
제40회 첨단구조재료 심포지엄

초 록 집



대한금속·재료학회

THE KOREAN INSTITUTE OF
METALS AND MATERIALS

재료강도분과위원회

일 시: 2026년 09월 03일(목) ~ 09월 04일(금)

장 소: 원뎀그랜드 부산

주 최: 대한금속·재료학회

주 관: 대한금속·재료학회 재료강도분과위원회

공동주관: 한국재료연구원 소재혁신선도본부

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대한금속·재료학회 재료강도분과에서는 이러한 요구에 선제적으로 대응하고 구조재료 분야의 최신 연구성과를 공유하기 위해 매년 ‘첨단구조재료 심포지엄’을 개최해 오고 있습니다. 철강, 내열·에너지, 경량·항공, 적층제조, 고엔트로피합금, 나노역학 및 모델링 등 전 분야를 아우르는 발표와 토론을 통해 산·학·연 연구자들이 지식과 통찰을 나누는 학술 교류의 장으로 자리매김해 왔습니다.

특히 올해는 첨단산업의 기술 수요에 부응하고자 용접·접합 분야를 새로운 세션으로 추가하였습니다. 소재의 제조와 접합, 구조 신뢰성을 연계하여 구조재료 연구의 외연을 넓히는 계기가 되기를 기대합니다.

올해로 제40회를 맞이하는 이번 심포지엄은 축적해 온 학술적 성과와 교류의 전통을 되돌아보고, 우리나라 구조재료 연구의 새로운 도약을 모색하는 특별한 자리입니다. 선배 연구자들의 헌신과 후배 연구자들의 도전이 어우러져, 첨단구조재료가 나아가야 할 미래 방향을 논의하는 시간이 되기를 바랍니다.

바다가 보이는 부산에서 열리는 이번 심포지엄이 깊이 있는 학술 토론과 함께 연구자 간의 따뜻한 소통과 새로운 협력이 시작되는 자리가 되도록 회원 여러분의 관심과 참여를 부탁드립니다. 아울러 성원과 후원을 보내주신 여러 기관과 후원사 관계자 여러분께 깊은 감사를 드립니다. 회원 여러분의 건강과 연구 발전을 기원하며, 재료강도분과는 앞으로도 우리나라 구조재료 연구와 소재산업의 발전, 그리고 국제 경쟁력 향상에 기여할 수 있도록 최선을 다하겠습니다.

2026년 9월
(사) 대한금속·재료학회 재료강도분과위원장
김 정 한

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제 40 회 첨단구조재료 심포지엄
09월 03일 [목]
제 1 발표회장

- 기조강연
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재료강도학의 방법론적 진화: 실험 - 디지털 트윈 - AI 융합을 통한 첨단구조재료 설계

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Methodological Evolution in Materials Strength: Designing Advanced Structural
Materials through the Integration of Experiments, Digital Twins, and AI

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초록

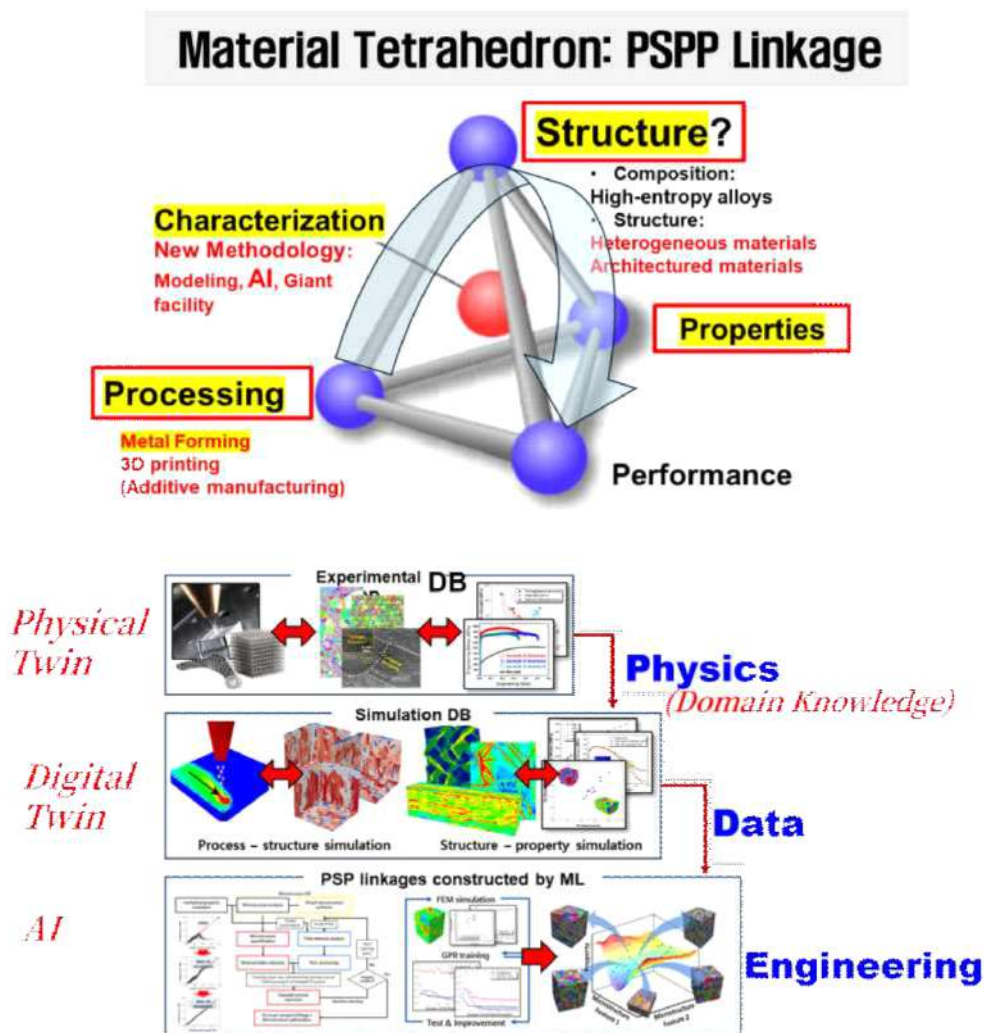
재료강도학은 구조재료의 변형, 강화, 파괴, 피로, 환경취화를 이해하고 제어하기 위한 핵심 학문으로 발전해 왔다. 그러나 첨단구조재료의 설계 공간이 고엔트로피 합금, 헤테로 구조 재료, 적층제조 금속, 극한환경 구조재료로 확장되면서, 기존의 경험적 시행착오나 개별 실험 중심 접근만으로는 공정 - 조직 - 특성 - 성능 간의 복잡한 상호작용을 충분히 해석하기 어려워지고 있다. 본 강연에서는 재료강도학의 방법론이 어떻게 실험, 디지털 트윈, 인공지능의 융합을 통해 진화하고 있는지 논의하고자 한다.

강연의 중심 개념은 재료사면체(material tetrahedron)에 기반한 공정 - 조직 - 특성 - 성능, 즉 PSPP (Processing-Structure-Property-Performance) 연계이다. 이 틀에서 실험은 단순한 검증 수단이 아니라 실제 재료, 실제 공정, 실제 미세조직, 실제 기계적 거동을 제공하는 physical twin으로 기능한다. 특히 최근의 재료강도 실험은 기존의 인장·압축·피로 시험을 넘어, 가속기 기반 X선 및 중성자 분석, in situ SEM/TEM 변형 관찰, 디지털 이미지 상관법, 나노인덴팅, EBSD, 3차원 원자탐침, 다중스케일 현미경 분석 등으로 확장되고 있다. 이러한 최신 실험 기법은 변형과 손상 과정을 원자 - 나노 - 마이크로 - 매크로 스케일에서 정량화하고, 디지털 모델과 AI 모델이 의존해야 할 물리적 기준 데이터를 제공한다.

디지털 트윈은 실험에서 관찰된 물리 현상을 구성방정식, 유한요소해석, 결정소성, 원자동역학, 미세조직 민감 모델링 등을 통해 가상 공간에 재현하는 역할을 한다. 이를 통해 실험으로 직접 접근하기 어려운 응력·변형률 분배, 결함 형성, 상변태, 손상 개시, 공정 중 열·역학 이력 등을 해석할 수 있다. 여기에 설명가능 인공지능, 능동학습, 베이지안

최적화, 미세조직 이미지 분석, 대리모델 기반 최적화가 결합되면, 방대한 공정 - 조직 - 특성 설계 공간에서 유망한 후보를 빠르게 탐색하고, 최소한의 실험과 계산으로 최대의 물리적 정보를 얻을 수 있다.

본 강연에서는 이러한 통합 방법론을 헤테로구조 재료, 고엔트로피 및 중엔트로피 합금, 적층제조 금속, 수소취화 저항 합금, 극저온 및 고온용 구조재료 연구 사례와 연결하여 소개한다. 핵심 메시지는 명확하다. AI는 실험과 물리적 통찰을 대체하는 도구가 아니다. 재료강도학의 미래는 신뢰도 높은 실험이 현실을 제공하고, 디지털 트윈이 물리를 재현하며, AI가 탐색과 최적화를 가속하는 순환형 연구 체계 속에서 열릴 것이다. 이러한 실험 - 디지털 트윈 - AI 융합은 첨단구조재료 설계를 경험적 최적화에서 예측적·물리기반·데이터가속 설계로 전환시키는 핵심 방법론이 될 것이다.



세라믹 입자 강화와 적층제조 상호보완적 특성: CM247LC와 탄화물 입자를 예시로

이민제, 이태규*

국립한밭대학교 신소재공학과, 대전광역시 유성구 동서대로 125 (34158)

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Complementary Relationship between Ceramic Particle Reinforcement and Additive
Manufacturing: A Case Study on CM247LC and Carbide Particles

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ABSTRACT

Directed energy deposition (DED) is attractive for large-scale fabrication and repair, but its feedstock is effectively limited to alloys that solidify without cracking, which excludes many high-performance materials. Adding a ceramic reinforcement can relieve this limitation, but only if the reinforcement is delivered uniformly to every melt pool, which conventional blending or milling routes struggle to achieve without degrading the powder morphology. In this study, composite feedstock was prepared by SMART (Surface Modification And Reinforcement Transplantation), a room-temperature mechanical process that transplants reinforcement particles onto the surface of gas-atomized metal powder while preserving the spherical powder morphology. Since each powder particle carries its own reinforcement, DED of SMART feedstock is expected to produce a homogeneous metal matrix composite. The two are thus complementary: the reinforcement widens the range of alloys that can be deposited, while DED in turn provides a route to a homogeneous composite that is difficult to obtain by conventional bulk processing. This was demonstrated with CM247LC, a γ' -strengthened Ni-based superalloy that is highly susceptible to solidification cracking, using ZrC (1, 2 and 4 wt%), TiC and HfC (2 wt%) as reinforcements. XRD showed that the discrete carbide reflections of the composite powders were replaced by MC-type reflections in the as-built samples, indicating

dissolution during melting and re-precipitation as MC carbides. Microstructural observation revealed uniformly dispersed carbides, finer grains and markedly suppressed cracking relative to the unreinforced alloy, and a secondary carbide phase was frequently observed filling and terminating incipient solidification cracks. By decoupling printability from the chemistry of the matrix alloy, the SMART-DED route offers a general platform for extending the DED materials window beyond conventionally weldable alloys: the matrix can be chosen for its intrinsic performance, and the reinforcement chosen independently to deliver both processability and the target properties.

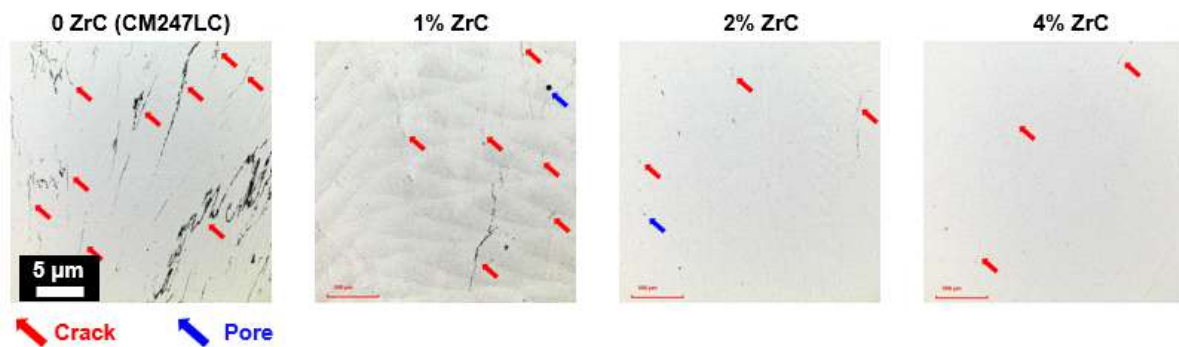


Fig. 1. Optical micrographs showing the suppression of cracking with increasing ZrC content in as-built CM247LC. Red arrows: cracks; blue arrows: pores.

Laser powder bed fusion으로 제조한 Fe-36Ni Invar 합금의 상온·극저온 열팽창계수 및 기계적 특성과 열처리 효과

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Thermal Expansion Coefficients and Mechanical Properties at Room and Cryogenic Temperatures of Fe - 36Ni Invar Alloy Fabricated by Laser Powder Bed Fusion, and the Effect of Heat Treatment

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ABSTRACT

Laser powder bed fusion (LPBF) process는 급속 냉각이 부여하는 높은 잔류응력으로 인해, 기존 제조 공정 대비 낮은 coefficient of thermal expansion (CTE)를 갖는 Fe - 36Ni Invar 합금을 제조할 수 있는 유망한 공정으로 주목받고 있다. 본 연구에서는 LPBF 공정으로 제조된 Fe-36Ni 합금의 미세조직, 상온과 극저온 환경에서의 CTE, 기계적 특성 등을 조사하고, LPBF 공정을 통해 얻는 급랭응고 효과를 유지하면서도 기계적 특성을 동시에 향상시키는 방안으로써, direct annealing 열처리를 제안하였다. 제조된 LPBF 시편은 상대 밀도가 약 98.7% 로 치밀하였으며, FCC 단일 상으로 구성되어 있었

다. LPBF 시편은 기존 공정으로 제조된 Fe-36Ni(이하 Wrought)보다 미세한 결정립과, 높은 dislocation density를 나타냈으며, 결정립 내부에 dislocation cell과 nano scale in-situ oxide precipitates 가 발달한 것이 관찰되었다. LPBF 시편의 상온 인장 특성은 항복 강도: 445 MPa, 인장 강도 511 MPa, 극저온 인장 특성은 항복 강도: 637 MPa, 인장 강도 839 MPa로 wrought 시편보다 우수한 강도 특성을 보였으며, 극저온 변형 과정에서 나타나는 변형 유기 마르텐사이트 변태가 wrought 합금의 25% 이하로 억제되었다. 열처리는 시편의 전위밀도와 잔류응력에 영향을 미쳤다. 300 °C에서 어닐링한 시편(HT300)은 0.93~1.41 ppm/K 수준의 낮은 CTE를 유지하면서도 인장강도와 연신율이 동시에 향상된 반면, 900 °C에서 어닐링한 시편(HT900)은 HT300 시편보다 연신율은 향상되었으나 CTE가 2배 이상 증가하였다. 상기 결과들을 바탕으로 LPBF Fe-36Ni의 상온·극저온 특성과 열처리 효과를 미세조직학적 관점에서 해석하였다.

직접 용융 증착된 IN625 초내열합금의 고온 변형 불안정성

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High temperature deformation instability of directed energy deposited IN625 superalloy

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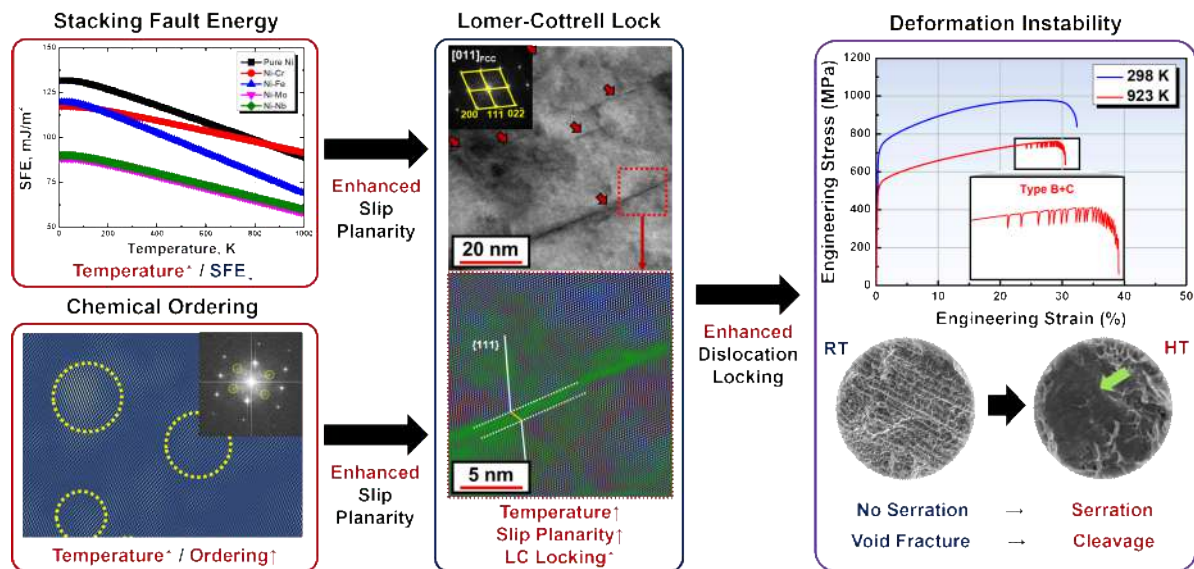
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ABSTRACT

Directed energy deposition (DED) of IN625 alloy is one of the important issues for applying maintenance, repair and overhaul of gas turbine systems. Recent studies reported the optimal DED processing parameters for IN625 and evaluated their mechanical properties under various conditions, but deformation instabilities are frequently observed at elevated temperatures. Because these deformation instabilities degrade overall mechanical properties of DED IN625 components, several researchers investigated possible mechanisms by segregation or secondary phases. However, it is still difficult to explain a detailed instability mechanism due to their complex microstructural evolution during DED. Therefore, in this work, deformation instability of DED IN625 alloy was investigated using direct observation methods and

first-principle density functional theory (DFT) calculations. The DFT calculation results revealed that the stacking fault energy (SFE) of IN625 reduced at elevated temperatures. Particularly, solute elements (e.g., Cr, Co, and Fe) may cause chemical short-range ordering (CSRO) in the matrix, and high-resolution transmission electron microscopy observed the CSRO extended from 1 nm (for 10% deformation) to 3 nm (for 30% deformation) at 923 K.

In summary, both the reduction of stacking fault energy (SFE) and the evolution of CSRO at elevated temperatures enhance slip planarity, facilitating the dissociation of partial dislocations during plastic deformation. Since Lomer-Cottrell locks are formed by $\{111\}$ partial dislocations in the IN625 alloy, dislocation locking and unlocking behaviors occur at elevated temperatures. Consequently, frequent Lomer-Cottrell locking, resulting from enhanced slip planarity, increases deformation instabilities in DED IN625 alloys under high-temperature conditions. Although facility constraints limit the ability to fully reveal the origin and statistical distribution of Lomer-Cottrell locking behavior, direct observation of stair-rod-shaped Lomer-Cottrell locks and their correlation with serrated flow effectively support the unique dislocation mechanisms observed during tensile tests at elevated temperatures.



선택적 레이저 용융법으로 제조된 스테인리스강 316L의 가·감속 구간에서 미세조직, 기계적 특성 및 부식 거동에 관한 연구

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Study of microstructure, mechanical properties, and corrosion behavior
at the acceleration/deceleration zones in stainless steel 316L fabricated
by selective laser melting

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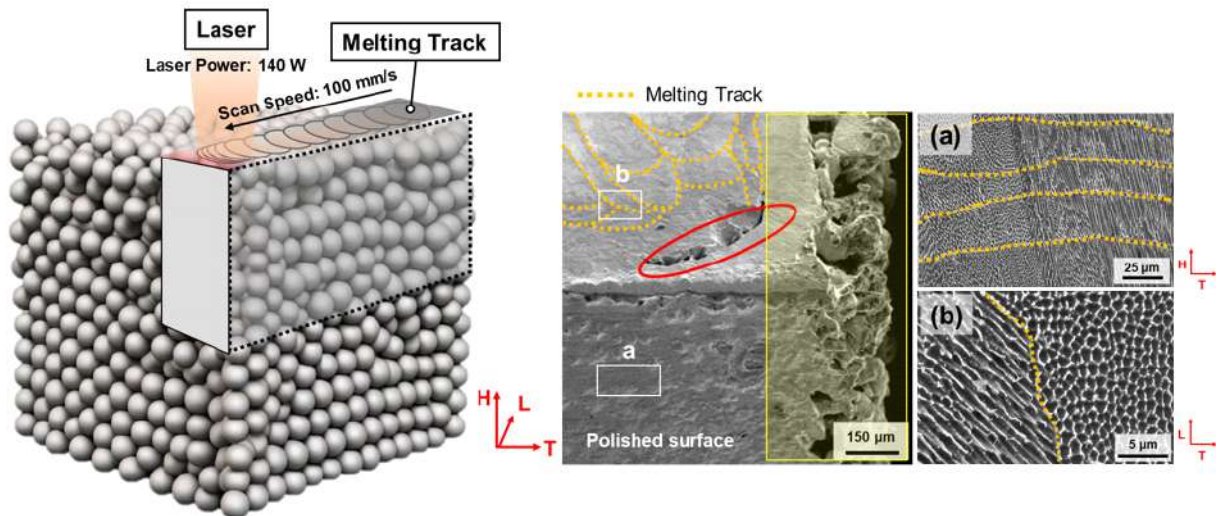
ABSTRACT

Selective laser melting (SLM) is an additive manufacturing technology capable of fabricating components with complex geometries while enabling precise control over phase constitution and elemental distribution. However, the use of galvanometer scanners in the SLM process inevitably generates acceleration and deceleration scanning zones. Consequently, these regions may exhibit microstructures and mechanical properties that differ substantially from those formed under constant scanning-speed conditions. In this study, the microstructural evolution of stainless steel 316L (SS 316L) fabricated by SLM was investigated, with particular emphasis on the acceleration and deceleration zones. Microstructural analyses revealed that these regions possessed distinctive features compared with the constant-speed zones, including irregular grain sizes and morphologies, the formation of sigma phases, and a high density of defects. These variations were attributed to changes in the laser energy input caused by fluctuations in the laser scanning speed.

Post-heat treatment of the SLM-fabricated SS 316L specimens was conducted at 1373 K. The results confirmed that residual stresses in the acceleration and deceleration zones were relieved and that annealing twins were formed after heat treatment. To evaluate the mechanical properties of these regions, tensile specimens

containing intentionally enlarged acceleration and deceleration zones were fabricated and subjected to tensile testing. The conventional SLM specimen exhibited a tensile strength of 527.16 MPa, whereas the specimens dominated by acceleration and deceleration zones showed considerably lower tensile strengths of 45.27 MPa before heat treatment and 22.02 MPa after heat treatment. The significant differences in microstructure and mechanical properties between the acceleration/deceleration zones and the constant-speed regions make it difficult to ensure uniform material properties and consistent quality, particularly in small-scale products and components. Therefore, mitigating such local inhomogeneities is expected to substantially improve the performance and reliability of SLM-fabricated products.

Furthermore, the acceleration and deceleration scanning zones resulted in high surface roughness on the side surfaces of the SLM-fabricated components. High surface roughness not only deteriorates the fatigue performance of SLM-fabricated parts but also reduces their corrosion resistance. To address this issue, a laser remelting process was applied to the surfaces of the SLM-fabricated specimens, and their corrosion behavior was evaluated before and after laser remelting.



HfC로 강화된 Inconel 718의 크리프 특성 분석

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Effect of HfC reinforcement on additively manufactured Inconel 718
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ABSTRACT

Nickel-based superalloy matrix composites fabricated by additive manufacturing have attracted considerable attention as a promising approach for improving high-temperature mechanical performance. In this study, HfC-reinforced Inconel 718 composites were fabricated by laser powder directed energy deposition (LP-DED), and their microstructural evolution, tensile properties, and creep behavior were systematically investigated. Composite powders containing up to 6 vol.% HfC were prepared using the surface modification and reinforcement transportation (SMART) process and deposited under identical LP-DED conditions. During deposition, HfC partially decomposed and participated in metallurgical reactions within the molten pool, resulting in the formation of (Hf,Nb,Ti)C carbides predominantly in the interdendritic regions. HfC addition also altered the solidification behavior and promoted the development of columnar grain structures. Specimens containing up to 3 vol.% HfC exhibited more than a 15% increase in room-temperature yield strength

compared with unreinforced Inconel 718, both before and after heat treatment, while satisfying the AMS 5663 specification. At 650 °C, the heat-treated specimen containing 3 vol.% HfC exhibited increases of more than 20% and 500% in yield strength and elongation, respectively. Furthermore, creep elongation and rupture life increased by approximately 300% and 400%, respectively. These improvements are attributed to the combined effects of secondary carbide formation and HfC-induced microstructural evolution. These results demonstrate that HfC reinforcement is an effective strategy for simultaneously improving the tensile and creep performance of additively manufactured Inconel 718 for high-temperature structural applications.

항공엔진 소재·부품 로드맵 수립 전략

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Strategy for Developing a Technology Roadmap for Aircraft Engine Materials and Components

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ABSTRACT

This study proposes a strategy for developing a roadmap for aircraft engine materials and components for the period 2026 - 2040. The roadmap was developed by comprehensively analyzing domestic and international technology trends, ongoing domestic R&D programs, and technology demands, followed by evaluation and expert review to select and visualize target technologies. Through this roadmap, the study aims to establish independent domestic capabilities from core material development to component demonstration, while creating a foundation for linking developed technologies to engine applications and their subsequent expansion into the civil aviation sector.

구조용 및 생체용 마그네슘 합금 설계

김정기, 민두원, 박성수
울산과학기술원 신소재공학과

Design of magnesium alloys for structural and biomedical applications

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Department of Materials Science and Engineering, UNIST

ABSTRACT

Magnesium (Mg) alloys have attracted considerable attention for both structural and biomedical applications owing to their exceptionally low density, high specific strength, and excellent biocompatibility. In structural applications, Mg alloys provide significant opportunities for lightweight transportation systems, contributing to improved energy efficiency and reduced carbon emissions. In the biomedical field, Mg has emerged as a promising material for biodegradable orthopedic implants and cardiovascular stents because it gradually degrades after fulfilling its mechanical function, eliminating the need for secondary removal surgery. Although the performance requirements differ between these applications, controlling corrosion or degradation behaviour while maintaining sufficient mechanical properties remains a common challenge. Therefore, developing alloy design strategies that simultaneously optimize strength and corrosion/degradation behaviour has become a central focus in magnesium alloy research.

Conventional Mg alloy development has relied primarily on alloying additions, thermomechanical processing, grain refinement, and purification to improve performance. In particular, reducing trace impurities such as Fe, Ni, and Cu through increasingly stringent purification has long been regarded as the most effective approach for improving corrosion resistance. While this strategy has enabled the production of ultra-high-purity Mg with excellent corrosion performance, the associated processing cost limits its widespread industrial application. Consequently, alternative approaches capable of improving corrosion resistance without relying solely

on purification have become increasingly important.

Recent advances have demonstrated that microstructural engineering provides a new design strategy for corrosion control. Rather than simply minimizing impurity content, controlling the distribution, morphology, and electrochemical characteristics of impurity-containing particles can effectively suppress microgalvanic corrosion. In particular, core-shell particle engineering enables impurity elements to be incorporated into electrochemically benign intermetallic particles, thereby reducing their cathodic activity and fundamentally changing the conventional relationship between impurity content and corrosion resistance. This approach provides a new framework for designing high-performance Mg alloys through particle engineering rather than expensive purification.

These developments indicate that magnesium alloy design is evolving from conventional composition-based optimization toward microstructure-driven engineering. Particle design offers a versatile strategy for tailoring corrosion and degradation behaviour while preserving mechanical performance, making it applicable to both lightweight structural alloys and biodegradable biomedical materials. Continued advances in microstructural engineering are therefore expected to accelerate the development of next-generation Mg alloys with improved durability for structural applications and controlled degradation for biomedical implants, providing a common design philosophy across these two important application fields.

마그네슘 합금 장갑판의 이방성 관통 거동 해석

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Anisotropic penetration behavior of Mg alloy armor plates

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ABSTRACT

Magnesium alloys are promising candidates for weight-critical protective structures owing to their low density. At room temperature, however, the hexagonal close-packed lattice of α -Mg activates only a few slip systems with ease, and thus plastic flow relies primarily on basal slip supplemented by deformation twinning. When rolling imprints a sharp basal texture, this crystal-level selectivity is amplified into a pronounced directional dependence of macroscopic behavior. Such anisotropy is well documented under quasi-static loading, yet little is known about how it operates under projectile impact at a high velocity. This study compares the perforation and penetration behavior of a strongly textured AZ31 Mg alloy plate struck along two orthogonal directions, tracing the observed differences from the crystallographic scale to the macroscopic failure pattern.

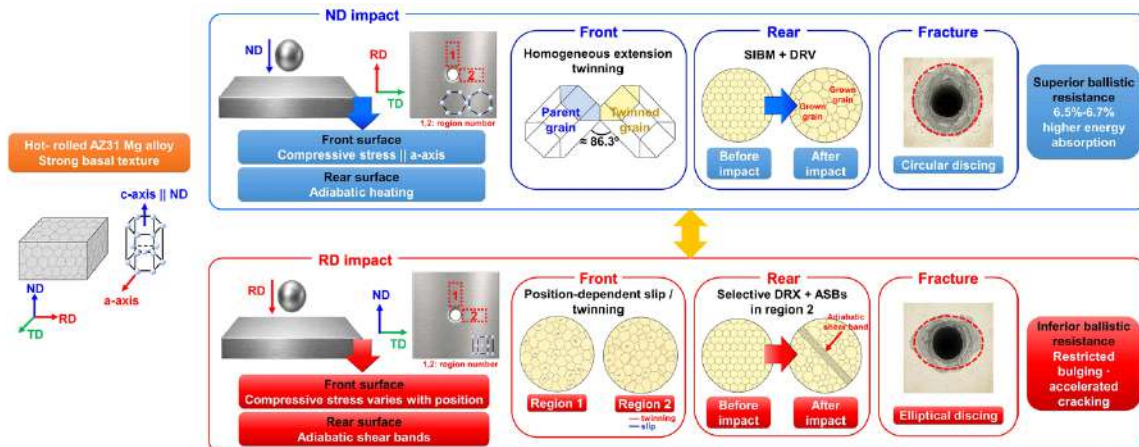
Square specimens were machined from a hot-rolled AZ31 Mg alloy plate whose basal poles clustered along the normal direction (ND), and the impact axis was aligned with either the ND or the rolling direction (RD). Spherical steel projectiles with 5 mm in diameter were launched by a combustion-driven gas gun at an average velocity of 884 m/s, and laser-sheet velocimetry quantified the kinetic energy dissipated by each plate. Crater-adjacent regions were examined by optical and scanning electron microscopy together with electron backscatter diffraction. Complementary finite-element (FE) simulations employed Hill's anisotropic yield criterion coupled with Voce hardening and a stress-state-dependent damage

formulation, and the computed local stresses were combined with Schmid-factor analysis to rank the activation propensity of slip and twinning modes.

