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1. Научная статья

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Фазовые трансформации в двухфазных сплавах $\text{Fe}_{95}\text{Ni}_{05}$ с градиентом размера зерен при ударном воздействии

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Аннотация — Проведено молекулярно-динамическое изучение структурно-фазовых изменений в ОЦК монокристаллах и образцах $\text{Fe}_{95}\text{Ni}_{05}$ с двухфазной градиентной зеренной структурой при ударной нагрузке. Зерна моделируемых образцов с ГЦК решеткой содержали ламели с ОЦК структурой и имели выраженную текстуру. Показано, что профиль ударной волны расщепляется на три фронта, которые формируют три зоны с характерными перестройками структуры: упругими, пластическими и пластическими/фазовыми. Различия в скоростях трех фронтов ведут к изменению размеров формируемых зон при распространении ударной волны. Так, размер зоны пластических изменений увеличивается из-за отставания фронта пластических/фазовых перестроек. Увеличение градиента размера зерен образца за счет более мелких зерен ведет к существенному уменьшению зоны пластичности. Такое поведение обусловлено подавлением генерации дислокаций в зернах малого размера. Показано, что ориентация ОЦК решетки монокристалла относительно направления ударной нагрузки существенно влияет на интенсивность фазовых превращений. При распространении ударной волны вдоль кристаллографического направления [110] происходят наиболее активные фазовые переходы, чем для ориентаций [111] и [112]. Волны разгрузки также инициируют фазовые трансформации за фронтом их распространения.

Ключевые слова: градиентная зеренная структура, двухфазный материал, ударная волна, фазовый переход, молекулярная динамика

Phase Transformations in Two-Phase Fe₉₅Ni₀₅ Alloys with Grain Size Gradient under Shock Loading

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Abstract — A molecular dynamics study of structural and phase changes in bcc single crystals and Fe₉₅Ni₀₅ samples with a two-phase gradient grained structure under shock loading was performed. Grains of the simulated samples with an fcc lattice contained lamellas with a bcc structure and had a pronounced texture. It was shown that the shock wave profile splits into three fronts, which form three zones with characteristic structural rearrangements: elastic, plastic, and plastic/phase. Differences in the velocities of the three fronts lead to a change in the sizes of the formed zones during shock wave propagation. Thus, the size of the plastic change zone increases due to the lag of the plastic/phase rearrangement front. An increase in the grain size gradient of the sample due to smaller grains leads to a significant decrease in the size of the plastic zone. This behavior is due to the suppression of dislocation nucleation in small grains. It is shown that the orientation of the bcc lattice relative to the direction of the shock loading significantly affects the intensity of phase transformations. When the shock wave propagates along the [110] crystallographic direction, the most active phase transitions occur than for the [111] and [112] orientations. Release waves also initiate phase transformations behind the front of their propagation.

Keywords: gradient grained structure, two-phase material, shock wave, phase transition, molecular dynamics

Финансирование

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2. Научная статья

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Влияние структурно-фазового состояния на физико-механические характеристики Fe-Mn сплава

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Аннотация — В работе представлено исследование различных структурно-фазовых состояний сплава Fe-Mn-5Si, полученных интенсивной пластической деформацией методами равноканального углового прессования и кручения под высоким давлением. Экспериментально измерены и проанализированы различные физико-механические характеристики сплава в аустенитном крупнозернистом, наноструктурном зеренно-субзеренном и двойниковом состоянии, а также в преимущественно мартенситном и двухфазном ультрамелкозернистом состоянии. Методами индентирования выявлено, что интенсивная пластическая деформация повышает модуль упругости, работу упругой деформации, а также упругую составляющую работы, уменьшая контактную жесткость индентора с деформированным материалом и работу пластической деформации. При этом двухфазное состояние сплава после деформации обладает наименьшими значениями модуля упругости и работы пластической деформации при наибольшем значении работы упругой деформации.

