanium carbide particles is 1000 MPa. The analysis of fracture surfaces reveals that the specimens experience subsurface fracture near the fatigue strength, and fracture sites are represented by facets where particles of the primary α phase accumulate and initiate cracks. It is experimentally shown and numerically confirmed that the presence of titanium carbide particles in the structure does not affect the fatigue strength of the alloy.

Keywords: titanium alloy, fatigue, titanium carbide, strength, SEM.

Финансирование

Работа выполнена при финансовой поддержке Министерства науки и высшего образования Российской Федерации в рамках Программы развития Уральского федерального университета имени первого Президента России Б.Н. Ельцина в соответствии с программой стратегического академического лидерства «Приоритет-2030».

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УДК 669.3'21:539.25
DOI 10.55652/1683-805X_2025_28_3_55-69
Поступила в редакцию 06.09.2024; после доработки 06.11.2024; принята к публикации 13.11.2024

Особенности структуры и свойств эквиатомного сплава Cu-Au, упорядоченного в поле внешних сил

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Атомно-упорядоченные золотомедные сплавы используются в технике, поэтому поиск способов повышения их механических свойств является актуальной научно-практической задачей. В представленной работе изучалось влияние растягивающих и сжимающих напряжений на формирование упорядоченной структуры, текстуры и физико-механических свойств эквиатомного сплава CuAu. Все эксперименты проводились на проволочных образцах Ø1.5 мм, которые в исходном состоянии были разупорядочены закалкой от 600°C или с использованием пластической деформации на 75%. Формирование упорядоченной структуры проводили при температуре 350°C, 24 часа; сжимающие напряжения в ходе этого отжига составляли 7 и 11 МПа; растягивающие напряжения составляли 7 и 20 МПа. Для сравнения использовались образцы, упорядоченные в свободном состоянии. Показано, что в результате отжига в поле сжимающих напряжений значительная часть коротких c-осей упорядоченной решетки выстраиваются вдоль направления действия силы. В свою очередь, отжиг под растяжением формирует иную текстуру: большинство коротких c-осей залегает в плоскости поперечного сечения образца. Оценка степени дальнего порядка (S) показала, что максимальный атомный порядок ($S \approx 0.95$) получен в образцах, отожженных в свободном состоянии. В ходе дилатометрического исследования, при температуре фазового превращения порядок → беспорядок выявлено резкое (на ~0.7%) увеличение длины образца, который после закалки был упорядочен в поле сжимающих напряжений. Установлено, что приложение сжимающей нагрузки в ходе упорядочения закаленных образцов вызывает повышение прочности и пластичности; растягивающие нагрузки приводят к их снижению. Выявлено, что механические свойства образцов, упорядоченных после предварительной деформации, практически не зависят от направления приложенной нагрузки. Обнаруженное явление объяснено отсутствием явной текстуры: использованные в работе малые нагрузки не приводят к развороту c-доменов при упорядочении высокопрочных деформированных образцов.

Ключевые слова: сплавы Cu-Au, фазовые превращения, рентгеноструктурный анализ, дилатометрическое исследование, механические свойства.

Features of the Structure and Properties of an Equiatomic Cu-Au Alloy Ordered in the External Force Field

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Atomically ordered gold-copper alloys have technological applications, which makes the search for ways to improve their mechanical properties an urgent scientific and practical task. The present paper studies the effect of

tensile and compressive stresses on the formation of an ordered structure, texture, and physicomechanical properties of an equiatomic CuAu alloy. All experiments were carried out on Ø1.5 mm wire specimens, which were initially disordered by quenching from 600 °C or plastic deformation by 75%. An ordered structure was formed at a temperature of 350 °C for 24 h; compressive stresses during annealing were 7 and 11 MPa; tensile stresses were 7 and 20 MPa. Comparison was made with specimens ordered in a free state. It is shown that annealing in the compressive stress field causes a significant part of the short c axes of the ordered lattice to align along the force direction. Annealing under tension forms a different texture, i.e. most of the short c axes lie in the cross section of the specimen. The estimation of the degree of long-range order (S) showed that the specimens annealed in a free state had the maximum atomic order ($S \approx 0.95$). According to the dilatometric study, the specimen quenched and ordered in the compressive stress field demonstrates a sharp (by ~0.7%) increase in the length at the temperature of order → disorder phase transformation. It is found that compressive loading during ordering of the quenched specimens increases their strength and ductility, while tensile loading decreases these characteristics. It is shown that the mechanical properties of the specimens ordered after preliminary deformation are almost independent of the load direction. This phenomenon is explained by the absence of a clear texture (small loads do not cause rotation of c domains during ordering of high-strength deformed specimens).