The two orientations produced consistently different outcomes. ND-impacted plates dissipated 6.5 - 6.7% more projectile kinetic energy than RD-impacted ones, and the disk-shaped fragments detached from their rear surfaces were nearly circular with aspect ratios of 1.04 - 1.07. RD impact instead generated elliptical discing elongated toward the transverse direction, with aspect ratios up to 1.70. In the 20-mm plates, which arrested the projectile, the ND orientation developed a pronounced rear-surface bulge (9.5% thickness increase versus 3.5% for RD) and remained essentially crack-free, whereas visible cracking accompanied the RD impact.

These contrasts stem from the geometry between the local compressive stress and the crystal lattice. Under ND impact, the radial compression generated by cavity expansion stays nearly perpendicular to the *c*-axes at every azimuthal position, keeping the resolved stress for extension twinning uniformly low; the front surface therefore twins profusely and homogeneously, while the rear surface coarsens through strain-induced boundary migration and dynamic recovery. Under RD impact, the angle between the compression axis and the *c*-axes varies around the crater, so the operative mechanism switches with position between basal slip and mixed slip - twinning. The FE analysis showed that this heterogeneous accommodation concentrates shear stress in one rear-surface sector, which recorded the highest local plastic-work density, the largest failed-element fraction, and the shortest strain-accumulation time. Plastic dissipation confined to such a narrow window favors localized adiabatic heating; consistently, this sector exhibited dense adiabatic shear bands containing ultrafine recrystallized grains and microcracks propagating along the bands. Early shear cracking here curtails bulging and steers the elliptical fracture path, explaining the inferior resistance of the RD orientation.

In conclusion, these results show that ballistic anisotropy in basal-textured Mg plates is governed by whether the impact geometry preserves a uniform relationship between the stress field and the lattice, offering a texture-based design principle for lightweight Mg armor components.



적층제조된 다층 CoCrNi - CoCrNi₂ 중엔트로피 합금의 나노역학적 특성 분석 연구

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Micromechanical behavior and the role of a compositionally
graded zone in an LPBF-processed multilayer CoCrNi-CoCrNi₂
medium-entropy alloy

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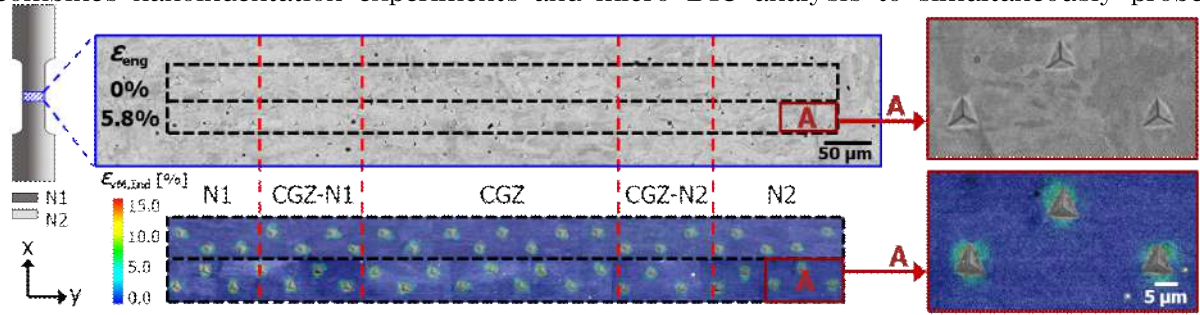
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ABSTRACT

This study investigates the micromechanical behavior of additively manufactured multilayer samples composed of alternating hard CoCrNi and soft CoCrNi₂ medium-entropy alloy (MEA) layers fabricated by laser powder bed fusion (L-PBF). Macro- and micro-scale mechanical testing and digital image correlation (DIC) analysis, together with finite element simulations, reveal coupled global - local deformation behavior and complex strain interactions within individual layers and interfacial regions. In addition, we developed a new quantitative approach that combines nanoindentation experiments and micro-DIC analysis to simultaneously probe



local strength and strain distribution. From all above results, we explored the micromechanical role of a compositionally graded zone between the layers and the underlying deformation mechanisms in the examined multi-layered MEA systems.

Figure 1. SEM images and the corresponding micro-DIC maps illustrating the arrays of nanoindentations. Magnified views of region “A” are shown on the right.

초미세 DIC 패턴을 통한 국부 변형 및 잔류응력 평가 기법

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Sub-micron DIC Pattern-based Technique for Local Deformation and Residual Stress
Evaluation

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ABSTRACT

The adoption of advanced packaging technologies such as 3D ICs and HBM is driving continuous miniaturization in semiconductor structures. These structures involve complex multilayer geometries and heterogeneous interfaces, where residual stresses inevitably arise from mismatches in thermal expansion, lattice constants, and local processing conditions. Such stresses can drive cracking, delamination, and other critical reliability issues at film and interfacial levels. Quantitative evaluation of local residual stresses is therefore essential for robust packaging design and long-term device performance.

Conventional techniques—including wafer curvature, X-ray diffraction (XRD), and Raman spectroscopy—struggle to assess stress distributions in patterned and multilayer thin films. Their limitations stem from material dependence and insufficient spatial resolution. To overcome these challenges, we present a residual stress evaluation method that integrates the classical slitting technique with Focused Ion Beam (FIB) micromachining and high-resolution Digital Image Correlation (DIC).

A key enabling element of this method is the generation of sub-micron-scale DIC patterns, which are essential for resolving highly localized displacement fields. Two

independent patterning approaches were proposed to this end: electron-beam (e-beam) lithography, which offers precise, well-controlled pattern formation with arbitrary design flexibility, and block co-polymer (BCP) self-assembly, which provides a simpler and more cost-effective route to sub-100nm features via microphase separation. In this method, patterns defined by either approach are protected by a sacrificial polymer during FIB milling. Local stress relaxation is induced by FIB milling, and the resulting displacement fields around the milled region are captured via DIC. Based on linear elastic theory, these displacement fields are analyzed in conjunction with finite element simulations to reconstruct the residual stress state at the corresponding location. This provides a semi-non-destructive, high-resolution mapping approach suited for thin-film structures in semiconductor packaging.

Finite element simulations were conducted to validate key assumptions and assess the method under non-equibiaxial stress states common in anisotropic or multilayered systems. Results confirm that the proposed approach can accurately interpret complex stress states independent of the patterning method used, offering a powerful tool for reliability assessment and design optimization in advanced packaging technologies.

This presentation will cover the theoretical framework, experimental implementation of both the e-beam lithography- and BCP-based DIC patterning approaches, and numerical validation of the FIB- μ DIC slitting method, highlighting its potential for addressing critical reliability challenges in semiconductor packaging.

2차원 몬테카를로 팻츠 모델의 임계 거동과 질서상 - 무질서상 간 계면 에너지 연구

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Critical behavior and interfacial energy at the order-disorder transition
in the 2D MC Potts Model

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ABSTRACT

The order-disorder transition in the Ising model, the two-spin case of the Potts model, has been extensively studied to predict the transition temperature and to elucidate its thermodynamic nature. This is because the Ising model provides a simple yet powerful description of the ferro-para magnetic transition at the Curie temperature. In contrast, the Potts model, the case for the multiple Q (≥ 2) spins, has found its broader applications in predicting microstructural evolution during coarsening processes such as grain growth, recrystallization, and sintering. Unfortunately, the order-disorder transition of the Potts model has not been, however, as broadly investigated, largely because its transition is analogous to melting, or solidification in reverse, in microstructural evolution. Furthermore, the Potts model accommodates multiple spin states, making the prediction of its transition behavior inherently more complex than that of the Ising model. In this study, we investigate the characteristics of the order-disorder transition in the 2D Potts model on a square lattice via a Monte Carlo Potts model simulation. The simulation results are also compared with the predictions of the mean field theory. From the simulations, both the nature of the transition and the critical temperature are obtained. It is found that the critical

behavior of the Potts model strongly depends on the number of spin states (Q), and that this trend is in accordance with the mean field theory predictions. Furthermore, the interface energy between the ordered and disordered phases is evaluated using the mean field theory, and its associated thermodynamic behavior is examined through Monte Carlo Potts model simulations. Thermodynamic interpretations of these phenomena are also presented.

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제 2 발표회장

- Session 1
- Session 2

초내열합금의 인공지능 접근법

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Artificial Intelligence Approaches for Superalloys

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ABSTRACT

An artificial intelligence (AI)-based framework was proposed to search for Ni- and Co-base polycrystalline superalloys with improved high-temperature strength, creep and oxidation-resistant properties. The proposed AI-based framework consists of forward machine learning (ML) models optimized to predict high-temperature strength, creep and oxidation-resistant properties, and the denoising diffusion probabilistic model for the generation of synthetic compositions. A composition-processing-property database was built through the literature survey and selected experiments, and pre-processed to train and optimize ML models. The denoising diffusion probabilistic model was adopted to generate a virtual superalloy compositional pool out of collected original Ni- and Co-base superalloy compositions. Pre-trained ML models were used to predict high-temperature strength, creep and oxidation-resistant properties for each of generated virtual superalloy compositions. Finally, virtual superalloy compositions were screened to search for new Ni- and Co-base superalloys having superior high-temperature strength, creep and oxidation-resistant properties. Ni- and Co-base superalloys newly developed from the proposed AI framework were experimentally validated. Also, their metallurgical foundation was thoroughly assessed.

적층제조용 Hf-free 247 grade 내열합금 개발 및 결정립계 강화원소 제어를 통한 균열 억제와 크리프 특성 향상

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Alloy Design of a Hf-free 247 Grade Superalloy for AM Achieving Crack Suppression
and Enhanced Creep Resistance through GB Strengthening Element Control

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ABSTRACT

High γ' 247 type Ni-based superalloys possess excellent high temperature properties but are classified as nonweldable, which has limited their application in additive manufacturing. In this study, a Hf-free 247 grade superalloy, CW247, was developed by redesigning the CM247LC chemistry to reduce raw material cost and to suit electron beam additive manufacturing, using a multiscale design framework that combines Thermo-Calc thermodynamic calculations with DFT based planar fault energy calculations. The designed alloy was fabricated into a dense specimen by SEBM and exhibited high strength retention at 871 °C, whereas liquation cracks were observed along high angle grain boundaries. TEM analysis revealed that the cracks originated from constitutional liquation of Nb and Zr bearing MC carbides, with local melting and resolidification products identified. Based on this mechanism, a modified alloy, CW247-D, was designed by reducing Nb and C, removing Zr, and adding B. Atom probe tomography confirmed that B segregated to the grain boundaries in place of Zr. As a result, cracking was markedly suppressed, and the creep rupture life at 815 °C and 448 MPa improved from 76 h to 662 h, reaching a level comparable to conventionally cast CM247LC. This work demonstrates that grain boundary

strengthening element control serves as an effective design factor that simultaneously achieves crack suppression and high temperature performance in superalloys for additive manufacturing.

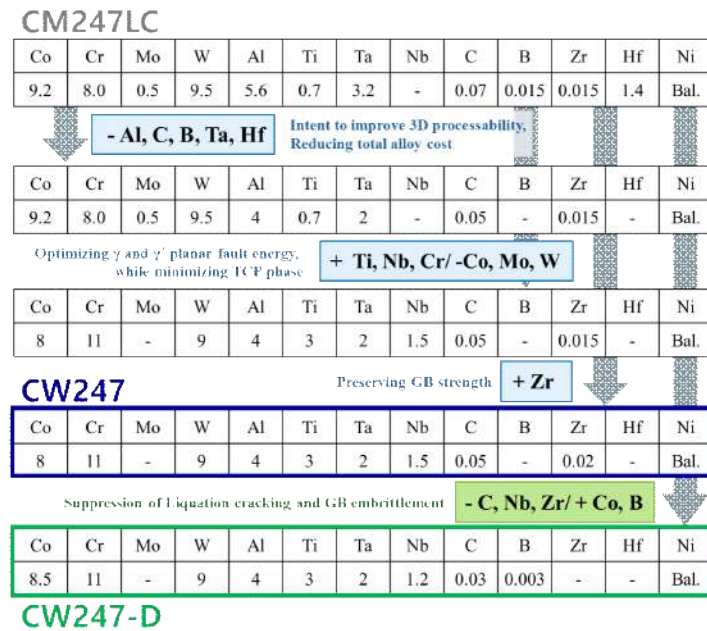


Fig. 1. Schematic of alloy design of Hf-free 247 grade superalloy for AM.

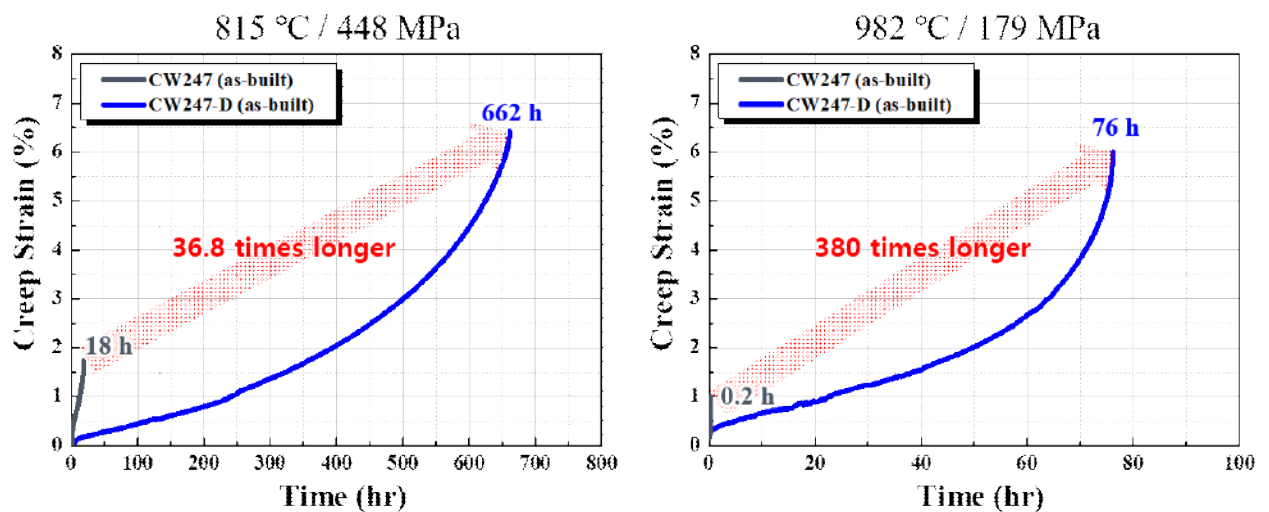


Fig. 2. Comparison of creep curves between CW247 and CW247-D (as-built).

분무열분해 및 볼밀링 공정에 따른 순수 Ni 기반 산화물분산강화 합금의 미세조직, 기계적 특성, 및 용융염 부식 거동

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고온 용융염은 우수한 열전달 특성과 낮은 증기압으로 용융염 원자로 등 차세대 열에너지 시스템의 열매체로 주목받고 있으나, 염화물계 용융염에 의한 부식과 고온 기계적 특성 저하는 구조재의 장기 적용을 제한하는 주요 요인이다. 본 연구에서는 고온 용융염 환경용 Ni 기반 산화물분산강화(Oxide Dispersion Strengthened, ODS) 소재를 대상으로, 복합분말 제조공정과 벌크화 공정이 미세조직, 기계적 특성 및 부식 거동에 미치는 영향을 종합적으로 평가하였다. ODS 복합분말은 그림 1에 나타난 바와 같이 분무열분해(Spray Pyrolysis, SP), 볼밀링(Ball Milling, BM) 및 표면개질 기반 복합분말 제조공정(SMART)으로 제조하였으며, 방전 플라즈마 소결(Spark Plasma Sintering, SPS)과 직접 에너지적층(Directed Energy Deposition, DED)을 통해 벌크화하였다. 제조된 소재에 대해 산화물 분포, 결정립 구조, 경도 및 인장 특성을 분석하고, NaCl - MgCl₂ 계 고온 용융염 침지시험을 통해 부식 거동을 평가하였다.

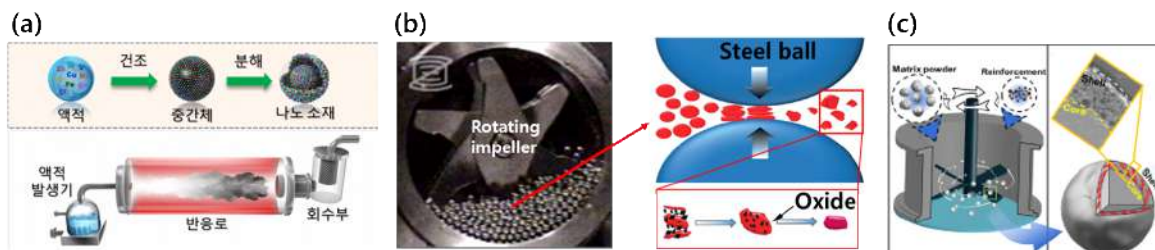


그림 1. Ni 기반 ODS 복합분말 제조공정의 모식도: (a) 분무열분해(SP), (b) 볼밀링(BM), (c) 표면개질 기반 복합분말 제조공정(SMART).

분석 결과, SPS 소재의 경도와 인장 특성은 복합분말 제조공정에 따라 뚜렷한 차이를 나타냈다. BM 공정은 결정립 미세화와 결합 밀도 증가를 통해 높은 강도를 유도하여 1Y₂O₃-BM 소재에서 가장 높은 경도(296 HV0.2)와 항복강도(651 MPa)를 나타냈으나, 산화물의 국부적 응집으로 인해 연신율이 2.6%까지 급격히 감소하였다. 반면, SP 공정은 산화물을 기지 내에 상대적으로 균일하게 분산시켜, 1Y₂O₃-SP 소재에서 순수 Ni 대비

약 3.5배 높은 항복강도(447 MPa)와 함께 27.6%의 연신율을 유지함으로써 강도 - 연성 균형 확보에 유리하였다. 표면개질 기반 공정은 분말 공급성과 적층 안정성을 개선하였으며, DED 소재는 급속 용융·응고에 의해 SPS 소재와 구별되는 방향성 미세조직과 산화물 분포를 나타냈다. 용융염 부식 거동은 표면 MgO계 부식생성물의 연속성, 산화물 분산 상태 및 계면 건전성에 의해 지배되었으며, 산화물이 균일하게 분산된 소재에서는 안정적인 표면 부식이 관찰된 반면 산화물 응집 영역에서는 용융염의 국부적 침투와 불균일 부식이 촉진되었다. 이러한 결과는 Ni-ODS 합금의 고온 강도와 용융염 내식성이 산화물 첨가량보다 복합분말 제조법, 산화물 분산 상태 및 최종 벌크화 공정에 의해 지배됨을 보여주며, 두 특성의 동시 확보를 위해서는 분말 제조공정과 SPS·DED 공정의 연계를 통한 산화물 분산 및 계면 구조의 정밀 제어가 필요함을 시사한다.

주제어: 산화물분산강화(ODS) 합금, 용융염 부식, 복합분말 제조공정, 방전 플라즈마 소결(SPS), 직접에너지적층(DED)

적층결함에너지에 따른 초극저온 불연속 소성유동

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Effect of Stacking Fault Energy on
Discontinuous Plastic Flow at Ultra-Low Temperatures

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ABSTRACT

Discontinuous plastic flow (DPF) at ultra-low temperatures is one of the primary factors limiting the mechanical stability and reliability of structural materials used in cryogenic environments. However, the microstructural factors governing the characteristics of DPF, particularly the magnitude of stress drops, remain poorly understood. In this study, we demonstrate that stacking fault energy (SFE), a key material parameter controlling plastic deformation, plays a decisive role in determining DPF behavior at ultra-low temperatures.

To investigate this effect, the SFE was systematically tailored by varying the Ni and Co contents in face-centered cubic (FCC) $\text{Fe}_{55}\text{Cr}_{12.5}\text{Ni}_x\text{Co}_{(25-x)}\text{Mo}_{7.5}$ medium-entropy alloys. Tensile tests were conducted at 4.2 K to evaluate the deformation behavior. As the SFE increased, the magnitude of stress drops was significantly reduced, resulting in more stable plastic flow. Microstructural characterization revealed that low-SFE alloys deformed predominantly by planar slip, where extensive dissociation of perfect dislocations into partial dislocations promoted frequent interactions among

partial dislocations and the formation of strong dislocation barriers, leading to pronounced stress drops. In contrast, higher SFE facilitated wavy slip by promoting dislocation cross-slip, thereby suppressing the formation of dislocation barriers and effectively mitigating DPF.

열간압연으로 제조된 Incoloy 825 클래드재 와 Inconel 625 클래드재의 미세조직과 기계적 성질 비교 연구

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A comparative study on the microstructures and mechanical properties of hot-rolled
Incoloy 825 and Inconel 625 clad plates

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초록

본 연구에서는 유사한 열간압연 공정을 통해 제조된 Incoloy 825/API X65 클래드재와 Inconel 625/API X65 클래드재의 접합부 미세조직, 원소 확산 거동, 미소경도, 전단 물성 및 파단 거동을 비교하여 니켈 합금의 종류가 접합 특성과 전단 파괴 거동에 미치는 영향을 분석하였다. Inconel 625/API X65 에서는 Incoloy 825/API X65 보다 API X65 측의 탈탄층이 두껍게 형성된 반면, 니켈 합금 측의 침탄층은 CP825에서 더 두껍게 형성되었다. Incoloy 825/API X65 의 접합부 부근에서는 입내에 TiC와 $M_{23}C_6$ 탄화물이 관찰되었으며, 결정립계를 따라 $M_{23}C_6$ 탄화물이 연속적으로 석출된 심한 침탄 조직이 형성되었다. 반면, Inconel 625/API X65 에서는 입내와 결정립계에 (Nb,Ti)C 탄화물이 비교적 드물게 분포하였다. 또한 접합부 부근에서 측정된 Fe, Ni 및 Cr의 확산 거리는 Inconel 625/API X65 에서 Incoloy 825/API X65 보다 짧게 나타났다. 이는 Inconel 625에 함유된 Nb와 상대적으로 높은 Ni 함량이 열간압연 중 원소의 확산을 억제하였기 때문으로 판단된다.

두 클래드재 모두 ASTM 규격에서 요구하는 140 MPa 이상의 전단강도를 나타내어 양호한 접합 건전성을 보였다. 한편, 접합부 부근 원소 확산은 Incoloy 825/API X65 가 더 많았음에도 불구하고, Inconel 625/API X65 는 Incoloy 825/API X65 보다 우수한 전단강도와 전단 변위를 나타냈으며, 전단 파단은 Inconel 625/API X65 의 경우 API X65 의 탈탄층 영역에서 발생한 반면, Incoloy 825/API X65 에서는 접합부를 따라 발생하였다. 이러한 전단 파단 위치의 차이는 니켈 합금층과 API X65 사이의 미소경도 차이가

Inconel 625/API X65 에서 더 크게 나타났기 때문에 판단된다. 추가적인 열처리를 통해 Incoloy 825/API X65 의 니켈 합금층과 API X65 사이의 경도 차이를 증가시킨 결과, 전단 파단 위치가 접합부에서 API X65 측으로 일부 이동하였다. 이를 통해 니켈 합금과 API X65 사이의 상대적인 경도 차이가 니켈 합금 클래드재의 전단 물성 및 파단 위치를 결정하는 요소 중에 하나임을 확인하였다.

Metal-Material Extrusion으로 제조한 AISI D2 고탄소 공구강의 열처리 및 HIP-URQ에 따른 미세조직, 인장 물성 변화

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Effect of heat treatment and HIP-URQ on the microstructure and tensile properties of
AISI D2 high carbon tool steel fabricated by metal material extrusion

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ABSTRACT

Metal Material Extrusion (MEX) is a sintering-based additive manufacturing process that is more suitable for fabricating materials with high thermal gradients or high reflectivity than processes employing high-energy heat sources, such as lasers or arcs. In this study, the microstructures and tensile properties of AISI D2 high-carbon tool steel fabricated by the MEX process were investigated before and after heat treatment. In addition, hot isostatic pressing combined with uniform rapid quenching (HIP-URQ) was proposed as a post-processing route to simultaneously improve mechanical properties while maintaining the microstructural uniformity achieved through the MEX process. Uniform Rapid Quenching (URQ) is an emerging technology that enables rapid cooling through uniform gas quenching following the HIP process, thereby maximizing microstructural refinement compared with conventional HIP. AISI D2 tool steel specimens fabricated by MEX were subjected to HIP-URQ treatment at the austenitizing temperature, hereafter referred to as HU, followed by standard heat treatment (HT). For comparison, the as-built specimen (AB) was subjected to conventional heat treatment involving austenitization and oil quenching (AQ-HT). Microstructural observations revealed that the AB specimen exhibited a porosity of 2.293% owing to defects such as air gaps and pores, and

consisted of uniformly distributed M_7C_3 carbides within a ferritic matrix. After HU treatment, these defects were substantially reduced, resulting in a marked decrease in porosity to 0.061%. The matrix phase also transformed into martensite with a small amount of austenite. After heat treatment, both the AQ-HT and HU-HT specimens consisted of martensite and M_7C_3 carbides, although differences were observed in the size and distribution of the constituent phases. The measured hardness values were 231.20 HV for AB, 649.24 HV for AQ-HT, and 705.76 HV for HU-HT, demonstrating that the application of UH effectively improved hardness. Tensile testing of the heat-treated specimens showed tensile strengths of 2352.57 MPa for HU-HT and 2089.15 MPa for AQ-HT, with corresponding elongations of 2.37% and 1.21%, respectively. Thus, the application of HU-HT nearly doubled the elongation and increased the tensile strength by 12.61%. Based on these results, an effective strategy for improving the microstructure and mechanical properties of MEX-fabricated components through the application of the HIP-URQ process was discussed.

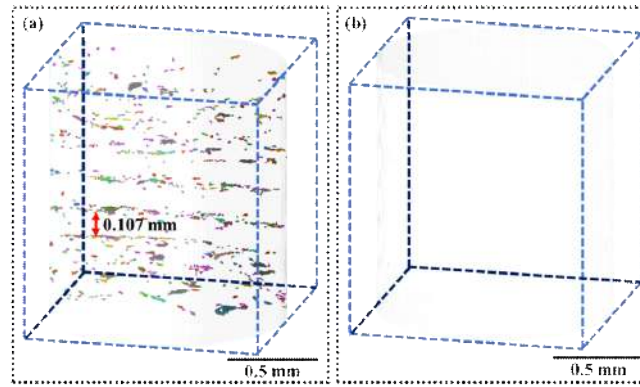


Fig. 1. XCT image of MEX D2 (a)AQ-HT and (b)HU-HT specimens

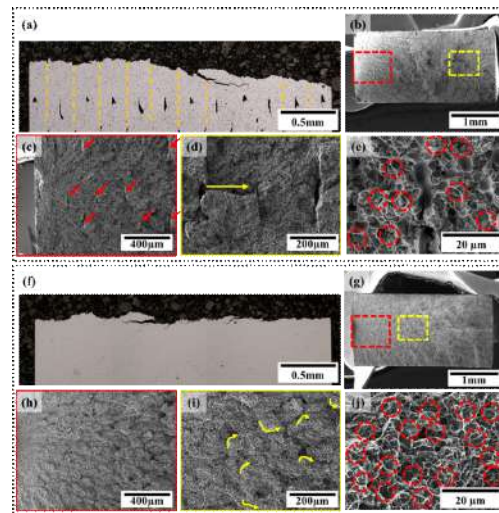


Fig. 2. Microstructural characteristics of the Kelvin lattices: (a) SEM-BSE image in the stress-relieved condition and (b1 - b3) TEM analyses after heat treatment.

빅데이터 기반 내화강 개발 및 고온 기계적 특성 분석

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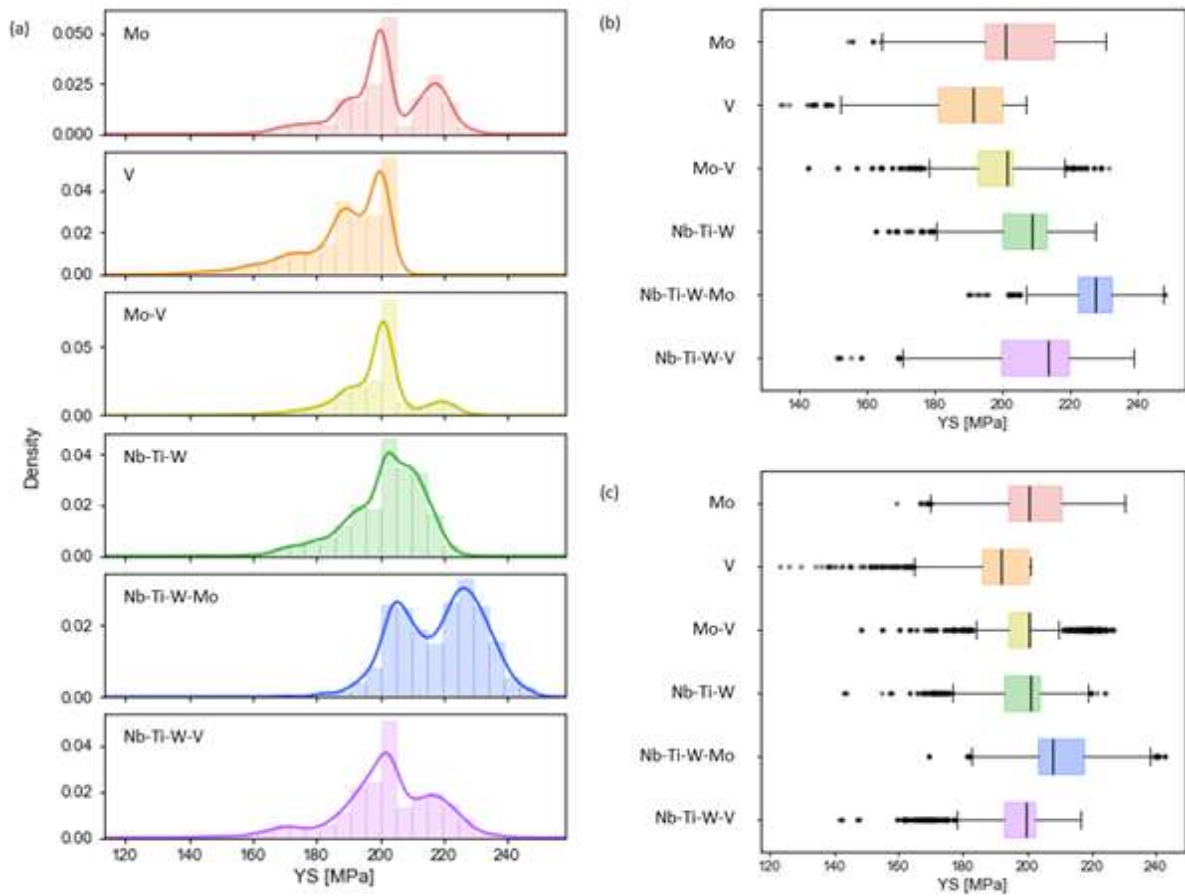
초록 (Abstract)

초고층 건축물의 증가에 따라 구조물의 안전성을 확보하기 위한 설계 기술과 함께 내화 및 내진 특성을 갖춘 건축 구조용 철강재에 대한 수요가 증가하고 있다. 그러나 기존의 내화강 개발은 특정 합금 원소를 중심으로 조성을 제한적으로 변화시키는 방식에 머물러 있어, 탐색 가능한 조성 공간이 협소하고 개발 속도가 느리다는 한계가 있다.