Ключевые слова: Fe-Mn-5Si сплав; равноканальное угловое прессование; кручение под высоким давлением, наноиндентирование; модуль упругости; микроструктура; фазовый состав; микротвердость.

The influence of structural-phase state on the physical and mechanical characteristics of Fe-Mn alloy

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Abstract—The paper presents a study of various structural and phase states of the Fe-Mn-5Si alloy obtained by severe plastic deformation using equal-channel angular pressing and high-pressure torsion. Various physical and mechanical characteristics of the alloy in the austenitic coarse-grained, nanostructured grain-subgrain and twinned states, as well as in the predominantly martensitic and two-phase ultrafine-grained states, were experimentally measured and analyzed. Using indentation methods, it was found that intense plastic deformation increases the modulus of elasticity, the work of elastic deformation, and the elastic component of the work, reducing the contact rigidity of the indenter with the deformed material and the work of plastic deformation. In this case, the two-phase state of the alloy after deformation has the lowest values of the modulus of elasticity and the work of plastic deformation at the highest value of the work of elastic deformation.

Keywords: Fe-Mn-5Si alloy; equal-channel angular pressing; high-pressure torsion, nanoindentation; Young's modulus; microstructure; phase composition; microhardness

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3. Научная статья

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Микроструктура и механические свойства механически легированного сплава Al-Zr-Mn-Cu

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Аннотация — Разработка материалов и технологических режимов обеспечения повышенной удельной прочности актуальная задача, решение которой важно для разных отраслей транспортного машиностроения. В данной работе проведен анализ эволюции параметров структуры и механических свойств сплава Al–5%Zr–4%Mn–2%Cu, полученного механическим легированием с последующей консолидацией гранул при температурах 350–450 °С. Обработка смеси шихтовых компонентов в течение 10 ч в высокоэнергетической планетарной шаровой мельнице формирует наноструктурированные гранулы пересыщенного твердого раствора на основе алюминия с размером зерен 20–30 нм и микротвердостью ~460 HV. После компактирования и отжига происходит рост зерен до 90 нм с выделением частиц вторых фаз Al₆Mn, Al₂₀Cu₂Mn₃ и Al₃Zr и формирование зон свободных от выделений по границам гранул. Микротвердость гранул после нагрева до температуры компактирования снижается до ~300–340 HV, а твердость компактов не

превышает 280 HV ввиду остаточной пористости. Наименьшую пористость (0.5 %) имеют образцы, консолидированные при 450 °С, предел текучести которых достигает ~700 МПа при комнатной температуре и ~170 МПа при 350 °С по результатам испытаний на одноосное сжатие.

Ключевые слова: алюминиевые сплавы, пересыщенный твердый раствор, механическое легирование, дисперсоиды, микроструктура, механические свойства.

Microstructure and mechanical properties of mechanically alloyed Al-Zr-Mn-Cu alloy

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Abstract — The development of materials and processing regimes for the enhancement of specific strength is a challenge for the aviation, aerospace, and transportation industries. The evolution of the microstructural parameters and mechanical properties of the Al – 5 %Zr – 4 %Mn – 2 %Cu alloy during mechanical alloying followed by hot pressing at temperatures between 350 and 450 °C. A high-energy ball milling for ten-hour period led to the formation of nanostructured granules of aluminum based solid solution. The consolidated granules with a grain size of 20 – 30 nm and microhardness of ~460 HV. After hot pressing and further annealing, grain size increased up to ~90 nm, the Al₃Zr, Al₆Mn and Al₂₀Cu₂Mn₃ phases precipitated and the formation of zones free from secretions along the boundaries of the granules. The microhardness of the granules after annealing to the compaction temperature decreases to ~300 – 340 HV, and the hardness of the hot pressed samples does not exceed 280 HV, which is attributed to residual porosity. The lowest porosity (0.5 %) is found in samples consolidated at 450 °C, the compression yield strength of which reaches ~700 MPa at room temperature and ~170 MPa at a testing temperature of 350 °C.