Keywords: Cu-Au alloys, phase transformations, X-ray diffraction analysis, dilatometric study, mechanical properties.

Финансирование

Работа выполнена в рамках государственного задания Минобрнауки России для ИФМ УрО РАН.

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6. *Научная статья*

УДК 541.64.7:544.23:539.2:519.6
DOI 10.55652/1683-805X_2025_28_3_70-74
Поступила в редакцию 09.09.2024; после доработки 26.11.2024; принята к публикации 03.12.2024

Фрактальный анализ механических свойств в сложенных графеновых аэрогелях

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Структуры оригами показали значительный потенциал в области создания композитов с повышенными механическими свойствами. Ранее были поучены высокопористые сложенные графеновые аэрогели (СГА) из листов оксида графена, сложенных посредством координационных и электростатических взаимодействий между атомами кислорода и Cu^{2+}. Однако влияние параметров поровой структуры на механические свойства СГА было недостаточно изучено. Поэтому в этой статье проведено параметрическое исследование пористой структуры СГА в рамках фрактальной теории с использованием фрактальной размерности (D_f). Механическое поведение СГА проанализировано в рамках фрактальной модели гомогенизации среднего поля. Результаты показали, что упругие свойства СГА имеют нелинейную тенденцию к снижению по мере увеличения D_f. Расхождение между механическими характеристиками, предсказанными моделью, и экспериментальными результатами составило менее 4%, что подтверждает достоверность модели. Благодаря однородной пористой структуре СГА имеют высокую прочность на разрыв (106.74 КПа). Это исследование может служить теоретической основой для создания и оптимизации графеновых аэрогелей с повышенными механическими свойствами. Кроме того, при использовании аналогичного математического аппарата возможно применение модели для исследования других важных физических свойств, таких как теплопроводность и термомеханическая связь.

Ключевые слова: нанокомпозит, пористость, механические свойства, фрактал, гомогенизация среднего поля.

Fractal analysis of mechanical properties in folded graphene aerogels

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Origami structures have shown significant potential for designing composites with excellent mechanical properties. In our previous work, graphene oxide (GO) sheets were folded through coordination and electrostatic interactions between oxygen atoms and Cu^{2+} to construct highly porous folded graphene aerogels (fGA). However, the influence of pore structure parameters on the mechanical properties of fGA was not fully explored. Therefore, based on fractal theory, the pore structure of fGA was parametrically quantified using the fractal dimension (D_f) in this paper. The mechanical behavior of fGA was analyzed using the mean-field homogenization fractal model (MHFM). The results revealed that the elastic properties of fGA exhibited a nonlinear decrease trend as D_f increased. The error between the mechanical properties predicted by the model and the experimental results was less than 4%, and the accuracy of the model was confirmed. The homogeneous pore structure of fGA contributed to its high tensile strength (106.74 KPa). This study provided strong theoretical support for designing and optimizing graphene aerogels with superior mechanical properties. Additionally, based on the analogous mathematical framework, the model has great potential for exploring other important physical properties, such as thermal conductivity and thermal-mechanical coupling.

Keywords: nanocomposite, porosity, mechanical properties, fractal; mean-field homogenization.

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УДК 621.822.6:539.3
DOI 10.55652/1683-805X_2025_28_3_75-79
Поступила в редакцию 06.03.2025; после доработки 01.04.2025; принята к публикации 04.04.2025

Экспериментальное исследование соотношений динамической и статической жесткости в резинометаллических пружинах