본 연구에서는 이러한 한계를 극복하기 위해 열역학 시뮬레이션 기반의 고속·대량 스크리닝을 수행하였다. 이를 통해 방대한 합금 조합에 대한 고온 조건 (600 °C, 180분)에서의 기계적 물성을 예측하고, 관련 빅데이터베이스를 구축하였다 <그림 1>. 또한 고온 기계적 특성의 발현 메커니즘을 규명하기 위해 특정 원소의 함량을 변화시키는 방식으로 데이터베이스를 세분화하였으며 <그림 1>, 각 세분화된 데이터베이스로부터 대표 내화강 조성 6종을 도출하였다.

도출된 조성에 대해 고온 인장 시험과 미세조직 분석을 수행한 결과, 6종의 합금 중 3종이 내화강 규격인 상온 항복강도 대비 고온 항복강도 2/3 이상을 만족하는 것으로 확인되었다. 실험 결과, V는 단독으로 첨가될 때보다 다른 합금 원소와의 상호작용을 통해 고온 기계적 특성에 더욱 큰 영향을 미치는 것으로 나타났다. 또한 Mo, V, Ti는 석출 강화에 기여하는 핵심 원소로 확인되었다. 특히 Mo를 첨가하지 않은 Ti-Nb-V-W 합금계에서도 원소 간 상호작용에 의해 강화 효과가 크게 향상되는 것을 확인하였다.

본 연구는 고가의 전략 원소인 Mo를 대체할 수 있는 유망 합금 조성 설계안을 제시하는 동시에, 다성분계 합금에서 합금 원소 조합에 따른 고온 기계적 특성 변화 메커니즘을 규명하였다. 이러한 결과는 차세대 고성능 내화강 설계를 위한 기초 자료로 활용될 것으로 기대된다.



<그림 1> 열역학 시뮬레이션을 기반으로 구축한 합금 구성 원소 조합별 고온 조건 (600 및 700 °C, 180분)에서의 기계적 물성 빅데이터베이스: (a) 600 °C 조건에서 약 12,000개 합금 조성 및 공정조건에 대한 빅데이터베이스, (b) 600 °C 조건에서의 합금 조성별 기계적 물성 상자그림, (c) 700 °C 조건에서의 합금 조성별 기계적 물성 상자그림

석출강화와 결정립 미세화 강화의 시너지 상호작용을 통한 Super-Invar 합금의 강도 - 열팽창 특성 상충관계 극복

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Overcoming the strength-thermal expansion trade-off by synergistic interplay of precipitation and grain refinement hardening in Super-Invar alloy

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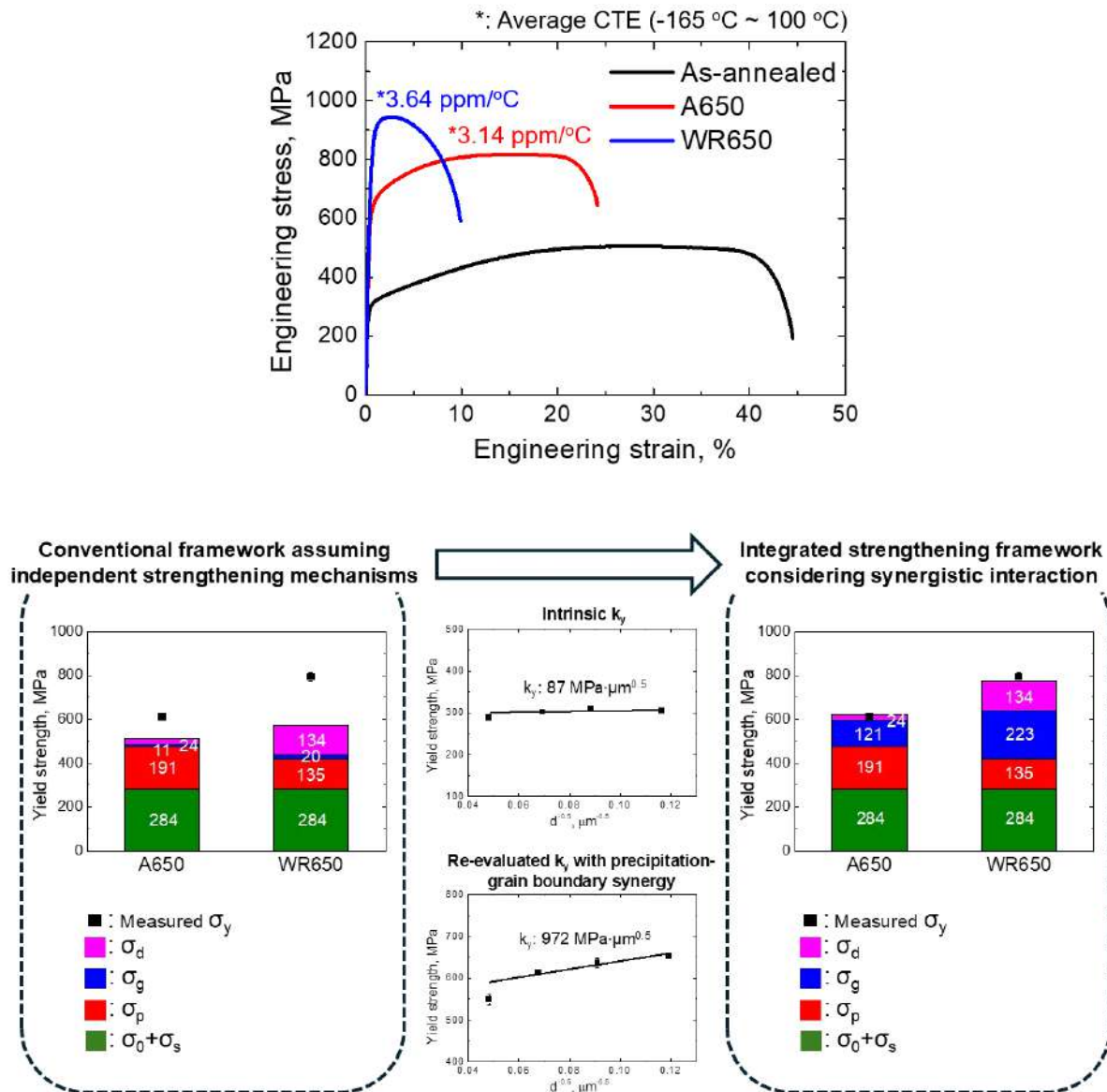
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ABSTRACT

This study aims to enhance the strength of a Ti- and Al-containing Super-Invar alloy (Fe-39.2Ni-3.54Co-1.02Ti-1.22Al, in wt.%) through multiple strengthening mechanisms via warm rolling. Following solution treatment, conventional aging at 650 °C for 10 h (A650) and warm rolling at 650 °C with 60% reduction (WR650) were evaluated. Both routes induced needle-shaped γ' -Ni₃(Ti,Al)cellular precipitates along grain boundaries via discontinuous precipitation (DP) and coherent nanoscale spherical γ' within grain interiors via continuous precipitation (CP). Warm rolling successfully refined the grain thickness along the normal direction to 19 μ m and increased dislocation density. Consequently, the WR650 specimen achieved an exceptional yield

strength of 794 MPa (compared to 612 MPa for A650 and 291 MPa for the as-annealed state) while maintaining a low coefficient of thermal expansion (CTE) of 3.64 ppm/°C. Quantitative analysis revealed that the independent consideration of strengthening mechanisms significantly underestimates the yield strength. This discrepancy is resolved by a unique synergy where cellular DP precipitates at grain boundaries act as highly effective barriers to slip transfer, drastically increasing the Hall-Petch coefficient (k_y) from 87 to 972 MPa· $\mu\text{m}^{1/2}$. This framework provides a promising pathway for balancing high strength and low CTE in Super-Invar alloys.



LPBF SS304L의 집합조직 및 결정립 크기에 따른 극저온 마르텐사이트 변태와 쌍정 거동

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Texture- and Grain-Size-Dependent Martensitic Transformation and
Twinning Behavior of LPBF SS304L at Cryogenic Temperature

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ABSTRACT

Achieving a simultaneous gain in strength and ductility in additively manufactured metastable alloys hinges on how phase stability and processing defects interact, and this coupling becomes decisive at cryogenic temperatures. Here, laser powder bed fused (LPBF) SS304L specimens with distinct crystallographic textures and grain sizes were tensile-tested at 298 K and 77 K to trace strain-induced martensitic transformation (SIMT) kinetics and the resulting fracture behavior. Grain refinement accelerated SIMT, and the accompanying work hardening became so localized within the gauge that macroscopic failure migrated to the specimen shoulder. Coarse grains alone were not sufficient to avoid this: only when a strong α -fiber texture was present was SIMT suppressed enough to retain plastic stability and keep fracture inside the gauge at 77 K, whereas a Goss-dominated coarse-grained specimen underwent rapid SIMT and a high twinning rate, losing cryogenic elongation and again failing at the shoulder. Fractography revealed that the role of processing defects is itself temperature-dependent – oxide inclusions nucleated microvoids for ductile coalescence at 298 K, but once the matrix was stiffened by α' -martensite at 77 K the same inclusions acted as critical stress concentrators. The cryogenic integrity of

LPBF SS304L is therefore governed by a competition between texture-controlled phase stability and the inclusion sensitivity of the hardened matrix.

고경도 보론강의 석출 거동과 충격인성에 미치는 Al 및 Ti 복합 첨가의 영향

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Combined Effect of Al and Ti Additions on Precipitation Behavior and Impact
Toughness of High-Hardness Boron Steels

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ABSTRACT

In thick steel plates requiring sufficient hardenability, boron is one of the most effective microalloying elements because solute boron segregates to austenite grain boundaries and suppresses ferrite nucleation. However, nitrogen readily reacts with boron to form BN, reducing the amount of solute boron available for grain boundary segregation and thereby deteriorating hardenability. To suppress BN formation, Al and Ti are commonly added to preferentially fix nitrogen. Owing to their different thermodynamic affinities for nitrogen and precipitation behaviors, Al and Ti lead to distinct partitioning behaviors of nitrogen and boron. Therefore, understanding the combined effects of Al and Ti on the partitioning behavior of nitrogen and boron is essential for optimizing the hardenability and impact toughness of boron steels. In this study, tempered martensitic boron steels with different Al and Ti contents were systematically investigated. Thermodynamic calculations together with SEM, EBSD, TEM, and Nano-SIMS analysis were employed to characterize the precipitation behavior and microstructure and to track how nitrogen and boron partitioned among these phases, whereas Vickers hardness and Charpy impact tests were conducted to

evaluate the corresponding mechanical properties. Thermodynamic calculations predicted that Ti(C,N) preferentially precipitated prior to BN formation, whereas increasing the Al content promoted AlN and boride formation. Consistent with the thermodynamic predictions, SEM and TEM analyses confirmed the formation of coarse $\text{Ti(C,N)/(Ti,Nb)(C,N)}$ precipitates together with fine Ti(C,N) , AlN, and NbC precipitates. Although all steels exhibited similar martensitic microstructures, prior austenite grain sizes, and hardness, the effect of Ti addition on impact toughness depended strongly on the Al content. In the Low Al steels, Ti addition improved impact toughness by suppressing BN formation, thereby increasing the amount of solute boron available for grain boundary segregation. In contrast, the High Al steels already exhibited sufficient nitrogen fixation by Al, and additional Ti promoted boride formation, which reduced the amount of grain boundary segregated boron and consequently deteriorated the impact toughness. These findings demonstrate that the interaction between Al and Ti governs how nitrogen and boron partition through precipitation behavior rather than changes in the martensitic microstructure, thereby determining the impact toughness of boron steels and providing guidelines for optimizing alloy design.

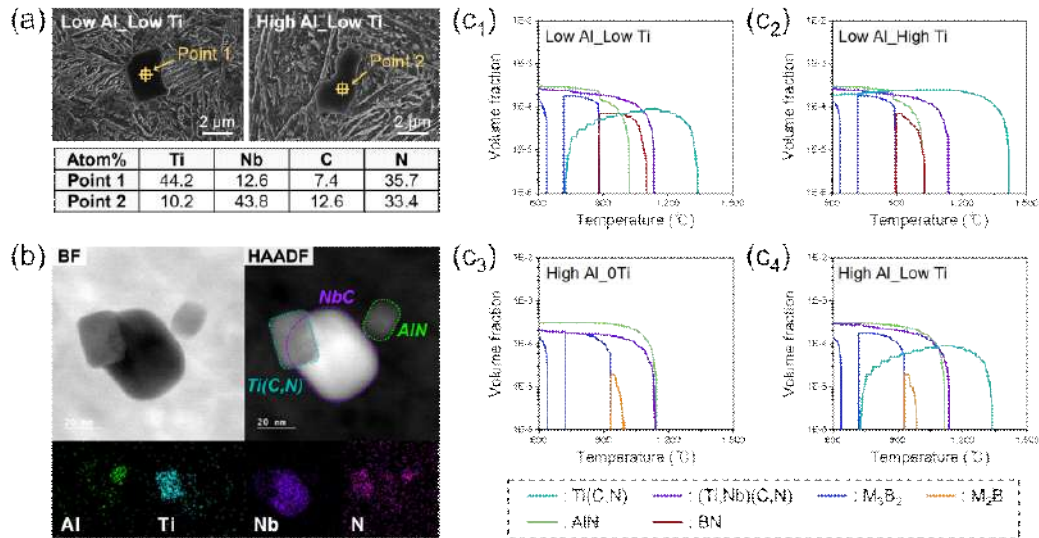


Fig. 1 (a) SEM images and EDS point analysis of coarse M(C,N) precipitates. (b) STEM image and EDS elemental maps of a complex precipitate consisting of Ti(C,N), AlN, and NbC in the High Al_Low Ti steel. (c) Equilibrium phase fraction calculations showing the precipitation behavior of Ti(C,N), (Ti,Nb)(C,N), AlN, BN, M₃B₂, and M₂B.

미세조직 균일화를 통한 2.0 GPa급 초고강도 핫스탬핑 강의 수소취성 저항성 향상 연구

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Enhanced Hydrogen Embrittlement Resistance and Bendability of 2.0 GPa
Ultra-High-Strength Hot Stamping Steel via Mn-Band Suppression and
Microstructural Homogenization

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ABSTRACT

To meet the demanding requirements for automotive lightweighting and enhanced structural crash safety, a novel 2.0 GPa-grade ultra-high-strength hot stamping steel was successfully developed through the combined suppression of Mn banding, reduction of Mn alloy content, and precise Nb - Mo microalloying.

By controlling the hot-rolling coiling temperature (CT) below the pearlite-formation regime, Mn segregation was effectively minimized, leading to an extremely homogeneous martensitic microstructure after hot stamping. Grain refinement achieved through this process reduced the concentration of reversible hydrogen at microstructural traps and hindered hydrogen accumulation. This significantly suppressed embrittlement at prior austenite grain boundaries (PAGBs), markedly mitigating overall hydrogen embrittlement (HE) susceptibility.

Mechanical property evaluations revealed that the low-CT processing route improved V-bending performance—a key metric for anti-intrusion crash performance—by 31%. Fractographic analysis confirmed a fundamental shift in the failure mechanism from premature brittle intergranular fracture to a energy-absorbing ductile fracture mode. Step-load test evaluations further corroborated the enhanced HE resistance, with the low-CT material significantly outperforming conventional 1.5 GPa hot stamping steels.

Notably, additional performance gains in hydrogen resistance and toughness were realized following simulated paint-bake tempering, attributed to favorable micro-carbide precipitation dynamics during the thermal cycle.

To elucidate the fundamental mechanisms governing these improvements, the nanoindentation indentation size effect (ISE) was systematically evaluated. The ISE analysis established critical correlations between localized microstructural homogenization, carbide precipitation dynamics, and the intrinsic plastic deformation response of the martensitic matrix during severe bending and impact deformation. Overall, these findings demonstrate that achieving extreme microstructural uniformity through targeted process optimization is paramount to securing both superior mechanical crashworthiness and environmental reliability in next-generation ultra-high-strength automotive steels.

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제 3 발표회장

- Session 1
- Session 2

용접금속 조성 변화에 따른 1.5 GPa급 자동차용 초고강도 마르텐사이트강의 용접부 미세조직, 기계적 성질 및 수소취성 저항성 변화에 대한 연구

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Effects of weld metal composition on the microstructure, mechanical properties, and hydrogen embrittlement in GMA welds of 1.5 GPa grade martensitic steel for automobile

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ABSTRACT

Since the materials experience an extreme thermal cycle during welding process, the welds have microstructures and properties completely different from the base metal. Therefore, research on the characteristics of welded joints is essential to ensure the integrity of structures. Recently, the use of advanced high-strength steels (AHSSs) in automobile has continuously increased to reduce weight of vehicle and improve passenger safety. Due to the addition of high amounts of alloying elements, the welds of AHSSs generally exhibit inferior properties compared to the base metal.

In this study, the effects of weld metal composition on the microstructure, mechanical properties, and hydrogen embrittlement in the welds of 1.5 GPa grade

martensitic steel were investigated. For this purpose, we prepared gas metal arc (GMA) welds of martensitic steel containing different Ni, Nb, and Ti contents. The weld microstructures were characterized by scanning electron microscopy (SEM), electron backscattered diffraction (EBSD), transmission electron microscopy (TEM), and atom probe tomography (APT) analyses. The mechanical properties of the welds were evaluated by micro-tensile tests. Conventional high Ni weld exhibited a higher fraction of martensite with a lower fraction of retained austenite due to its high hardenability, resulting in the highest strength but the lowest ductility. Nb addition instead of Ni made the weld microstructure finer and increased the fraction of retained austenite, achieving the best combination of strength and ductility. A sole addition of Ti without increasing Nb content in the weld increased grain size by promoting the formation of acicular ferrite at high temperature, finally decreasing the strength and ductility. Finally, the resistance to hydrogen embrittlement was evaluated by in-situ slow strain rate tests (in-situ SSRT), and the results showed that Nb addition enhanced the resistance to hydrogen embrittlement by the precipitation of nano-sized MX particles and the grain refinement.

핵융합로 구조용 저방사강 용접부 미세조직 및 기계적 성질에 미치는 Zr 첨가 효과에 대한 연구

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Effects of Zr addition on the microstructure and mechanical properties in the welds of
advanced reduced activation alloy for fusion reactor

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ABSTRACT

최근 탄소 배출에 따른 기후변화 위기 및 자원고갈에 따른 에너지 수급 문제를 해결하기 위해 다양한 대체 에너지원 개발에 관한 연구들이 진행되고 있다. 핵융합 에너지는 바닷물로부터 추출한 중수소를 연료로 사용하므로 자원고갈의 위험이 없으며, 탄소 배출이 없는 친환경 에너지원으로 알려져 있다. 또한, 핵융합 발전은 원자력 발전과 대비하여 높은 에너지를 얻을 수 있으며, 방사능 누출 및 폭발의 위험이 없어 미래 에너지원으로서 많은 연구가 진행되고 있다.

핵융합로 블랑켓은 초고온 플라즈마를 감싸고 있는 핵심부품으로서 핵융합 반응 시 발생하는 중성자의 운동에너지를 열에너지로 변환시키며, 고속의 중성자와 방사선으로부터 진공용기 및 초전도 자석을 보호하는 역할을 한다. 이에 따라 핵융합로 블랑켓 소재는 우수한 고온 기계적 성질 및 중성자 조사 취화에 대한 높은 저항성이 필요하다. 저방사강(Reduced Activation Ferritic/Martensitic steel, RAFM steel)은 우수한 고온 기계적 성질 및 중성자 조사 취화 저항성뿐만 아니라 대량 생산성 및 우수한 용접성 등으로 인해 가

장 유력한 블랭킷 구조용 후보 소재로 개발이 진행되고 있다.

본 연구에서는 Zr 첨가형 저방사강인 ARAA (Advanced Reduced Activation Alloy)의 용접부 미세조직을 분석하고 상온 및 고온 기계적 성질을 평가하였으며, 이에 대한 Zr 첨가 효과에 관해 연구하였다. 이를 위해 Zr 함량이 다른 ARAA 판재를 준비하였으며, 각각에 대해 TIG (Tungsten Inert Gas) 용접을 실시하였다. 한편, TIG 용접 시 용접재료는 각각의 판재와 동일한 조성을 가지는 합금을 사용하였다. 모재 및 용접부 미세조직은 SEM, EBSD, TEM, APT 분석을 통해 확인하였으며, 상온 및 고온에서의 기계적 성질은 비커스 경도, 인장시험, 피로시험, 크리프 시험을 통해 평가하였다. 미세조직 분석 결과, Zr 첨가는 미세 MX particle 생성 및 Zr-rich cluster 형성을 촉진하는 것으로 확인되었으며, 이에 따라 모재 및 용접부의 상온 및 기계적 성질 향상에 기여하였다.

레이저 빔 와블링 공정을 통한 알루미늄-구리 이종 접합부의 기계적 특성 향상 연구

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Enhanced fatigue properties of Al-Cu dissimilar lap joints via laser beam wobbling

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ABSTRACT

When manufacturing battery packs for Electrical Vehicles (EVs), dissimilar joints between aluminum tab and copper tab are essential to connect each Li-ion cells. Laser welding is one of the effective processes for battery pack manufacturing due to the high accuracy and high speed of process. However, when laser welding aluminum and copper, the formation of brittle intermetallic compounds (IMCs), such as θ , η and γ , significantly degrades the mechanical properties of the joints. As these joints undergo continuous cyclic stresses during driving, improving fatigue properties are required for the long-term reliability of EVs.

In this research, we investigated the effect of laser beam wobbling on the microstructure and the mechanical properties of dissimilar welds. Laser wobble welding was performed with different wobbling amplitude (a , $a=0, 0.1, 0.4$ and 0.5 mm) and the specimens were named $a0$, $a1$, $a0.4$ and $a5$ after their amplitude. The microstructure and the distribution of IMCs were observed with scanning electron microscope (SEM) coupled with energy dispersive X-ray spectroscopy (EDS). The distribution of Cu atoms was characterized with electron probe micro analyzer (EPMA). To analyze the fatigue properties, load controlled tension-tension fatigue tests were performed with a frequency of 10 HZ and a stress ratio of $R=0.1$.

The microstructure analysis revealed that increasing the wobbling amplitude

effectively suppressed the formation of IMCs. In the a0 and a1, a thick layer of IMCs, composed of Θ , η and γ , formed at the center of the welds. However, increasing the wobbling amplitude significantly suppressed the upward flow of the molten copper, which resulted in reduced formation of IMCs in aluminum fusion zone. Also, the Cu rich IMCs were formed at Cu fusion line.

The fatigue life and strength of the welds were evaluated via S-N curves, which indicated that increasing the wobbling amplitude led to a substantial improvement in fatigue performance. a0 showed shorter fatigue life due to the Cu rich IMCs in Al fusion zone. However, as the formation of IMCs was reduced in a4, the welds fractured at Cu base metal which resulted in longer fatigue life. In a0, the fracture site shifted from Al fusion zone to Cu fusion zone as the fatigue load decreased. In contrast, in a4, the sample fractured at Cu base metal regardless of fatigue load. (figure 2)

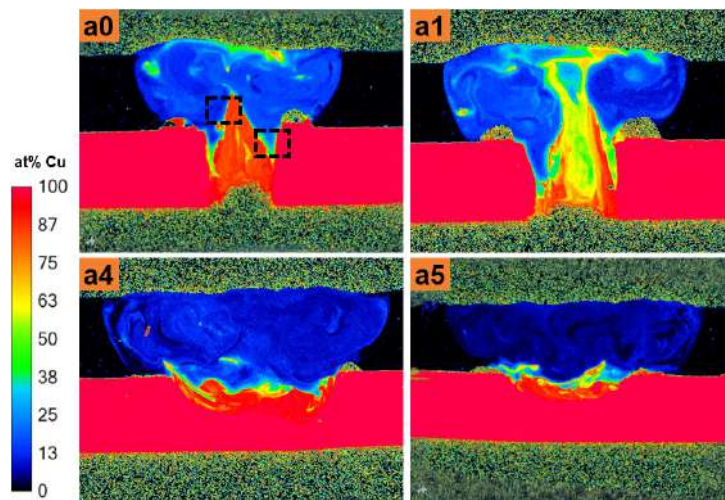


figure 1. Electron Probe Micro-Analyzer results of the Al-Cu dissimilar laser welds

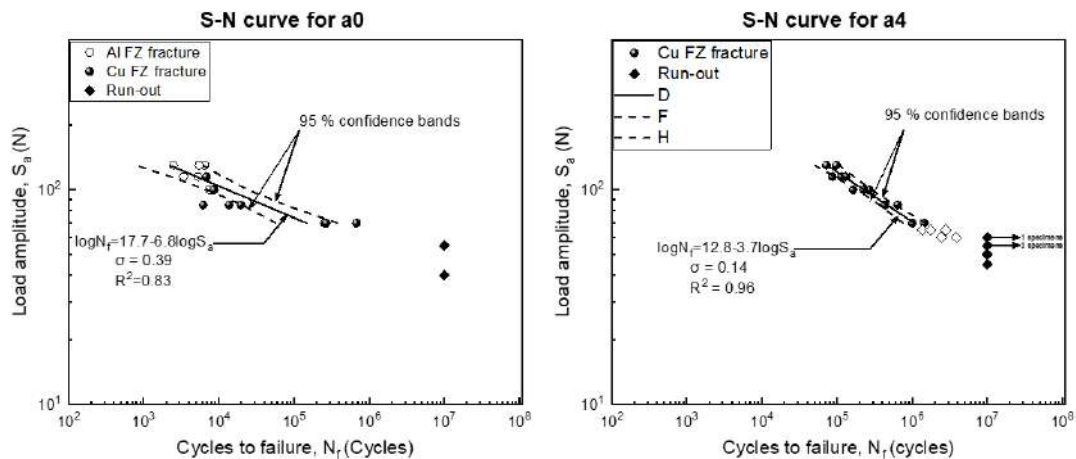


figure 2. S-N curves for the Al-Cu laser lap joints

기가급 강재의 용접부 물성 예측과 용접 솔루션

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Prediction of Weld Properties and Welding Solutions for Giga-Grade Steels

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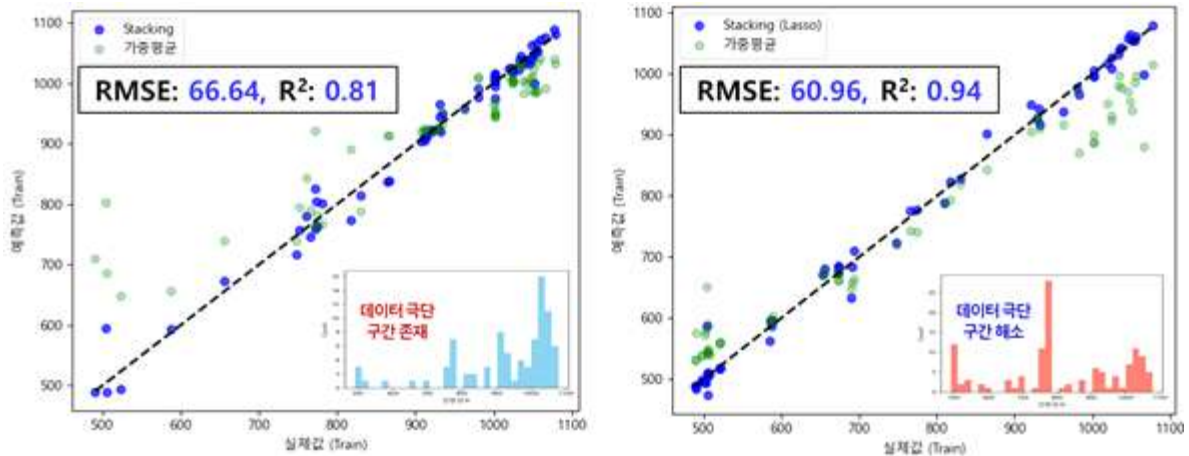
Solution Research Institute, Technical Research Laboratory, POSCO

ABSTRACT

최근 전기자동차 시장의 성장에 따라 배터리 탑재로 인한 차체 하중 증가에 대응하고자, 고내구성 및 고강성을 동시에 만족하는 초고강도 철강 부품의 적용에 대한 산업적 니즈가 지속적으로 증가하고 있다. 그러나 소재의 강도가 기가급 이상으로 초고강도화됨에 따라 용접부의 취화(Embrittlement) 위험이 대두될 뿐만 아니라, GMA(Gas Metal Arc) 용접 과정에서 발생하는 열영향부(Heat Affected Zone, HAZ)의 급격한 미세조직 변화 및 연화(Softening) 현상으로 인해 차체 구조 신뢰성을 확보하는 데 기술적 한계가 존재한다. 특히 용접부의 기계적 특성은 용접 전류, 전압, 속도 및 입열량 등 다수의 공정 변수와 소재 변수가 비선형적 상호작용을 일으키므로, 기존의 실험적 접근(Trial & Error)만으로는 정밀한 물성 예측과 최적 공정 조건 도출에 한계가 존재한다. 이에 따라 공정 데이터 기반의 인공지능(Artificial Intelligence, AI) 예측 기술을 활용하여 용접 품질을 정량적으로 제어하고 공정을 최적화할 수 있는 기술 개발의 필요성이 강조되고 있다.

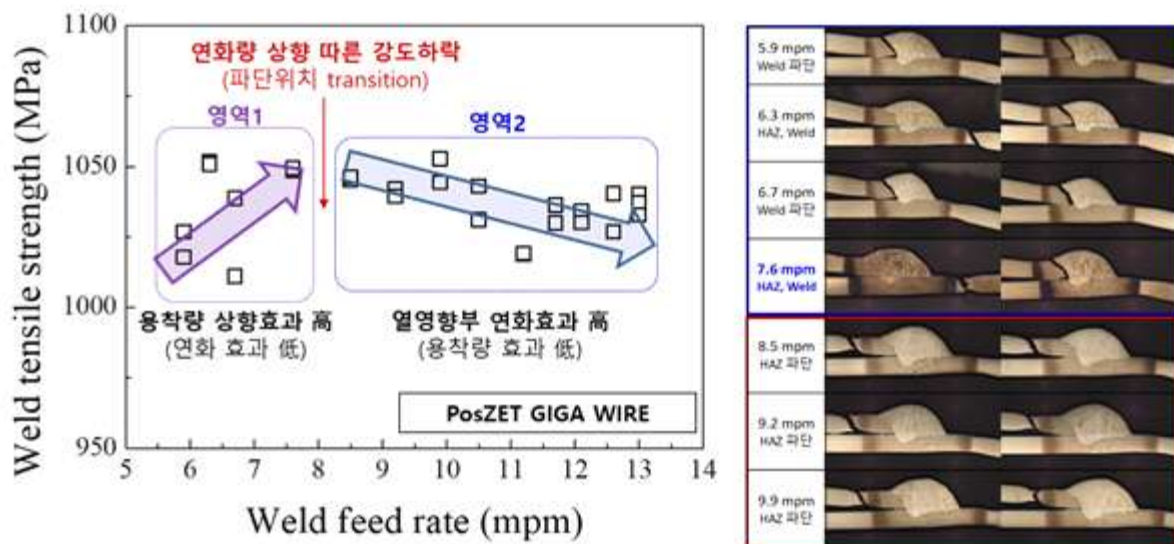
본 연구에서는 용접 전류, 전압, 속도 등 다차원 공정 변수와 용접부의 기계적 물성 간에 존재하는 복잡한 비선형적 상호작용을 정밀하게 모사하고 예측 정확도를 극대화하기 위한 AI 기반 물성 회귀예측 모델을 구축하였다. 용접 실험의 물리적 제약으로 인해 발생하는 소량의 극단 공정 조건 데이터 및 클래스 불균형 문제는 AI 모델의 예측 편향을 초래하는 주요 원인이 된다. 이러한 한계를 극복하고자 본 연구에서는 오버샘플링 기반의 데이터 증강(Data Augmentation) 기법을 도입하여 희소 영역 내 데이터의 분포 정합성을 체계적으로 확보하였다. 이를 통해 학습 데이터의 편향을 최소화하고 모델의 과적합(Overfitting)을 효과적으로 방지함과 동시에, 미학습 공정 영역에 대한 예측 정확도와 일반화 성능(Generalization capability)을 유의미하게 향상시켰다.