Keywords: aluminium alloys, supersaturated solid solution, mechanical alloying, dispersoids, microstructure, mechanical properties

Финансирование

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4. Научная статья

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Особенности взаимодействия компонентов при спекании порошковых смесей Ti-Al-(Fe-Fe₂O₃)

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Аннотация — Исследован фазовый состав и микроструктура спеченных порошковых материалов на основе многокомпонентных смесей Ti+Al+(Fe+Fe₂O₃), где одним из компонентов является порошок окисленной стальной стружки. Рассмотрено два варианта соотношения титана и алюминия при одинаковом объемном содержании порошка стружки. Обнаружено, что присутствие в исходном порошке стружки оксида железа не гарантирует формирование отдельных фаз оксида алюминия. При вакуумном спекании как в первом варианте состава, так и во втором, преимущественно образуются алюминиды железа. Также отмечено образование тройных интерметаллидов TiFe₂Al и сложных оксидов FeTiO₃.

Ключевые слова: Спекание, порошковый материал, структура, фазообразование, интерметаллиды.

Interaction Features of Components during Sintering of Powder Mixtures Ti-Al-(Fe-Fe₂O₃)

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Abstract—The phase composition and microstructure of sintered powder materials based on multicomponent mixtures of Ti+Al+(Fe+Fe₂O₃), where one of the components is an oxidized steel swarf powder, has been studied. Two variants of the ratio of titanium and aluminum with the same volume content of swarf powder are considered. It was found that the presence of iron oxide in the initial swarf powder does not guarantee the formation of separate aluminum oxide phases. During vacuum sintering, both in the first version of the composition and in the second one, iron aluminides are mainly formed. The formation of ternary intermetallides TiFe₂Al and complex oxides FeTiO₃ was also noted.

Keywords: Sintering, powder material, structure, phase formation, intermetallics

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5. Научная статья

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Структура и свойства ионно-плазменных покрытий на основе переходных металлов и их нитридов, нанесенных на поверхность бериллиевой бронзы

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Аннотация — Исследованы микроструктура, фазовый состав и трибологические свойства покрытий, нанесенных на бериллиевую бронзу для повышения её износостойкости. Рассмотрены композиционные и градиентные покрытия на основе меди и титана, а также однослойные и многослойные покрытия TiN и CrN/TiN. Установлено, что композиционные и градиентные покрытия Cu-Ti имеют многофазную структуру с равномерным или градиентным распределением титана по сечению покрытия в зависимости от режимов ионно-плазменного напыления. Многослойные покрытия CrN/TiN демонстрируют четкую периодичность слоев с толщиной слоя 250 нм (16-слойное) и 125 нм (32-слойное). Однослойное покрытие TiN характеризуется столбчатой структурой толщиной 4 мкм. Для улучшения адгезии покрытий TiN и CrN к подложке использовался переходный слой Cu-Ti, который снижает напряжения на границе раздела и повышает адгезионную прочность. Скретч-тестирование подтвердило хорошую адгезию всех покрытий, при этом покрытия выдерживают нагрузки от 10 Н (однослойное и 16-слойное) до 30 Н (CrN с подслоем Cu-Ti). Трибологические испытания показали, что изнашивание покрытий происходит по механизму микроабразивного трения, за исключением композиционного и градиентного Cu-Ti покрытий, которые разрушаются по адгезионно-хрупкому механизму. Наибольшую износостойкость демонстрируют 32-слойное покрытие CrN/TiN и покрытия с подслоем Cu-Ti. Результаты исследования показывают, что использование многослойных структур и переходных слоев Cu-Ti значительно улучшает механические и трибологические свойства покрытий, нанесенных на бериллиевую бронзу, что делает их перспективными для применения в условиях повышенных нагрузок и износа.

Ключевые слова: Бериллиевая бронза, ионно-плазменные покрытия, микроструктура, трение, скретч-тест.