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Резинометаллические пружины находят широкое применение в промышленности, в частности как виброгасители, благодаря своей способности гасить динамические нагрузки. Динамическая жесткость резинометаллических пружин играет решающую роль в определении собственной частоты системы, поскольку между ними существует прямая связь. Поэтому точное определение динамической жесткости имеет важное значение при выборе резинометаллической пружины для конкретного применения. Однако оценка динамической жесткости представляет собой значительную проблему из-за сложного взаимодействия между резиновыми и металлическими компонентами, особенно с учетом вязкоупругих свойств резины и геометрии пружины. Вязкоупругий отклик резины и его изменение при различных скоростях деформации обусловлен микро- и мезомасштабной конфигурацией полимерных цепей, частиц наполнителя и их связью с металлическими компонентами. Приблизительные значения динамической жесткости часто рассчитывают через статическую жесткость, что упрощает задачу, но может привести к неточному прогнозированию динамического поведения пружины. В этой статье представлен экспериментальный метод оценки динамической жесткости с использованием электродинамического вибростенда, который позволяет более точно характеризовать реакцию пружины на динамическую нагрузку. Проведено сравнение с аналитическим методом, основанным на статической жесткости, с указанием его ограничений. Кроме того, уточнен диапазон значений динамической жесткости, рассчитанных через статическую жесткость, что повышает точность прогнозирования динамического поведения.

Ключевые слова: резинометаллическая пружина, вибропередача, динамическая жесткость, электродинамический вибростенд.

Experimental Investigation into Dynamic and Static Stiffness Relationships in Rubber–Metal Springs

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Rubber–metal springs are widely used in industrial applications, particularly as vibration absorbers, due to their ability to mitigate dynamic loads. The dynamic stiffness of rubber–metal springs plays a crucial role in determining the natural frequency of a system as natural frequency is directly related to dynamic stiffness. Therefore, the accurate determination of dynamic stiffness is essential when selecting an appropriate rubber–metal spring for a given application. However, the assessment of dynamic stiffness presents a significant challenge due to the complex interaction between the rubber and metal components, particularly when considering the viscoelastic properties of rubber and the geometric properties of a spring. The viscoelastic response of rubber and its change at different strain rates are governed by the micro- and mesoscopic configuration of polymer chains, filler particles, and their bonding to metal components. Consequently, dynamic stiffness is often approximated using the static stiffness measurements, which simplifies the problem but may lead to inaccuracies in predicting the true dynamic behavior of the spring. In this paper, we present an experimental method for the dynamic stiffness assessment using an electrodynamic shaker, which allows for a more accurate characterization of the spring response to dynamic loading. This method is compared to an analytical approach based on static stiffness, highlighting the

limitations of the latter approach. Furthermore, we propose an improved range for calculating dynamic stiffness by static stiffness, enhancing the predictive accuracy for dynamic behavior.

Keywords: rubber–metal spring, vibration transmissibility, dynamic stiffness, electrodynamic shaker.

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УДК 538.9
DOI 10.55652/1683-805X_2025_28_3_80-90
Поступила в редакцию 20.09.2024; после доработки 17.10.2024; принята к публикации 24.10.2024

Влияние зернограничных сегрегаций атомов Mg на механические характеристики ультрамелкозернистого сплава Al-Mg-Zr

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Предлагается теоретическая модель, которая описывает микромеханизм пластической деформации в ультрамелкозернистом (УМЗ) сплаве Al-Mg-Zr, структурированном методом кручения под высоким давлением (КВД), с сегрегациями атомов Mg в границах зерен (ГЗ), образовавшимися в процессе КВД. В рамках модели пластическая деформация осуществляется за счет испускания решеточных дислокаций из тройных стыков ГЗ, содержащих ряды внесенных зернограничных дислокаций, закрепленных на атомах Mg, которые образуют сегрегации на ГЗ. Эти сегрегации выступают в качестве препятствий для скольжения внесенных зернограничных дислокаций, затрудняя формирование дислокационных скоплений вблизи тройных стыков ГЗ и снижая там концентрацию приложенного напряжения, что приводит к значительному упрочнению сплава. На основе этой модели рассчитаны пределы текучести УМЗ сплава Al-Mg-Zr после КВД и после дополнительной термомеханической обработки (ТМО),

состоящей из низкотемпературного отжига и небольшой дополнительной деформации КВД. Обсуждается увеличение пластичности сплава, вызванное применением такой ТМО. Предложенная модель хорошо согласуется с имеющимися экспериментальными данными.

Ключевые слова: ультрамелкозернистые сплавы, зернограничные сегрегации атомов, дислокации, термомеханическая обработка, границы зерен.