예측 모델과 연계하여 120~130S급 PosZET GIGA 기술 기반의 최적 용접 공정 솔루션을 도출하였다. 특히 입열량 제어에 특화된 CMT(Cold Metal Transfer) 모드를 적용하여 마르텐사이트 기지를 갖는 기가급 강재의 열영향부 연화를 효과적으로 억제하였으며, 이를 통해 기존 70S급 와이어 적용 조건 대비 최대 39.4%의 인장강도 향상 효과를 검증하였다.



[데이터 증강 적용 전(左)/후(右)에 따른, 데이터 분포 및 용접부 물성예측 결과]

나아가 PMC(Pulse Multi Control) 모드 기반의 고속 용접 기법을 도입하여 열이력 및 냉각속도를 제어함으로써, 기존 저속의 CMT 조건 대비 최소 7.8% 이상의 추가적인 인장강도 증가를 달성하였다. 이를 통해 접합부의 우수한 기계적 성능 확보와 동시에 공정 생산성을 제고할 수 있는 최적의 공정 윈도우(Process window)를 도출하였다.



[와이어 송급량에 따른 GMA 용접부 물성 및 파단 거동]

본 연구는 기가급 초고강도 마르텐사이트강의 GMA 용접부 물성을 정밀 모사하는 데이터 기반 AI 예측 모델과 PosZET 기술 기반 용접솔루션을 개발하고 그 유효성을 정량적으로 검증하였다. 이러한 연구 성과는 전기차 시장 확대에 발맞추어 차체 경량화와 충

돌 안전성을 동시에 달성할 수 있는 핵심 기술 체계를 구축함과 동시에 더 나아가 소재 개발부터 용접 공정 최적화, 품질 검증에 이르는 데이터 기반의 통합 솔루션을 제공함으로써, 차세대 친환경 모빌리티 산업의 기술 경쟁력 확보에 기여할 것으로 기대된다.

이종금속소재의 미세조직 연계 물성 및 접합강도에 미치는 공정변수 영향 연구

이광석

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Study on the Effect of Process Parameters on the Microstructure-correlated
Mechanical Properties and Bonding Strength of Dissimilar Metallic Materials

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ABSTRACT

이종 금속 소재(dissimilar metallic materials). 즉 클래드 금속(clad metal)은 상호 배타적인 다기능적 특성을 동시에 발휘하도록 설계된 금속 소재의 대표적인 예로, 해당 금속을 요구하는 수요산업의 특정 요구 사항을 충족하기 위해 다양한 금속(모재 및 클래딩재) 조합에 대한 연구 및 산업 적용이 진행되고 있다. 이러한 클래드 금속을 제조할 때, 공정의 편의성, 생산성, 그리고 소재 접합의 용이성 등 경제적 이점 덕분에 롤 본딩(roll bonding) 방식이 가장 널리 적용된다. 이종금속 사용자가 요구하는 핵심 특성은 이종 금속 자체의 물성, 성형성과 더불어 계면 접합 강도인데, 이는 롤 본딩 공정 조건에 따른 모재 및 계면의 미세조직 변화와 필수불가결한 관계가 있다. 이러한 맥락에서, 한국재료연구원 재료공정연구본부에서 필자가 그간 수행해 왔던 다양한 조합의 이종금속 판재의 제조공정 및 후공정변수에 따른 미세조직 변화와 그에 따른 기계적 특성에 미치는 롤 본딩 및 어닐링(annealing) 조건의 영향을 소개하고자 한다.

계층적 표면구조 형성과 분자 계면결합을 이용한 Cu - Zn 합금/고분자 복합재의 직접접합 연구

신다슬

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Direct Joining of Cu - Zn Alloy/Polymer Composites through Hierarchical Surface
Structuring and Molecular Interfacial Bonding

Da Seul SHIN

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ABSTRACT

금속 - 고분자 하이브리드 구조체는 금속의 높은 기계적 강도와 전기·열전도성, 고분자의 경량성, 내식성 및 형상 설계 자유도를 동시에 활용할 수 있어 전기·전자부품, 전기자동차 및 경량 구조부품 분야에서 적용이 확대되고 있다. 그러나 구리계 합금과 비극성 폴리프로필렌은 표면에너지와 화학적 반응성이 크게 다르므로 안정적인 계면접합을 형성하기 어렵다. 본 연구에서는 UNS C26800 Cu - Zn 합금과 유리섬유 강화 폴리프로필렌(PP-GF30)의 고강도 사출성형 직접접합을 위하여, 계층적 표면구조 형성과 트리아진 기반 분자 계면결합을 결합한 표면처리 기술을 개발하였다. Cu - Zn 합금 표면에 전처리, 에칭, 화학산화 및 양극산화를 순차적으로 적용하여 CuO_x/ZnO 기반의 마이크로·나노 다공성 구조를 형성하였으며, 이후 트리아진계 화합물을 이용하여 금속과 고분자 사이의 화학적 연결이 가능한 유·무기 복합 계면층을 도입하였다. 양극산화 전압이 증가함에 따라 표면의 기공률과 거칠기가 증가하였으며, 용융 PP-GF30의 기공 침투에 의한 기계적 맞물림 효과가 향상되었다. 또한 XPS 분석을 통해 Cu - S 및 Zn - S 결합과 Si - O - Cu/Zn 결합에 기반한 트리아진·실란계 계면층의 형성을 확인하였다. 최적화된 25 V 양극산화 조건에서 평균 인장전단 접합강도 28.3 MPa와 최대 29.4 MPa를 나타냈으며, 파단면에서는 금속 - 고분자 계면의 단순 박리가 아닌 PP-GF30 잔류와 계면층 파괴가 복합적으로 발생하였다. 이러한 결과는 계층적 다공성 구조에 의한 기계적 맞물림과 트리아진 매개 화학적 계면결합의 상승효과가 Cu - Zn 합금/고분자 복합재의 접합강도 향상에 효과적임을 보여준다. 본 기술은 별도의 접착제를 사용하지 않으면서 사출성형 공정과 연계할 수 있어 전기·전자 및 전동화 부품용 금속 - 고분자 하이브리드 구조체 제조에 활용될 수 있을 것으로 기대된다.

XM-19 전자빔 용접소재의 1 dpa 양성자 조사에 따른 용접 조직 별 경화 거동

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Zone-dependent hardening behavior of electron beam welded XM-19 after 1 dpa
proton irradiation

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ABSTRACT

XM-19 austenitic stainless steel combines high strength and high-temperature corrosion resistance with good post-irradiation ductility and radiation resistance, making it attractive for small modular reactor (SMR) structures. Electron beam welding (EBW), widely used for thick reactor internals, imposes a steep weld thermal history that produces microstructural heterogeneity across the joint and may alter the local irradiation response. In this study, an EBW XM-19 joint was irradiated with 2.0 MeV protons at 360 °C as an accelerated emulation of reactor-relevant damage, and the zone-dependent irradiation hardening of the fusion zone (FZ), coarse-grained HAZ (CG-HAZ), fine-grained HAZ (FG-HAZ), and base metal (BM) was quantified by depth-resolved TD nanoindentation with Nix - Gao indentation size effect (ISE) correction. Stopping and Range of Ions in Matter (SRIM) calculation, cross-sectional electron channeling contrast imaging (ECCI), and nanoindentation consistently identified a damaged layer extending to approximately 19.8 μm , and the stable nominal 1 dpa $\pm$ 0.2 (0.8 - 1.2 dpa) window at 6 - 13.5 μm was adopted as the primary comparison basis. At nominal 1 dpa, the self-referenced hardening increment was

1.14, 1.01, 1.00, and 0.72 GPa for BM, FZ, FG-HAZ, and CG-HAZ, respectively after normalization by the unirradiated hardness of each zone, CG-HAZ showed the lowest and FZ and FG-HAZ the highest irradiation-hardening sensitivity. When referenced to the unirradiated BM, the weld zones were initially softer than the base metal and hardened non-uniformly after irradiation, and the cross-weld hardness heterogeneity ($H_{\max} - H_{\min}$) widened from 0.69 to 0.98 GPa, indicating that irradiation may amplify rather than relax the weld-induced heterogeneity. These results suggest that the post-irradiation weakest zone would be a more appropriate basis for assessing EBW joints in SMR applications, and direct characterization of the underlying irradiation-induced defects would be required to clarify the governing mechanism.

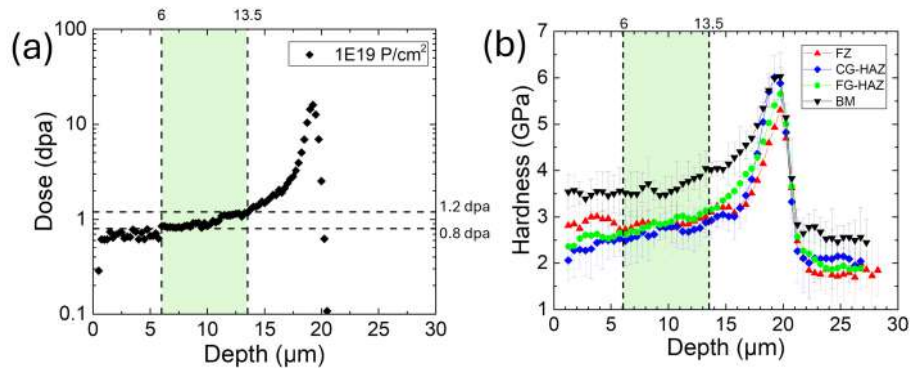


Fig. 1. Proton-irradiation damage-depth validation and selection of the nominal 1 dpa analysis window. (a) SRIM-derived depth-dpa profile with the nominal 1 dpa $\pm$ 0.2 (0.8-1.2 dpa); (b) ISE-corrected depth-resolved nanoindentation hardness profiles of FZ, CG-HAZ, FG-HAZ, and BM along the irradiation-depth direction.

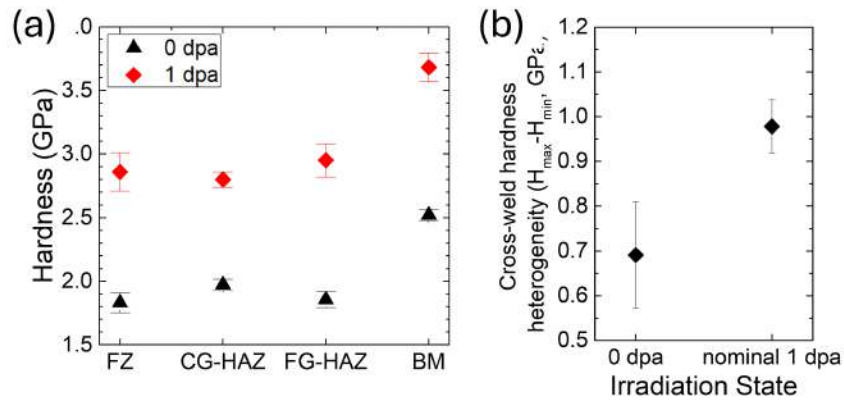


Fig. 2. Zone-dependent irradiation hardening at nominal 1 dpa measured. (a) Hardness of each zone at 0 dpa and nominal 1 dpa; (b) cross-weld hardness heterogeneity, defined as $H_{\max} - H_{\min}$ across all zones, before irradiation and at nominal 1 dpa, showing the widening from 0.69 to 0.98 GPa.

전기차 배터리 패키징을 위한 이종 금속(Cu-Steel) 및 동종 금속(Al-Al) 레이저 용접부의 결합 제어 및 용접성 향상 연구

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ABSTRACT

전기차 배터리 시스템의 고출력·고용량화에 따라 모듈 및 팩 제조 공정에서 구리-스틸(Cu-Steel) 이종 금속 및 알루미늄-알루미늄(Al-Al) 동종 금속 간 고품질 레이저 용접 기술의 중요성이 더욱 커지고 있다. 그러나 이종 금속 접합 시에는 소재 간 열물리적 성질 차이로 인한 금속간화합물(IMCs) 형성 및 균열 문제가 발생하며 알루미늄 동종 용접 시에는 높은 열전도율과 반사율로 인해 안정적인 용융부 확보 및 스파터, 표면 불량 제어가 까다롭다. 본 연구에서는 Cu-Steel 이종 접합부와 Al-Al 동종 접합부의 용접 신뢰성을 각각 높이기 위해 재료 표면 제어와 레이저 공정 제어 방식을 적용하고 그 개선 효과를 분석하였다. 첫 번째, Cu-Steel 이종 용접에서는 균열을 방지하기 위해 Cu 표면에 Ni-P 코팅을 도입하고 코팅 두께(0, 7, 25, 50 μm)에 따른 미세조직과 기계적 특성 변화를 분석하였다. 코팅이 없는 조건에서는 용융부 내부의 국소적인 구리 결손 영역 발생과 깨지기 쉬운 상 분리로 인해 심각한 균열이 관찰되었다. 그러나 Ni 코팅 두께가 증가함에 따라 Ni 성분이 충분히 녹아들어 잘 섞이지 않는 철과 구리의 성질을 완화시켰으며 IMCs 형성을 억제하고 응고 조직을 미세하게 만들어 균열 발생을 효과적으로 제어함을 확인하였다. 두 번째, Al-Al 동종 용접에서는 공정 정밀도와 용접 안정성을 극대화하기 위해 듀얼 빔 레이저(Dual beam Laser) 공정을 적용하였다. 단일 빔 용접 시 발생하는 과도한 열 손상과 표면 불량을 완화하기 위해 레이저 출력 및 빔 프로파일을 최적화하였다. 용융부 단면 형상과 면적 분석 결과 듀얼 빔을 통해 키홀의 구동 안정성을 확보하고 스파터 발생을 줄임으로써 깊이와 넓이가 안정적으로 제어된 결합 없는 건전한 알루미늄 용접부를 확보하였다. 결론적으로 본 연구는 Cu-Steel 접합에서의 재료적 접근(Ni 코팅)과 Al-Al 접합에서의 공정적 접근이 각 금속 조합의 고유한 용접 결함을 해결하고 안정성을 확보하는 핵심 공정임을 확인하였다.

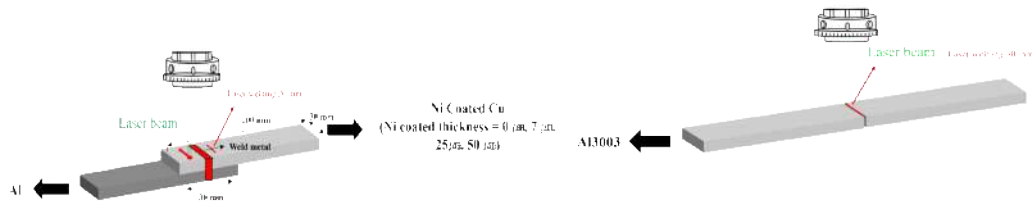
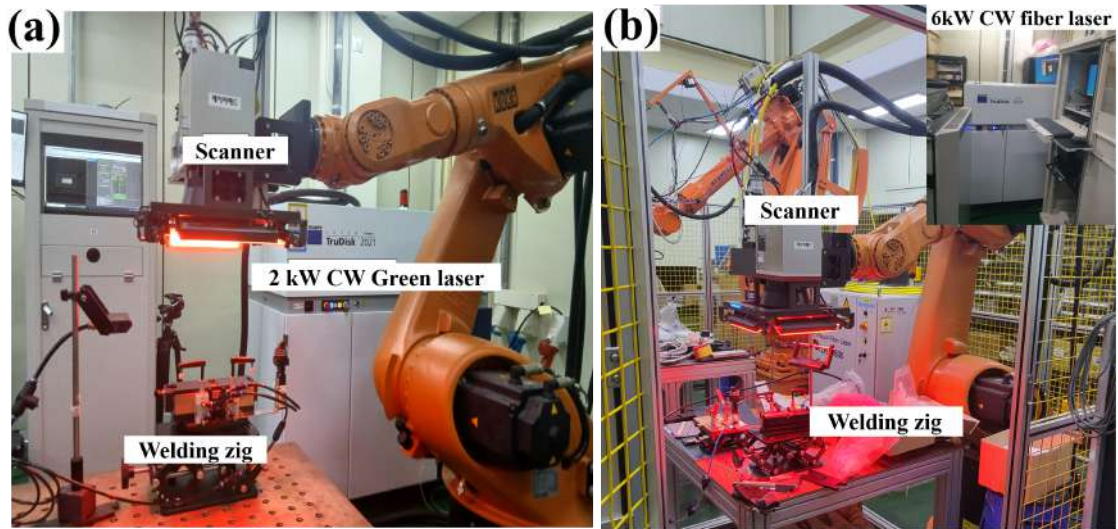


그림 1. 그림 1. 레이저 용접을 위한 실험 장치 및 개식도: (a) 2 kW CW 그린 레이저 시스템을 이용한 Cu-Al 이종 레이저 용접 실험 방법 (b) 6 kW CW파이버 레이저 시스템을 이용한 Al-Al 동종 레이저 용접 실험 방법.

keyword: Aluminum, copper, steel, laser, welding

트리아진 기반 AA8079 분자접합 처리를 통한 유리섬유 강화 폴리프로필렌과의 접합 특성에 대한 연구

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전기차용 리튬이차전지의 파우치 필름은 나일론 외층, 알루미늄 호일, 그리고 캐스트 폴리프로필렌 내층이 접착제를 매개로 적층된 다층막 구조를 가진다. 이 중 알루미늄 호일은 수분 및 가스 배리어 기능을, 폴리프로필렌 내층은 전해액에 대한 화학적 안정성과 열융착성을 담당한다. 그러나 폴리프로필렌은 비극성이며 표면 자유에너지가 낮고 C-C 및 C-H 결합의 반응성이 낮아 금속과의 직접 결합이 성립하지 않으므로, 산업계는 크로메이트 처리층과 무수말레인산 변성 접착제를 개재하는 방식에 의존한다. 접착제 층은 고온다습 환경에서 실록산 결합의 가수분해를 겪으며 시효 시간이 증가함에 따라 접합강도가 지속적으로 감소한다. 또한 접착제 층과 코팅층이 차지하는 두께는 셀 적층 밀도를 제한하고, 전해액 침투 경로로 작용하여 층간 박리와 누액의 기점이 된다. 파우치형 배터리의 대용량화가 진행됨에 따라 접착제 층을 유지한 채 표면 개질만으로 상기 문제를 해결하는 것에는 한계가 있으며, 접착제를 근본적으로 배제한 알루미늄-고분자 직접접합 기술의 확보가 요구된다. 트리아진 유도체는 금속 표면과 공유결합을 형성하는 동시에 자체 중합을 통해 고분자와의 결합 경로를 제공할 수 있어 분자접합의 매개체로 주목받고 있다. 본 연구에서는 알칼리 및 산 에칭으로 표면 Fe-Al 금속간화합물과 자연 산화층을 제거한 8079 알루미늄 박막을 트리아진 수용액 중에서 양극으로 하여 전해처리함으로써, 표면 나노기공의 형성과 수산화 표면을 경유한 트리아진 티올의 라디칼 중합을 동시에 유도한다. 이 과정에서 알루미늄 표면에 C-S-O-Al 결합으로 고정된 랜덤 공중합체 층이 형성되며, 나노기공에 의한 기계적 맞물림과 중합층에 의한 화학적 결합이 함께 작용하는 계면이 구현된다. 표면 활성화를 거친 접합체는 상용 접착 필름을 상회하는 접합강도를 나타내며 우수한 접합강도를 확인할 수 있었다. 또한, 고온-고습 시효와 저온-고온 열충격 반복 조건에서 접합강도의 유의한 저하는 나타나지 않았고, LiPF₆ 기반 카보네이트 혼합 전해액에 고온 침지한 이후에도 초기 강도가 유지되어, 접착제 층의 부재가 전해액 침투 경로를 차단한다는 설계 의도가 확인되었다. 그림 1에서 볼 수 있듯이, 투과전자현미경 관찰 결과 계면에는 알루미늄 산화층과 분자 결합층이 균열 없이 연속적으로 존재하였다.

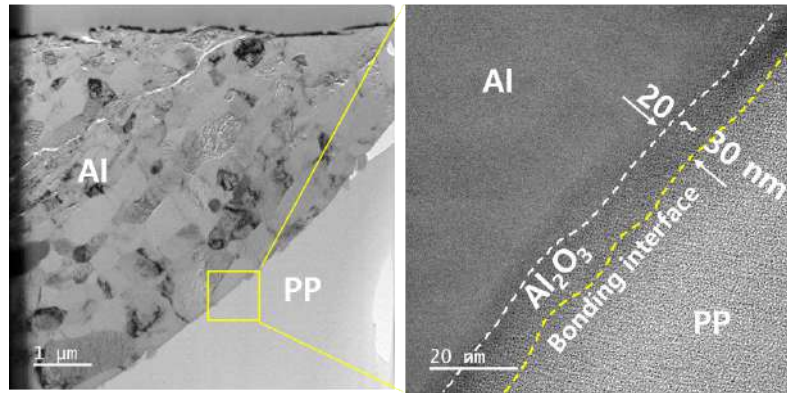


그림 1. 트리아진 기반 표면활성화 처리 후 접합된 알루미늄-폴리프로필렌 계면

접합된 시트는 롤투롤 라미네이션 공정을 거쳐 딥드로잉 성형되었으며, 성형 코너부에서 폴리프로필렌 층의 상당한 두께 손실이 발생하였음에도 불구하고 계면 박리는 관찰되지 않았다. 실험적으로 관찰된 계면 결합 거동의 원자 수준 해석을 위하여 밀도범함수이론 계산과 분자동역학 해석을 병행하여 폴리프로필렌 사슬의 전자밀도 분포와 트리아진 분자의 반응 활성점 분석을 통해 계면에서의 결합 형성 경로를 규명하였다.

CoCrFeMnNi 고엔트로피 합금의 피로균열전파 저항성 향상에 미치는 미세조직의 영향

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Effect of Microstructure on Fatigue Crack Propagation Resistance
in a CoCrFeMnNi High-Entropy Alloy

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ABSTRACT

In this study, rolling and subsequent recrystallization were employed to enhance the fatigue crack propagation resistance of a CoCrFeMnNi high-entropy alloy. The recrystallized conditions achieved substantially higher fatigue crack propagation thresholds, whereas the deformation-dominated specimens displayed a strong dependence on loading orientation. DIC measurements combined with crack-tip EBSD characterization demonstrated that recrystallization delays the onset of strain localization and facilitates more homogeneously distributed deformation ahead of the crack tip. Crack-path analysis confirmed that near-threshold resistance cannot be accounted for by apparent crack tortuosity alone; instead, it is controlled by the density of crack-boundary intersections, the local response at each interaction, and the geometry of these intersections. TEM observations further revealed that crack-tip deformation became concentrated along a crystallographically defined twin boundary, suggesting that twin boundaries serve as localized interaction sites rather than universal obstacles to crack advance. The superior resistance of the optimally recrystallized condition is therefore attributed to a favorable microstructure combining a low-dislocation-density matrix with an effective network of boundary interactions.

가설 기반 멀티 에이전트 LLM 프레임워크(AlloyAgents)를 활용한 효율적 합금 설계 방안

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Efficient Alloy Design Using AlloyAgents: A Hypothesis-Driven Multi-Agent LLM Framework

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ABSTRACT

Alloy development is fundamentally limited by physical experimentation: every candidate must be cast and characterized before its properties can be verified. Although optimization methods reduce the number of required experiments, they treat each candidate as a feature vector and leave no record of the scientific reasoning behind the search. We present AlloyAgents, a multi-agent framework built on large language models (LLMs) that makes this reasoning explicit and testable. Role-specialized agents collaborate through a shared board of mechanistic hypotheses generated by the system itself. Every hypothesis is required to be falsifiable and is paired with a machine-readable criterion for its own refutation. At each round, the highest-priority hypotheses are compiled into an acquisition policy that guides the next experiment. A deterministic scorer ranks candidate alloys using the available evidence, a fixed evidential rule—not an LLM—settles or refutes each hypothesis, and a dedicated Skeptic agent challenges every settlement before it is accepted.

We evaluated AlloyAgents on a closed oracle of several hundred cast aluminum alloys with physically measured properties, targeting two stiffness-oriented objectives: Young's modulus and specific modulus. AlloyAgents consistently identified qualifying alloys faster than a carefully tuned Bayesian optimization baseline, discovering its

first specification-satisfying alloy with its very first selection. Every selected alloy was accompanied by a property prediction committed before measurement, achieving useful predictive accuracy, while most refuted hypotheses were independently confirmed by the complete dataset. These advantages remained consistent across multiple LLM backbones. Taken together, these results demonstrate that AlloyAgents not only accelerates alloy discovery with fewer experiments, but also transforms materials optimization from a black-box search into an explicit, hypothesis-driven process of scientific discovery, in which every experimental decision is traceable, falsifiable, and reproducible.

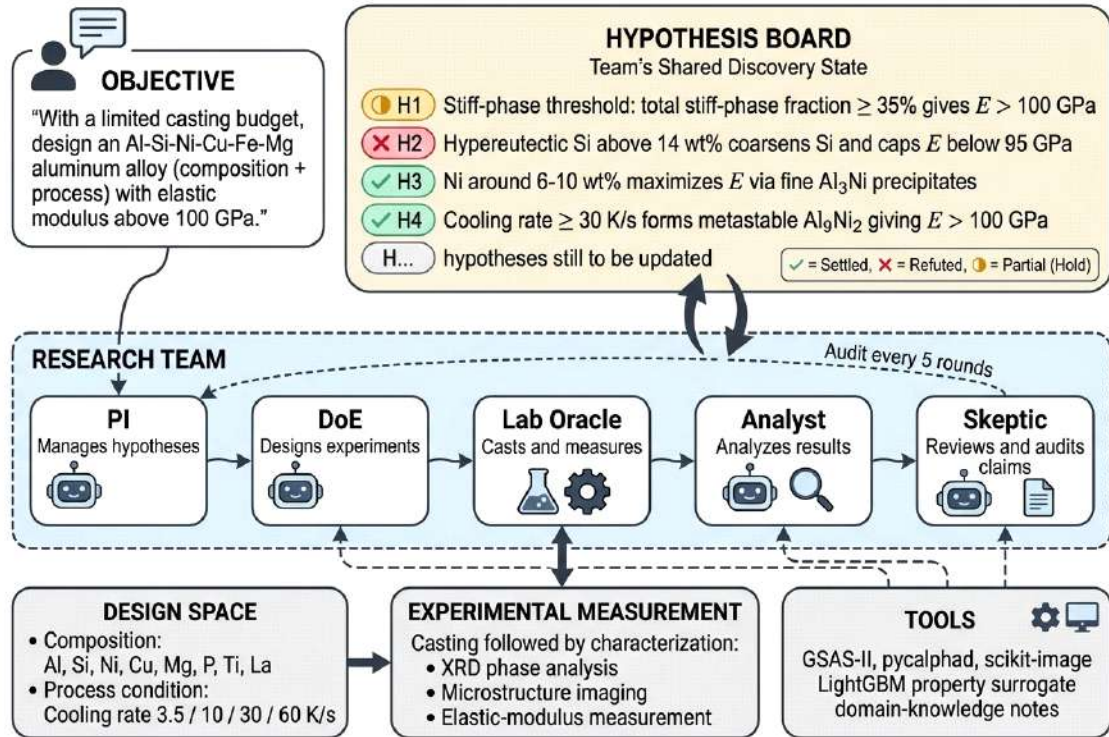


Figure 1. Overview of the AlloyAgents framework. Four LLM agents and a laboratory oracle interact through a shared hypothesis board: the PI creates and prioritizes claims, the DoE agent converts the leading claim into a predicted experimental batch, the Analyst returns measurements to the board as evidence, and the Skeptic challenges every claim that is eligible to be settled. The framework returns a portfolio of qualifying alloys together with the fully tested board.

고용강화 및 침입형 원소 제어를 이용한 Nb 기반 초고온 구조재료의 조성 설계

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Composition Design of Nb-Based Refractory Alloys through Solid-Solution
Strengthening and Interstitial Control

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Shi-Hoon Choi², and Jin-Yoo Suh^{1,*}

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ABSTRACT

Nb-based refractory alloys have attracted considerable attention as potential structural materials for extreme-temperature applications because of their high melting temperature, relatively low density, and excellent solid-solution strengthening capability. However, designing Nb alloys with both high strength and sufficient ductility remains challenging due to the combined effects of substitutional alloying elements and interstitial impurities, particularly oxygen.

In this study, Nb-rich alloys containing various alloying elements were systematically designed and experimentally evaluated to establish practical guidelines for composition optimization. Candidate alloys were fabricated by vacuum arc melting, followed by cold rolling and recrystallization heat treatment at temperature higher than 1000 °C. Heat treatments under ultra-high vacuum and mechanical pump-level vacuum were employed to control interstitial oxygen uptake while maintaining identical alloy

compositions.

Mechanical properties were characterized using Vickers hardness, tensile testing, ONH analysis, and EBSD observations. The experimental results demonstrate that atomic size mismatch is an effective parameter for selecting promising alloy compositions with a favorable balance between strength and ductility. Several newly designed alloys exhibited yield strengths exceeding those of commercial Nb-based reference alloys while maintaining comparable or superior elongation. Furthermore, controlled oxygen uptake during heat treatment produced measurable interstitial strengthening, whereas appropriate alloy design successfully suppressed excessive embrittlement.

Based on these results, several candidate Nb-based alloys with improved mechanical performance were identified. The present work demonstrates that simultaneous control of substitutional alloying and interstitial elements provides a practical strategy for developing next-generation refractory alloys for high-temperature structural applications.