Structure and Properties of Ion-Plasma Coatings Based on Transition Metals and Their Nitrides Deposited on the Surface of Beryllium

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Abstract — The microstructure, phase composition, and tribological properties of coatings deposited on beryllium bronze to enhance its wear resistance were investigated. Composite and gradient Cu-Ti coatings, as well as single-layer and multilayer TiN and CrN/TiN coatings, were examined. It was found that composite and gradient Cu-Ti coatings exhibit a multiphase structure with either a uniform or gradient titanium distribution across the coating cross-section, depending on the ion-plasma spraying parameters. Multilayer CrN/TiN coatings displayed a well-defined layer periodicity, with individual layer thicknesses of 250 nm (16-layer coating) and 125 nm (32-layer coating). The single-layer TiN coating featured a columnar microstructure and had a total thickness of 4 μm. To enhance the adhesion of TiN and CrN coatings to the substrate, a Cu-Ti

interlayer was applied, reducing interfacial stresses and improving bond strength. Scratch tests confirmed good adhesion for all coatings, with the coatings sustaining loads ranging from 10 N (single-layer and 16-layer coatings) up to 30 N (CrN coating with a Cu-Ti interlayer). Tribological tests revealed that most coatings wear via a microabrasive friction mechanism, except for the composite and gradient Cu-Ti coatings, which fail through an adhesive-brittle mechanism. The 32-layer CrN/TiN coating and the coatings with a Cu-Ti interlayer exhibited the highest wear resistance. The findings demonstrate that multilayer architectures and Cu-Ti interlayers significantly enhance the mechanical and tribological properties of beryllium bronze coatings, making them promising for high-load and high-wear applications.

Keywords: Beryllium bronze, ion-plasma coatings, microstructure, friction, scratch test

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6. Научная статья

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Влияние концентрации легирующих элементов в титановых сплавах Ti-6Al-4V и Ti-4Al-3V

на формирование макро- и микроструктуры при проволочном аддитивном электронно- лучевом производстве

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Аннотация — В работе приведены результаты сравнительных исследований формирования макро- и микроструктуры при электронно-лучевом аддитивном производстве титановых сплавов марок Ti-6Al-4V и Ti-4Al-3V с аналогичной системой легирования и различным содержанием алюминия и ванадия. Целью исследования было оценить влияние содержания легирующих элементов (Al и V) на структурно-фазовое состояние сплавов и их свойства. Проведенные исследования показывают, что для обоих сплавов характерна достаточно высокая степень анизотропии структуры и свойств, но для сплава с меньшим содержанием алюминия и ванадия это выражено более ярко. При увеличении содержания легирующих элементов происходит снижение размера зерен в титановом сплаве и изменение структурно-фазового состояния сплава. Формирование сложноорганизованной структуры с распадом β -пластин на α_2 -Ti₃Al и α'' -Ti приводит к повышению прочностных показателей в сплаве Ti-6Al-4V в сравнении со сплавом Ti-4Al-3V, для которого основными структурными составляющими после печати являются α -фаза с достаточно малой долей прослоек β -фазы. Для обоих сплавов характерна значительная анизотропия свойств как при испытании на статическое растяжение, так и при усталостных испытаниях и ударной вязкости. При растяжении сплава Ti-4Al-3V наибольшая прочность и наименьшая пластичность материала характерна для образцов, испытанных в диагональном направлении, а наименьшая прочность и наибольшая пластичность для образцов, испытанных в направлении выращивания. Для сплава Ti-6Al-4V данная закономерность также прослеживается, но менее ярко выражена. Несмотря на то, что средние значения предела прочности для образцов сплава Ti-6Al-4V превосходят сплав Ti-4Al-3V более чем на 200 МПа, а показатель микротвердости более чем на 1,0 ГПа, сплав Ti-4Al-3V обладает достаточно хорошими показателями печатаемости и за счет меньшей стоимости может применяться для получения деталей методом ЭЛАП.