Effect of Grain Boundary Segregations of Mg Atoms on Mechanical Properties of Ultrafine-Grained Al-Mg-Zr Alloy

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A theoretical model is proposed to describe the micromechanism of plastic deformation in an ultrafine-grained Al-Mg-Zr alloy structured by high-pressure torsion (HPT) with grain boundary segregations of Mg atoms formed during HPT. In the model, plastic deformation is realized due to the emission of lattice dislocations from triple grain junctions of grain boundaries (GB), which contain arrays of extrinsic grain boundary dislocations that are pinned by Mg atoms segregated at GB. These segregations act as obstacles to sliding of extrinsic grain boundary dislocations, thus hindering the formation of dislocation pileups near the GB triple junctions and reducing the stress concentration at them, which leads to significant strengthening of the alloy. This model is used to calculate the yield strength of the ultrafine-grained Al-Mg-Zr alloy after HPT and after additional thermomechanical treatment consisting of low-temperature annealing and slight deformation by HPT. An increase in the alloy plasticity due to such thermomechanical treatment is discussed. The proposed model agrees well with the available experimental data.

Keywords: ultrafine-grained alloys, grain boundary segregations of atoms, dislocations, thermomechanical treatment, grain boundaries.

Финансирование

Работа выполнена при финансовой поддержке Российского научного фонда (грант № 22-19-00292).

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9. *Научная статья*

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УДК 539.32
DOI 10.55652/1683-805X_2025_28_3_91-106
Поступила в редакцию 23.09.2024; после доработки 19.11.2024; принята к публикации 19.11.2024

Гиперупругая модель сдвигового запаздывания

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На основе анализа деформации представительного объема выведена микромеханическая модель, описывающая упругий модуль композита, армированного однонаправленными короткими волокнами, при растяжении материала в направлении армирования. Анализ включает точное решение уравнений гиперупругости в деформированной матрице и приближенное решение уравнений для материала волокна. Решение построено для неогуковского материала. Получены формулы, связывающие упругую энергию деформации композита с макроскопической продольной деформацией, а также формулы, описывающие продольную и радиальную деформацию материала матрицы и волокна. В качестве главного результата получена формула, которая связывает начальный тангенциальный упругий модуль композита (аналог модуля Юнга для линейных материалов) с механической характеристикой материалов, составляющих композит (а именно, отношением упругих модулей матрицы и волокна), а также с геометрической характеристикой волокон (отношением длины волокна к его диаметру) и с объемной долей волокон в композите. Приведено сравнение результатов с другими аналитическими моделями, а также с известными результатами численного моделирования методом конечных элементов и методом граничных элементов. Результаты обобщают известную модель Shear Lag (SL) на гиперупругие материалы, и получены с помощью более строгого анализа, чем исходная модель.

Ключевые слова: композит с короткими волокнами, shear lag model, модуль Юнга, нелинейная упругость.

Hyperelastic Shear Lag Model

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Based on the analysis of deformation of a representative volume, a micromechanical model is derived to describe the elastic modulus of a composite reinforced with unidirectional short fibers under tension in the reinforcement direction. The analysis includes an exact solution to the hyperelastic equations for the deformed matrix and an approximate solution to the equations for the fiber material. The solution is provided for a Neo-Hookean material. Formulae are derived to relate the elastic strain energy with the macroscopic longitudinal strain of the composite, as well as to describe the longitudinal and radial deformation of the matrix and fiber material. The main result is a formula that relates the initial tangential elastic modulus of the composite (an analog of Young's modulus in linear elasticity) to the mechanical characteristics of the composite constituents (namely, the

ratio of the elastic moduli of the matrix and fiber), as well as to the geometric characteristics (length-to-diameter ratio) and volume fraction of fibers in the composite. The derived results are compared with the findings of other analytical models, as well as with the known results of numerical simulation by the finite element and boundary element methods. The results generalize the well-known shear lag (SL) model to hyperelastic materials and are obtained using a more rigorous analysis than the original model.

Keywords: short-fiber composite, shear lag model, Young's modulus, nonlinear elasticity.