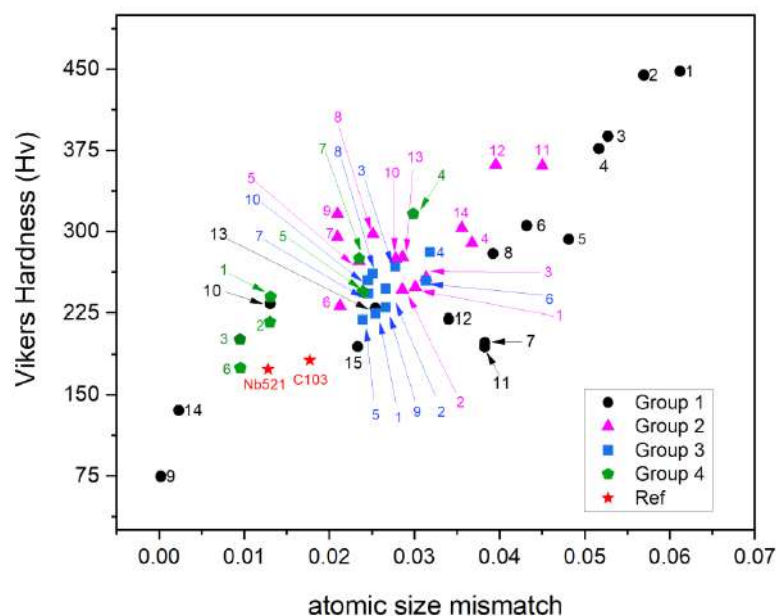


그림 1. 제조된 합금들의 atomic size mismatch parameter와 측정된 경도값

제 40 회 첨단구조재료 심포지엄
09월 04일 [금]
제 1 발표회장

- Session 3
- Session 4

비정질 CuZrTi 합금의 구조적 이질성에 따른 부식 특성 분석

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Structural heterogeneity-dependent corrosion behavior in amorphous CuZrTi thin films

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ABSTRACT

Metallic glasses have attracted considerable attention for structural applications owing to their unique combination of high strength, large elastic limit, and excellent corrosion resistance. Among them, the Cu-Zr-Ti system exhibits a high glass-forming ability and excellent electro-chemical stability owing to atomic size mismatch among its constituent elements. However, despite the absence of crystalline defects and long-range structural order, metallic glasses contain intrinsic nanoscale spatial heterogeneity arising from variations in local atomic packing density and structural stability. Such heterogeneity has been identified as a key structural feature governing the mechanical response, relaxation dynamics, and deformation behavior of metallic glasses. However, a lack of understanding remains regarding the influence of nanoscale structural heterogeneity on the corrosion behavior, including pitting corrosion in Cu-Zr-Ti metallic glasses. In this study, the structural heterogeneity of amorphous Cu-Zr-Ti thin films was quantitatively characterized using amplitude-modulation atomic force microscopy (AM-AFM). Statistical phase-angle distribution analysis and correlation function fitting were employed to evaluate characteristic parameters associated with nanoscale heterogeneity. The influence of structural heterogeneity was subsequently investigated by comparing the as-deposited

and annealed states.

몬테 카를로 시뮬레이션을 이용한 금속 박막 적층시 미세구조 변화 연구

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A Monte Carlo simulation for the microstructural evolution of the thin metallic film
during deposition

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ABSTRACT

The evolution of the microstructure during the deposition of the metallic thin film is predicted using a Monte Carlo Potts model. This model incorporates two primary dynamic mechanisms for microstructural evolution: 1) spin exchange, which mimics the mutual diffusion between matter and void, and 2) spin flip, which simulates the grain growth. The detailed explanation on the proposed Potts model, including the realization of the deposition process, is presented. Using the model, one can make reliable predictions on the microstructural evolution during a thin film deposition as a function of process parameters. The key processing parameters we focus on here are the deposition rate of the monomers on the substrate, the temperature of the system, and the kinetic energy of the monomers on being deposited. The influence of processing parameters on microstructural evolution is summarized as follows: 1) the increase in deposition rate leads to the reduction in grain size; 2) as the substrate temperature is elevated, the average grain size increases; 3) the higher kinetic energy the monomer has on deposition, the more columnar the grain morphology becomes.

The resultant microstructural characteristics obtained from the proposed model are found to be analogous to those predicted by the structure zone model. It is also found that thin film microstructure is formed through the competition between deposition and diffusion, allowing for understanding thin film microstructural evolution and growth kinetics.

반도체용 차세대 Ru 배선의 기계적 신뢰성

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Mechanical Reliability of Next-Generation Ru Interconnects for Semiconductor Applications

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ABSTRACT

Sustaining performance improvements in semiconductor systems increasingly requires innovations in interconnect materials. As Cu linewidths approach the electron mean free path, enhanced surface and grain-boundary scattering causes a pronounced increase in resistivity. The resulting resistance crossover at sub-20-nm pitches has motivated the adoption of alternative metals with more favorable nanoscale transport characteristics, among which Ru is considered a leading candidate.

While the reliability of conventional Al and Cu interconnects has been discussed primarily in terms of current- and temperature-driven atomic transport, the introduction of nanoscale Ru interconnects raises additional concerns related to stress evolution and interfacial fracture. The high elastic modulus of Ru can strongly influence the mechanical driving force for interfacial failure. Conventional adhesion characterization methods provide quantitative measurements of interfacial fracture resistance but cannot fully represent failure in nanoscale patterned interconnects, where linewidth, thickness, confinement, and processing history affect the local stress state.

This study discusses the mechanical reliability of Ru metallization, with particular

emphasis on the relationships among interconnect geometry, size-dependent Ru behavior, stress evolution, and interfacial fracture. The results highlight the need for a mechanics-based framework that connects thin-film-scale adhesion measurements with failure behavior in future nanoscale Ru interconnect structures.

단결정 ZnO 마이크로필러의 결정방위 의존적 전자빔 유도 소성

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Orientation-Dependent Electron-Beam-Induced Plasticity in Single-Crystalline ZnO Micropillars

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ABSTRACT

Ceramic materials generally exhibit limited plastic deformation at room temperature because of their strong ionic and covalent bonding and the high resistance to defect motion. Recent in-situ electron microscopy studies have shown that electron-beam irradiation can modify the mechanical response of oxide ceramics without significant thermal effects or permanent irradiation damage. While such effects have been reported in silica-based oxides through mechanisms such as viscoplastic deformation and mechanically assisted amorphization, it remains important to clarify how electron-beam irradiation influences dislocation-mediated plasticity in crystalline oxides.

In this study, we investigate the electron-beam effect on room-temperature plastic deformation in single-crystalline ZnO, with particular emphasis on crystallographic orientation dependence. ZnO has a wurtzite crystal structure and exhibits highly anisotropic plasticity because the activation of basal, prismatic, and pyramidal slip systems depends strongly on loading orientation. To examine how electron-beam irradiation affects slip activation, ZnO micropillars with different crystallographic orientations were fabricated and compressed using an in-situ SEM picoindenter under controlled beam conditions.

This study examines the possibility that the effect of electron-beam irradiation on plastic deformation in single-crystalline ZnO may vary with crystallographic orientation. By comparing the yielding behavior, flow response, and post-deformation morphology under different loading orientations, we explore whether the degree of the electron-beam effect could be associated with the activated slip system rather than with a uniform softening mechanism.

These findings extend the concept of electron-beam-assisted ceramic plasticity to orientation-dependent dislocation activity in ZnO. They also highlight the importance of considering electron-beam-sample interactions in in-situ indentation and micropillar compression experiments, while suggesting a possible route for probing and controlling slip-system-dependent plasticity in small-scale oxide ceramics.

압입시험과 물리 기반 FE-CNN 프레임워크를 이용한 바우싱거 효과 식별

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Indentation-Based Identification of the Bauschinger Effect
Using a Physics-Guided FE - CNN Framework

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ABSTRACT

The Bauschinger effect, the reduction in yield stress upon load reversal, is conventionally characterized by the tension-compression test (TCT), which is impractical for thin sheets, weldments, or locally deformed regions. We propose a physics-guided FE-CNN framework that identifies the key kinematic hardening parameters of the Yoshida-Uemori (Y-U) model (C , R_{sat} , b) from the load-depth ($P-h$) curves and directional surface profiles of spherical indentation on pre-strained specimens. The directional asymmetry of the surface profile encodes the developed back-stress as the identification signal. Extended to all six Y-U parameters, the framework reproduced the experimental TCT for three steels (SNT355M, SUS304, and SPC980Y) with high accuracy, enabling the local assessment of the Bauschinger effect from surface indentation.

1. Introduction

Indentation offers a easy-to-perform alternative for local characterization; here we propose a physics-guided FE - CNN framework that identifies the Y - U kinematic hardening parameters from the $P - h$ curve and directional surface profiles of spherical indentation, using the directional asymmetry that encodes the pre-strain-induced back-stress as the physical basis for identification.

2. Methodology

Specimens pre-strained to 0 - 16% were indented with a 250 μm -radius tungsten carbide sphere, and the longitudinal and transverse surface profiles were measured by laser confocal microscopy. An FE indentation database (Abaqus/Explicit with a Y - U VUMAT; 1,024 sets for the three-parameter and 2,048 for the six-parameter identification) was used to train a dual-branch CNN that processes the $P - h$ curve and the directional profiles in parallel, with Gaussian noise augmentation.

3. Results & discussion

Pre-strain raised the $P - h$ curve and produced a directional asymmetry Δz that grows with the developed back-stress. A sensitivity analysis showed that the three parameters leave distinct, position-dependent fingerprints: C dominates the sub-indenter $P - h$ response, whereas (R_{sat}, b) is recorded most strongly in the asymmetry profile ($p^2 = 0.98$ at 2% pre-strain). Three-parameter identification was robust to the pre-strain combination ($R^2 \geq 0.99$). The six-parameter extension reached a mean R^2 of 0.957, and the cyclic responses of SNT355M, SUS304, and SPC980Y reconstructed from indentation agreed well with the experimental TCT curves, including the Bauschinger transient.

4. Conclusion

A physics-guided FE - CNN framework identifies the Bauschinger effect from spherical indentation. Exploiting the directional asymmetry of the surface profile together with the $P - h$ curve, it stably identifies the Y - U parameters and, validated on three steels, enables the local assessment of the Bauschinger effect without compression testing.

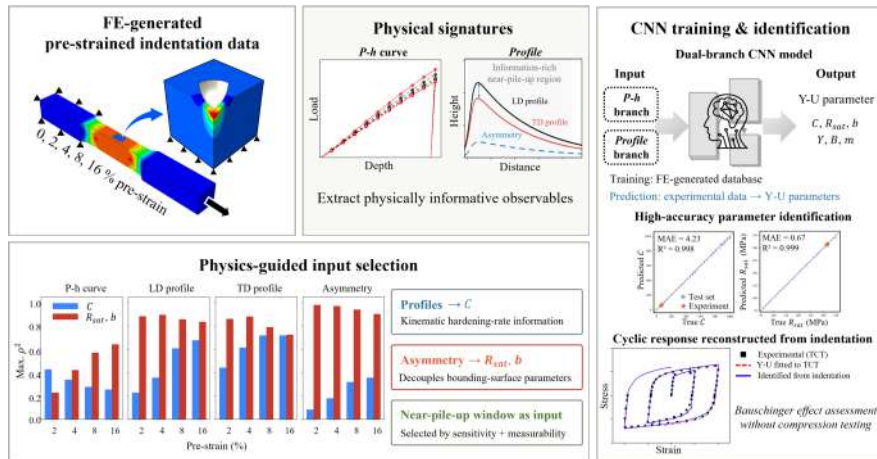


Fig. 45. Overview of the physics-guided FE - CNN framework, from FE-generated indentation responses of pre-strained specimens and physics-guided input selection to dual-branch CNN identification of the Y - U parameters reproducing the experimental cyclic response.

Acknowledgement

This study was financially supported by the Nano & Material Technology Development Program through the National Research Foundation of Korea (NRF) funded by Ministry of Science and ICT (NRF-2021M3A7C2089767(RS-2020-NR056406) and RS-2024-00445448).

Ti-6Al-4V 옥텟트러스 격자구조체의 미세조직 제어 및 압축 변형 거동 연구

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Microstructure dependent post-yield stress-drop behavior of Ti-6Al-4V Octet-truss
lattice structure

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ABSTRACT

Understanding how geometry and microstructure affect post-yield stress-drop behavior is essential for improving the compressive deformation stability of Ti-6Al-4V octet-truss lattice structures. Although octet-truss lattices are stretch-dominated structures, abrupt stress drops can occur during compression due to strut buckling and fracture. This behavior can be exacerbated in Ti-6Al-4V lattices fabricated by laser powder bed fusion (LPBF), as rapid cooling produces a brittle α' martensitic microstructure. In this study, the lattice structures were heat-treated to transform the α' martensite into a more ductile $\alpha+\beta$ microstructure, thereby improving their deformation stability. Ti-6Al-4V octet-truss lattices with

strut diameters of 0.4, 0.5, and 0.6 mm were fabricated by LPBF and subsequently heat-treated at 900 °C for 10, 30, 60, and 120 min. The as-built specimens exhibited a fine α' martensitic microstructure, whereas the heat-treated specimens exhibited a coarsened $\alpha+\beta$ microstructure with increased lath thickness and β -phase fraction. The node regions also exhibited thicker laths than the strut regions because of greater heat accumulation during the LPBF process. Compression tests revealed that all specimens exhibited post-yield stress drops. Increasing the strut diameter enhanced buckling resistance, promoted more uniform axial deformation, and improved plateau stability. Importantly, heat treatment suppressed localized collapse and mitigated abrupt stress drops, particularly in the specimens with strut diameters of 0.5 and 0.6 mm. These results demonstrate that the compressive deformation behavior of LPBF-fabricated Ti-6Al-4V octet-truss lattices is governed by the combined effects of geometry and microstructure.

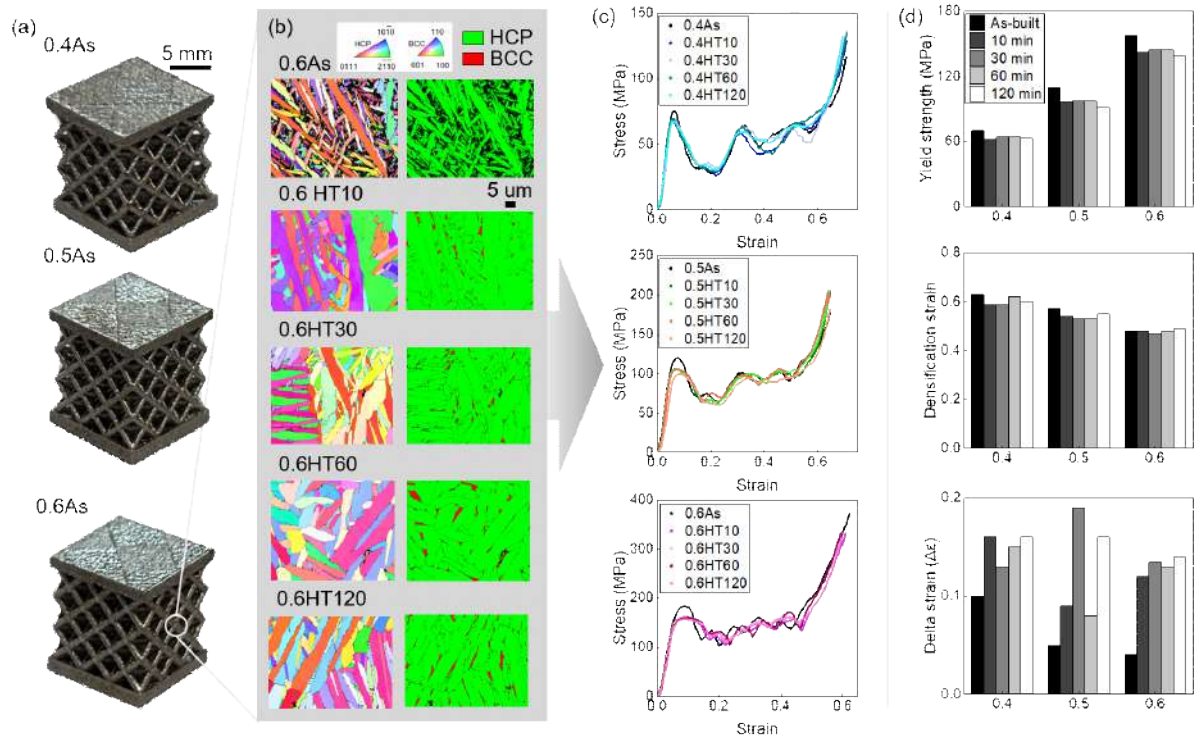


Figure 1. (a) Photographs of LPBF-fabricated Ti-6Al-4V octet-truss lattice specimens with strut diameters of 0.4, 0.5, and 0.6 mm. (b) EBSD inverse pole figure (IPF) and phase maps of the 0.6 mm specimens in the as-built condition and after heat treatment at 900 °C for 10, 30, 60, and 120 min. (c) Compressive stress - strain curves as a function of strut diameter and heat-treatment condition. (d) Yield strength, densification strain, and strain difference ($\Delta\epsilon$) extracted from the corresponding stress - strain curves.

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Defect Dynamics Modeling for Nanomechanics: Bridging Discrete Defects and
Multiscale Mechanical Response

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ABSTRACT (11 point, Bold, Center alignment)

Understanding how individual crystalline defects collectively govern the mechanical behavior of materials is a fundamental challenge in nanomechanics. This talk presents a defect dynamics modeling (DDM) framework that concurrently couples discrete dislocation dynamics with the finite element method to bridge defect-scale mechanisms and continuum mechanical response across multiple length scales. By explicitly resolving dislocation nucleation, motion, and interactions under realistic boundary conditions, the framework provides physically interpretable predictions of deformation, strengthening, and failure in crystalline materials.

Applications of the proposed framework include size-dependent plasticity in small-scale structures, precipitation strengthening, irradiation-modified deformation in oxide crystals, and defect-controlled damage evolution. These studies demonstrate how dislocation interactions with precipitates, interfaces, and evolving defect structures govern strain hardening, localization, and mechanical reliability. To further extend the applicability of large-scale simulations, physics-informed machine learning surrogate models are developed to reproduce discrete dislocation dynamics with substantially improved computational efficiency while preserving the underlying stochastic deformation characteristics.

The presented framework establishes a unified computational platform for multiscale nanomechanics by connecting atomistic mechanisms, mesoscale defect evolution, and macroscopic constitutive behavior. It provides new insights into structure - property

relationships and offers a predictive tool for designing advanced structural materials with enhanced strength, reliability, and damage tolerance.

고온 수소 환경에 노출된 순수 탄탈륨의 기계적 거동 연구

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A Study on the Mechanical Behavior of Pure Ta Exposed to Hydrogen Environments
at Elevated Temperatures

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ABSTRACT

Pure tantalum (Ta) is a refractory metal widely used in high-temperature and harsh environments owing to its excellent thermal stability and corrosion resistance. During elevated-temperature processing, however, it is susceptible to hydrogen exposure, which can alter its mechanical properties and induce hydrogen embrittlement. Pure Ta is exposed to hydrogen at 10 torr over the temperature range of 400 - 1000 °C to investigate the effects of hydrogen exposure at elevated temperatures on hydrogen uptake and mechanical response. The Vickers hardness value of the hydrogen-exposed specimens reaches a maximum at 600 °C, and thermal desorption spectroscopy (TDS) analysis confirms a correlation between temperature and hydrogen uptake. X-ray diffraction (XRD) reveals lattice expansion associated with hydrogen incorporation, while scanning Kelvin probe microscopy (SKPM) shows

a decrease in surface work function associated with hydrogen dissolution. These results suggest that the observed hardening is most consistent with predominantly interstitial hydrogen together with defect-associated retained hydrogen. Tensile testing further demonstrates that specimens exposed to hydrogen at 600 °C exhibit increased ultimate tensile strength but reduced ductility, accompanied by brittle fracture behavior, indicating the occurrence of hydrogen embrittlement. To address the challenges associated with elevated-temperature processing, friction stir spot welding (FSSW) is investigated as a solid-state joining approach. Electron backscatter diffraction (EBSD) analysis reveals that dynamic recrystallization under optimized processing conditions results in significant grain refinement and enhanced hardness in the stir zone. These findings demonstrate that FSSW is a promising solid-state joining technique for improving the structural reliability of pure Ta.

선 압축 및 어닐링을 통해 쌍정이 제거된 이중 집합조직이 AZ31 마그네슘 판재의 저주기 피로 거동에 미치는 영향

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Effect of twin-free bi-texture produced by pre-compression
and annealing on low-cycle fatigue behavior of AZ31 Mg sheet

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ABSTRACT

Rolled Mg alloys exhibit pronounced deformation anisotropy because their strong basal texture aligns the c-axes of most grains approximately parallel to the sheet normal direction (ND). Consequently, the activation of slip, {10 - 12} twinning, and detwinning varies considerably with loading direction. Under cyclic loading, such texture-dependent deformation can produce non-uniform deformation partitioning among differently oriented grain populations and reduced deformation compatibility at their interfaces. The resulting local stress and strain concentrations may promote fatigue-damage accumulation and cause specific microstructural regions to act as preferential crack-initiation sites. Therefore, clarifying the relationship among crystallographic texture, deformation-mode partitioning, cyclic stress asymmetry, and crack initiation is essential for improving the fatigue resistance of wrought Mg sheets. In this study, twin-free bi-textured AZ31 Mg sheets were fabricated to clarify the effect of crystallographic texture on low-cycle fatigue (LCF) behavior. An as-rolled (AR) sheet was precompressed along the rolling direction (RD) to plastic strains of 3% and 6% and subsequently annealed at 400 °C for 1 h, producing 3PCA and 6PCA, respectively. Precompression generated an RD-oriented texture component through {10-12} extension twinning, while annealing removed residual twin boundaries while retaining the crystallographic reorientation.

The AR sheet exhibited a strong ND basal texture, whereas 3PCA and 6PCA developed twin-free bi-textures dominated by ND- and RD-oriented components,

increasing the compressive-to-tensile yield-strength ratio from 0.47 to 0.92 and 1.54, respectively. Fatigue life increased in the order $AR < 3PCA < 6PCA$ as the half-life mean stress shifted toward compression, which suppressed crack opening in 6PCA. Furthermore, the effective energy parameter, $P_{\text{eff}} = \Delta W_p + 2.04(\sigma_m \times \varepsilon_a)$, which incorporates the mean-stress effect, provided more accurate fatigue-life predictions than the conventional total-strain-energy parameter.

직접에너지적층 인코넬 718에서 지르코니아 유도 주상정-등축정 천이의 공정 윈도우 의존성 규명

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Mechanistic origin of the process-window-dependent zirconia-enabled
columnar-to-equiaxed transition in Inconel 718 during directed energy deposition

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ABSTRACT

직접에너지적층 공정으로 제조된 인코넬 718 적층재는 고입열로 인해 조대한 주상정 결정립과 강한 집합조직이 형성되며, 이는 기계적 물성 저하 및 이방성을 유발한다. 본 연구는 200 nm, 2 wt.% 지르코니아 나노 분말 접종을 적용한 인코넬 718 적층재에서 주상정-등축정 천이 (CET)가 발생하는 기구를 실험-전산유체역학 (CFD)-응고 계면 안정성 모델을 통합하여 정량적으로 규명하였다. EBSD 분석 결과, IZ-250.1000 (250 W, 1000 mm/min) 조건에서 결정립 미세화, 등축정 분율 증가 및 텍스처 약화가 극대화 되었다. FE-SEM/FE-TEM 분석을 통해, 충분히 높은 실제 체적 에너지 밀도 조건에서 지르코니아 환원이 촉진되어 산화물이 형성되고 그 주변에 준안정상 L1₂ 구조 Al₃Zr 금속간 화합물이 형성되어 강력한 불균일 핵생성 사이트로 작용함을 확인하였다. CFD 기반 시뮬레이션을 이용하여 용융풀 대류 (외측/상향 유동) 강화에 따른 마랑고니 수 및 페클렛 수 증가, 열 구배 완화 및 응고 속도 증가를 정량화 하였고, Gäumann CET 기준에 매핑한 결과 등축정 형성 조건에서 $\frac{G^{3.4}}{V}$ 감소, 초기 핵생성 밀도 (N₀), 핵생성 밀도 (N) 및 핵생성률 (I) 증가가 동시에 나타났다. 이러한 결과는 지르코니아 나노 분말 접종에 의한 화학적 핵생성 활성화와 용융풀 내부의 열·유체역학적 제어가 결합될 때 주상정-등축정 천

이 (CET)가 극대화될 수 있음을 정량적으로 입증한 것으로, 고성능 니켈기 초합금의 미세조직 제어를 위한 새로운 야금학적 가이드라인을 제시한다.

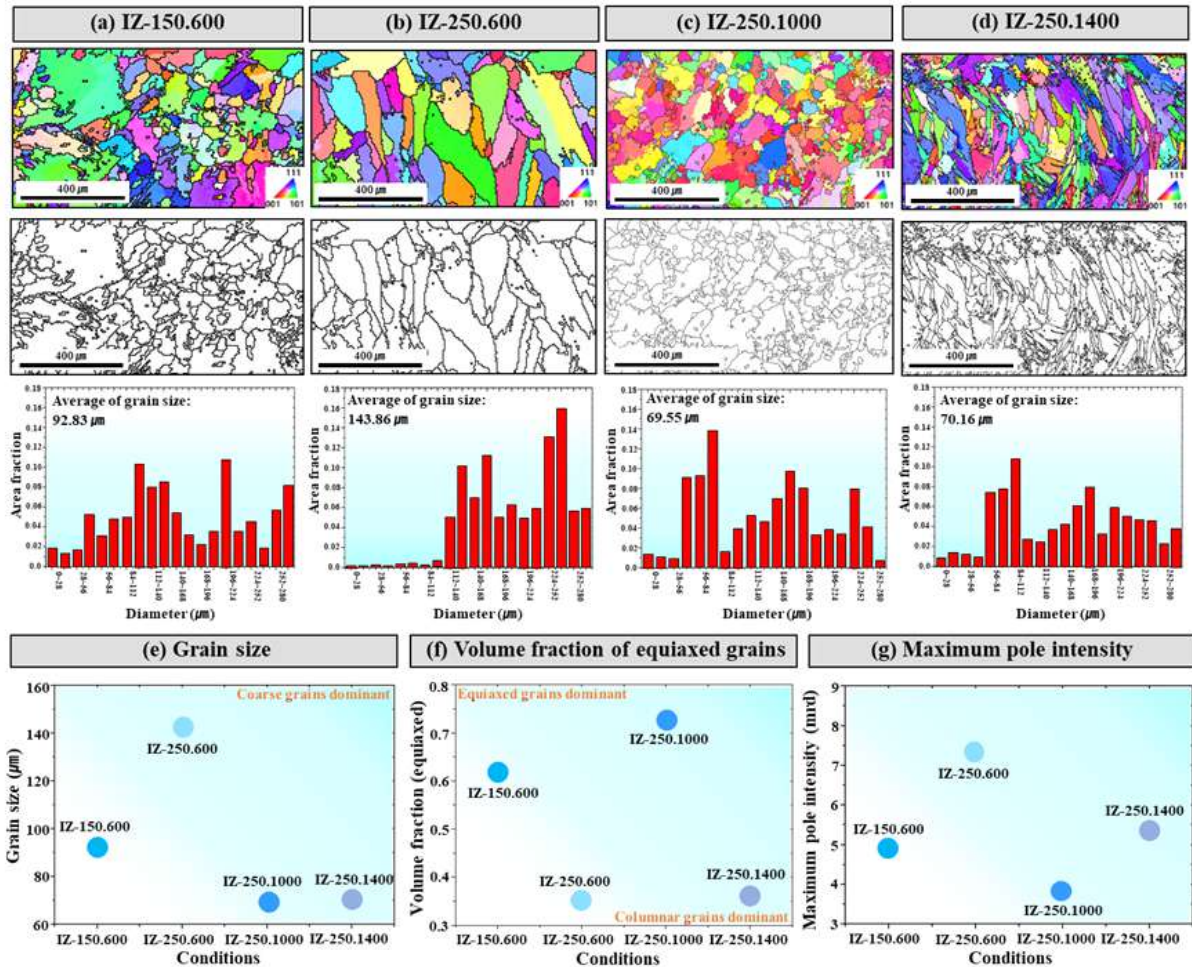


Fig. 1. Analysis of the grain properties of Inconel 718-zirconia deposits through process variables: (a) IZ-150.600, (b) IZ-250.600, (c) IZ-250.1000, (d) IZ-250.1400, (e) grain size, (f) volume fraction of equiaxed grains, and (g) maximum pole intensity. Equiaxed grains were formed under specific process variables.

제 40 회 첨단구조재료 심포지엄
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제 2 발표회장

- Session 3
- Session 4

Ti 첨가에 따른 핵융합로 구조용 저방사화강(RAFM)의 피로 및 크리프-피로 거동

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Fatigue and Creep-fatigue behavior of Ti-added Reduced Activation
Ferritic-Martensitic (RAFM) steel

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ABSTRACT

Reduced activation ferritic/martensitic (RAFM) steels are promising candidate structural materials for fusion reactors. They were developed from conventional 9Cr - 1Mo steels, which exhibit excellent high-temperature strength, creep resistance, and a low coefficient of thermal expansion. However, alloying elements such as Nb and Mo in 9Cr - 1Mo steels become highly radioactive after neutron irradiation. Therefore, these elements were replaced with low-activation elements such as W, Ta, and V to develop RAFM steels. As a result, RAFM steels retain mechanical properties

comparable to those of 9Cr - 1Mo steels while providing superior irradiation resistance. Despite these advantages, a comprehensive understanding of fatigue, creep, and creep - fatigue behavior is essential before RAFM steels can be applied as structural materials in fusion reactors. Establishing a reliable mechanical property database is also required.

In this study, the fatigue and creep - fatigue behaviors of a Ti-added RAFM steel were investigated to further improve the mechanical performance of conventional RAFM steels. To evaluate the effect of Ti addition, the Ti-added alloy was compared with Eurofer97 steel. Eurofer97 has the same base composition except for Ti and is currently considered a candidate structural material for the International Thermonuclear Experimental Reactor (ITER).

After normalizing and tempering, RAFM steels exhibit a tempered martensitic microstructure similar to that of conventional 9Cr - 1Mo steels. Tempering also produces Cr-rich $M_{23}C_6$ carbides along prior-austenite and martensite lath boundaries, together with fine intragranular MX precipitates. These precipitates strongly influence fatigue and creep - fatigue behavior. In the present study, Ti addition was expected to suppress the coarsening of $M_{23}C_6$ carbides while promoting the formation of fine MX precipitates, thereby improving the mechanical properties.

Fatigue and creep - fatigue tests were conducted at 550 °C, corresponding to the operating temperature of fusion reactor structural components. Fatigue tests were performed under total strain amplitudes of 0.4%, 0.8%, and 1.2%. Creep - fatigue tests were carried out under total strain amplitudes of 0.8% and 1.2% with a tensile dwell time of 10 min. The effects of Ti addition were analyzed through SEM, EBSD, and TEM observations, and the corresponding fatigue and creep - fatigue mechanisms are discussed.