Ключевые слова: электронно-лучевое аддитивное производство (ЭЛАП), высокопроизводительная 3D-печать, титановые сплавы, макроструктура, микроструктура, структурно-фазовое состояние

The influence of the content of alloying elements in titanium alloys Ti-6Al-4V and Ti-4Al-3V on the macro- and microstructure in wire-feed electron beam additive manufacturing

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Abstract—This paper outlines the results of investigating the structural arrangement at different scales in Ti-6Al-4V and Ti-4Al-3V titanium alloys that share the same alloying elements but have differing amounts of aluminum and vanadium. The research indicates that both alloys display a notable anisotropy of structural and mechanical properties that is more pronounced in the alloy with reduced aluminum and vanadium levels. Increasing the alloying element content results in reduced grain size in the titanium alloy and alters its structural and phase characteristics. The development of a complicated structure comprising α_2 -Ti₃Al, α'' -Ti, and β -Ti phases in the α/β -lath structures results in enhanced strength characteristics of the Ti-6Al-4V alloy in comparison with the Ti-4Al-3V alloy, in which the primary structural elements following printing consist of the α -phase with a minor fraction of β -phase interlayers. Both alloys exhibit pronounced anisotropy in their mechanical response during static tensile tests as well as in fatigue and impact toughness evaluations. In tensile testing, the Ti-4Al-3V alloy samples tested in the diagonal direction exhibit the greatest strength and the lowest ductility, while those tested in the growth direction show the lowest strength and the greatest ductility. Such a tendency is also observed in the Ti-6Al-4V alloy, although it is less distinct. Although the average tensile strength of the Ti-6Al-4V alloy samples exceeds that of the Ti-4Al-3V alloy by over 200 MPa and the microhardness value by more than 1.0 GPa, the Ti-4Al-3V alloy demonstrates reasonable printability characteristics and can be utilized for producing components via the WEBAM method due to its lower cost.

Keywords: wire-feed electron beam additive manufacturing (WEBAM), high-performance 3D printing, titanium alloys, macrostructure, microstructure, structural-phase state

Финансирование

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7. Научная статья

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Применение электронно-лучевого проволочного производства для получения крупногабаритных изделий промышленного назначения

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Аннотация — Проведены исследования закономерностей структурообразования при изготовлении крупногабаритных модельных образцов аддитивных изделий из никелевых сплавов и сталей в сопоставлении с полученными ранее данными по сплавам на основе

титана, алюминия, меди и др. Проведенные исследования показывают, что формирование структурно-фазового состояния никелевых сплавов и сталей в большой степени зависит от типа сплава и легирующих элементов. Длительное время существования ванны расплава и возникающее перераспределение легирующих элементов для сплавов типа Inconel 625 является весомой проблемой при печати, в то время как для сплавов типа Inconel 718 и высоколегированных никелевых жаропрочных сплавов характерны высокие механические свойства. При этом, сегрегации легирующих элементов по границам дендритов могут быть неустраняемыми термической обработкой при формировании в данных областях нерастворимых карбидных частиц. Печать аддитивных изделий из аустенитных нержавеющей сталей приводит к формированию дендритных колоний, а для феррито-перлитных сталей характерно формирование равноосной зеренной структуры. Для сталей различного типа и никелевых сплавов, а также биметаллических элементов на их основе, не характерно формирования дефектов в виде пор или трещин. В зоне структурного градиента формируется плавная зона перехода от одного материала к другому. Полученные данные демонстрируют тот факт, что проволочная аддитивная электронно-лучевая технология является одной из наиболее приемлемых для изготовления деталей из сталей и никелевых сплавов различного типа, включая биметаллические элементы на их основе.