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УДК 531.355:537.634:539.371
DOI 10.55652/1683-805X_2025_28_3_107-119
Поступила в редакцию 11.09.2024; после доработки 30.09.2024; принята к публикации 30.09.2024

Индуцированные переменным полем колебания частиц в магнитоактивном эластомере в условиях мезоскопического магнитомеханического гистерезиса

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Предложена базовая модель мезоскопической динамики магнитоактивного эластомера (МАЭ). В качестве элементарной ячейки МАЭ выбрана пара сферических линейно намагничивающихся частиц, погружённых в упруговязкий эластомер типа Кельвина. Исследованы вынужденные колебания указанной системы под действием магнитного поля, состоящего из постоянной и переменной компонент. В определённой амплитудно-частотной области рассматриваемая пара демонстрирует особенное поведение,

выражающееся в резком переходе (коллапсе) от конечного расстояния между частицами к плотному контакту. В статике такое поведение описывается как бистабильность и проявляется в виде магнитомеханического гистерезиса: деформация как функция приложенного поля имеет область двузначности. Продемонстрировано, что, в зависимости от набора материальных параметров системы и характеристик поля, для колебаний пары возможны различные стационарные циклы. Показано, что повышение частоты переменной компоненты поля блокирует гистерезисные эффекты. На качественном уровне описано поведение системы при высокой частоте осцилляций.

Ключевые слова: магнитоактивный эластомер, мезомеханика, магнитомеханический гистерезис, вынужденные колебания.

Title Particle Oscillations Induced by an Alternating Field in a Magnetoactive Elastomer under Conditions of Mesoscopic Magnetomechanical Hysteresis

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A basic model is proposed for the mesoscopic dynamics of a magnetically active elastomer (MAE). The MAE unit cell consists of a pair of spherical linearly magnetizing particles immersed in a Kelvin-type viscoelastic elastomer. Forced oscillations of this system in a magnetic field with both constant and variable components are investigated within a specific amplitude-frequency range. In this range, the pair exhibits a distinctive behavior, which consists in a sudden transition (collapse) from a finite distance between the particles to tight contact. This phenomenon, known as bistability, is described in statics as magnetomechanical hysteresis, where deformation as a function of the applied field shows an ambiguous region. It is demonstrated that, depending on the material parameters and field characteristics, various stationary oscillation cycles are possible. In addition, increasing the frequency of the variable field component reduces hysteresis effects. The system behavior at high oscillation frequencies is described qualitatively.

Keywords: magnetoactive elastomer, mesomechanics, magnetomechanical hysteresis, forced oscillations.

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С. 107–119

11. *Научная статья*

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УДК 621.7.044:004.89
DOI 10.55652/1683-805X_2025_28_3_120-125
Поступила в редакцию 03.10.2024; после доработки 27.10.2024; принята к публикации 30.10.2024

Усовершенствованный алгоритм оптимизации поиска положения атомов для прогнозирования длины трещин в стальных балках

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Предложен новый метод точного определения длины трещин в поврежденных стальных балочных конструкциях, основанный на геометрически уточненной модели конечных элементов и усовершенствованном, так называемом Lévy–ASO, алгоритме оптимизации поиска положения атомов (ASO). Ключевой особенностью алгоритма Lévy–ASO является генерация случайных длин шагов, определяемых распределением Леви. Это позволяет расширить перемещения для увеличения пространства поиска или сузить их для использования потенциальных пространств поиска, тем самым создавая условия глобальной оптимальности. Новая стратегия поиска повышает способность алгоритма ASO находить глобально оптимальное решение и избегать локальной оптимальности. Сравнение эффективности Lévy–ASO и ASO проведено на примере 23 классических тестовых функций, которые указывают на более высокую точность и скорость сходимости Lévy–ASO по сравнению с исходным алгоритмом. Эффективность и надежность Lévy–ASO для определения длины трещин стальных балок подвержена с помощью серии экспериментов на стальных балках с трещинами длиной 2, 4, 8 и 10 мм. На основе экспериментально полученных и рассчитанных с помощью модели конечных элементов значений частот колебаний получена целевая функция. Использование алгоритма Lévy–ASO позволяет оптимизировать целевую функцию, которая выведена на основе анализа модели конечных элементов с уточненными геометрическими координатами длины трещины. Показана эффективность предложенного метода и применимость алгоритма Lévy–ASO для решения различных инженерных задач оптимизации

Ключевые слова: контроль структурных повреждений, алгоритм оптимизации поиска положения атомов, уточнение модели конечных элементов, показатель длины трещины, распределение Леви, SAP2000-OAPI