Fe-이온 조사에 따른 RAFM 강의 수소 트래핑 및 국부 기계적 거동

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Effects of Fe-ion Irradiation on Hydrogen Trapping and Local Mechanical Behavior of
RAFM Steel

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ABSTRACT

Reduced activation ferritic - martensitic (RAFM) steel is a leading candidate structural material for fusion blanket systems operating under simultaneous high-temperature, neutron irradiation and hydrogen-isotope environments. Although irradiation-induced defects, such as vacancy cluster, void, cavity, have been widely reported to enhance hydrogen trapping, their combined influence on hydrogen trapping and the local mechanical response of the shallow irradiation layer has not yet been fully clarified. To characterize the local mechanical response of the irradiation layer, plastometry-based indentation plastometry (PIP) was employed to evaluate its stress-strain response and strain-hardening behavior. In this study, RAFM steel was subjected to Fe-ion irradiation followed by electrochemical hydrogen charging. Thermal desorption spectroscopy (TDS), PIP, and transmission electron microscopy (TEM) were used to characterize hydrogen trapping, local mechanical behavior, and irradiation-induced microstructural changes, respectively. Fe-ion irradiation increased hydrogen trapping, particularly in the high-temperature desorption region. PIP revealed irradiation hardening together with reduced strain-hardening capability after hydrogen charging. Detailed TEM observations revealed irradiation-induced matrix defects, including defect clusters, without appreciable changes in precipitate morphology, suggesting that these defects were primarily responsible for the enhanced hydrogen trapping and the associated decrease in local mechanical behavior.

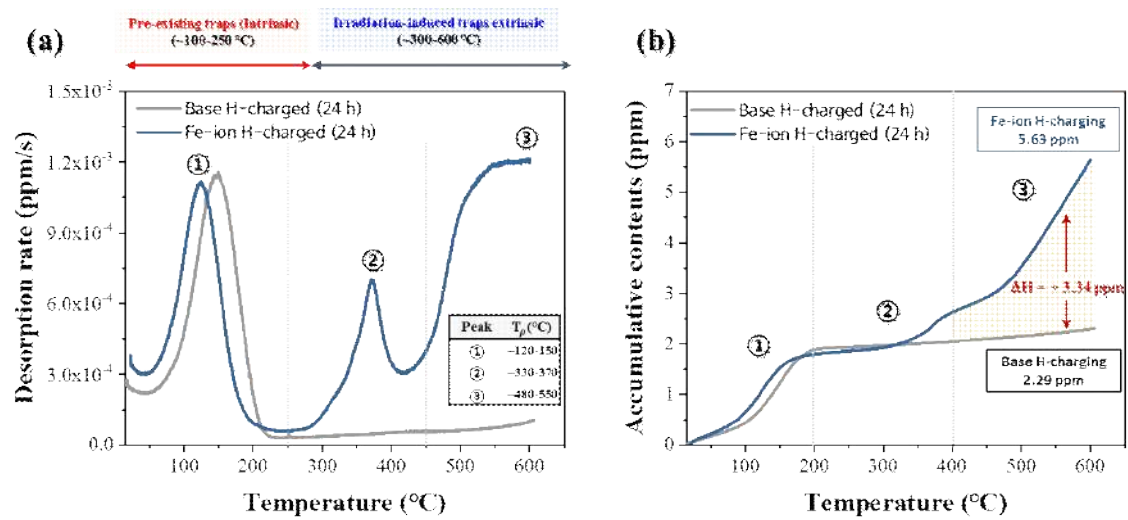


Fig. 1 Hydrogen trapping behavior of RAFM steel before and after Fe-ion irradiation: (a) TDS desorption profiles showing enhanced high-temperature trapping sites after irradiation, and (b) cumulative hydrogen contents indicating increased hydrogen trapping.

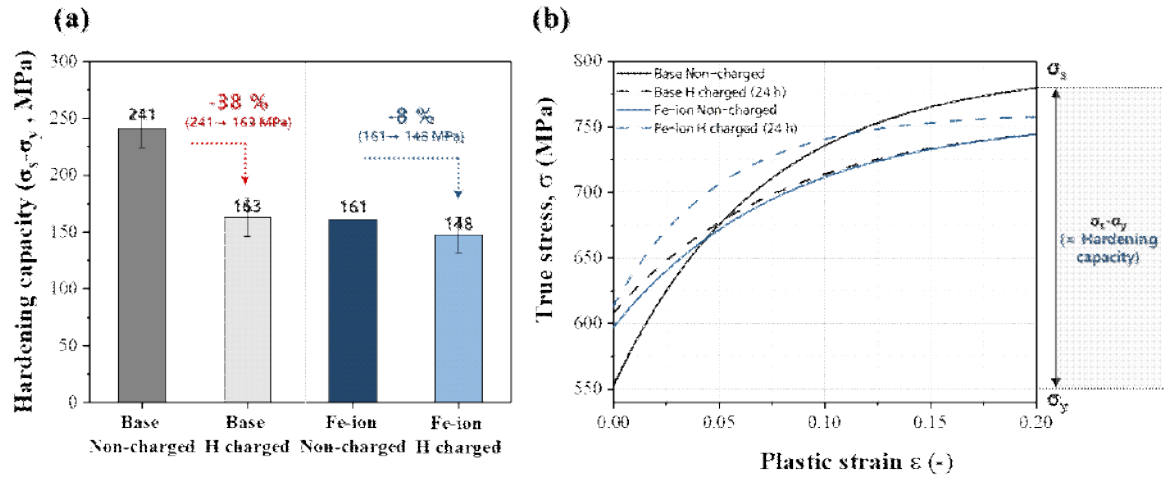


Fig. 2 Local mechanical behavior evaluated by plastometry-based indentation plastometry (PIP): (a) hardening capacity and (b) true stress-plastic strain curves before and after Fe-ion irradiation and hydrogen charging.

손상 내성 강화형 방향성 라멜라 조직 설계를 통한 중망간강의 강도 및 수소취성 저항성 동시 향상

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Simultaneous Enhancement of Strength and Hydrogen Embrittlement Resistance in
Medium-Mn Steel through Damage-Tolerant Directional Lamellar Morphology

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ABSTRACT

A damage-tolerant microstructural approach was explored to concurrently improve the strength and hydrogen embrittlement (HE) resistance of medium-Mn steel. An Fe - 8Mn - 0.2C - 3Al - 0.2V (wt.%) alloy was intercritically annealed and subsequently warm-rolled to form a directional lamellar (DL) structure comprising elongated tempered martensite (α'_T) and retained austenite (γ_R) aligned with the rolling direction. Its mechanical and hydrogen-related properties were compared with those of steels possessing interwoven lamellar and nanoscale globular microstructures produced through conventional processing routes. The DL-structured steel achieved the highest strength while retaining favorable ductility. This superior mechanical response was associated with microstructural refinement, increased dislocation density, and enhanced transformation-induced plasticity (TRIP) arising from the high fraction of γ_R phase. More importantly, the DL morphology provided greater resistance to hydrogen-assisted fracture despite its high strength and pronounced TRIP activity. Rather than propagating continuously along preferential microstructural paths, hydrogen-assisted cracks were repeatedly deflected through branching and delamination transverse to the principal crack-growth direction. These damage-tolerant events impeded crack advance and reduced the effective driving force for fracture. The elevated dislocation density in γ_R may also have contributed by

increasing hydrogen trapping and limiting hydrogen diffusion. The results indicate that directional control of multiphase morphology offers a promising route for achieving both high mechanical strength and robust HE resistance in medium-Mn steels.

열처리 조건에 따른 고실리콘 강판의 재결정 거동 및 집합조직 변화

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Recrystallization behavior and texture evolution of high-Si steel under different
annealing conditions

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ABSTRACT

High-Si steels are widely used in electromagnetic devices due to their excellent soft magnetic properties. These properties are influenced not only by the silicon content but also by the microstructure developed during the thermomechanical processing. It is well known that a strong ((100)//ND) cube texture is crucial for enhancing magnetic performance in High-Si steels. However, conventional processing routes, such as hot/cold rolling, tend to develop dominant γ -fiber ((111)//ND) and α -fiber ((110)//RD) textures, both of which are detrimental to magnetic properties. Unfortunately, enhancing the cube texture during the thermomechanical process remains a significant challenge up to date. To achieve such a goal, many studies have focused on optimizing alloy compositions, casting methods, and/or rolling directions. Although these methods can promote cube texture formation, their feasibility for industrial applications remains limited. In this study is explored a practical strategy for texture optimization through the final annealing process, only. The effects of heating rate and annealing temperature on recrystallization behavior and texture evolution in High-Si steel are systematically investigated. Electron backscatter diffraction (EBSD) analysis is conducted to elucidate the key factors

governing γ -fiber suppression and cube texture enhancement during recrystallization. These findings provide practical guidance for optimizing the final annealing process to improve the magnetic performance of High-Si steel sheets.

최종 소둔 분위기에 따른 무방향성 실리콘강의 표면 미세구조 변화와 철손의 상관관계

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Surface microstructure and iron loss in non-oriented silicon steel
under different final annealing atmospheres

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ABSTRACT

Non-oriented silicon steel is widely used for electric motor cores because it combines high magnetic flux density, low iron loss, and nearly isotropic magnetic behavior within the sheet plane. However, energy loss, which is iron loss, occurs during operation of motor because microstructural features and geometrical constraints of steel impede magnetic domain-wall motion during magnetization and demagnetization. The iron loss is generally divided into hysteresis loss, classical eddy current loss, and anomalous loss. One effective approach for reducing eddy current loss is to decrease the sheet thickness, and thin-gauge electrical steels have therefore attracted considerable attention. However, as the thickness decreases, the relative contribution of the surface regions to the iron loss becomes more significant. Because the surface microstructure is strongly influenced by the atmosphere used during final annealing, clarifying the relationship between surface microstructural evolution and iron loss is important for optimizing the performance of thin-gauge non-oriented silicon steel.

In this study, non-oriented silicon steel sheets with surface microstructures were

produced by controlling the nitrogen to hydrogen ratio during final annealing. The characteristics of the surface layer, interfacial roughness, and near-surface inclusions were examined, and their effects on iron loss were evaluated. The findings demonstrate how the final annealing atmosphere governs surface microstructural development and how these changes affect the iron loss of thin-gauge non-oriented silicon steel.

전기화학적으로 유기된 마르텐사이트 상변태 메커니즘의 규명

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Elucidation of the Mechanism Governing Electrochemically-Induced Martensitic Transformation

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ABSTRACT

Martensitic transformation in metastable austenitic stainless steel was observed during both anodic electrochemical polishing (AEP) and cathodic hydrogen charging (CHC). AEP induced surface-limited transformation via charge accumulation, and CHC led to transformation influenced by Lorentz forces acting on charged hydrogen species. Experiments, FEM, and DFT analyses revealed that hydrogen cations (H^+) generate a larger martensitic driving force as stress than neutral hydrogen (H^0) due to interstitial volumetric expansion and charge imbalance-induced local lattice distortion. These findings suggest that H^+ is the primary driver of CHC-induced martensitic transformation through electro-mechanical coupling.

1. Introduction

Martensitic transformation is a diffusionless change from austenite to martensite, typically triggered by mechanical, thermal, or chemical stimuli. While mechanical transformation is well-known, electrochemical mechanisms remain unclear. This study

examines CHC-induced transformation, focusing on the role of hydrogen's charge state (H^0 vs. H^+), using experiments and simulations including Lorentz force-assisted charging, FEM, and DFT analysis.

2. Experimental Method

The material was a metastable austenitic stainless steel (0.022 wt% C, 10 wt% Ni, 16.5 wt% Cr), processed for a fully austenitic microstructure. A magnetic field was applied perpendicular to the current during CHC (50 mA/cm², 24 h), generating Lorentz forces that selectively acted on charged species. EBSD confirmed enhanced martensite in Lorentz-affected regions, implying H^+ involvement. Hydrogen diffusion was simulated using FEM with TDS-validated uptake (~17 ppm). DFT modeled H^+ by removing one electron per H atom, ensuring charge neutrality.

3. Results & discussion

Lorentz-assisted CHC experiments revealed increased martensite in affected areas (37.5%) versus unaffected ones (22.1%), with deeper hydrogen penetration when the Lorentz force acted along depth. FEM reproduced this gradient, and DFT showed that H^+ induces much greater stress (up to 10 GPa) than H^0 (~1.1 GPa) due to both interstitial volumetric expansion and local lattice distortion caused by charge imbalance. When H^+ exceeded 53%, the stress surpassed the critical transformation energy, matching the experimentally observed 20–30 μ m depth (Figure 1). Thermodynamic analysis indicated that 53–90% of hydrogen exists as H^+ under CHC, supporting its dominant role via electro-mechanical coupling.

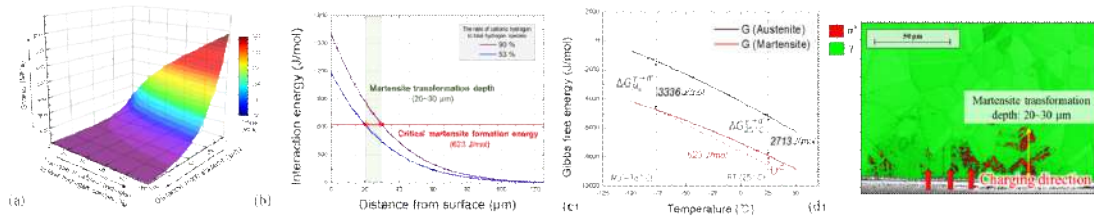


Figure. 1. (a) Stress distribution from DFT based on hydrogen concentration; (b) Interaction energy vs. depth for different H^+ ratios; (c) Gibbs free energy difference between α' and γ at 25 °C and -78 °C (Thermo-Calc); (d) EBSD showing martensitic transformation depth after CHC.

4. Conclusion

Hydrogen cations (H^+) play a key role in CHC-induced martensitic transformation. Unlike H^0 , which causes stress through interstitial volumetric expansion effect alone, H^+ alters interatomic potentials, further distorting the lattice by charge imbalance. This dual mechanism leads to higher stress and drives transformation.

Acknowledgement

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT) (Nos. 2021R1A2C3005096, RS-2024-00445448, RS-2023-00261543, 2022R1A2C1005505, and 2022M3F3A2A01073562).

마르텐사이트강의 구오스테나이트 입계 취약성 원인 분석 :계면 특성과 용질 편석의 상관관계

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Why Are Prior Austenite Grain Boundaries (PAGBs) Vulnerable to Cracking?
:Relationship between Grain Boundary Character and Solute Segregation

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ABSTRACT

Solute segregation significantly influences the interfacial strength and fracture behavior of steels. In martensitic steels, cracks preferentially propagate along prior austenite grain boundaries (PAGBs) [1, 2], whereas other hierarchical boundaries (packet, block, sub-block boundary) exhibit a much lower susceptibility to cracking. Since the amount of solute segregation can be strongly affected by the crystallographic character and coherency of a boundary [3, 4], different hierarchical boundaries in martensite are expected to exhibit distinct segregation behaviors. To clarify the origin of the high cracking susceptibility of PAGBs, it is therefore necessary to quantitatively evaluate solute segregation at different hierarchical boundaries and correlate it with their grain boundary character. In this study, solute segregation at various hierarchical boundaries in martensitic steel was systematically investigated with particular emphasis on the effect of boundary character on segregation behavior.

An Fe - 0.1C - 3Mn (mass%) alloy was austenitized at 1100 °C for 30 min and water-quenched to obtain a fully martensitic microstructure, followed by tempering at 550 °C for 24 h. Prior austenite grain boundaries, packet boundaries, block/sub-block boundaries, and lath boundaries were identified using electron backscatter diffraction

(EBSD). The grain boundary character was further determined by grain boundary trace analysis using cross-sectional observations prepared by focused ion beam (FIB) milling. Solute segregation at each boundary was quantitatively analyzed using three-dimensional atom probe (3DAP) tomography.

Segregation of C and Mn was observed at the martensitic boundaries, and the amount of segregation was quantified in terms of interfacial excess, Γ (atoms nm^{-2}). The segregation level increased in the order of V1/V1 lath boundaries < V1/V4 $\approx$ V1/V2 < V1/V6 $\approx$ V1/V17, with packet boundaries and PAGBs exhibiting the highest segregation levels. This tendency showed good agreement with the calculated grain boundary energies. Boundaries with higher coherency exhibited lower grain boundary energies and lower levels of solute segregation, whereas less coherent, higher-energy boundaries showed enhanced segregation. These results demonstrate that boundary character plays a critical role in determining the extent of solute segregation in lath martensite through its influence on grain boundary energy. The present findings provide a microstructural basis for understanding the pronounced solute segregation and consequent cracking susceptibility of PAGBs compared with other hierarchical boundaries in martensitic steels.

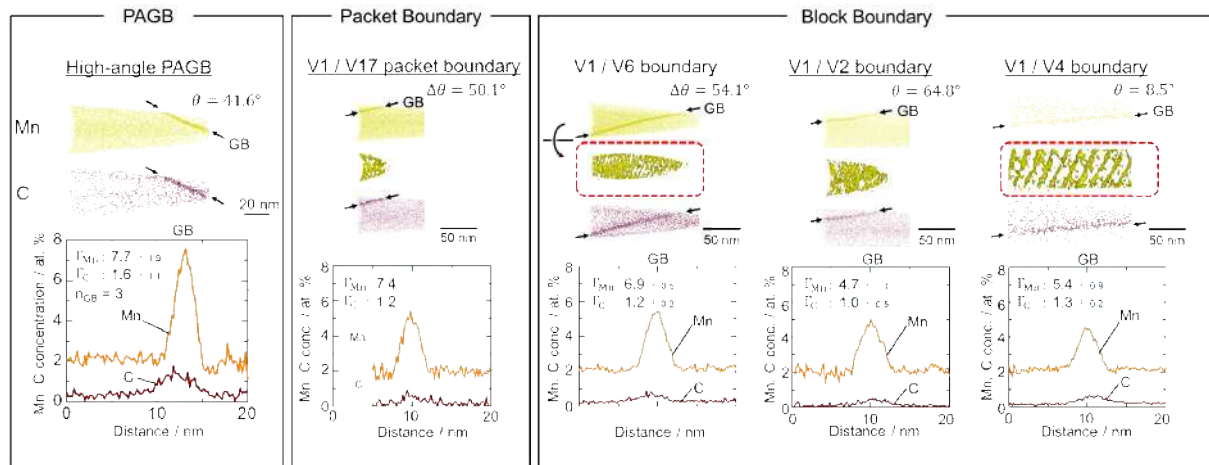


Fig. 1. 3D-APT analysis on PAGB, Packet Boundary, Block Boundaries

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VC 강화 고망간강의 탄소 의존적 격자 부정합도 및 석출 조대화에 따른 전단-루핑 천이와 항복강도 예측

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Elucidating the shearing-to-looping transition in VC-strengthened high-Mn steels
: Interplay between carbon-dependent lattice misfit and precipitate coarsening

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ABSTRACT

고망간 오스테나이트강은 우수한 극저온 인성과 경제성으로 인해 LNG 저장 및 수송용 구조재료로 주목받고 있으나, 오스테나이트 기지의 낮은 항복강도는 산업적 적용을 제한하는 주요 요인이다. 이에 본 연구에서는 Fe-22Mn-(0.7, 0.8, 0.9)C-1.0V(wt.%) 열간압연 고망간강을 대상으로 상온 인장시험과 EBSD, XRD, TEM 분석, 기하학적 위상 분석(GPA) 및 Thermo-Calc 계산을 통합하여 탄소 함량에 따른 미세조직, VC 석출 거동과 오스테나이트/VC 계면 특성이 항복강도에 미치는 영향을 규명하였다.

탄소 함량이 증가함에 따라 항복강도는 471 MPa에서 715 및 754 MPa로 향상되었으나, 0.8C와 0.9C 사이의 증가량은 39 MPa로 둔화되어 비선형적 거동이 나타났다. TEM 및 EBSD 분석 결과, VC 면적분율은 0.887%에서 1.620 및 3.757%로 증가하였으며, VC에 의한 재결정 지연 및 결정립 성장 억제로 재결정립 크기는 14.97 μm 에서 약 7.37 및 7.63 μm 로 미세화되었다. Orowan 루핑만을 적용한 기존의 항복강도 모델은 항복강도를 각각 455, 568 및 675 MPa로 예측되어 실험값과 차이를 나타냈다. HRTEM-GPA 분석에서는 VC가 오스테나이트와 미스핏 전위를 수반하는 준정합 계면을 형성하였으며, 탄소 증가에 따른 오스테나이트 격자 팽창으로 오스테나이트/VC 격자 미스핏이 5.55%에서 4.10 및 2.90%로 감소하였다. 이를 바탕으로 Friedel 전단과 Orowan 루핑을 통합한 석출강화 모델을 적용하였으며, 기구 천이 임계반경은 2.69 - 4.10 nm로 계산되었다. 이를 통해 탄소 함량 증가에 따른 항복강도의 비선형적 거동은 VC 크기분포 변화에 수반되는 석출강화 기구의 천이에 기인한 것으로 해석되었다. 0.8C강에서는 반경 4 nm 이하의 미세 VC가 다수 분포하여 Friedel 전단 항이 전체 석출강화에 크게 기여함으로써 항복강도가 급격히 증가한 반면, 0.9C강에서는 VC 조대화에 따라 Orowan 루핑 항의 상대적 기여도가 증가하면서 추가적인 항복강도 증가가 제한되었다.

이러한 결과는 탄소가 단순한 고용 강화 원소를 넘어 VC 분율, 결정립 미세화 및 오스테나이트/VC 계면 정합성을 조절하여 석출강화 기구를 변화시키는 핵심 합금설계 변수이며, 계면 정합성과 석출물 크기분포의 제어가 고강도 고망간강 설계를 위한 효과적인 전략임을 시사한다.

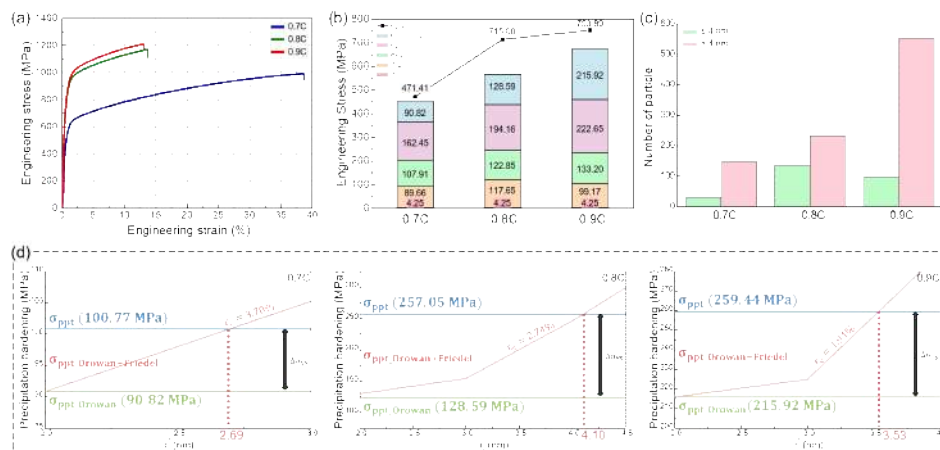


Fig. 1. 탄소 함량에 따른 (a) 공칭 응력-변형률 곡선, (b) Orowan 루핑만을 고려한 강화기구별 항복강도 기여분과 실험값의 차이, (c) 반경 4 nm를 기준으로 구분한 VC 입자 수 분포 및 (d) 크기 의존적 Friedel 전단-Orowan 루핑 천이를 고려한 통합 석출강화 모

텔과 임계반경 산출.

바나듐 함량이 고망간강의 VC 재용해 및 탈탄에 의한 표면 ϵ -마르텐사이트 형성에 미치는 영향 분석

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Effect of vanadium content on VC dissolution and decarburization-induced surface
 ϵ -martensite formation in high-Mn steels

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ABSTRACT

고망간 오스테나이트강은 우수한 극저온 인성으로 인해 LNG 저장 및 수송용 구조재료로 주목받고 있으나, 고온 공정 중 발생하는 표면 탈탄은 오스테나이트 안정도를 저하시켜 ϵ -마르텐사이트 변태를 유발할 수 있다. 바나듐(V)은 일반적으로 VC 석출을 통한 강화 및 결정립 미세화 원소로 활용되지만, 고온 열처리 중 VC가 용해될 경우 방출된 탄소가 탈탄에 따른 표면 탄소 손실을 부분적으로 보충하고 국부적인 오스테나이트 안정도에 영향을 줄 가능성이 있다.

본 연구에서는 Fe-22Mn-0.6C-(0.4, 0.5)V (wt.%) 고망간강을 1000 °C에서 30분 동안 대기 또는 아르곤 분위기에서 열처리하고, EBSD, EPMA 및 SEM 분석과 TC-PRISMA, DICTRA 및 VC 용해 속도론 계산을 통합하여 V 함량에 따른 VC 거동, 표면 탄소 농도 및 ϵ -마르텐사이트 형성의 관계를 평가하였다. EPMA 및 EBSD 분석 결과, 아르곤 열처리재에서는 뚜렷한 깊이 방향의 탄소 결핍과 광범위한 ϵ -마르텐사이트 형성이 나타나지 않은 반면, 대기 열처리재에서는 내부에서 표면으로 갈수록 탄소 농도가 감소하는 탈탄층과 표면 ϵ -마르텐사이트가 형성되었다. 대기 열처리 후 0.5V강과 0.4V강의 최외곽 탄소

농도는 각각 0.38 및 0.30 wt.%였으며, 표면부 ϵ -마르텐사이트 면적분율은 각각 27.78 및 42.98%로 측정되었다. 반면 두 강의 중심부는 대기 열처리 후에도 오스테나이트 단상을 유지하여, 표면 ϵ -마르텐사이트는 탈탄에 따른 국부적인 오스테나이트 불안정화에 의해 형성된 것으로 판단하였다. TC-PRISMA 분석을 통해 0.5V강이 열처리 전 더 큰 VC 분율을 가지며 열처리 과정에서 더 많은 VC가 용해될 수 있음을 확인하였으며, 이에 수반된 오스테나이트 기지의 탄소 농도 증가량도 더 큰 것으로 계산되었다. SEM 분석 결과, 아르곤 열처리 후 중심부-표면 VC 면적분율 차이는 0.4V강과 0.5V강에서 각각 0.020 및 0.025%로 작았던 반면, 대기 열처리 후에는 각각 0.154 및 0.304%로 증가하여 탈탄된 표면에서 VC 분율이 감소하였음을 보여주었다. 또한 V 확산 지배 VC 용해 모델에서 상대적 VC 용해 속도인자는 조사된 탄소 농도 범위에서 0.5V강이 0.4V강보다 높았으며, 두 강 모두 기지 탄소 농도가 감소할수록 증가하였다. 반면, 오스테나이트 기지 내 탄소 확산만을 고려한 DICTRA 계산에서는 두 강 사이에 유사한 탈탄 거동이 예측되어, 실험에서 관찰된 0.5V강의 상대적으로 높은 표면 탄소 농도를 기지 조성에 따른 탄소 확산 차이만으로 설명하기 어려웠다.

이러한 실험 및 계산 결과는 0.5V강의 더 큰 VC 저장량과 높은 용해 경향에 수반되는 탄소 재분배가 탈탄에 의한 표면 탄소 손실을 부분적으로 보충하고, 이에 따라 오스테나이트 안정도 저하와 ϵ -마르텐사이트 형성을 완화했을 가능성을 뒷받침한다. 본 연구는 고망간강에서 V와 VC의 역할이 석출강화와 결정립 미세화에 한정되지 않으며, 고온 공정 중 표면 탄소 보충과 탈탄 유기 ϵ -마르텐사이트 상변태를 제어하기 위한 합금 및 공정 설계변수로 활용될 수 있음을 시사한다.

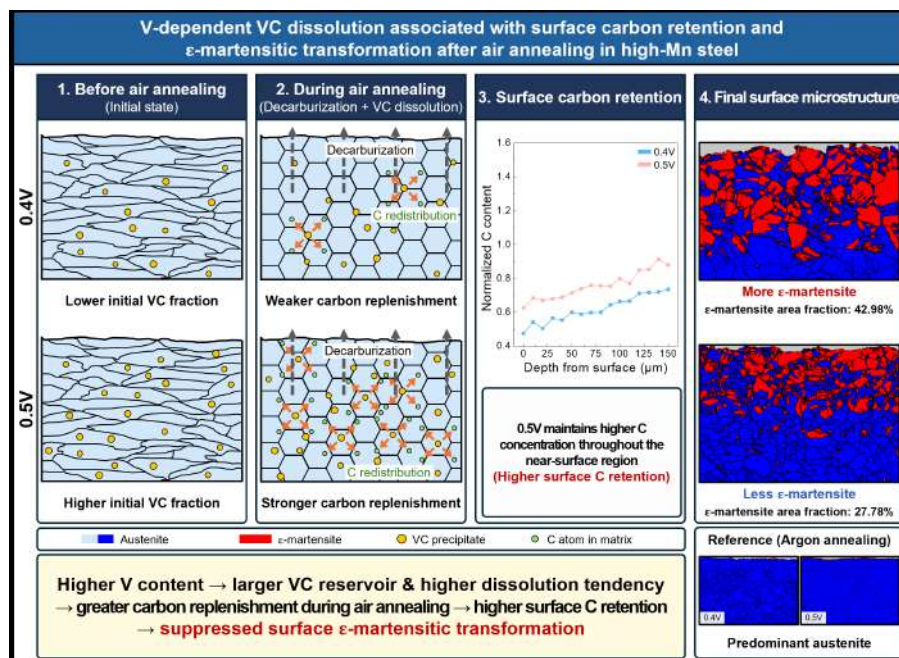


Fig. 1. VC 재용해에 수반되는 탄소 재분배 기구 및 대기 열처리 후 V 함량에 따른 표면 탄소 농도와 ϵ -마르텐사이트 형성 거동.

Si 및 Al-Si 첨가 퀀칭-파티셔닝(Q&P)강의 수소취성 거동 비교

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ABSTRACT

본 연구에서는 서로 다른 합금 설계 전략으로 개발된 두 종류의 퀀칭-파티셔닝(Q&P)강, 즉 Si강과 AlSi강의 수소취성(hydrogen embrittlement, HE) 거동을 비교하였다. 두 강은 템퍼드 마르텐사이트, 베이나이트 및 잔류 오스테나이트(retained austenite, RA)로 구성된 유사한 미세조직을 나타냈으나, AlSi강의 경우 구 오스테나이트 결정립계 부근에 약 5%의 페라이트가 추가로 존재하였다. 저변형률속도 인장시험 결과, 두 강의 확산성 수소 함량이 거의 동일함에도 불구하고 AlSi강은 Si강보다 현저히 낮은 수소취성 저항성을 나타냈다. 파면 분석에서도 수소 주입된 Si강은 연성 파면을 나타낸 반면, AlSi강은 표면 인근 영역에서 수소 유기 입계 파괴가 관찰되어 이러한 결과를 뒷받침하였다. AlSi강의 낮은 수소취성 저항성은 페라이트/마르텐사이트 계면에서의 변형 국부화, 페라이트의 존재로 인한 수소 확산성 증가, 그리고 Si의 일부를 Al로 대체함에 따라 시멘타이트 형성이 더욱 활발해져 잔류 오스테나이트의 안정성이 감소한 복합적인 영향에 기인한 것으로 판단되었다.