Ключевые слова: электронно-лучевое аддитивное производство, высокопроизводительная 3D-печать, никелевые сплавы, стали, макроструктура, микроструктура, структурно-фазовое состояние

Application of wire and electron beam technologies for the production of large-sized industrial products

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Abstract—This paper focused on the structural features of large-scale nickel-based alloy and steel samples and compares them with previously obtained data on titanium, aluminum, copper, and other alloys. These studies demonstrate that the structural and phase state of nickel-based alloys and steels largely depends on the alloy type and alloying elements. The long life of a melt pool and resulting partitioning of alloying elements for Inconel 625 alloys pose a significant printing challenge, while Inconel 718 alloys and high-alloy nickel-based high temperature alloys exhibit excellent mechanical properties. Furthermore, partitioning of alloying elements along dendrite boundaries can be unavoidable by heat treatment due to the formation of insoluble carbide particles in these areas. Printing austenitic stainless steels results in a structure organized into dendritic colonies, while ferrite-pearlite steels are characterized by the formation of a grain structure. Various types of steels and nickel-based alloys, as well as bimetallic components based on them, do not typically exhibit defects such as pores or cracks. A smooth transition zone from one material to another is formed in the structural gradient zone. The obtained data demonstrate that wire and feed electron beam additive technology is one of the most suitable for the manufacture of parts from various types of steels and nickel-based alloys, including bimetallic components based on them.

Keywords: electron beam additive manufacturing, high-performance 3D printing, nickel-based alloys, steels, macrostructure, microstructure, structural-phase state

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Влияние ротационной ковки на структуру, текстуру и свойства прутков из биосовместимого β -сплава Ti-39Nb-7Zr

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Abstract — В данном исследовании изучены структура, текстура и механические свойства прутков из β -сплава Ti-39Nb-7Zr после интенсивной пластической деформации методом

ротационнойковки (РК). Моделирование методом конечных элементов (МКЭ) выявило неравномерное распределение напряжений в прутках, характеризующееся преимущественно растягивающими напряжениями в сердцевине и сжимающими напряжениями на поверхности. Статистический анализ данных ориентационной микроскопии показал наличие микроструктурного градиента: как толщина деформированных зёрен, так и размер рекристаллизованных зёрен уменьшались от центра к поверхности, в то время как доля рекристаллизованных зёрен возрастала. Процесс РК индуцировал градиентную текстуру с различной ориентацией зёрен в центральной и приповерхностной областях. Увеличение твёрдости в приповерхностных слоях было обусловлено измельчением зерна. Расчёты фактора Тейлора показали незначительное влияние текстуры на механические свойства. Модуль упругости по сечению прутка оставался постоянным и составлял 75 ± 1 ГПа, что свидетельствует о достижении поверхностного упрочнения без изменения упругих свойств.

Keywords титановые псевдо- β -сплавы, текстура, ротационная ковка, биоинертность, структура, механические свойства

Impact of Rotary Forging on the Structure, Texture, and Properties of Rods Made of a Biocompatible β -alloy Ti-39Nb-7Zr

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Abstract — In this study, we examined the structure, texture, and mechanical properties of β -alloy Ti-39Nb-7Zr rods following intensive plastic deformation through rotary forging (RF). Finite element method (FEM) simulations revealed an uneven stress distribution within the rods, characterized by predominantly tensile stresses in the core and compressive stresses at the surface. Statistical analysis of orientation microscopy data indicated a microstructural gradient: both the thickness of deformed grains and the size of recrystallized grains decreased from the core to the surface, while the proportion of recrystallized grains increased. The RF process induced a gradient texture, with distinct grain orientations in the central and near-surface areas. An increase in hardness in the near-surface layers was attributed to grain refinement. Taylor factor calculations showed a minor effect of texture on the mechanical properties. The elastic modulus across the rod section remained consistent at 75 ± 1 GPa, suggesting that surface hardening was achieved without altering elastic properties.

Keywords: titanium pseudo- β -alloys, texture, rotary forging, bioinertness, structure, mechanical properties

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