Improved Atom Search Optimization (ASO) for Crack Length Prediction in Steel Beams

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This paper presents a new method for accurately determining the crack length in damaged steel beam structures. The proposed method combines the geometric updating technique of the finite element model (FEM) with a new variant of atom search optimization (ASO) called Lévy–ASO. The key feature of the Lévy–ASO algorithm is that it generates random step lengths determined by the Lévy distribution. Based on these step lengths, Lévy–ASO can achieve wider movements to expand the search space or narrower movements to exploit the potential search spaces, which is close the global optimum. It leads to a new search strategy within the ASO algorithm, effectively improving its ability to find the global optimum solution and escape the local optimum. To compare the effectiveness of Lévy–ASO with the original ASO, 23 classical benchmark functions are used as the first example. The comparison results show the superiority of Lévy–ASO over the original ASO in both accuracy and convergence rate. Then, a series of experiments were conducted on damaged steel beams with the crack lengths of 2 mm, 4 mm, 8 mm, and 10 mm to demonstrate the effectiveness and reliability of Lévy–ASO in determining the crack length of steel beams. Based on the vibration frequencies measured in these experiments and obtained from the finite element (FE) model, an objective function is established. The process of finding the crack length is carried out using the Lévy–ASO algorithm to optimize the objective function, which is established based on the analysis of the FEM where the geometric coordinates of the crack length are adjusted. This study proves the effectiveness of the proposed method, and the Lévy–ASO algorithm is recognized as a promising optimization algorithm for solving various engineering optimization problems.

Keywords: structural damage detection, atom search optimization algorithm, FEM updating, crack length indicator, Lévy distribution, SAP2000-OAPI

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12. *Научная статья*

УДК 624.073.4:539.4:519.6
DOI 10.55652/1683-805X_2025_28_3_126-130
Поступила в редакцию 11.09.2024; после доработки 28.11.2024; принята к публикации 02.12.2024

Анализ статической прочности композитной боковой балки тележки с помощью численного моделирования с учетом связующего элемента

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Высокоскоростная железная дорога позволяет не только повысить пропускную способность, но и снизить энергопотребление и выбросы загрязняющих веществ, а также способствует экономическому развитию. Основным элементом высокоскоростного электропоезда является тележка, которая выполнят функции опоры, рулевого управления, торможения, движения и амортизации. Боковая балка тележки представляет собой толстую композитную конструкцию, которая подвержена расслоению под нагрузкой. Прогнозирование расслоения методом конечных элементов может значительно повысить эффективность конструкции. В статье разработана модель короткой колесной базы 14T, 16T и облегченной рамы тележки. Рассчитаны макроскопические механические свойства. Выполнено моделирование расслоения в ABAQUS с использованием связующего элемента нулевой толщины. После статического анализа прочности при заданных условиях, проведен расчет прочности элемента. Оптимизация структуры слоя позволяет избежать повреждения тележки в рабочих условиях. Показано, что теория эквивалентных модулей композитных материалов применима к численному анализу расслоения, а эффективная структура слоя увеличивает прочность соединения слоев.

Ключевые слова: расслоение, связующий элемент, композитная боковая балка тележки.

Static strength analysis of the composite bogie side beam via numerical simulation using the cohesive element

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High-speed railway not only meets the demand for capacity, but also saves energy and reduces emissions, and helps economic development. As the core component of the high-speed electric multiple unit (EMU), the bogie plays the role of bearing, steering, braking, driving, and shock absorption. The bogie side beam is a thick composite structure, which is prone to delamination failure during loading. Prediction of structural delamination by the finite element method can effectively improve the design efficiency. In this paper, a model is established for the short 14T and 16T wheelbase and the lightweight bogie frame structure, and the macroscopic mechanical properties are calculated and predicted. The zero-thickness cohesive element in ABAQUS is used to simulate the delamination damage in the component. Static strength analysis is carried out for the given operation condition, and then the strength of the component is obtained. Due to optimization of the ply design, there is no damage to the bogie under operation conditions. It is illustrated that equivalent modulus theory for composites is suitable for the numerical analysis of delamination damage, and the effective ply design increases the interlayer strength.

Keywords: delamination damage, cohesive element, composite bogie side beam.

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