LPBF AlSi10Mg 합금의 Si 네트워크 및 석출 거동 제어를 위한 미세조직 기반 열처리 설계

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Microstructure-Based Heat-Treatment Design for Controlled Si-Network Evolution
and Precipitation in LPBF AlSi10Mg Alloy

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ABSTRACT

Laser powder bed fusion (LPBF) enables the fabrication of geometrically complex AlSi10Mg components with high material efficiency. Owing to the rapid solidification and cyclic thermal history inherent to LPBF, the as-built alloy develops a non-equilibrium microstructure consisting of a fine cellular α -Al matrix surrounded by a continuous eutectic Si network. This refined structure provides high strength but is generally accompanied by limited ductility and pronounced microstructural heterogeneity [1]. Post-heat treatment is therefore required to achieve an improved strength - ductility balance. Conventional T6 treatment promotes the formation of strengthening precipitates such as β'' and Guinier - Preston (GP) zones. However, high-temperature solution treatment also causes pronounced fragmentation and coarsening of the eutectic Si network, resulting in substantial strength loss relative to the as-built condition [2]. Stress-relief annealing improves ductility but generally provides insufficient strength. Therefore, a heat-treatment strategy that preserves the beneficial as-built microstructure while introducing additional precipitation strengthening is required. In this study, a microstructure-based heat-treatment strategy was developed for LPBF AlSi10Mg by separating the roles of annealing and aging. The as-built alloy was compared with conventionally T6-treated, annealed, and

modified heat-treated conditions. The T6 treatment produced β'' precipitates and GP zones but caused extensive disruption and coarsening of the eutectic Si network. In contrast, annealing partially fragmented the Si network and promoted the formation of nanoscale Si precipitates, improving ductility and work-hardening capacity at the expense of strength. Based on these results, a subsequent aging treatment was introduced to recover the strength lost during annealing while retaining the beneficially modified Si network. As shown in Fig. 1, the modified heat treatment produced a complex microstructure comprising a partially disrupted eutectic Si network, nanoscale Si precipitates, and GP zones. This microstructural combination suppressed tensile-strength loss while maintaining improved ductility relative to the as-built condition. Strengthening-mechanism analysis further indicated that the improved strength retention originated from the combined contributions of the retained Si network, nanoscale Si precipitates, and GP zones. In addition, stacking faults were identified in the as-built alloy, and their possible formation during the LPBF process was considered.

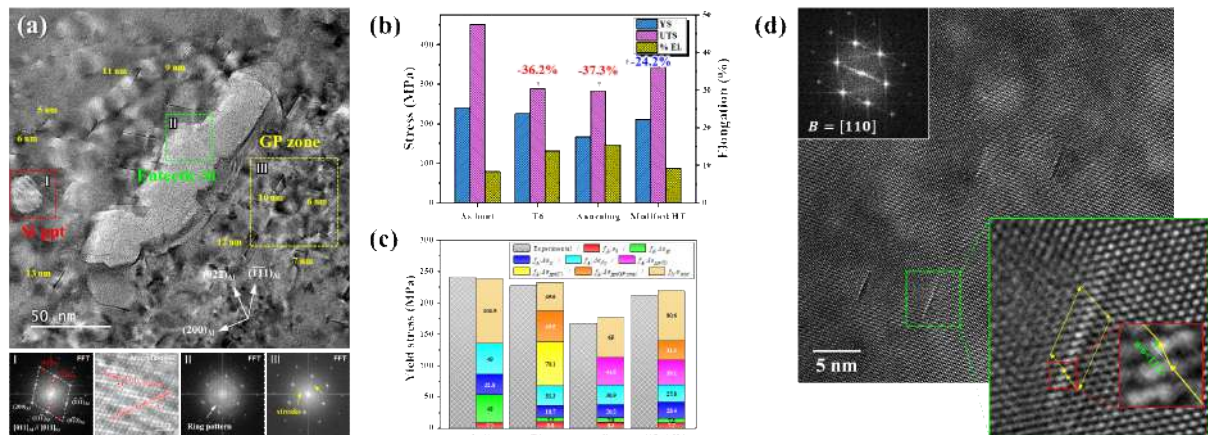


Fig. 1. Microstructure and mechanical response of LPBF AlSi10Mg subjected to the modified heat treatment: (a) TEM image showing the partially disrupted eutectic Si network, nanoscale Si precipitates, and GP zones; (b) tensile properties under different heat-treatment conditions; (c) comparison of the experimentally measured yield strengths with the calculated strengthening contributions; and (d) HRTEM image showing stacking faults in the as-built alloy.

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제 40회 첨단구조재료 심포지엄
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- Session 3
- Session 4

초저온 불연속 소성 제어를 위한 고엔트로피 합금 설계

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Alloy Design for Controlling Discontinuous Plastic Flow at Ultra-low Temperatures

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ABSTRACT

This study presents an alloy design strategy that simultaneously enhances strength and controls discontinuous plastic flow in high-/medium-entropy alloys at ultra-low temperatures of 4.2 K. Although discontinuous plastic flow near 0 K should be mitigated to ensure structural reliability, conventional cryogenic alloys often exhibit complex microstructures and deformation mechanisms, making it difficult to isolate the role of individual microstructural parameters. To overcome this limitation, the present work employs systematic alloy design to decouple the effects of individual microstructural factors. A single-phase medium-entropy alloy with a face-centered cubic structure and dislocation-dominated deformation behavior was selected as the model alloy, and its tensile response was systematically compared at room temperature and liquid helium temperature (4.2 K) for different grain sizes. This approach revealed that the severity of discontinuous plastic flow is primarily governed by the dislocation density. With this insight, a precipitation-strengthened high-entropy alloy was designed by introducing coherent precipitates as a strengthening mechanism that does not inherently require an increase in dislocation density. The alloy achieves high strength with sufficient ductility at 4.2 K while exhibiting markedly smaller stress drops, demonstrating that discontinuous plastic flow can be effectively mitigated. These findings provide important insights for the design of next-generation cryogenic alloys with improved mechanical reliability.

L1₂ 나노 석출물을 통한 중엔트로피 합금의 4.2 K 초고강도 및 기계적 안정성 향상

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L1₂ nano-precipitates enable ultrahigh strength and mitigate flow instability
at 4.2 K in a medium-entropy alloy

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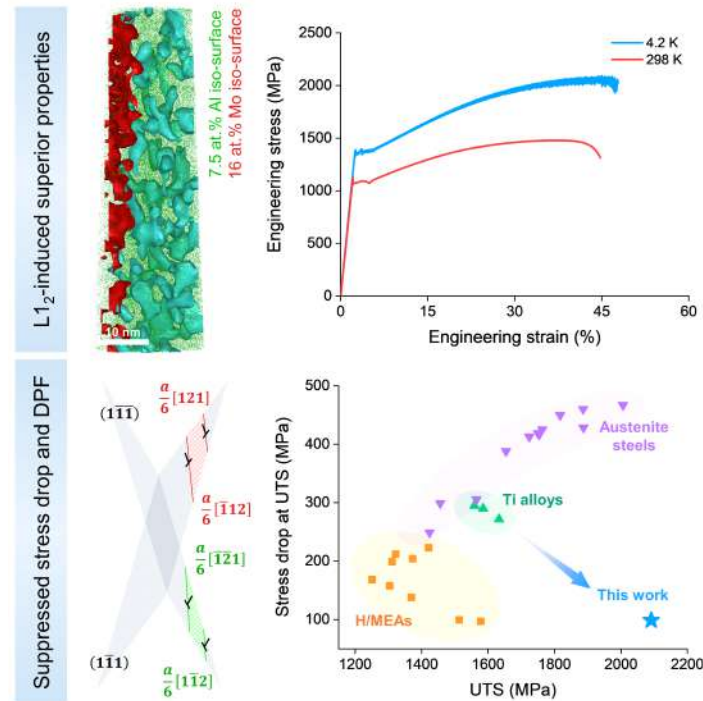
ABSTRACT

Structural materials for aerospace and hydrogen-energy systems must retain high strength, ductility, and stable plastic flow under extreme cryogenic conditions. Although grain refinement, high dislocation densities, and hard second phases can substantially increase strength, these conventional approaches often intensify strain localization and discontinuous plastic flow at ultralow temperatures. The resulting abrupt stress drops can compromise the mechanical reliability of structural

components operating near liquid-helium temperature.

Here, we develop a precipitation-strengthened $\text{Co}_{36}\text{Ni}_{46}\text{Mo}_{11}\text{Al}_7$ medium-entropy alloy designed to simultaneously enhance strength and suppress plastic-flow instability at 4.2 K. The alloy-design strategy combines increased lattice friction through compositional tuning with a high density of coherent L1_2 nano-precipitates. At 4.2 K, the optimized alloy exhibits an exceptional tensile strength of approximately 2.1 GPa, a total elongation of 48%, and a markedly reduced stress-drop magnitude of approximately 99 MPa. Microstructural analyses reveal that the coherent L1_2 precipitates effectively impede dislocation glide while preserving interfacial compatibility with the FCC matrix. Their interaction with moving dislocations promotes the formation of stable Hirth locks and distributes dislocation activity, thereby limiting the development of severe strain localization and catastrophic dislocation avalanches.

Cryogenic loading - unloading - reloading tests further reveal a low back-stress contribution despite the ultrahigh flow strength. This indicates that strengthening arises predominantly from an increase in effective stress rather than from long-range internal stresses generated by extensive dislocation pile-ups. The enhanced lattice friction and coherent L1_2 nano-precipitates restrict dislocation glide while promoting spatially distributed dislocation interactions and Hirth-lock formation, thereby mitigating strain localization and dislocation avalanches. These findings establish a compelling alloy design strategy that offers a viable pathway toward cryogenic structural materials with exceptional strength, ductility, and mechanical stability.



4.2-1000 K 넓은 온도 범위 환경용 고강도 CrCoNi 기반 고엔트로피 합금 개발

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High-strength CrCoNi-based high-entropy alloy
for the wide temperature range from 4.2 to 1000 K

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ABSTRACT

The development of structural materials capable of sustaining high mechanical performance over a wide temperature range is essential for applications involving aerospace, and energy system. However, achieving high strength from cryogenic to elevated temperatures remains challenging because the dominant deformation and strengthening mechanisms vary substantially with temperature. In face-centered-cubic (FCC) alloys, planar defects such as stacking fault (SF), lock, deformation twins can effectively enhance strain hardening at cryogenic temperatures. In contrast, dynamic recovery and thermally activated dislocation motion progressively reduce dislocation storage at elevated temperatures. Accordingly, a microstructural design capable of providing effective strengthening across different temperature regimes is required.

In this study, a CrCoNi-based high-entropy alloy was developed through a dual-precipitates strategy involving two scales of ordered L1₂ precipitates and Nb-rich Laves phases. The heat treatment produced coarse and fine L1₂ precipitates with distinct morphologies and spatial distributions, together with Laves phases

preferentially located near grain boundaries. The resulting heterogeneous precipitation architecture provided multiple length scales for dislocation interactions and enhanced resistance to plastic deformation over a wide temperature range. In addition, the coarse and fine $L1_2$ precipitates were expected to contribute differently to dislocation shearing and bypassing, while the grain-boundary-associated Laves phases provided additional resistance to localized deformation. This multiscale arrangement therefore enabled the alloy to maintain effective strengthening even as the dominant carrier of plasticity changed with temperature.

The present alloy exhibited yield strengths (YS) of 1640, 1501, and 1311 MPa at 4.2, 77, and 298 K, respectively. High strength was retained at elevated temperatures, with YS of 1233 MPa at 800 K, 1185 MPa at 900 K, and 1048 MPa at 1000 K. Considerable tensile ductility was maintained up to 900 K, whereas the elongation decreased at 1000 K owing to the increased susceptibility to intergranular fracture. Despite this reduction in ductility, the present alloy still preserved a YS exceeding 1 GPa at 1000 K, demonstrating its strong resistance to thermal softening.

Transmission electron microscopy (TEM) images revealed a clear transition in the dominant deformation mechanisms with increasing temperature. At 77 K, extensive SF, dislocation walls, locking, and deformation twins contributed to sustained strain hardening. At 900 K, despite enhanced dynamic recovery, the $L1_2$ precipitates continued to impede dislocation motion through shearing and Orowan bypassing, while the Nb-rich Laves phases acted as strong local barriers. These observations indicate that the deformation behavior was not governed by a single mechanism over the wide temperature range, but rather by the temperature-adaptive strengthening.

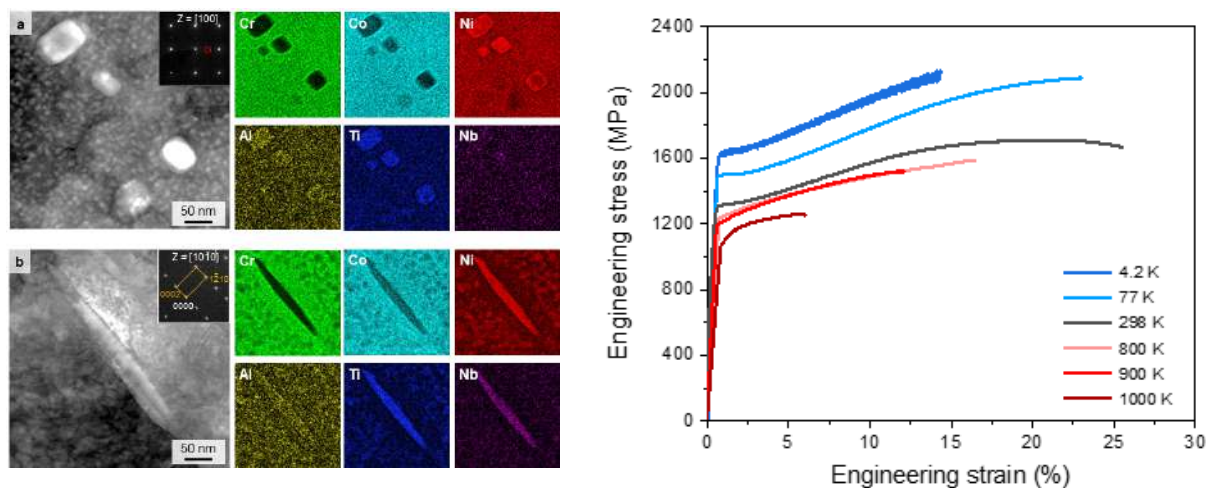


Fig. 1. (Left image) TEM images and corresponding elemental maps showing the dual-precipitate microstructure. (Right image) Engineering stress - strain curves of the present alloy measured from 4.2 to 1000 K.

제조 방법을 달리한 Ti6Al4V 합금의 15 K 에서의 수소 취성과 변형 거동

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Effects of fabrication methods on hydrogen embrittlement and deformation behavior of
Ti6Al4V alloy at 15 K

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ABSTRACT

Ti6Al4V (Ti64) alloy is widely used in aerospace applications because of its high strength, toughness, and corrosion resistance. However, ultra-cryogenic temperatures and hydrogen (H)-rich environments present significant challenges for aerospace components. This study investigated how fabrication methods affect hydrogen embrittlement and the deformation behavior of Ti64 at 15 K. Specifically, Ti64 was fabricated by directed energy deposition, hot rolling, and tungsten inert gas welding, followed by electrochemical H-charging at room temperature and mechanical testing at 15 K. Prior to H-charging, the deformation behavior at 15 K was characterized by mechanical twinning and dislocation slip. The different fabrication methods produced distinct microstructures, thereby influencing H uptake during H-charging. Consequently, the amount of TiH₂ formed varied among the Ti64 samples. Moreover, microstructural characterization revealed that the morphology of TiH₂ depended on the local H concentration. The spatial distribution of TiH₂ and the presence of solute H resulted in distinct brittle-fracture characteristics. After H-charging, H/TiH₂-assisted cracks significantly reduced the effective load-bearing cross-sectional area. Finally, the hot-rolled sample exhibited the highest resistance to hydrogen embrittlement, whereas the other samples showed greater susceptibility to

hydrogen-assisted cracking due to higher hydrogen uptake and deeper hydrogen-affected regions.

고망간강 용접 위치에 따른 초극저온 쌍정유기소성(TWIP) 거동 및 변형-파괴 메커니즘 연구

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A Study on the Cryogenic Twinning-Induced Plasticity (TWIP) Behavior and
Deformation-Fracture Mechanisms in Different Welding Zones of High-Manganese
Steel

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ABSTRACT

As liquid hydrogen emerges as a key renewable energy source for carbon neutrality, its storage and transportation demand materials capable of withstanding ultra-low temperatures (≤ 20 K). In such environments, metals often experience cryogenic embrittlement, and welding can further degrade mechanical properties. This study investigates the mechanical behavior and deformation mechanisms of the base metal (BM), heat-affected zone (HAZ), and welding zone (WZ) of high-manganese (high-Mn) steel at room and cryogenic temperatures. High-Mn steel exhibits a twinning-induced plasticity (TWIP) mechanism driven by a stacking fault energy of 20 - 40 mJ/m². To comprehensively evaluate the position-dependent properties of the welding, we analyzed the initial microstructure, precipitates, and hardness across the distinct regions. Furthermore, we assessed the mechanical performance at varying temperatures and conducted detailed fractographic and microstructural analyses on

dislocation and twin structures to elucidate the governing deformation and fracture mechanisms of the welded joints.

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Development of Additively Manufactured Burn-Resistant Superalloys for Space
Launch Vehicles

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ABSTRACT

The next-generation space launch vehicle will employ a staged-combustion cycle engine, in which an oxidizer-rich preburner operates above 200 bar of high-pressure oxygen to drive the turbopump. Under such extreme oxygen environments, metallic components can ignite and burn at temperatures well below their melting points, so the preburner and turbopump require heat-resistant alloys with intrinsic burn resistance. The U.S. Air Force Research Laboratory and Aerojet Rocketdyne demonstrated additively manufactured preburner components of the low-ignition nickel superalloy Mondaloy 200™, and SpaceX developed the SX-300/SX-500 alloys with excellent oxidation resistance up to 800 bar oxygen. However, these alloy compositions are proprietary and subject to export controls, making independent development of a domestic alloy indispensable. The target alloy must simultaneously achieve (1) burn resistance in high-pressure oxygen, (2) additive manufacturability, and (3) high toughness at elevated temperatures.

Commercial superalloys exhibit a clear trade-off: burn-resistant alloys such as

Haynes 214, MA754, and Monel K500 lack strength, whereas high-strength alloys such as Inconel 718 and Waspaloy show poor burn resistance. In addition, precipitation-strengthened superalloys with high Al/Ti contents suffer from solidification, liquation, and strain-age cracking during additive manufacturing, together with low creep ductility caused by elemental segregation, porosity, and residual stress. To overcome these barriers, we are developing an accelerated alloy design framework. Yield strength is predicted from the γ' precipitate volume fraction and anti-phase boundary energy for CALPHAD-predicted precipitate compositions, while printability is screened using criteria including a γ' fraction, a solidification range, and a strain-age cracking index.

The research encompasses gas-atomization powder production technology for additive manufacturing aimed at 100 kg-class scale-up, quantitative evaluation of oxidation resistance in high-pressure oxygen, and construction of an ASTM G124 standard promoted-ignition test facility for comparative ranking of candidate compositions. Toughening is pursued through thermomechanical treatment, hot isostatic pressing, and creep testing, in collaboration with KAERI. In preliminary experiments, a low ignition alloy powder based on newly-designed compositions (high Ni, low Al, Cr) was successfully gas-atomized and deposited by directed energy deposition. This integrated approach is expected to provide an indigenous burn-resistant, printable, and tough superalloy for staged-combustion rocket engines of future space launch vehicles.

Acknowledgments

This work was supported by National Research Foundation of Korea (NRF) grants funded by the Ministry of Science and ICT (RS-2024-00402378)

Plate 지지구조와 후열처리 공정 도입을 통한 IN718 기반 Kelvin lattice structure의 기계적특성 향상

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Enhancement of the Mechanical Properties of IN718-Based Kelvin Lattice Structures
through Plate-Based Design and Post-Heat Treatment

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ABSTRACT

Inconel 718 lattice structures are promising lightweight components because they combine the high-temperature mechanical and environmental resistance of the alloy with the high specific strength and energy-absorption capability of cellular architectures. In this study, Kelvin plate and Kelvin truss lattices were fabricated by laser powder bed fusion, and the effects of post-heat treatment on their microstructure, mechanical properties, and deformation behavior were investigated.

Heat treatment reduced the fractions of Laves and δ phases and promoted the formation of fine γ' / γ precipitates of approximately 20 nm, thereby improving the mechanical performance of both lattice structures. The Kelvin plate lattice exhibited higher specific strength and specific energy absorption than the Kelvin truss lattice. After heat treatment, its specific energy absorption reached 24.90 J/g, which was approximately 1.38, 1.18, and 1.88 times higher than those of the heat-treated truss, stress-relieved plate, and stress-relieved truss lattices, respectively.

Heat treatment also mitigated the pronounced strain localization observed in the stress-relieved condition, while the Kelvin plate topology promoted a broader and more uniform distribution of deformation. The improved mechanical response is therefore attributed to the combined effects of the load-supporting plate architecture and precipitation-strengthened microstructure. These results demonstrate that

coordinated control of lattice topology and microstructure is an effective strategy for developing lightweight metallic lattices with high specific strength and enhanced energy-absorption capability.

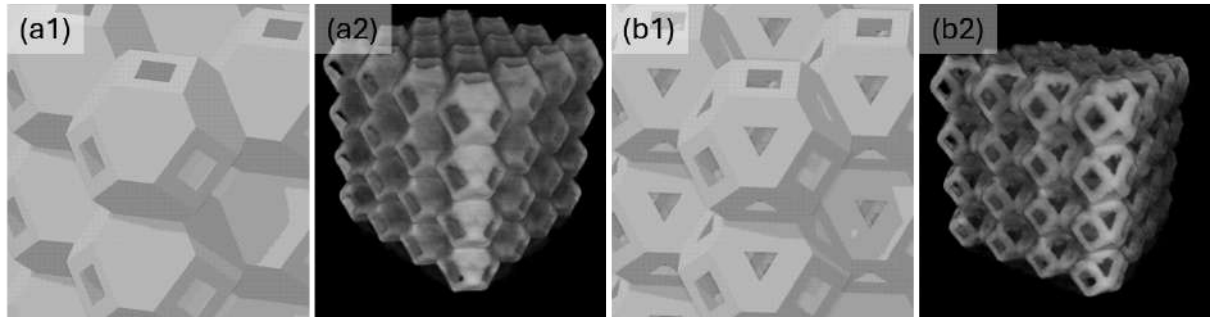


Fig. 1. CAD models and μ -CT reconstructions of the Kelvin lattices: (a1, a2) plate and (b1, b2) truss.

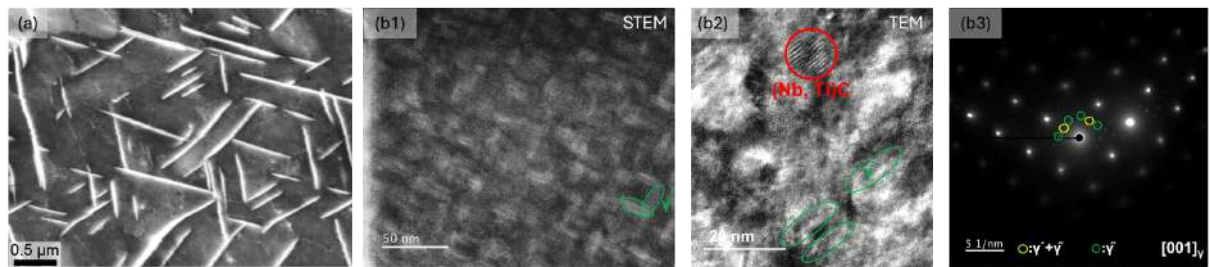


Fig. 2. Microstructural characteristics of the Kelvin lattices: (a) SEM-BSE image in the stress-relieved condition and (b1 - b3) TEM analyses after heat treatment.

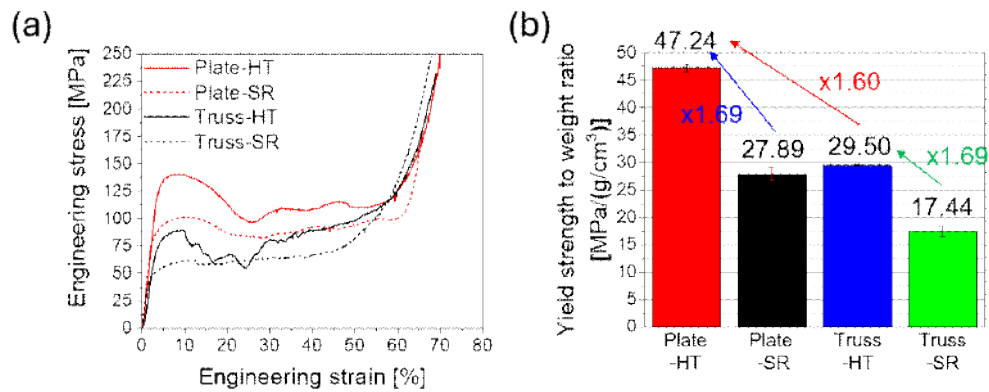


Fig. 3. Room-temperature compressive properties of the Kelvin lattices: (a) engineering stress - strain curves and (b) yield strength-to-weight ratios.

Inconel 718의 고온 크리프 거동에 미치는 미세조직의 영향 및 Omega법 적용성 평가

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Evaluation of Microstructural Effects on the High Temperature Creep Behavior of
Inconel 718 and the Applicability of the Omega Method

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ABSTRACT

Creep tests of Inconel 718 at 621 - 900 °C were analysed with the Larson-Miller (LMP) and Omega (Ω) methods and SEM. As γ'' dissolved and δ coarsened, n fell from 15.2 to 4.8; a hyperbolic sine Ω correlation cut the LOOCV RMSE of $\log t_r$ from 0.248 to 0.141.

Keywords: Inconel 718, Creep, Omega method, Larson-Miller parameter, δ phase

1. 서론

Inconel 718은 가스터빈 엔진 고온 부품에 널리 쓰이나[1], 주 강화상 γ'' (Ni_3Nb)는 650°C 이상에서 조대화 후 δ 상으로 변태하며[2] 과도한 입계 δ 상은 크리프 공동의 생성 기점이 된다[3,4]. 800°C 이상에서는 γ' 까지 재고용되어 석출강화가 소실된다[5].

LMP법[6]은 단일 상수로 이러한 열화를 반영하지 못하나, Prager[7]의 Omega(Ω)법은 크리프 속도가 누적 변형률에 지수적으로 증가하는 관계로 손상과 잔여 수명을 함께 기술하며 API 579-1[8]에 채택되어 있다. 본 연구는 두 기법을 미세조직과 연계해 비교하였다.

2. 실험 방법

표점거리 16 mm·직경 4 mm 시편을 정하중 시험기(ARTE-200, MTDI)로 621°C/662~965, 704°C/413~620, 900°C/50~100 MPa에서 파단까지 시험하고 그림부를 절단하여 SEM 관찰하였다.

3. 결과 및 고찰

파단시간은 621℃ 12~3,449 h, 704℃ 19~472 h, 900℃ 14~206 h, 파단 진변형률은 8.1~10.8, 12.5~16.7, 36.1~46.6 %였다(Fig. 1a~c). 응력지수는 15.2, 8.6, 4.8로 감소하여($Q = 532 \text{ kJ/mol}$) 전위 고착에서 전위 상승으로의 기구 전이를 뜻한다[5]. 621℃는 미세 γ'' 가 유지된 반면 704℃는 판상 δ 가 조대화하였고 900℃는 $\gamma'' \cdot \gamma'$ 이 완전 재고용되었다(Fig. 2a~d).

LMP 상수 최적화로 $C = 28.4$ 를 얻어 관례값 20 대비 오차가 30% 감소하였다. 교차검증 RMSE는 LMP 0.248, 맥법칙형 오법 0.239로 대등하나 쌍곡사인 함수[9,10] 적용 시 0.141로 개선되었다(Fig. 1d~f). 900℃에서 2차 LMP 마스터커브는 $\sigma \approx 21 \text{ MPa}$ 에서 최대 나타나 예측 수명이 427 h로 제한되며, 900℃ 2점 검정 RMSE는 오법 0.171, LMP 0.670이었다.

Ω 는 621℃ 34~83, 704℃ 43~56, 900℃ 10~14로 감소해 파단연성의 역수처럼 거동하였다($\Omega \cdot \epsilon_f = 6.2 \pm 1.7$). 단면 감소만으로 기대되는 $\Omega_{\text{geom}} = n + 1$ 대비 $\Omega/\Omega_{\text{geom}}$ 이 3.9, 5.1, 2.1 이어서 900℃ 손상의 절반이 단면 감소에 기인하며 넥킹(Fig. 2e, f)과 일치한다.

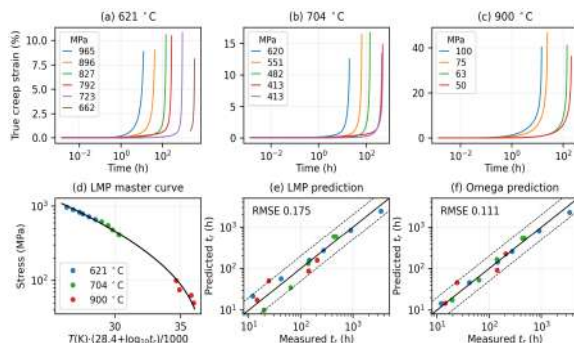


Fig. 1. (a~c) Creep curves; (d) LMP master curve; measured vs. predicted t_r by (e) LMP and (f) Omega.

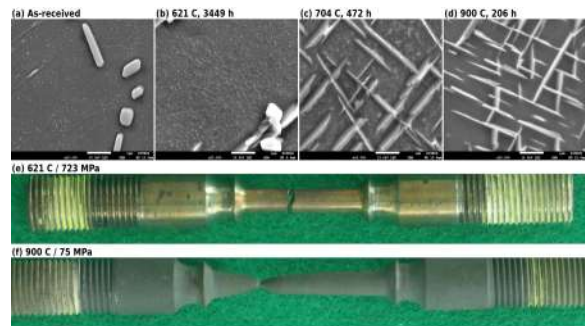


Fig. 2. SEM: (a) as-received, (b) 621 °C, (c) 704 °C, (d) 900 °C; ruptured specimens (e) 621 °C, (f) 900 °C.

4. 결론

(1) 응력지수 15.2 $\rightarrow$ 4.8의 감소는 γ'' 유지 $\rightarrow$ 판상 δ 조대화 $\rightarrow$ $\gamma'' \cdot \gamma'$ 완전 고용과 대응하였다. (2) LMP는 상수 C 를 최적화해야 하며($C = 28.4$) 관례값 20 고정 시 오차가 30% 증가한다. (3) 쌍곡사인 오법의 교차검증 RMSE는 0.141로 LMP(0.248)보다 우수하다. (4) 900℃에서 LMP는 원리적 한계를 갖는 반면 오법은 소수 데이터로도 안정적인다.

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확률론적 파괴 역학 코드 PROFAS-PIPE를 활용한 재료 열화 고려 CASS 배관 건전성 평가 연구

안동현*, 이봉상
한국원자력연구원 재료안전기술연구부
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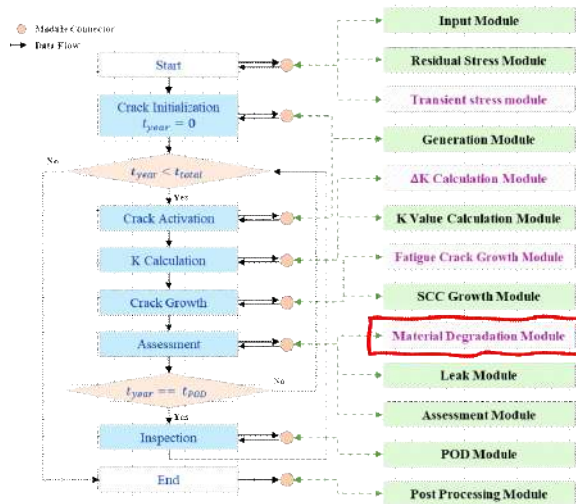
Assessment of Material Degradation Effects on CASS Piping Integrity Based on the
Probabilistic Fracture Mechanics Code PROFAS-PIPE

Dong-Hyun Ahn*, Bong-Sang Lee
Korea Atomic Energy Research Institute Materials Safety Technology Research
Division

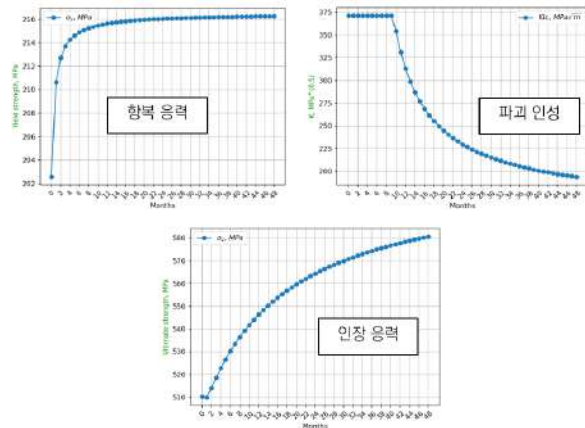
ABSTRACT

안전성이 최우선인 산업계에서는 구조물 건전성 평가 시 기존 결정론적 접근법의 과도한 보수성을 완화하고, 현실적인 평가를 통해 유지보수 비용을 최적화하기 위해 확률론적 파괴역학(PFM) 기반의 평가 연구가 활발히 진행되고 있다. PFM은 다양한 내부 불확실성 인자들이 구조물에 미치는 영향을 정량적인 파손 확률로 산출할 수 있다는 장점이 있다. 원자력 산업에서도 이러한 흐름에 맞춰 전산 기반의 평가 코드 개발이 이루어지고 있으며, 한국원자력연구원(KAERI)은 2010년부터 원자로 압력 용기(Reactor Pressure Vessel, RPV)와 배관 구조물(Piping) 평가를 위한 PROFAS(PRObabilistic Failure Analysis System) 코드 체계를 자체 구축해 왔다. 특히 관 구조물에 특화된 PROFAS-PIPE 코드는 2018년 개발 이래 International Atomic Energy Agency 주도 국제 공동연구(Coordinated Research Project)에 참여했으며, 현재 Electric Power Research Institute 주도 국제 공동 벤치마크에 참여하며 지속적인 고도화 및 검증을 진행 중이다. 한편, 원전 내부 배관에 널리 사용되는 CASS(Cast Austenitic Stainless Steel) 재료는 고온 환경에 장기 노출 시 인성 저하를 동반하는 열시효 취화(thermal aging embrittlement) 현상을 겪는다. 그러나 CASS 재료의 조대한 결정립 특성상 초음파 탐상 등의 기존 비파괴 측정(NDE) 방식이 제대로 적용되기 어려워, 정확한 균열 측정을 기반으로 하는 결정론적 건전성 평가를 적용하는 데에는 근본적인 한계가 존재한다. 따라서 본 연구는 이러한 측정의 불확실성에 따른 건전성 평가 제약을 극복하고자, PROFAS-PIPE 코드 내에 CASS 재료의 열화 특성을 반영한 새로운 모듈을 탑재하였다.

이를 통해 열시효에 따른 재료 거동 변화가 관 구조물의 파손 확률에 미치는 영향을 확률론적으로 평가하였으며, 본 연구 결과는 향후 초음파 검사 한계를 지닌 CASS 배관의 구조 건전성을 합리적으로 관리하고 수명 평가를 수행하기 위한 기술적 근거로 활용될 수 있을 것으로 기대한다.



<PROFAS-PIPE 코드 구성>



<열 취화에 따른 CASS 재료 물성 변화>

광학현미경 사진 기반 딥러닝을 이용한 단결정 초내열합금의 성장방향 예측

공병욱, 안상규, *서성문
(주)에이스이엔지, *재료연구원
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Construction of a Deep Learning Model for Clear Grain Boundary Detection and Assessment of Training Data Effectiveness

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ACE ENG Co, Changwon, 51392, Korea,
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ABSTRACT

Growth direction of single-crystal superalloys is usually measured by SEM-EBSD, which is costly and slow. This study tests whether optical microscopy images alone can predict the growth direction of single-crystal CMSX-4 specimens, using EBSD-measured directions (IPF coordinates theta1/theta2) as ground truth. CNN (EfficientNetB0/ResNet50, transfer learning) and texture (GLCM/Gabor) features were regressed with a GroupKFold-XGBoost stacking ensemble. The model reached a mean 3D angular error of about 3 degrees on test images, reproducible across five random seeds, showing optical images alone can estimate single-crystal growth direction.

1. 서론

CMSX-4와 같은 Ni기 단결정 초내열합금은 성장방향([001] 근방)이 크리프/피로 특성에 직접 영향을 미쳐 정확한 파악이 중요하다. 표준 방법인 SEM-EBSD는 장비 시간/비용 부담이 커서 다수 시편을 신속히 선별하기 어려운 반면, 절단면 광학현미경 사진(그림1)은 훨씬 저렴하고 빠르게 확보 가능하다. 본 연구는 딥러닝 기반 이미지 분석으로 광학현미경 사진만으로 단결정 성장방향을 예측할 수 있는지 확인하고, 예측 정확도를 실제 결정학적 의미를 갖는 3차원 방향각 오차로 평가하였다.

2. Data 전처리 및 학습 방법

- 단결정CMSX-4 초내열합금 절단면 광학현미경 사진 607장(그림1)과 SEM-EBSD IPF

를이용해 확보된 좌표(theta1,theta2) Data을 Label로 Data로 활용

- 학습 성능 향상을 위해 전처리 파라미터 후보(CLAHE/Bilateral/ Morphology /Threshold)를 RandomForest 대리모델 기반 GroupKFold 비교로 최적화 전처리 실시. EfficientNetB0(1320차원), ResNet50(2088차원) Transfer learning을 이용해 각 모델 별로 이미지 특징을 추출하고 각각 GLCM/Gabor 텍스처 특징(40차원)을 결합해 특징 중요도 기준 상위 150개로 차원 축소를 실시.
- 추출된 feature를 다양한 모델과 학습 parameter 최적화를 통해 모델을 theta1/theta2를 직접 회귀하고 방향 공간에서 집계한 후, 두 backbone을 스택킹 앙상블로 결합하여 3D 단위벡터 변환 방향각 오차 기준으로 최종 모델을 선정.

3. 결과 및 요약

- Direct 회귀+ 스택킹 앙상블 조합이 가장 우수했으며, Test set 평균3D 방향각 오차 약 3.0°(R2 0.94 내외)를 달성하였다.

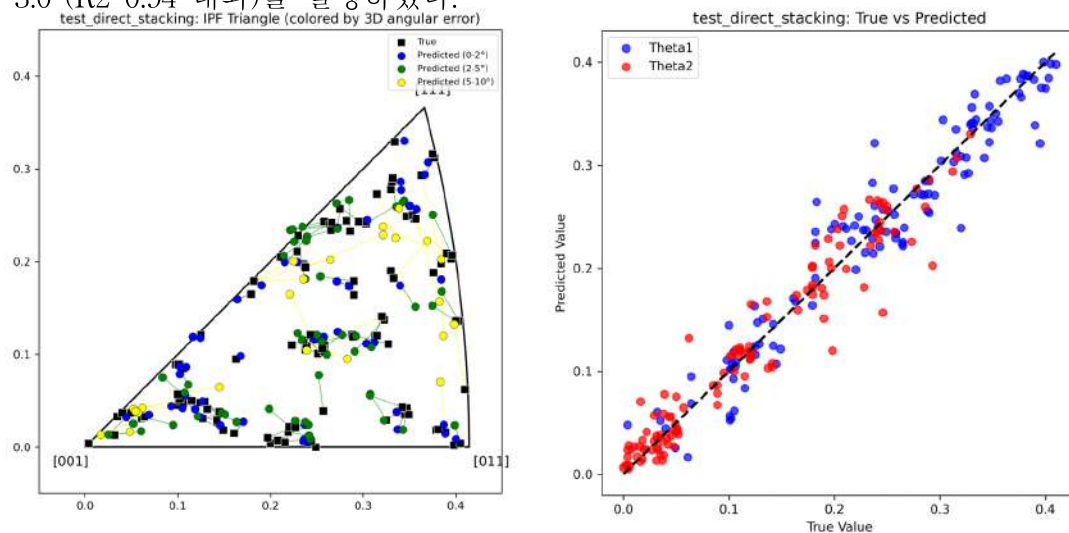


그림1. IPF 삼각형: 예측 성장방향(각도오차 색상) vs EBSD 실측 방향 비교(Test set)

- 본 결과는SEM-EBSD 없이 광학현미경 사진만으로 성장방향 추정이 가능함을 보여준다. 이 결과는 유사특성을 갖는 대부분의 초합금에도 적용 가능할 것으로 사료된다.

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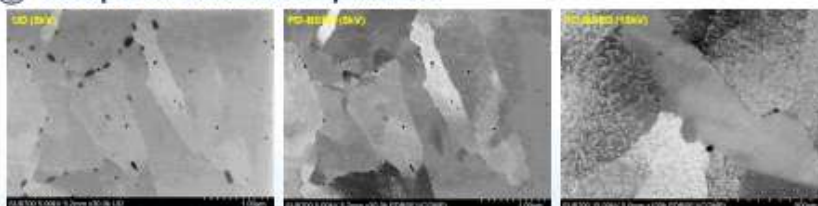
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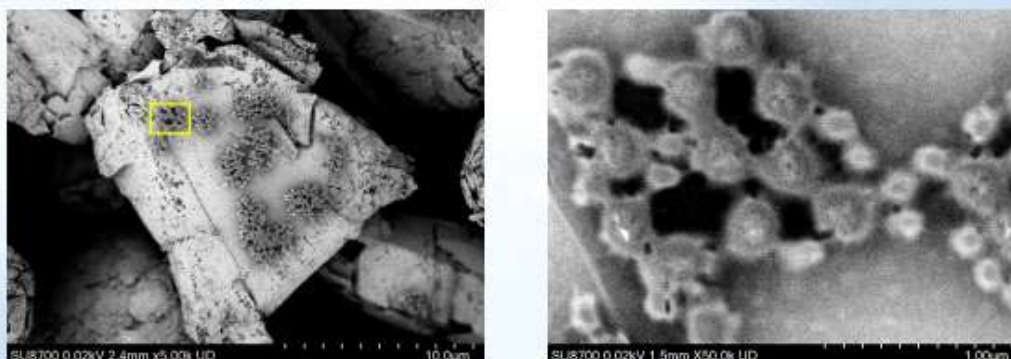


UD : SE signal, less channeling effect, enhancing precipitate distribution

PD-BSED : BSE signal, crystallographic information such as grain size, orientation and defect enhanced by channeling contrast



Ultra low-voltage application for battery materials



Specimen: Binder's distribution on cathode material's surface of Lithium-ion battery (LIB). Courtesy of Hajime Okui, DAINEN MATERIAL Co., Ltd.

It shows the SEM images of binder residues adhering on the lithium-ion battery anode active material surface using a normal optical system at the accelerating voltage of 20 V without applying the sample bias. If the accelerating voltage were set to a several hundred volts, topographic features of the sample disappeared due to the charge-up effect, and morphology of the binder would be difficult to see. However, by decreasing the accelerating voltage to 20 V as shown in image (left), the binder was shown clearly. Image (right), enlarged from the yellow frame in image.

Dual monitors with 6-signal simultaneous display



Multi-Channel image can be displayed on the screen. 2, 4 or 6 signals including the chamber scope or SEM MAP image can be displayed imultaneously on a single monitor. (left)

The dual-monitor configuration supports enhanced productivity plus expanded workspace and allows the operation panel to be customized with submenus positioned anywhere on either screen. (right)





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영 · 장 · 분 ·리 · 목 · 록 (명) : 필드시험
영 · 장 · 유효 · 기 · 간 : 2023년 08월 04일

본 기 기구별 평가결과가합일 제23호, 제24호에 따라 본 기 인정 범위를 다음과 같이 하고, 2023. 11.25. 2023. 12. 31. 2024. 1. 31. 2024. 2. 29. 2024. 3. 31. 2024. 4. 30. 2024. 5. 31. 2024. 6. 30. 2024. 7. 31. 2024. 8. 31. 2024. 9. 30. 2024. 10. 31. 2024. 11. 30. 2024. 12. 31. 2025. 1. 31. 2025. 2. 29. 2025. 3. 31. 2025. 4. 30. 2025. 5. 31. 2025. 6. 30. 2025. 7. 31. 2025. 8. 31. 2025. 9. 30. 2025. 10. 31. 2025. 11. 30. 2025. 12. 31. 2026. 1. 31. 2026. 2. 29. 2026. 3. 31. 2026. 4. 30. 2026. 5. 31. 2026. 6. 30. 2026. 7. 31. 2026. 8. 31. 2026. 9. 30. 2026. 10. 31. 2026. 11. 30. 2026. 12. 31. 2027. 1. 31. 2027. 2. 29. 2027. 3. 31. 2027. 4. 30. 2027. 5. 31. 2027. 6. 30. 2027. 7. 31. 2027. 8. 31. 2027. 9. 30. 2027. 10. 31. 2027. 11. 30. 2027. 12. 31. 2028. 1. 31. 2028. 2. 29. 2028. 3. 31. 2028. 4. 30. 2028. 5. 31. 2028. 6. 30. 2028. 7. 31. 2028. 8. 31. 2028. 9. 30. 2028. 10. 31. 2028. 11. 30. 2028. 12. 31. 2029. 1. 31. 2029. 2. 29. 2029. 3. 31. 2029. 4. 30. 2029. 5. 31. 2029. 6. 30. 2029. 7. 31. 2029. 8. 31. 2029. 9. 30. 2029. 10. 31. 2029. 11. 30. 2029. 12. 31. 2030. 1. 31. 2030. 2. 29. 2030. 3. 31. 2030. 4. 30. 2030. 5. 31. 2030. 6. 30. 2030. 7. 31. 2030. 8. 31. 2030. 9. 30. 2030. 10. 31. 2030. 11. 30. 2030. 12. 31. 2031. 1. 31. 2031. 2. 29. 2031. 3. 31. 2031. 4. 30. 2031. 5. 31. 2031. 6. 30. 2031. 7. 31. 2031. 8. 31. 2031. 9. 30. 2031. 10. 31. 2031. 11. 30. 2031. 12. 31. 2032. 1. 31. 2032. 2. 29. 2032. 3. 31. 2032. 4. 30. 2032. 5. 31. 2032. 6. 30. 2032. 7. 31. 2032. 8. 31. 2032. 9. 30. 2032. 10. 31. 2032. 11. 30. 2032. 12. 31. 2033. 1. 31. 2033. 2. 29. 2033. 3. 31. 2033. 4. 30. 2033. 5. 31. 2033. 6. 30. 2033. 7. 31. 2033. 8. 31. 2033. 9. 30. 2033. 10. 31. 2033. 11. 30. 2033. 12. 31. 2034. 1. 31. 2034. 2. 29. 2034. 3. 31. 2034. 4. 30. 2034. 5. 31. 2034. 6. 30. 2034. 7. 31. 2034. 8. 31. 2034. 9. 30. 2034. 10. 31. 2034. 11. 30. 2034. 12. 31. 2035. 1. 31. 2035. 2. 29. 2035. 3. 31. 2035. 4. 30. 2035. 5. 31. 2035. 6. 30. 2035. 7. 31. 2035. 8. 31. 2035. 9. 30. 2035. 10. 31. 2035. 11. 30. 2035. 12. 31. 2036. 1. 31. 2036. 2. 29. 2036. 3. 31. 2036. 4. 30. 2036. 5. 31. 2036. 6. 30. 2036. 7. 31. 2036. 8. 31. 2036. 9. 30. 2036. 10. 31. 2036. 11. 30. 2036. 12. 31. 2037. 1. 31. 2037. 2. 29. 2037. 3. 31. 2037. 4. 30. 2037. 5. 31. 2037. 6. 30. 2037. 7. 31. 2037. 8. 31. 2037. 9. 30. 2037. 10. 31. 2037. 11. 30. 2037. 12. 31. 2038. 1. 31. 2038. 2. 29. 2038. 3. 31. 2038. 4. 30. 2038. 5. 31. 2038. 6. 30. 2038. 7. 31. 2038. 8. 31. 2038. 9. 30. 2038. 10. 31. 2038. 11. 30. 2038. 12. 31. 2039. 1. 31. 2039. 2. 29. 2039. 3. 31. 2039. 4. 30. 2039. 5. 31. 2039. 6. 30. 2039. 7. 31. 2039. 8. 31. 2039. 9. 30. 2039. 10. 31. 2039. 11. 30. 2039. 12. 31. 2040. 1. 31. 2040. 2. 29. 2040. 3. 31. 2040. 4. 30. 2040. 5. 31. 2040. 6. 30. 2040. 7. 31. 2040. 8. 31. 2040. 9. 30. 2040. 10. 31. 2040. 11. 30. 2040. 12. 31. 2041. 1. 31. 2041. 2. 29. 2041. 3. 31. 2041. 4. 30. 2041. 5. 31. 2041. 6. 30. 2041. 7. 31. 2041. 8. 31. 2041. 9. 30. 2041. 10. 31. 2041. 11. 30. 2041. 12. 31. 2042. 1. 31. 2042. 2. 29. 2042. 3. 31. 2042. 4. 30. 2042. 5. 31. 2042. 6. 30. 2042. 7. 31. 2042. 8. 31. 2042. 9. 30. 2042. 10. 31. 2042. 11. 30. 2042. 12. 31. 2043. 1. 31. 2043. 2. 29. 2043. 3. 31. 2043. 4. 30. 2043. 5. 31. 2043. 6. 30. 2043. 7. 31. 2043. 8. 31. 2043. 9. 30. 2043. 10. 31. 2043. 11. 30. 2043. 12. 31. 2044. 1. 31. 2044. 2. 29. 2044. 3. 31. 2044. 4. 30. 2044. 5. 31. 2044. 6. 30. 2044. 7. 31. 2044. 8. 31. 2044. 9. 30. 2044. 10. 31. 2044. 11. 30. 2044. 12. 31. 2045. 1. 31. 2045. 2. 29. 2045. 3. 31. 2045. 4. 30. 2045. 5. 31. 2045. 6. 30. 2045. 7. 31. 2045. 8. 31. 2045. 9. 30. 2045. 10. 31. 2045. 11. 30. 2045. 12. 31. 2046. 1. 31. 2046. 2. 29. 2046. 3. 31. 2046. 4. 30. 2046. 5. 31. 2046. 6. 30. 2046. 7. 31. 2046. 8. 31. 2046. 9. 30

Tensile test specimen (room temp./high temp.)	High/low cycle fatigue (HCF/LCF) test specimen
Creep test specimen	Fatigue Crack Growth Rate (FCGR) test specimen
Microstructure specimen	Thermomechanical fatigue (TMF) test specimen
Electrode Resistance specimen	Specific heat specimen
Thermal expansion coefficient specimen	Modulus of elasticity specimen
Heat conduction specimen	Density specimen

인장시험기

- 상온인장
- 고온인장

크립시험기

- Creep 시험
- Stress Rupture시험

피로시험기

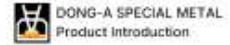
- HCF
- LCF
- FCGR
- TMF

분석시험

- 미세조직 분석
- 매크로에칭 분석
- 화학 분석

E. aceask0530@naver.com

자원 순환을 이끄는 특수금속 & 첨단합금 글로벌 리더



[한국특수금속은 특수금속 재활용화 기술을 기반으로 제강용 원료와 특수합금 소재를 생산·공급하는 소재 전문기업입니다.
타이타늄 잉곳, 봉재, 선재 및 정밀주조품을 생산하며, 글로벌 시장에 고품질 소재를 공급하고 있습니다.]

01 제강용 원료



타이타늄 스펀지 대체품
(Titanium Cobble)

- Easy to Use
- Superior to TG-100/90 Sponge
- Cost-Effective
- No Fire Risk - No Fines - No Dust



페로타이타늄
(Ferro-Titanium)

- Size : (Bulk)5.0~50.0 mm
(Powder for Cored Wire)0~1.7 mm / 0~2.0 mm
- Production Capacity : 300 MT/month
- Cost-Effective / Deoxidizer



피드스톡
(FeedStocks)

- Custom Size
- Easy to Use
- ASTM Compliant, 100% Inspection
- Processed by Sorting, Cutting & Shot Blasting

주요 적용 산업



Aerospace



Defense

02 소재 및 가공제품



잉곳 (Ingot)

- Ti Base
Ø230 × 2,800 mm, 130~500 kg
- Ni Base
Ø230 × 2,800 mm, 180~740 kg
- Co/Ni Base
Ø230 × 3,000 mm, 230~950 kg



봉재 (Round Bar)

- Available Alloys
Inconel 625, Inconel 718, F75
- Applications
Aerospace, Power Generation, Medical



CCAW
(Copper Clad Aluminum Wire)

- Cu 15% (10% & 20% Available)
- Ø2.05~5.19 mm
- Up to 60% Lighter
- Up to 50% Lower Cost
- ~250% Longer Length
- ASTM B566 Compliant



선재 (Wire rod)

- Alloy Grades
- Invar
- Ultra-High-Strength Invar
- Inconel 625
- Inconel 718
- F75 (Cobalt Chrome)

INVAR Fe 64% + Ni 36% 합금, 온도 변화에 따른 길이 변화가 거의 없는 초저열팽창 합금.

일반 인바 와이어 (Invar)

- Tensile Strength : 620~720 MPa
- Used in Precision Instruments
- Ultra-Low Thermal Expansion Alloy
- Used in Optical & Aerospace Components

초고강도 인바 와이어 (Invar-X)

- Tensile Strength : 1,250~1,300 MPa
- Used in HTLS Conductors
- Extremely Low CTE
- Used in Aerospace & Space Cable Systems

Power & Energy



가공송전선용 중용량 케이블



극저온 케이블용 부품



초전도 케이블 자열팽창 보강재



항공우주 케이블

Aerospace



위성 안테나 전개 와이어



극저온 정밀 스프링 로드

두산에너지빌리티

소형모듈원전

수소터빈

HELLO [CLEAN] TOMORROW

우리가 만드는 건

기술의 혁신을 담은, 깨끗하고 풍요로운 내일입니다.

두산은 수소터빈, 해상풍력, 소형모듈원전(SMR)으로
더 청정하고 안정적인 에너지를 공급합니다.

에너지의 한계가 없는 내일, 두산이 만들어 갑니다.

DOOSAN

해상풍력

조성 입력만으로 필요한 물성을 바로 예측합니다!

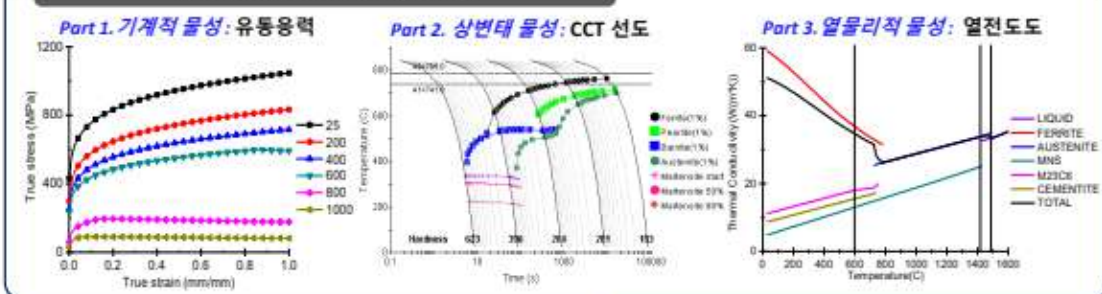
다양한 합금계의 기계적, 열물리적, 상변태 물성을 빠르게 계산하세요.



STEP 1. 조성입력 → STEP 2. 필요한 계산 항목 선택 → STEP 3. 조건 입력 및 계산



다양한 물성 계산 (예시)



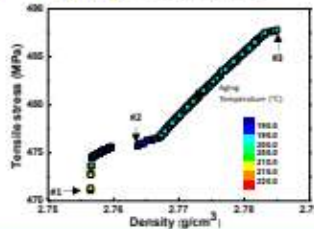
MPO (Material Properties Optimizer)

사용자가 목표하는 물성을 만족하는 최적의 조성 및 공정조건(열처리)을 제안합니다.

STEP 1. 조성 및 조건 입력 → STEP 2. 계산 및 탐색 → STEP 3. 최적화된 조건 제안

[Al-Cu-Mg계 구조용 합금 설계 예시]

- ✓ 합금 설계 목적 : 강도 최대 & 저밀도
- ✓ 시효 온도 조건 (°C) : 160 < 온도 < 220
- ✓ 시효 시간 (h) : 0.5 < 시간 < 8
- ✓ 조성 변경 원소 : Cu, Mg, Mn



No	온도 (°C)	시간 (h)	인장 강도 (MPa)	밀도 (g/cm³)
1	220.0	0.5	471.1	2.76
2	192.7	7.8	475.7	2.76
3	195.6	8.0	487.8	2.78
...	...	...	...	...
273	195.2	7.9	485.9	2.78

최적화 조성

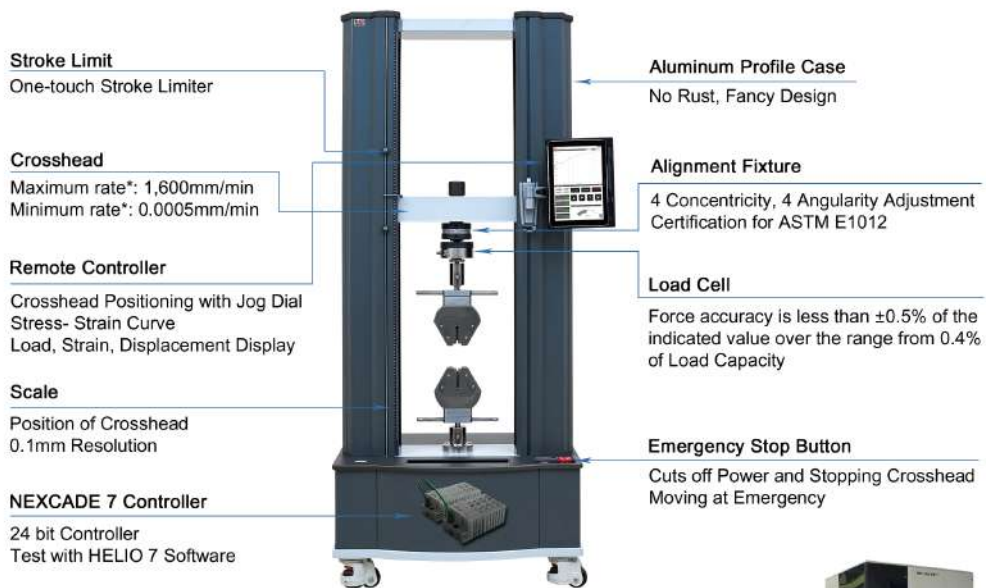
#2 : Al-4.13Cu-1.75Mg- 0.30Mn





재료시험기, 마모시험기, Full Accessories 등 개발 및 생산

RB301 Universal Testing Machine



Metallography 장비 및 소모품

Cutting 부터 Polishing 까지 전 공정 제품
다양한 제품군



(주)알앤비

(34029) 113-6, Techno jungang-ro, Yuseong-gu, Daejeon, Korea Tel: 82-42-935-0490 Fax: 82-42-935-0496
E-mail: webmaster@randb.co.kr Home page: www.randb.co.kr Shop : www.shop.randb.co.kr

Meet New Generation of

Metal Additive Manufacturing

DED Multi-material Technology from Research to Industry

Business Area



System Line-up

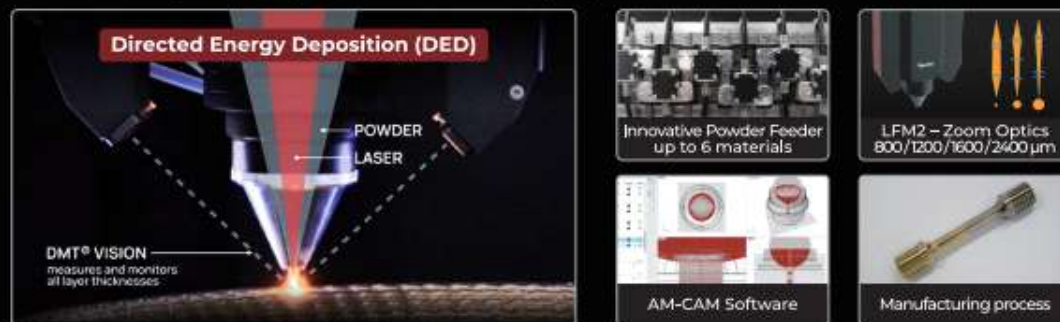
Systems with optimized shapes and features for each application



* Providing system customization with optimized features for each industry and customer needs.

Core Technologies

Core technologies developed in-house for industry-optimized & efficient features





ElectroPuls® All Electric Dynamic Test Systems

With more than ten years of running tests over billions of cycles, ElectroPuls systems are the established materials testing machines using patented linear motor technology. With model capacities up to 20 kN, ElectroPuls systems offer slow-speed static testing and high-frequency dynamic fatigue testing with hundreds of hertz capability.



Dynamic Linear Force Capacity	±N	1,000		3,000		10,000		20,000
Torque Capacity	±Nm	-		*25		*100		*130
Linear Stroke	mm	60		60		60		75
Torsional Rotation		-		*±135° as standard, user configurable to ±16 revolutions		*±135° as standard, user configurable to ±16 revolutions		*±135° as standard, user configurable to ±16 revolutions

* Note: The spec with (*) in front is for Linear-Torsion



No Oil



Low Energy



Low Noise



Small Footprint



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광고_코나솔

광고_(주)프론틱스

사업영역

Value Creation

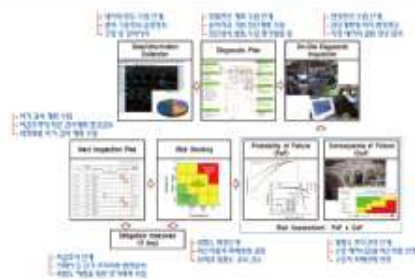
(주)피레타는 에너지 및 항공분야 주요 설비의 건전성 및 수명평가, 실시간 온라인 감시/관제시스템 구축, 초내열합금등 신소재 개발에 필요한 다양한 특성 DB 구축을 주 사업분야로 삼고있는 One Stop Total Consulting 회사입니다.



에너지, 항공분야

건전성 평가 및 수명 평가

국가 핵심설비의 상시 운용과 안정성 보장을 위해 핵심 설비에 대한 특수 비파괴 검사 및 건전성 평가



IoT, AI 활용

온라인 모니터링 시스템 개발

취약설비의 상시 감시를 위한 광섬유/AE센서 활용, 온라인 인공지능 예지진단 시스템(PHM)



고온 금속재료

특성시험 및 평가, DB구축

가속열화시험, 고온인장시험, 피로시험 크리프시험, 기계적 열적 피로(TMFP)시험

